# The China-in-Global Energy Model

Tianyu Qi, Niven Winchester, Da Zhang,
Xiliang Zhang and Valerie J. Karplus

MIT JOINT PROGRAM
SCIENCE
POLICY
GLOBAL CHANGE

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY of GLOBAL CHANGE

TSINGHUA - MIT
China Energy & Climate Project

Report No. 262
May 2014

The MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the 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 one of a series 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,
*Program Co-Directors*

**For more information, contact the Program office:**
MIT Joint Program on the Science and Policy of Global Change

**Postal Address:**
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139 (USA)

**Location:**
Building E19, Room 411
400 Main Street, Cambridge

**Access:**
Tel: (617) 253-7492
Fax: (617) 253-9845
Email: ***globalchange@mit.edu***
Website: ***http://globalchange.mit.edu/***

# The China-in-Global Energy Model

Tianyu Qi[§†*], Niven Winchester[§], Da Zhang[§†], Xiliang Zhang[†] and Valerie J. Karplus[§]

## Abstract

*The China-in-Global Energy Model (C-GEM) is a global Computable General Equilibrium (CGE) model that captures the interaction of production, consumption and trade among multiple global regions and sectors – including five energy-intensive sectors – to analyze global energy demand, $CO_2$ emissions, and economic activity. The C-GEM model supplies a research platform to analyze China's climate policy and its global implications, and is one of the major output and analysis tools developed by the China Energy and Climate Project (CECP) – a cooperative project between the Tsinghua University Institute of Energy, Environment, and Economy and the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change. This report serves as technical documentation to describe the C-GEM model. We provide detailed information on the model structure, underlying database, key parameters and its calibration, and important assumptions about the model. We also provide model results for the reference scenario and a sensitivity analysis for two key parameters: autonomous energy efficiency improvements (AEEI) and the elasticity of substitution between energy and value added.*

## Contents



[*] Corresponding author: Tianyu Qi, E-mail: apollo110110@gmail.com. Institute of Energy, Environment

[§] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room E19-411, Cambridge, MA, USA.

[†] Institute of Energy, Environment and Economy, Tsinghua University, Beijing, China.

## 1. INTRODUCTION

The China-in-Global Energy Model (C-GEM) is a multi-regional, multi-sector, recursive-dynamic, computable general equilibrium (CGE) model of the global economy. The model is one of the primary analysis tools developed by the China Energy and Climate Project (CECP), a cooperative effort of the Tsinghua Institute of Energy, Environment, and Economy and the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change. The primary goal of the model is to simulate existing and proposed energy and climate polices in China in order to analyze their impact on technology, inter-fuel competition, the environment, and the economy within a global context.

China has recently become the world's largest energy consumer and source of greenhouse gas emissions. Given the scale of China's economy and energy system, its energy trends and climate policies will have a significant impact on global climate change mitigation; the C-GEM is a new tool to predict and study the global implications of this economic growth and energy use. The structure of the C-GEM is similar to other recursive dynamic global CGE models, such as the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005); however, the C-GEM differs from comparable models in that it utilizes a combination of China's official data and the eighth release of the Global Trade Analysis Project (GTAP) data (Narayanan *et al.*, 2012). The model also includes a detailed representation of energy-intensive sectors in all global regions, and provides China-specific estimates for the cost of advanced technologies.

This report provides a detailed description of the C-GEM model, and will proceed as follows. In Section 2, we describe the theoretical basis and structure of the C-GEM model, as well as the construction of the underlying database. We describe the static core of the C-GEM model in Section 3, and dynamic extensions in Section 4. In Section 5 we describe the treatment of advanced technologies. Section 6 contains the model's reference projection and the impact of two important sources of uncertainty—the rate of autonomous energy efficiency improvement (AEEI) and elasticity of substitution between energy and value added. We conclude the report with a summary of our work in Section 7.

## 2. MODEL STRUCTURE AND DATA

The C-GEM is a CGE model with supplemental accounting for energy and emissions quantities. Its basic structure is derived from the Walrasian general equilibrium theory formalized by Arrow and Debreu (Arrow and Debreu, 1954; Sue Wing, 2004). A key advantage of CGE frameworks is their ability to capture policy impacts across interlinked sectors of the economy, including commodity and factor market interactions and bilateral trade relationships. CGE models are well-established tools used to undertake quantitative analysis of the economic impacts of energy and environmental policies (Paltsev *et al.*, 2005; Rausch *et al.*, 2010).

CGE models simulate the circular flow of goods and services in the economy within and between each world region, as shown in **Figure 1**.

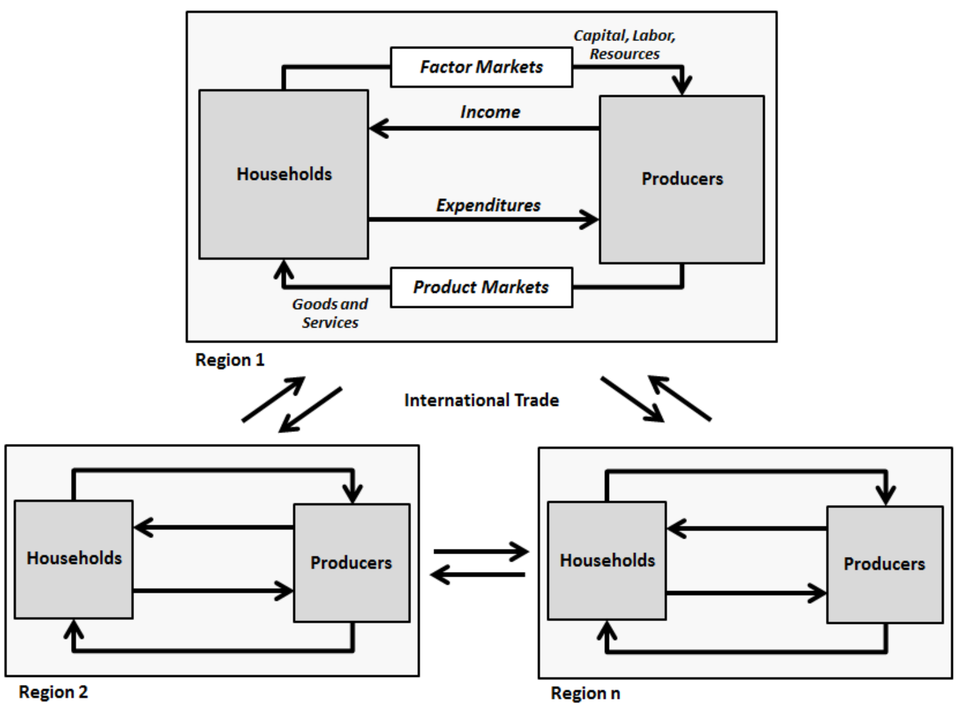


**Figure 1.** Economy-wide circular flow of goods and services in the C-GEM.

The arrows in Figure 1 connecting the regions show the flow of goods and services between pairs of regional economies. Firms (producers) purchase factor inputs (such as labor, capital and land) from factor markets, and intermediate goods and services from product markets, then use them to produce final goods and services. Consumers (households) sell their labor, capital, and other endowments in the factor markets to obtain income, and purchase producers' final goods and services from the product markets. Producers maximize profits from given input costs, and consumers maximize utility while satisfying a budget constraint. Relative prices adjust endogenously to maintain equilibrium across product and factor markets.

Households allocate income to private consumption and savings. The saving rate is exogenously set and fixed in each time period in the recursive-dynamic framework. Households in the C-GEM are assumed to be homogenous, so that one representative household in each region owns all the factors of production and receives all factor payments. Taxes, collected by governments, are imposed on most transactions as specified in the benchmark year data. The government in the C-GEM is modeled as a passive entity that collects tax revenue and recycles the money in a lump sum to each household as a supplement to their income from factor returns (Sue Wing, 2004). The expenditure of the government in each region is fully funded by households.

International trade links the various regions; products from one region can be exported to the rest of the world, and imported goods can enter domestic product markets following the Armington assumption (Armington, 1969). However, in the C-GEM, international trade is limited to the product market; factors such as labor and capital endowments are not mobile across regions. The international capital flows that account for the trade imbalance between regional pairs in the base year are assumed to be reduced to zero in a linear fashion through 2050.

### 2.1 Model Regions

The C-GEM disaggregates the world into 19 geographic regions, as shown in **Table 1** and **Figure 2**.

We aggregate the C-GEM regions on the basis of economic structural similarities, membership in trade blocks, and geographical relationships. According to the definitions used by the International Monetary Fund (IMF, 2012), regional aggregates can be separated into two distinct groups: developed economies and developing economies. The major developed economies (United States, Canada, Japan, European Union and Australia-New Zealand) and major developing countries (China, India, South Africa, Russia and Brazil), as well as major oil suppliers (primarily the Middle East region) are explicitly represented. In the C-GEM, we further disaggregate the major economies around China into individual regions (e.g., South Korea, Developed Asia and Southeast Asia’s developing countries).

**Table 1.** Definition of geographic regions in the C-GEM.

| **Regions in the C-GEM** | **Countries in region** |
|---|---|
| *Developed Economies* | |
| United States (USA) | United States of America |
| Canada (CAN) | Canada |
| Japan (JPN) | Japan |
| South Korea (KOR) | South Korea |
| Developed Asia (DEA) | Hong Kong, Taiwan, Singapore |
| Europe Union (EUR) | Includes EU-27 plus countries in the European Free Trade Area (Switzerland, Norway, Iceland) |
| Australia-New Zealand (ANZ) | Australia, New Zealand, and other territories (Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories) |
| *Developing Economies* | |
| China (CHN) | Mainland China |
| India (IND) | India |
| Developing South-East Asia (SEA) | Indonesia, Malaysia, Philippines, Thailand, Vietnam, Cambodia, Laos, Southeast Asian countries not elsewhere classified |
| Rest of Asia (ROA) | Bangladesh, Sri Lanka, Pakistan, Mongolia and Asian countries not classified elsewhere |
| Mexico (MEX) | Mexico |
| Middle East (MES) | Iran, United Arab Emirates, Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia |
| South Africa (ZAF) | South Africa |
| Rest of Africa (AFR) | African countries not elsewhere classified |
| Russia (RUS) | Russia |
| Rest of Eurasia (ROE) | Albania, Croatia, Belarus, Ukraine, Armenia, Azerbaijan, Georgia, Turkey, Kazakhstan, Kyrgyzstan，European countries not classified elsewhere |
| Brazil (BRA) | Brazil |
| Latin America (LAM) | Latin American countries not classified elsewhere |

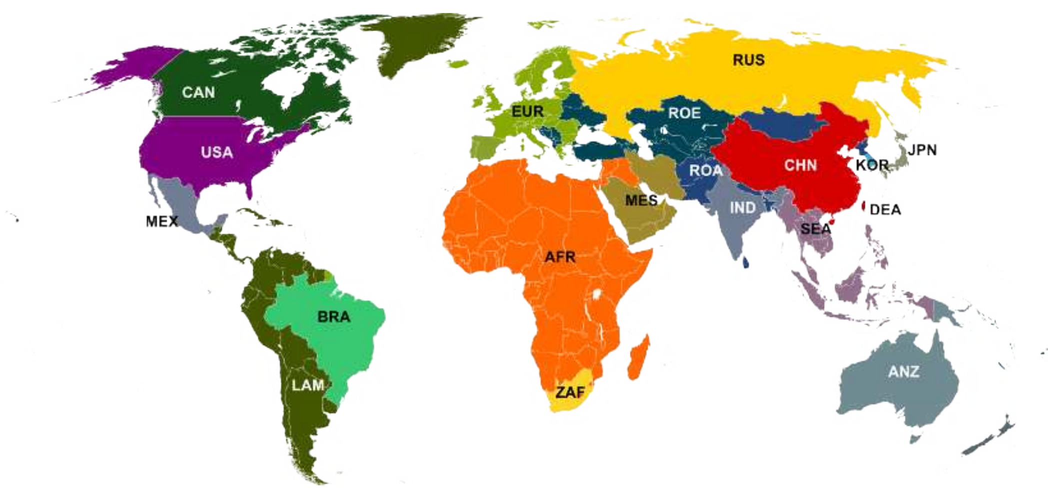


**Figure 2.** A map of regions represented in the C-GEM.

### 2.2 Model Sectors

Production within each region is comprised of 20 industry sectors, shown in **Table 2**. This aggregation includes a variety of energy production sectors and energy-intensive industries. Among other sectors, five energy production sectors (coal, crude oil, natural gas, refined oil and electricity), and five energy-intensive sectors (non-metallic mineral products, iron and steel, non-ferrous metals products, chemical rubber products and fabricated metal products) are described in detail below.

**Table 2.** Descriptions of the 20 industry sectors in the C-GEM.

| Type | Sector | Description |
|---|---|---|
| Agriculture | Crops (CROP) | Food and non-food crops produced on managed cropland |
| | Forest (FORS) | Managed forest land and logging activities |
| | Livestock (LIVE) | Animal husbandry and animal products |
| Energy | Coal (COAL) | Mining and agglomeration of hard coal, lignite and peat |
| | Oil (OIL) | Extraction of petroleum |
| | Gas (GAS) | Extraction of natural gas |
| | Petroleum (ROIL) | Refined oil and petro chemistry products |
| | Electricity (ELEC) | Electricity and heat generation, transmission and distribution |
| Energy-Intensive Industry | Non-Metallic Minerals Products (NMM) | Cement, plaster, lime, gravel and concrete |
| | Iron & Steel (I&S) | Manufacture and casting of iron and steel |
| | Non-Ferrous Metals Products (NFM) | Production and casting of copper, aluminum, zinc, lead, gold and silver |
| | Chemical Rubber Products (CRP) | Basic chemicals, other chemical products, rubber and plastics |
| | Fabricated Metal Products (FMP) | Sheet metal products (except machinery and equipment) |
| Other Production | Food & Tobacco (FOOD) | Manufacture of food products and tobacco |
| | Mining (MINE) | Mining of metal ores, uranium, gems and other mining/quarrying |
| | Construction (CNS) | Construction of houses, factories, offices and roads |
| | Equipment (EQUT) | Machinery and equipment, including electronic equipment |
| | Other Industries (OTHR) | Other industries |
| Services | Transportation Services (TRAN) | Pipeline transport, and water, air and land transport (passenger and freight) |
| | Other Services (SERV) | Communication, finance, public services, dwellings and other services |

### 2.3 Strengths and Weaknesses of the CGE Approach

The growing application of CGE models has drawn ever more attention to their strengths and weaknesses. CGE models offer a theoretically consistent framework that relies on transparent assumptions and calibration to observed data. CGE models also permit quantitative assessment of general equilibrium effects, which is essential for analyzing climate policies that broadly affect relative energy costs. However, CGE models abstract from the level of technology-specific detail that is represented in bottom-up models. These limitations make CGE models useful for comparative statics and directional effects, but CGE model outputs cannot be reliably interpreted as forecasts of future events. Additionally, results from CGE models can be heavily dependent on assigned elasticities of substitution between inputs in production and utility functions; as such, it is prudent to implement sensitivity analyses around key elasticity parameters.

### 2.4 Model Data Processing

As a multi-regional CGE model, the C-GEM is parameterized and calibrated based on a balanced social accounting matrix (SAM) for each region. A SAM is an array of input-output accounts that quantifies the flow of goods and services in a benchmark period (Sue Wing, 2004). The C-GEM functions based on both the Global Trade Analysis Project database (GTAP) (Narayanan *et al.*, 2012) and China's official economy and energy dataset. The C-GEM is formulated and solved as a mixed complementarity problem using MPSGE, the Mathematical Programming Subsystem for General Equilibrium (Mathiesen, 1985; Rutherford, 1995, 1999) and the Generalized Algebraic Modeling System (GAMS) mathematical modeling language (Rosenthal, 2012) with the PATH solver (Dirkse and Ferris, 1995). The C-GEM tracks the physical flows of carbon-based fuels and resources in the economy through time, as well as associated emissions of carbon dioxide ($CO_2$). Non-$CO_2$ greenhouse gases are not currently represented.

#### *2.4.1 GTAP Dataset*

The C-GEM employs Version 8 of the GTAP dataset (GTAP 8). GTAP 8 is a global database that integrates national accounts of production and consumption (in the form of input-output tables) together with bilateral trade flows for industry sectors and geographic regions in 2007 (Narayanan *et al.*, 2012). The volume of energy consumption and bilateral trade in 2007 are also represented in GTAP 8. Energy volume data in GTAP are mainly sourced from the International Energy Agency's *Extended Energy Balances* dataset (McDougall and Lee, 2006).

In developing the C-GEM, we incorporate the GTAP 8 dataset with GAMS using a modified version of GTAPinGAMS, originally developed by Rutherford and Paltsev (Rutherford, 2010).[1] GTAPinGAMS allows a flexible aggregation of sectors and regions upon the 57 sectors and 129 regions included in the database; we employ this function to aggregate the GTAP 8 database into the 20 sectors and 19 regions described in Section 2.1.

---

[1] The GTAP database is bundled with a model coded using the General Equilibrium Modeling PACKage (GEMPACK) software (Harrison & Pearson, 1996), but the database is also used with models written using other software.

### *2.4.2 China Dataset*

In the C-GEM, we replace the GTAP 8 economic and energy data for China with data from official domestic data sources in China. We source economic data from China's 2007 national input-output table, which provides balanced benchmark accounts for value added, intermediate inputs, and final consumption for 135 industry sectors (National Bureau of Statistics of China, 2009). These 135 sectors can be mapped to the sectoral aggregation in the C-GEM, with the exception of the oil and natural gas sectors, which are combined into one sector in China's national statistics. As the individual representation of oil and natural gas is important for energy policy assessment, we have separated oil and natural gas into two sectors according to their value shares in the GTAP 8 database. We then map the resulting 136 sectors to the 20 C-GEM sectors.

We source energy volume data from China's 2007 Energy Balance Table and China's Industry Energy Consumption Table (National Bureau of Statistics of China, 2008). These tables contain detailed information on intermediate and final energy consumption for 39 industrial sectors as well as for households in 2007. The energy balance tables also cover most of the sectors in the C-GEM except transportation, which is grouped with "Storage, Postal, & Telecommunications Services." We isolate the energy quantities in the transportation sector in proportion to corresponding energy quantity shares in the GTAP 8 database. To keep energy values and volume data consistent with China's official statistics, we calibrate them using energy price information from the 2008 Price Year Book of China (China Price Year Book Press, 2009). In the process of merging the GTAP and China domestic data sources, to avoid adjusting trade balances in other regions, we hold fixed the GTAP 8 values for China's energy and economic bilateral trade.

Once China's national data is used to replace the GTAP 8 data for China, it is no longer balanced. Thus we rebalance the revised dataset by adopting a least-squares method as described in Rutherford (2010), with the following formulae applied for each region *r*.

$$\min_{vfm,vifm,vdfm} \sum_i \Big[\sum_f vfm_{f,i,r}\Big(\frac{vfm_{f,i,r}}{\overline{vfm}_{f,i,r}}-1\Big)^2 + weight_{i,g,r}\sum_g \Big(vdfm_{i,g,r}\Big(\frac{vdfm_{i,g,r}}{\overline{vdfm}_{i,g,r}}-1\Big)^2 + vifm_{i,g,r}\Big(\frac{vifm_{i,g,r}}{\overline{vifm}_{i,g,r}}-1\Big)^2\Big)\Big] \tag{1}$$

$$\text{s.t.}\quad \begin{array}{l}\Big(\sum_g vdfm_{i,g,r} + \overline{vxm}_{i,r}\Big)(1-\overline{rto}_{i,r}) = \sum_j vdfm_{j,i,r}(1+\overline{rtfd}_{j,i,r}) + \\ \sum_j vifm_{j,i,r}(1+\overline{rtfi}_{j,i,r}) + \sum_f vfm_{f,i,r}(1+\overline{rtf}_{f,i,r})\end{array}\text{, for each } i$$

$$\sum_g vifm_{i,g,r} = \overline{vim}_{i,r}\text{, for each } i$$

Overlined values are parameters (initial variable values), and others are variables adjusted in the balancing routine. $vfm_{f,i,r}$ is factor *f* input in sector *i* (alias set: *j*), region *r*. $weight_{i,g,r}$ is the weight used to control the deviation of variable from its initial value (items related to energy production and energy use are set to be 100, others are 1; this procedure aims to minimize the deviation of values in the energy sector given that these quantities in China's national statistics are viewed as more reliable). $vdfm_{i,g,r}$ is the domestic intermediate input from sector *i* to sector/activity *g, where g* is the union set of all *i* sectors and all activities including private consumption, government consumption and investment.

For each region *r*: $vifm_{i,g,r}$ is the imported intermediate input from sector *i* to sector/activity *g*; $\overline{vxm}_{i,r}$ and $\overline{vim}_{i,r}$ are, respectively, the total volumes of exports and imports for sector *i*; $\overline{rto}_{i,r}$ is the output tax of sector *i;* $\overline{rtfd}_{j,i,r}$ and $\overline{rtfi}_{j,i,r}$ are consumption taxes on domestic/imported intermediate goods applied, respectively, to goods produced in sector *j,* and goods used in sector *i*; $\overline{rtf}_{f,i,r}$ is the value-added tax on factor *f* used in sector *i*.

The objective function is optimized subject to market clearance and zero-profit conditions for each region. When applying this optimization routine, the input-output data balanced for each region and bilateral trade values produce a database with equilibrium in all markets. The balanced global economic and energy database forms the basis for the SAM tables that represent the energy and economic value flows for regions in the C-GEM.

## 3. THE STATIC MODEL

This section describes in detail the static core of the C-GEM. The static model captures a snapshot of the relationships of producers, consumers, government and international bilateral trade within the economy. These relationships are updated in each time period, as described in the next section. This section describes the base year (2007) model parameterization.

### 3.1 Mathematical Formulation of a CGE Model

The C-GEM is set up and solved as a mixed complementarity problem in which the equilibrium conditions are comprised of a system of weak inequalities and complementary slackness conditions (between equilibrium variables and equilibrium conditions) (Böhringer *et al.*, 2003; Paltsev *et al.*, 2005).

#### *3.1.1 Producer Behavior*

In each region *r*, the representative producer in sector *i* chooses a level of output $y_{r,i}$, values of primary factors $k_{r,fi}$, and an intermediate input $x_{r,ji}$ in order to maximize profit, subject to the characteristics of the production function $\varphi_{r,i}$, which describes the structure of currently available production technologies in sector *i*. The function of the producer's decisions can be expressed as:

$$\begin{aligned} &\max \pi_{r,i} = p_{r,i} y_{r,i} - C_{r,i}(p_{r,j}, w_{r,f}, y_{r,i}) \\ &s.t. \quad y_{r,i} = \varphi_{r,i}(x_{r,ji}, k_{r,fi}) \end{aligned} \tag{2}$$

Where $\pi_{r,i}$ is profit, $C_{r,i}$ represents the cost function for sector $i$ in region $r$, $p_{r,i}$ is the price of good $i$, and $w_{r,f}$ is the price of factor $f$.

Constant elasticity of substitution (CES) functional forms are used to model the cost function. CES functions are frequently used to model production and consumption in CGE models. The constant return to scale (CRS) assumption of the CES function simplifies the production optimizing problem described in Equation 2. From Shepard's Lemma, the demand functions for intermediate inputs $x_{r,ji}$ (Equation 3) and factor inputs $k_{r,fi}$ (Equation 4) for production sector $i$ are given as follows:

$$x_{r,ji} = y_{r,i} \frac{\partial c_{r,i}}{\partial p_{r,j}} \tag{3}$$

$$k_{r,fi} = y_{r,i} \frac{\partial c_{r,i}}{\partial w_{r,f}} \tag{4}$$

A broader discussion and detailed derivation of a CES function can be found in Pauw (2003) and Klump *et al.* (2011).

### *3.1.2 Consumer Behavior*

As described in Section 1.2, the representative agent is endowed with natural resources, labor and capital supply in region $r$. Representative agents choose different consumption goods to maximize their welfare ($W_{r,i}$) given their level of income ($M_{r,i}$).

$$\begin{aligned} &\max W_{r,i}(d_{r,i}) \\ &s.t. \quad M_{r,i} = \sum_i p_{r,i} d_{r,i} \end{aligned} \tag{5}$$

Where $W_{r,i}$ is a utility function with a CES form. Similar to production, consumption demand for goods $d_{r,i}$ is derived as follows:

$$d_{r,i} = m_r \frac{\partial E_r(p_{r,1}, p_{r,2}, \ldots, p_{r,i})}{\partial p_{r,i}} \tag{6}$$

Where $E_r\,(p_{r,1}, p_{r,2}, \ldots, p_{r,i})$ is the unit expenditure function given $p_{r,i}$, the price of good $i$.

### *3.1.3 Modeling Equilibrium*

Three classes of equations define the equilibrium in perfectly competitive markets (an assumption that can be relaxed in specific applications). A model solution must satisfy several conditions: zero profit, where the price of output reflects the cost of inputs;

market clearance, where supply equals demand; and income balance, where the income of an agent is equal to its expenditure.[2] Detailed formulations of these conditions can be found in Rutherford (2010).

## 3.2 Structure of Production Sectors

### *3.2.1 Primary Fossil Fuel Energy Sectors*

Primary fossil fuel energy sectors are coal, crude oil and natural gas. The nested structure of production in the C-GEM is shown in **Figure 3**, where $\sigma$ is used to denote the elasticity of substitution among inputs in a given nest. At the top of the nest, natural resources combine with non-resource inputs. In the sub-level of the non-resources input, there is a Leontief combination of non-energy intermediate inputs and a capital-labor-energy (KLE) bundle, which is comprised of a CES structure between energy and a value-added bundle. Capital and labor are combined using the Cobb-Douglas form of the CES function. The energy input bundle is further divided into a CES substitution between electricity and the fossil fuels bundle (coal, crude oil, refined oil and natural gas).

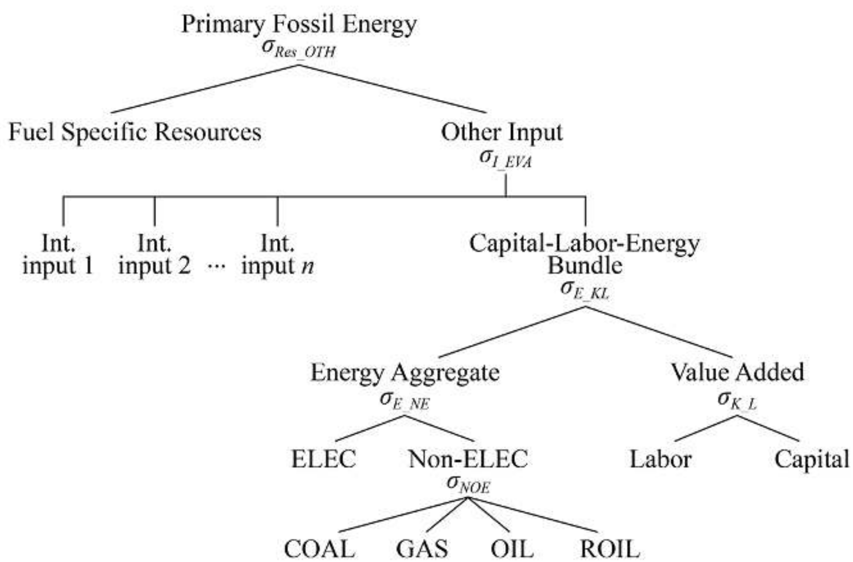


**Figure 3.** The structure of primary fossil energy sectors in the C-GEM.

### *3.2.2 Refined Oil Sector*

Refined oil is modeled differently from the other energy sectors. Unlike the primary fossil fuel sectors, the refined oil sector uses crude oil from the oil sector as a raw material for production. Given the lack of substitutes for crude oil in the refining process, oil enters as a Leontief intermediate input to the refined oil sector, as shown in **Figure 4**.

---

[2] In some circumstances the zero profit and market clearance conditions will not hold. Specifically, if unit costs are greater than the price, the commodity in question will not be produced, and if supply is greater than demand, the price of the associated good or factor will be zero.

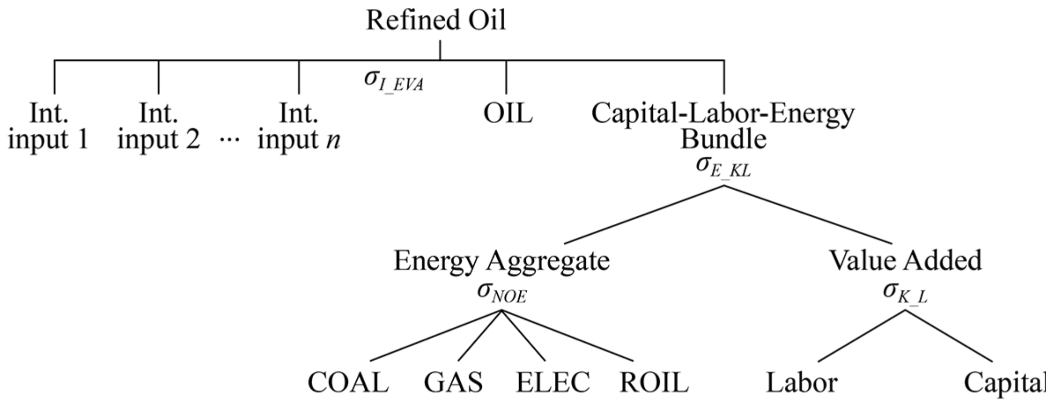


**Figure 4.** The structure of the refined oil sector in the C-GEM.

### *3.2.3 Electricity Sector*

The structure of the electricity sector is shown in **Figure 5**. The top two nests permit substitution among various generation technologies. Twelve types of power generation technologies are represented in the base version of C-GEM (as listed in **Table 3**). Five are existing technologies that produce at a large scale in the base year. Seven are advanced electricity generation technologies that do not operate at large scale or do not yet exist in the base year, but become available in later years, beginning production when their relative cost falls below the levelized cost of incumbent generation types.[3] The structure of these advanced technologies will be discussed in detail in the following sections.

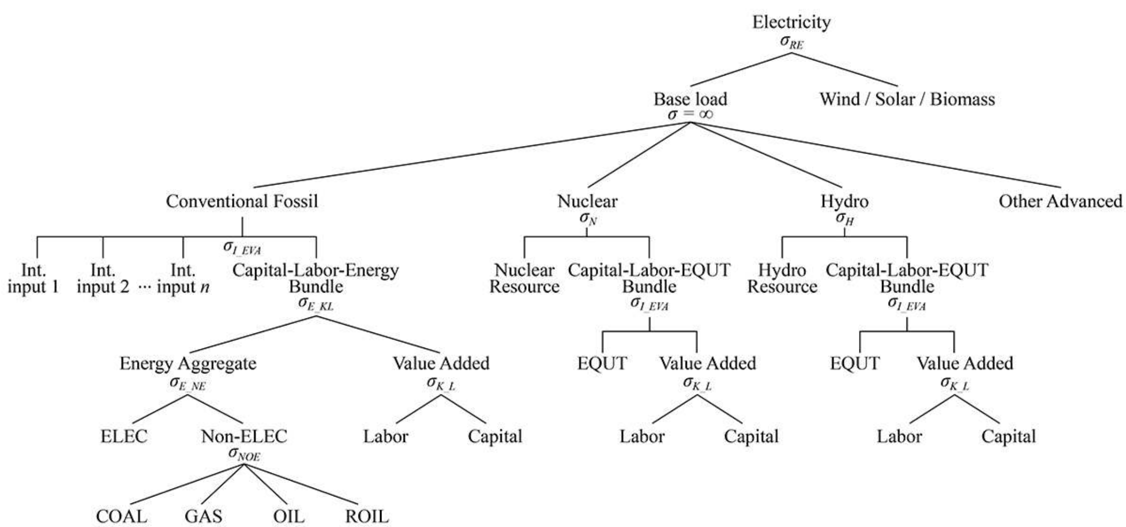


**Figure 5.** The structure of the electricity sector in the C-GEM.

[3] Advanced technologies that operate in the base year (e.g., wind electricity) are included in the input-output component of our database. Production activities specified for advanced technologies capture expansion of these technologies beyond those observed in the base year.

**Table 3.** Electricity technologies in the C-GEM.

| Existing Technologies | Advanced Technologies |
|---|---|
| • Coal<br>• Refined oil<br>• Gas<br>• Nuclear<br>• Hydro | • Wind<br>• Solar<br>• Biomass<br>• Natural Gas Combined Cycle (NGCC)<br>• Integrated Gasification Combined Cycle (IGCC)<br>• Natural Gas Combined Cycle with Carbon capture and storage (NGCC-CCS)<br>• Integrated Gasification Combined Cycle with Carbon capture and storage (IGCC-CCS) |

With the exception of wind, solar and biomass electricity, we treat advanced electric power generation technologies as perfect substitutes for existing technologies as shown in the second level of the nested structure in Figure 5. We capture transition costs associated with scaling up each technology, which fall with an increase in their share of total generation. Reflecting the variability of wind, solar and biomass generation, electricity from these sources is treated as an imperfect substitute for electricity from other sources. Production structures for advanced technologies are detailed in Section 5.

Conventional power generation consists of a Leontief combination of non-energy intermediate inputs and an energy-capital-labor bundle. Fossil fuels such as coal, oil and gas are included as imperfect substitutes for each other to avoid one fuel from taking over the market once its relative cost falls below that of its competitors.

We use supplementary information to describe hydro and nuclear power options within the structure of the C-GEM electricity sector. We parameterize these technologies using information from reports by the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA) and the International Energy Agency (IEA) (IAEA, 2008; OECD/NEA, 2010). The structure of the nuclear and hydro CES functions is simplified to focus on fuel resources, capital, labor and equipment as inputs to production.

#### *3.2.4 Energy-Intensive Sectors*

The model also represents five energy-intensive industry sectors: non-metallic mineral products; iron and steel; non-ferrous metal products; chemical, rubber and plastic products; and fabricated metal products. These sectors each have a common CES structure that includes a Leontief combination of non-energy intermediate inputs and the energy and capital-labor bundle (shown in **Figure 6**). A key feature of this production structure is the ability of producers to substitute among different energy sources and between aggregate energy and the capital-labor bundle.

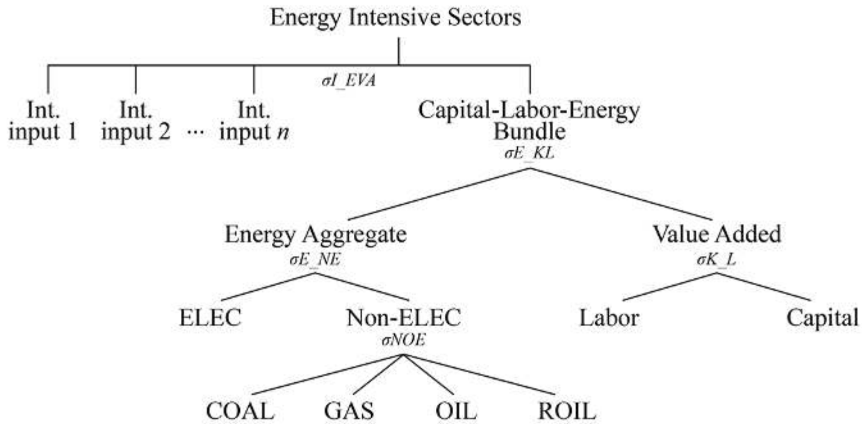


**Figure 6.** The structure of energy-intensive sectors in the C-GEM.

### *3.2.5 Agricultural Sector*

The agricultural sector follows a similar CES structure, and includes land in the production of agricultural output. As shown in **Figure 7**, the labor-capital bundle is located at the top level of the nest and trades off with the other-input bundle, which is made up of land and intermediate inputs. As the land input is crucial in agriculture, this structure provides flexibility in representing substitution between land and other inputs (e.g., machinery and fertilizer) following the approach of previous studies (Babiker *et al.*, 2001; Paltsev *et al.*, 2005).

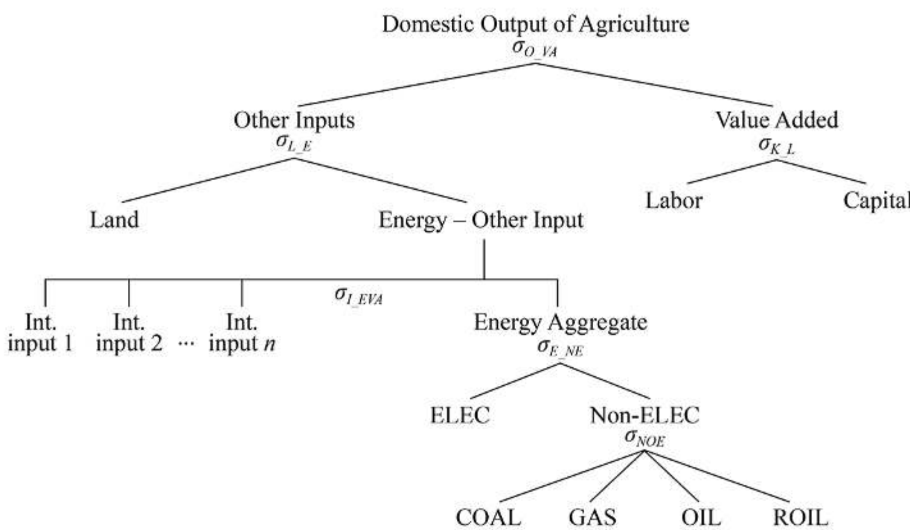


**Figure 7.** The structure of the agricultural sector in the C-GEM.

### *3.2.6 Other Production and Services*

The structure of the mining, food production, equipment, other industry and services sectors share the structure shown in **Figure 8**. Natural resources, mainly mineral resources, are a dedicated input to the mining sector. The elasticities employed in the production and utility functions are mainly adopted from the MIT EPPA model (Babiker *et al.*, 2001) and are reported in **Table 4**.

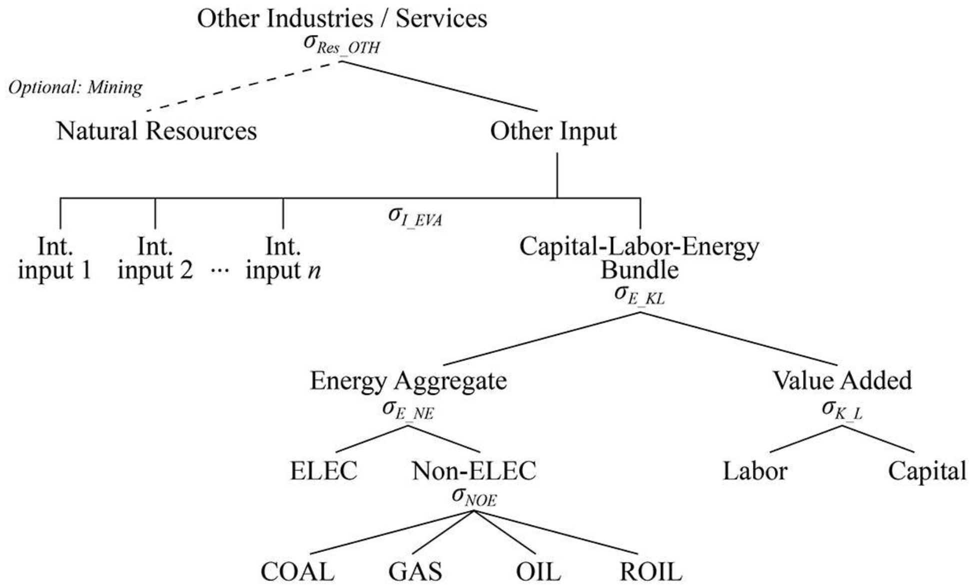


**Figure 8.** The structure of other industry and services sectors in the C-GEM model.

**Table 4.** Elasticities used in the C-GEM model, based on Babiker *et al.* (2001).

| | **Description** | **Value** | **Remarks** |
|---|---|---|---|
| *Production* | | | |
| $\sigma_{Res\_OTH}$ | Resources and other inputs | 0.6-0.7 | 0.6 for oil and gas; 0.7 for coal |
| $\sigma_{I\_EVA}$ | Intermediate input and Energy-Capital-Labor bundle | 0 | Applied in all sectors |
| $\sigma_{E\_KL}$ | Energy and Value-added bundle | 0.1-0.5 | 0.1 for electricity; 0.3 for agriculture; 0.4 for energy industry; 0.5 for other industry |
| $\sigma_{E\_NE}$ | Electricity and Non-electricity input bundle | 0.5 | Applied in all sectors |
| $\sigma_{NOE}$ | Among non-electricity energy input | 0.1-0.5 | Different values applied across sectors |
| $\sigma_{K\_L}$ | Capital and Labor | 1 | Applied in all sectors |
| $\sigma_{RE}$ | Wind & Solar and other electricity technologies | 1 | Applied in the electricity sector |
| $\sigma_{O\_VA}$ | Value-added and other input | 0.7 | Applied in the agriculture sector |
| *Consumption* | | | |
| $\sigma_{CS}$ | Consumption and savings | 1 | Applied in all regions |
| $\sigma_{CE}$ | Commodities and energy consumption | 0.25-0.5 | Different values applied across time periods |
| $\sigma_{CT}$ | Transportation and other goods | 0.5 | Applied in all regions |
| $\sigma_{c}$ | Among non-energy goods | 0.3-0.6 | Different values applied across regions and time periods |
| $\sigma_{E}$ | Among energy goods | 0.5 | Applied in all regions |
| $\sigma_{TRN}$ | Among public and private transportation | 0.5 | Applied in all regions |
| $\sigma_{R\_O}$ | Among fuels and other inputs | 1 | Applied in all regions |
| $\sigma_{E\_S}$ | Equipment and service inputs | 1 | Applied in all regions |
| *Trade* | | | |
| $\sigma_{DM}$ | Armington elasticity between domestic and import goods | 1-3 | 1 for electricity; 3 for other commodities |
| $\sigma_{MM}$ | Armington elasticity of import goods among regions | 0.5-6 | 0.5 for electricity; 6 for other commodities |

### 3.3 Household Consumption

Household consumption in the C-GEM is represented as shown in **Figure 9**. We use consumption, excluding savings, as a consistent measure for welfare accounting.[4] In the consumption bundle, we have separated private transportation from other goods and services, as it accounts for a large share of direct energy use by the household in many regions. Private transportation refers to transportation services supplied to the household through the purchase and operation of passenger vehicles. Inputs to the private transportation sector draw from the other industry (e.g., vehicle purchases), services (e.g., maintenance and repairs), and refined oil sectors. Purchased transportation – which is supplied by the transportation industry and includes both short- and long-distance road, air, rail, and marine modes – is included as a substitute for private vehicle transportation.

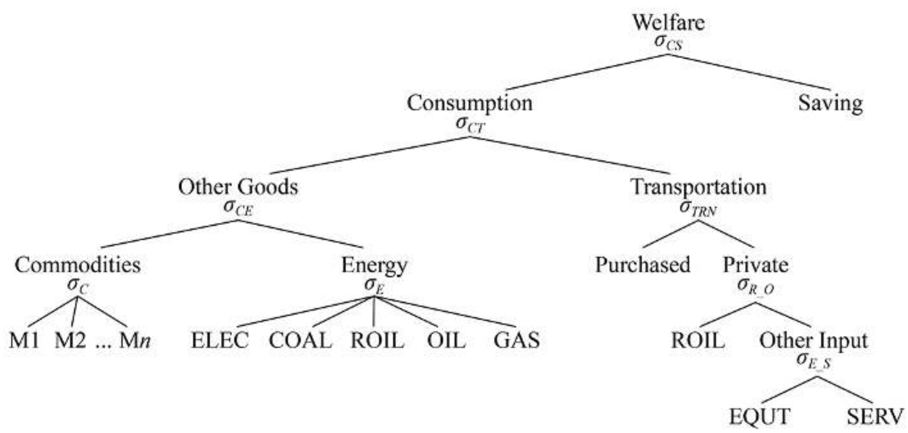


**Figure 9.** The structure of the household consumption function in the C-GEM.

### 3.4 Structure of International Trade

Production and consumption in each region in the C-GEM is linked through bilateral trade. Capturing these links allows the model to forecast how policy impacts propagate across regions. Trade flows in all goods, including energy products, are explicitly represented in the GTAP bilateral trade flow data sets for the base year 2007. All the other goods except crude oil are treated as Armington goods (Armington, 1969). Crude oil in the C-GEM is modeled as homogeneous good with a single global price, following its treatment in the MIT EPPA model (Paltsev *et al.*, 2005). The Armington CES structure is shown in **Figure 10**. The top level nest captures the tradeoff between domestic and imported goods, including imported goods that are comprised of imports from different regions. Bilateral trade flows, which include export taxes, import tariffs,

---

[4] We use consumption measured as equivalent variation in constant 2007 USD as a measure of welfare. We prefer to measure welfare using only consumption rather than income, as including savings in welfare calculations results in double counting of the impact through the savings channel (i.e., under an income measure of welfare, the impact of a change in savings would be counted in the current period and, through changes in investment and ultimately the capital stock, in future periods).

and international transport costs, are provided by the GTAP 8 data set and are represented in the C-GEM.

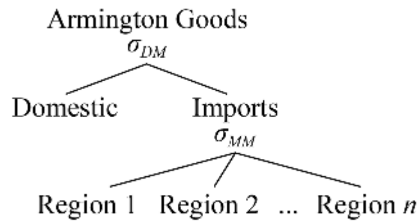


**Figure 10.** The Armington structure for imported goods in the C-GEM.

### 3.5 Government and Investment

As discussed in Section 1, the government in the C-GEM is modeled as a passive entity that collects tax revenue on intermediate inputs, outputs, and consumer expenditure and transfers it to the household as a lump-sum payment. Government expenditure is assumed to be part of final consumption and is fully funded by households. Government consumption decisions maximize utility subject to revenues available. Government consumption in the C-GEM adopts the same nested CES structure as household consumption.

Investment in the C-GEM is represented by a sector that produces an aggregate investment good using inputs from different sectors which sums to the level of aggregate investment. Investment becomes available as new capital in the next period and drives economic growth.

### 3.6 Emissions

In the C-GEM, $CO_2$ emissions are computed by applying constant emission factors to the fossil fuel energy flows of coal, refined oil and natural gas based on the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).[5] The emission factors are assumed to remain constant across regions and over time. Energy-related $CO_2$ emissions enter into a Leontief structure with fuel, implying that the reduction of emissions in production sectors can only be achieved with reductions in fuel use. In the current version of the C-GEM, only fossil-fuel-related $CO_2$ emissions are projected. However, the model framework could be readily extended to account for other non-$CO_2$ greenhouse gases including methane ($CH_4$), nitrous oxide ($N_2O$), perfluorocarbons (PFCs), hydrofluorocarbons (HFC) and sulfur hexafluoride ($SF_6$); other pollution gases such as sulfur dioxide ($SO_2$), carbon monoxide (CO) and nitrogen oxide ($NO_X$); and non-energy related emissions of $CO_2$.

[5] This inventory specifies that tons of $CO_2$ per exajoule (EJ) are 94.6 for coal, 73.3 for oil, and 56.1 for natural gas.

## 4. THE DYNAMIC MODEL

The static foundation of C-GEM was used to develop a recursive-dynamic model that allows assessment of energy markets and policy impacts through 2050. By solving the model in each period sequentially and then updating parameter values in the next period to reflect dynamic trends, a recursive-dynamic model assumes that economic agents make decisions based on information available in the current period only (Dellink, 2005). The dynamic process of the C-GEM is mainly driven by labor supply growth, capital accumulation, fossil fuel resource depletion, structural change in consumption, and the availability of new technologies. Here, we discuss each of these attributes.

### 4.1 Labor Supply and Productivity Growth

Labor supply in the C-GEM is driven by changes in the population and labor productivity in each region over time. For region *r* and time *t*, the supply of labor $L_{r,t}$ is scaled from its base-year value $L_{r,0}$ using both the population growth rate and the labor productivity growth rate $LPGR_{r,t}$.

$$L_{r,t} = L_{r,0} \times \frac{pop_{r,t}}{pop_{r,0}} \prod_{t} (1 + LPGR_{r,t}) \tag{7}$$

The population (*pop*) of each region in the C-GEM is specified as an exogenous long-term trend based on United Nations data (United Nations, 2012). In all regions except China, for region *r* and period *t* the labor productivity growth rate $LPGR_{r,t}$ is estimated using the historical GDP growth rate and future GDP projections from the IMF (IMF, 2012). For China's labor productivity growth rate, we calibrate the 2010 value at 11%, which is comparable with recent studies (Chansomphou and Ichihashi, 2013; Kang and Peng, 2013), using the 2010 GDP growth rate. We assume China's labor productivity growth rate is converging to 2.5%, choosing a functional form that allows current rates to move towards the target rate by 7% each year. The convergence speed is higher than the traditional 2% rate (Sala-i-Martin, 1996), as some recent review studies suggest that less developed countries like China are converging much faster than the 2% rate commonly specified (Abreu *et al.*, 2005; Chansomphou and Ichihashi, 2013).

### 4.2 Capital Accumulation

The evolution of capital over time in the C-GEM includes both old capital carried over from the previous period and new capital from investment, which is described as follows:

$$Capital_{r,t} = (1 - \delta_{r,t})^{ti} Capital_{r,t-1} + I_{r,t\text{-}1} \tag{8}$$

Where $\delta_{r,t}$ is the depreciation rate in region *r*, *ti* is the time interval (5 years in the C-GEM) and $I_{r,t-1}$ is new investment capital, which is equal to savings and is determined by total national income and the savings rate. In all countries except China, we assume the depreciation rate remains at 5% over time; we also assume China's depreciation rate is linearly converging from about 12% in 2010 (Bai *et al.*, 2006) to 6%. We calibrate the initial capital stock following Bai *et al.* (2006) and adopt the saving rate convergence path similar to that recommended in OECD *et al.* (2013), which falls from 48% in 2010 to 43% in 2020, 36% in 2030, 30% in 2040, and then remains constant through 2050.

### 4.3 Natural Resource Supply

All fossil fuel resources in the C-GEM are modeled as scarce resources subject to Hotelling valuation (Hotelling, 1931) in which unit production costs rise as resources are depleted. Natural resources enter at the top level of the production structure as described in Section 3.2, and trade off with a capital-labor-materials bundle. This substitution reflects the need for more capital and other inputs to recover additional fossil fuel resource as stocks are depleted.

The depletion module is formulated as follows. Energy resources $R$ in sector $e$ are subject to depletion over time based on the physical production of fuel $F$ in the previous period. Available energy resources $R_{e,r,t}$ in period $t$ in region $r$ can be expressed as

$$R_{e,r,t} = R_{e,r,t-1} - Ti \times F_{e,r,t-1} \tag{9}$$

This specification is designed to capture resource price evolution over an extended term. Short term, resource prices are influenced by many other factors, such as supply disruptions or shortages of refining capacity and are not modeled in the C-GEM.

### 4.4 Energy-Saving Technological Change

Observations of historical energy consumption, energy prices, and income growth in industrialized economies have exhibited a trend of energy efficiency improvement even when energy prices are constant or falling. Two possible explanations have been given for this trend: first, that productivity changes result in less energy use, and second, that rising incomes are accompanied by structural changes in the economy that reduce energy-intensive activities (Schmalensee *et al.*, 1998; Webster *et al.*, 2008). Many top-down energy and climate models adopt Autonomous Energy Efficiency Improvement (AEEI) parameters to project exogenous improvements in energy per unit of output by sector (Cao and Ho, 2009). The choice of these parameters can lead to significant differences in the estimated costs of mitigation (IPCC, 2001). Estimation of AEEI is usually conducted based on historical rates of energy-intensity changes or data from bottom-up models. An AEEI annual growth rate of 1% is commonly selected (Sue Wing and Eckaus, 2007). Other studies estimate values ranging from 0.4% to 1.5% (Manne and Richels, 1992).

The C-GEM differentiates AEEI values among different regions based on available literature estimates. For the developed regions, we adopt the 1% rate, as this value is mainly calibrated using data from developed regions (Grübler, 2003). For developing regions except China, a value of 1.5% is adopted, representing the expectation for these regions to have greater scope to raise energy efficiency (relative to developed regions). Cao and Ho (2009) suggest that a value of 1.7% will best reflect China's current status.

The actual path of energy use per unit of output depends on energy prices and price-dependent adjustments. We explore the implications of alternative values for AEEI growth rates in Section 6.

## 5. NEW TECHNOLOGIES

The C-GEM includes a suite of advanced backstop technology variables to allow analysis of the potential impact of energy supply technologies that are not yet commercial, and may enter the economy if and when they become cost-competitive with existing technologies (William, 1979). The cost of each new technology depends on the equilibrium price of all inputs, which are endogenously determined within the CGE framework.

**Table 5.** New backstop technologies in the C-GEM.

| | Technology | Description |
|---|---|---|
| *Perfect fossil energy substitutes* | Shale oil | Extracts and produces crude oil from oil shale |
| | Biofuel | Converts biomass into refined oil |
| | Coal gasification | Converts coal into a perfect substitute for natural gas |
| *Perfect fossil electricity substitutes* | IGCC | Produces electricity from coal using integrated gasification combined cycle (IGCC) technology |
| | IGCC-CCS | Produces electricity from coal using IGCC technology with carbon capture and storage |
| | NGCC | Produces electricity from natural gas using natural gas combined cycle (NGCC) technology |
| | NGCC-CCS | Produces electricity from natural gas using NGCC technology with carbon capture and storage |
| | Advanced nuclear | Generates electricity from nuclear energy beyond existing installed plants |
| *Imperfect fossil electricity substitutes* | Wind | Produces electricity from wind energy |
| | Solar | Produces electricity from solar energy |
| | Biomass electricity | Produces electricity from biomass energy |

We represent 11 classes of advanced technologies in the C-GEM as shown in **Table 5**. Three technologies produce perfect substitutes for conventional fossil fuels: shale oil, for crude oil; biomass, for refined oil; and coal gasification, for natural gas. Eight are electricity generation technologies: IGCC, IGCC with CCS, NGCC, NGCC with CCS, and advanced nuclear, which produce perfect substitutes for conventional fossil electricity output; and wind, solar and biomass, which are treated as imperfect substitutes for other sources of electricity due to their intermittency.

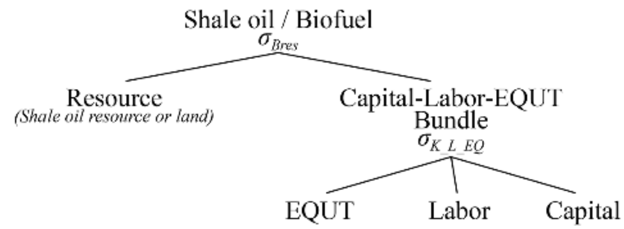


**Figure 11.** The structure for shale oil and biofuel production.

Although all are described with CES production functions, new technologies for oil, gas, and electricity are modeled separately with different structures in the C-GEM. For shale oil and biofuel, the CES production structure is shown in **Figure 11**. In this structure, the resources for shale are estimated oil shale reserves. Land – the main resource input to biofuel production – is subject to competition between biofuel and agricultural production for its use as an input. Both shale oil and biofuel production require capital, labor, and equipment inputs. For shale oil, $CO_2$ emissions from the extraction process are estimated to be 20% of the carbon content of total oil production (Paltsev *et al.*, 2005), and are entered as a Leontief input at the top of the CES layer (not shown).

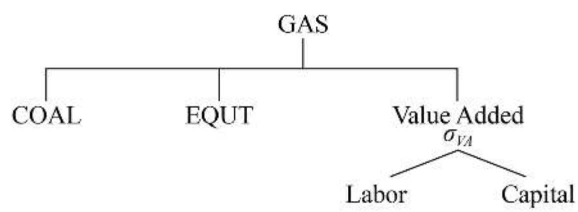


**Figure 12.** The structure for coal gasification production.

The CES production structure for the coal gasification technology is shown in **Figure 12**. Coal, equipment, and a value-added bundle enter as a Leontief structure at the top level of the production structure.

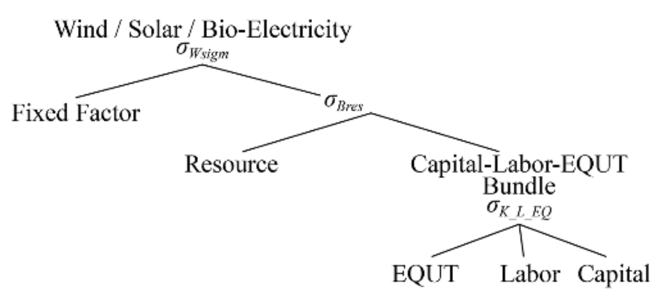


**Figure 13.** The production structure for wind, solar, and biomass electricity.

Wind, solar and biomass electricity have similar production structures (shown in **Figure 13**). A fixed factor is introduced in the top level of CES layers to control the penetration of the technologies as described in McFarland *et al.* (2004). Like biofuel, bio-electricity also requires land as a resource input and competes with the agricultural sector for this resource. Other inputs, including labor, capital, and equipment are intermediate inputs, similar to the case of shale oil and biofuel.

Advanced fossil-fuel generation technologies with CCS (IGCC-CCS or NGCC-CCS) share a similar production structure to that shown in **Figure 14**. In this CES nested structure, we describe the cost of electricity transmission and storage separate from that of electricity generation and capture. This separate representation allows for greater flexibility in the production structure. In scenarios where carbon emissions are taxed or limited by policy, carbon permits generated by the use of CCS enter in a CES nest with generation and capture. The base capture rate is assumed to be 95%. Substitution between the carbon permit input and sequestration allows deployment of additional capital and labor to capture a higher percentage of $CO_2$ emissions and ultimately reduce the required input of carbon permits. The penetration rate of CCS technology is further controlled by a fixed factor at the top level of the nested structure, similar to other backstop technology types.

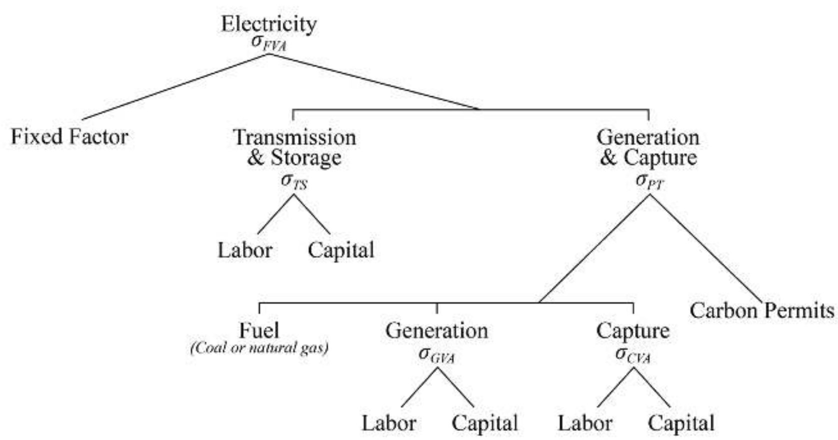


**Figure 14.** The production structure for electricity with CCS.

To specify the production cost of these new technologies, we first set input shares for each technology in each region. This evaluation is based on demonstration project information or expert elicitations (Babiker *et al.*, 2001; Paltsev *et al.*, 2005). A markup factor captures the increased expense of new technologies (compared to conventional fossil technologies), and all inputs to advanced technologies are multiplied by this markup factor. Estimations of markup factors for selected technologies in the C-GEM are shown in **Table 6**. The wind markup factor of 1.3 indicates that, at benchmark prices, wind power costs 30% more than conventional fossil electricity. Other markup factors are interpreted analogously.

For all regions except China, our markup factors for each technology are mainly based on a recent report by the Electric Power Research Institute comparing the technologies on a consistent basis (Electric Power Research Institute, 2011). Cost estimates are also sourced from the technical database of the Global Change Assessment Model (PNNL, 2012a, 2012b) and the MIT EPPA model (Paltsev *et al.,* 2005). For China, in addition to consulting the relevant literature (Huo and Zhang, 2012; Qiu, 2012; Wu *et al.,* 2010) we collect comments from industry experts on the technology cost.

**Table 6.** Markup factors for backstop technologies in the C-GEM.

| ***Backstop technologies*** | ***Markup factors[1]*** | |
|---|---|---|
| *Biofuels* | 1.0-2.4 | |
| *Shale oil* | 2.5-2.8 | |
| *Coal gasification* | 2.6 | |
| | **China** | **Other Regions** |
| *Wind* | 1.3[2] | 1.1-1.5 |
| *Solar* | 2010: 2.5<br>2015: 2.0<br>2020-2050: 1.5[3] | 1.8-2.5 |
| *Biomass electricity* | 1.8[4] | 1.2-1.8 |
| *IGCC-CCS* | 1.55[5] | 1.52-2.1 |
| *NGCC-CCS* | 2.35[6] | 1.42-1.9 |

[1]The base price for conventional power generation is assumed to be 0.4 yuan/KWh, the nationwide average coal-power cost.

[2]Wind power costs are based on expert elicitation based on average wind production costs (0.5-0.55 yuan/KWh).

[3]Solar PV costs in 2010 (1.0-1.15 yuan/KWh) are based on estimates from NDRC (2011). These costs decrease in 2015 (to 0.8 yuan/KWh) and again in 2020 (0.6 yuan/kWh). These reductions are based on the cost reduction target from the Ministry of Industry and Information Technology (MIIT, 2012).

[4]Biomass power costs (0.7 yuan/KWh) are based on expert elicitation.

[5]IGCC-CCS costs (0.65 yuan/kWh) are based on literature estimates (Rubin and de Coninck, 2005) and expert elicitation.

[6]NGCC-CCS are based on estimates from Rubin and de Coninck (2005).

## 6. MODEL REFERENCE SCENARIO IN THE C-GEM

### 6.1 The C-GEM Reference Scenario

The assumptions and parameters reported in the above sections underpin a reference projection of future economic activity, energy use and emissions for the 19 regions included in the C-GEM. In the following section, we present the reference scenario developed under our assumptions about labor productivity growth, exogenous changes in energy efficiency and new technology costs, among other factors. Projections are subject to a range of uncertainties; this reference scenario provides a point of comparison to other projections and serves as a benchmark for calculating the effects of policy interventions.

#### *6.1.1 Population and Gross Domestic Product*

In the reference scenario, we assign population values using the World Population Prospects from the United Nations (United Nations, 2012), shown in **Figure 15**. From this projection, the world's population is projected to exceed 9.5 billion in 2050 and reach 10.9 billion by the end of the century. Much of this growth will happen in developing regions, such as India and Africa. India is projected to surpass China in population to become the world's most populous country by around 2020. The population of Africa is also projected to grow rapidly and is estimated to double between 2010 and 2040. China's population is predicted to peak at around 1.4 billion in 2035, then drop back to its 2010 level by 2050.

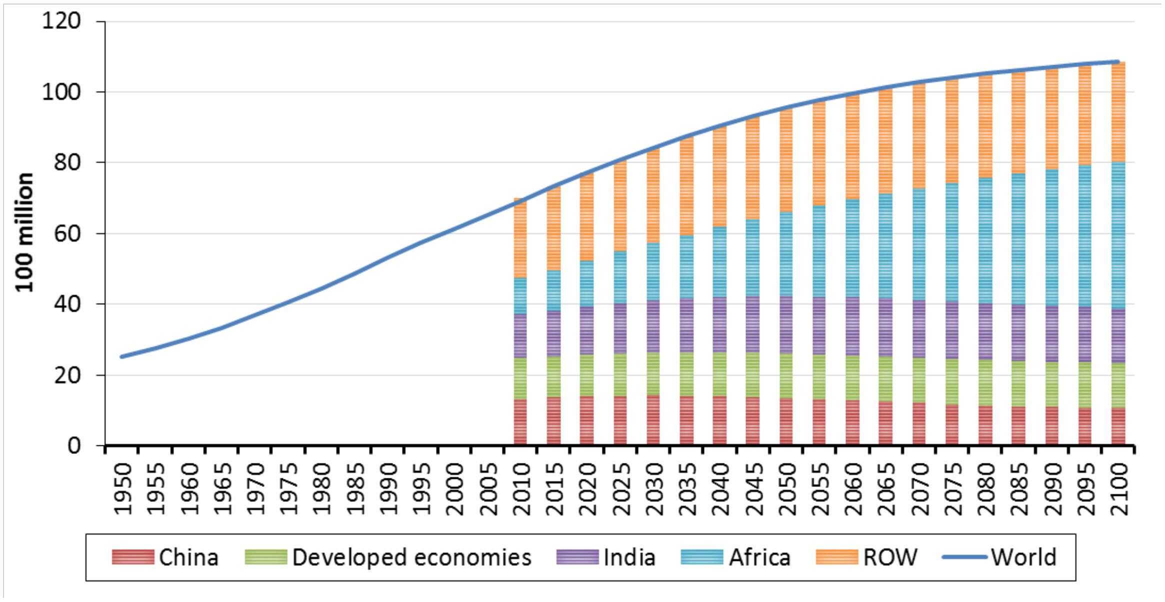


**Figure 15.** Global population prospects from the United Nations (100 million).

*Note:* Developed economies include USA, CAN, JPN, KOR, DEA, EUR and ANZ as listed in Table 1, similarly hereinafter.

**Figure 16** shows the gross domestic product (GDP) projections for the 19 regions in the C-GEM. The projection shows historical data for 2010 followed by the C-GEM projections for 2015 through 2050. With an annual average growth rate of 2.8%, global GDP triples between 2010 and 2050.

**Figure 17** details C-GEM regional GDP projections. The annual GDP growth rate for China is 7.5% from 2010–2015, 6.8% from 2015–2020, 4.8% from 2020–2030, and declines to 3.3% from 2030–2050. India is also assumed to grow very fast at an average of 5.4% per year. From 2010-2050, the average annual growth rate is 2.1% in the U.S. and 1.3% in the E.U.

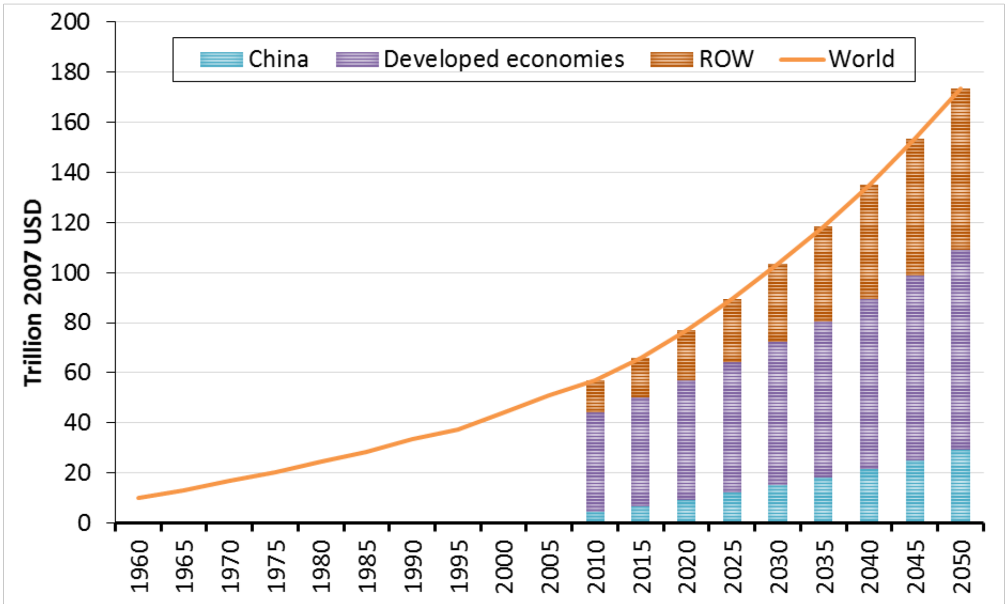


**Figure 16.** World GDP projections from the C-GEM.

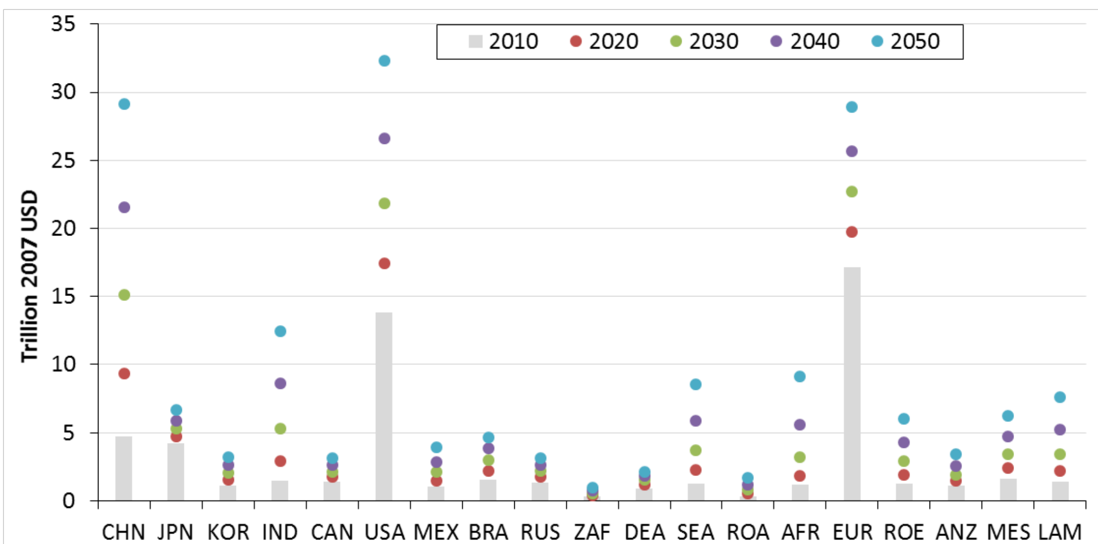


**Figure 17.** GDP projections for regions represented in the C-GEM.

### *6.1.2 Primary Energy Consumption and Emissions*

Global primary energy consumption in million of tons of oil equivalent (mtoe) units is displayed in **Figure 18**. Global primary energy consumption is predicted to be 85% higher in 2050 than in 2010. In the reference scenario, around 18% of energy demand will come from non-fossil fuel sources, such as nuclear and renewable energy.

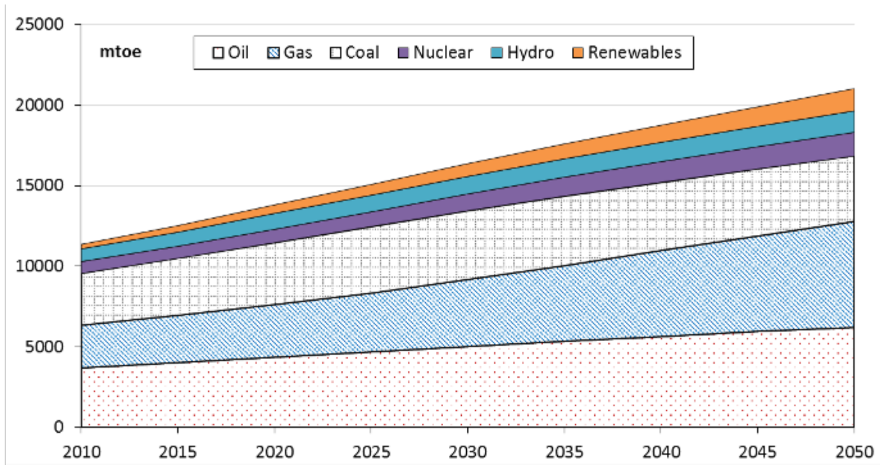


**Figure 18.** Global primary energy consumption (mtoe).

*Note:* Non-fossil power generation has been converted on the basis of thermal equivalence assuming 38% conversion efficiency in a modern thermal power station.

Global fossil fuel-related $CO_2$ emissions in millions of metric tons (mmt) are shown in **Figure 19**. $CO_2$ emissions are projected to grow at an average annual rate of 1.3% from 2010 to 2050, with industrial activity increasing globally.

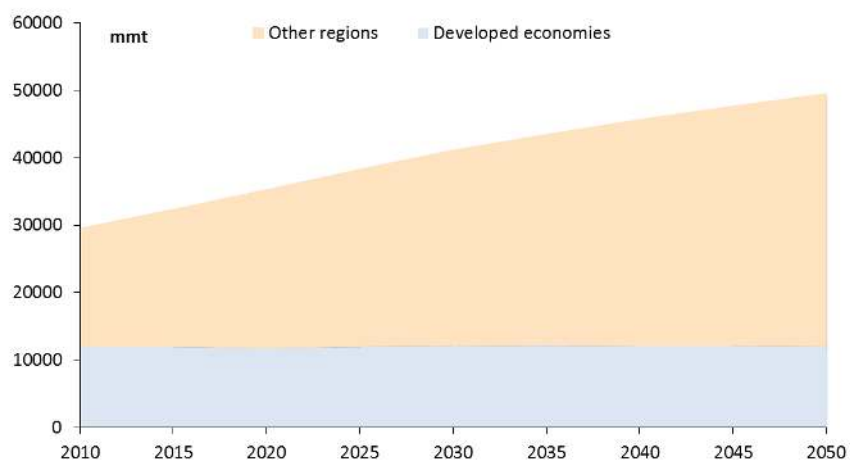


**Figure 19.** Global fossil fuel emissions (mmt).

## 6.2 Sensitivity Analysis: AEEI and Input Substitution

As previously discussed, future economic and energy projections are based on assumptions that are subject to significant uncertainty. It is necessary to understand the importance of input parameters in determining model outcomes. Previous research has focused on extensive sensitivity testing using the EPPA framework (Cossa, 2004; Jacoby *et al.*, 2009; Webster *et al.*, 2002; Webster *et al.*, 2008). Here we test two parameters that are identified as important in previous model sensitivity analyses: (i) the AEEI trend in each region over time; (ii) the substitution elasticity between the energy and capital-labor bundles, $\sigma_{E\_KL}$.

AEEI parameters describe exogenous trends in energy efficiency improvement by production sector and region. The value of $\sigma_{E\_KL}$ captures the difficulty in substitution between energy use and the capital-labor bundle, which reflects the sector- and region-specific energy abatement cost. Both of these parameters directly influence energy use in the production sectors. We have developed straightforward sensitivity cases for AEEI and $\sigma_{E\_KL}$ parameters by defining low, medium, and high values for each parameter. Parameter input values for these three different cases are listed in **Table 7**. For AEEI, we change the value for all sectors, while for the elasticity $\sigma_{E\_KL}$ we tested sensitivity only in the energy-intensive (EINT) and electricity (ELEC) sectors. **Table 8a and 8b** show the sensitivity of global total primary energy demand to alternative AEEI and $\sigma_{E\_KL}$ values.

**Table 7.** AEEI average annual growth rates and $\sigma_{E\_KL}$ values in high-, mid- and low- value cases for sensitivity analysis.

| AEEI value | AEEI average annual growth rate | | | $\sigma_{E\_KL}$ | |
|---|---|---|---|---|---|
| | *Developed regions* | *Other regions* | *China* | *EINT* | *ELEC* |
| Low case | 0.8% | 1.1% | 1.3% | 0.375 | 0.075 |
| Medium case | 1.0% | 1.5% | 1.7% | 0.5 | 0.1 |
| High case | 1.3% | 1.9% | 2.1% | 0.625 | 0.125 |

Through comparison of Tables 8a and 8b, we find that the AEEI and $\sigma_{E\_KL}$ produce different effects on total energy consumption. Total primary energy consumption and $CO_2$ emissions are 3% higher for low AEEI growth rates and 1% higher for low $\sigma_{E\_KL}$ values than for high values of these parameters. Additionally, in the reference scenario (without a carbon price), energy consumption is more sensitive to AEEI values than to $\sigma_{E\_KL}$ values, as the AEEI has a more direct impact on energy consumption, while $\sigma_{E\_KL}$ can reduce the energy use indirectly by allowing capital substitution in response to a price or policy shock. In the future, a more exhaustive set of sensitivity tests will be conducted on a full range of parameters to understand the underlying drivers of model outputs.

**Table 8a.** Total primary energy consumption and $CO_2$ emissions for the high, medium and low cases of the AEEI average annual growth. (Percentage changes are relative to the Medium case.)

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| **Medium AEEI** | | | | | | | | | |
| Total primary energy consumption (mtoe) | 10205 | 11244 | 12332 | 13467 | 14593 | 15606 | 16464 | 17237 | 17984 |
| Global emissions (mmt) | 29284 | 32127 | 35036 | 38119 | 41036 | 43476 | 45278 | 46827 | 48216 |
| **Low AEEI** | | | | | | | | | |
| Total primary energy consumption (mtoe) | 10249 | 11349 | 12514 | 13747 | 14975 | 16090 | 17053 | 17931 | 18783 |
| % Change | -0.4% | -0.9% | -1.5% | -2.1% | -2.6% | -3.1% | -3.6% | -4.0% | -4.4% |
| Global emissions (mmt) | 29430 | 32470 | 35630 | 39022 | 42251 | 44926 | 47002 | 48764 | 50294 |
| % Change | -0.5% | -1.1% | -1.7% | -2.4% | -3.0% | -3.3% | -3.8% | -4.1% | -4.3% |
| **High AEEI** | | | | | | | | | |
| Total primary energy consumption (mtoe) | 10160 | 11141 | 12155 | 13200 | 14234 | 15155 | 15924 | 16608 | 17269 |
| % Change | 0.9% | 1.9% | 3.0% | 4.1% | 5.2% | 6.2% | 7.1% | 8.0% | 8.8% |
| Global emissions (mmt) | 29138 | 31791 | 34461 | 37257 | 39892 | 42067 | 43666 | 45004 | 46207 |
| % Change | 1.0% | 2.1% | 3.3% | 4.5% | 5.6% | 6.4% | 7.1% | 7.7% | 8.1% |

**Table 8b.** Total primary energy consumption and $CO_2$ emissions for the high, medium and low cases of the $\sigma_{E\_KL}$ value. (Percentage changes are relative to the Medium case.)

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| **Medium Elasticity** | | | | | | | | | |
| Total primary energy consumption (mtoe) | 10205 | 11244 | 12332 | 13467 | 14593 | 15606 | 16464 | 17237 | 17984 |
| Global emissions (mmt) | 29284 | 32127 | 35036 | 38119 | 41036 | 43476 | 45278 | 46827 | 48216 |
| **Low Elasticity** | | | | | | | | | |
| Total primary energy consumption (mtoe) | 10212 | 11292 | 12427 | 13605 | 14763 | 15793 | 16658 | 17437 | 18186 |
| % Change | -0.1% | -0.4% | -0.8% | -1.0% | -1.2% | -1.2% | -1.2% | -1.2% | -1.1% |
| Global emissions (mmt) | 29310 | 32288 | 35343 | 38558 | 41560 | 44035 | 45835 | 47379 | 48747 |
| % Change | -0.1% | -0.5% | -0.9% | -1.2% | -1.3% | -1.3% | -1.2% | -1.2% | -1.1% |
| **High Elasticity** | | | | | | | | | |
| Total primary energy consumption (mtoe) | 10195 | 11179 | 12184 | 13218 | 14238 | 15155 | 15933 | 16625 | 17288 |
| % Change | 0.2% | 1.0% | 2.0% | 2.9% | 3.7% | 4.2% | 4.6% | 4.9% | 5.2% |
| Global emissions (mmt) | 29252 | 31909 | 34544 | 37299 | 39882 | 42042 | 43629 | 44952 | 46107 |
| % Change | 0.2% | 1.2% | 2.3% | 3.3% | 4.0% | 4.5% | 4.8% | 5.1% | 5.4% |

## 7. CONCLUSION

The China-in-Global Energy Model (C-GEM) simulates the interaction of production, consumption and trade among multiple global regions. As a computable general equilibrium (CGE) model with global coverage and energy system detail, C-GEM can be used to analyze the impact of energy and climate policies in scenarios under alternative assumptions about the availability and cost of advanced technologies. By describing the model structure, underlying database, key parameters and calibration, and important assumptions of the C-GEM, this report provides a guide for model users and a detailed reference to accompany studies that employ the C-GEM for policy analysis. This report also provides model results for the reference scenario and a sensitivity analysis for two key parameters: autonomous energy efficiency improvements (AEEI) and the elasticity of substitution between energy and value added. While modest, the sensitivity of energy and $CO_2$ emissions projections to parameter choices underscores the importance of being transparent about model assumptions and recognizing uncertainty in baseline projections when evaluating policy impacts. Policy comparisons developed using the C-GEM can help to inform energy and climate policy decision-making in China and around the world.

**Acknowledgments**

The authors thank Eni S.p.A., ICF International, Shell International Limited, and the French Development Agency (AFD), founding sponsors of the China Energy and Climate Project. We are also thankful for support provided by the Ministry of Science and Technology of China, the National Development and Reform Commission, and Rio Tinto China. We further gratefully acknowledge the financial support for this work provided by the MIT Joint Program on the Science and Policy of Global Change through a consortium of industrial sponsors and Federal grants, including the U.S. Department of Energy. This work is also supported by the DOE Integrated Assessment Grant (DE-FG02-94ER61937).

## 8. REFERENCES

Abreu, M.A., H.D. Groot and R. Florax, 2005: A Meta-analysis of Beta-convergence: The Legendary Two-percent. Tinbergen Instituut Discussion paper: Tinbergen Institute.

Armington, P.S., 1969: A theory of demand for products distinguished by place of production. *IMF Staff Papers,* 16, 159–176.

Arrow, K.J. and G. Debreu, 1954: *Existence of an Equilibrium for a Competitive Economy.* Econometrica*, 22*(3), 265–290. doi: 10.2307/1907353

Böhringer, C., T.F. Rutherford and W. Wiegard, 2003: Computable general equilibrium analysis: Opening a black box: ZEW, Zentrum für Europäische Wirtschaftsforschung.

Babiker, H.M., J.M. Reilly, M. Mayer, S.E. Richard, I. Sue Wing and R.C. Hyman, 2001: The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results. MIT JPRSPGC *Report 71*, February, 90 p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt71.pdf).

Bai, C., C. Hsieh and Y. Qian, 2006: The return to capital in China: National Bureau of Economic Research. Working Paper 12755, online (http://www.nber.org/papers/w12755).

Cao, J. and M. Ho, 2009: Changes in China's Energy Intensity: Origins and Implications for Long-Run Carbon Emissions and Climate Policies. *EEPSEA research reports*. Singapore (http://www.eepsea.net/pub/rr/2010-RR12-Jing Cao and Mun S HO.pdf).

Chansomphou, V. and M. Ichihashi, 2013: Structural change, labor productivity growth, and convergence of BRIC countries: Hiroshima University, Graduate School for International Development and Cooperation (IDEC). *Discussion Paper Series* 3(5).

China Price Year Book Press, 2009: *Price Year Book of China 2008*. Beijing: China Price Year Book Press.

Cossa, P.F., 2004: Uncertainty Analysis of the Cost of Climate Policies. Master of Science Thesis in Technology and Policy. Massachusetts Institute of Technology, Cambridge, MA.

Dellink, R., 2005: Modelling the costs of environmental policy: a dynamic applied general equilibrium assessment. Edward Elgar Publishing.

Dirkse, S. P. and M.C. Ferris, 1995: The PATH Solver: a non-monotone stabilization scheme for Mixed Complementarity Problems. *Optimization Methods and Software*, 5, 123–156.

Electric Power Research Institute, 2011: *Program on technology innovation: Integrated generation technology options*. Electric Power Research Institute: Palo Alto, California.

Grübler, A., 2003: *Technology and global change.* Cambridge University Press.

Harrison, W.J. and K. R. Pearson, 1996: Computing solutions for large general equilibrium models using GEMPACK. *Computational Economics*, Volume 9 (Issue 2), 83–127.

Hotelling, H., 1931: The economics of exhaustible resources. *The Journal of Political Economy*, 39(2), 137–175.

Huo, M. and D. Zhang, 2012: Lessons from photovoltaic policies in China for future development. *Energy Policy,* 51, 38–45.

IAEA, 2008: *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030*. Vienna: International Atomic Energy Agency.

IMF, 2012: *World Economic Outlook*. Washington, DC: International Monetary Fund.

IPCC, 2001: *IPCC Third Assessment Report – Climate Change 2001*, Working Group III: Mitigation, Chapter 7. Costing Methodologies, online (http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=266).

IPCC, 2006: *IPCC guidelines for National greenhouse gas inventories.* Hayama, Japan: Institute for Global Environmental Strategies (IGES).

Kang, L. and F. Peng, 2013: Economic Reform and Productivity Convergence in China. MPRA Paper *No. 50810*, online (http://mpra.ub.uni-muenchen.de/50810).

Klump, R., P. McAdam and A. Willman, 2011: The normalized CES production function - theory and empirics. European Central Bank.

Manne, A.S. and R.G. Richels, 1992: *Buying Greenhouse Insurance: The Economic Costs of $CO_2$ Emission Limits.* MIT Press, Cambridge, MA.

Mathiesen, L., 1985: Computation of economic equilibria by a sequence of linear complementarity problems. *Mathematical Programming Study*, 23(OCT), 144–162.

McDougall, R. and H. Lee, 2006: GTAP 6 Data Base Documentation—Chapter 17: An Energy Data Base for GTAP: Center for Global Trade Analysis.

McFarland, J.R., J.M. Reilly and H.J. Herzog, 2004: Representing energy technologies in top-down economic models using bottom-up information. *Energy Economics*, 26(4), 685–707.

MIIT, 2012: *The 12th Five-Year-Plan of Solar PV Industry*, online (http://www.miit.gov.cn/n11293472/n11293832/n12771663/14473764.html).

Narayanan, B., A. Aguiar and R. McDougall, 2012: Global Trade, Assistance, and Production: The GTAP 8 Data Base: Center for Global Trade Analysis, Purdue University (http://www.gtap.agecon.purdue.edu/databases/v8/v8_doco.asp).

National Bureau of Statistics of China, 2008: *2007 China energy statistical yearbook*. Beijing: China Statistics Press.

National Bureau of Statistics of China, 2009: *2007 China input-output tables*. Beijing: China Statistics Press.

NDRC, 2011: The National Development and Reform Commission (NDRC) announced feed-in tariffs for PV projects (http://www.mlr.gov.cn/xwdt/bmdt/201108/t20110801_912529.htm).

OECD, 2013: Long-term growth scenarios. In Å. Johansson, Y. Guillemette, F. Murtin, D. Turner, G. Nicoletti, C. Maisonneuve, P. Bagnoli, G. Bousquet and F. Spinelli (Eds.), *Economic department working papers*.

OECD/NEA, 2010: *Projected Costs of Generating Electricity.* OECD: Paris.

Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J.R. McFarland, M. Sarofim and H.M. Babiker, 2005: The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. MITJPSPGC *Report 125*, August, 72 p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf).

Pauw, K., 2003: Functional forms used in CGE models: Modeling production and commodity flows. (No. Background Paper 2003:5). Elsenburg, South Africa: The Provincial Decision-Making Enabling Project.

PNNL, 2012a: *Document of the Global Climate Assessment Model: Electricity* (http://wiki.umd.edu/gcam/index.php/The_Energy_System).

PNNL, 2012b: *Document of the Global Climate Assessment Model: Energy system*, (http://wiki.umd.edu/gcam/index.php/The_Energy_System).

Qiu, Y.M. and L.D. Anadon, 2012: The price of wind power in China during its expansion: Technology adoption, learning-by-doing, economies of scale, and manufacturing localization. *Energy Economics,* 34(3), 772–785.

Rausch, S., G.E. Metcalf, J.M. Reilly and S. Paltsev, 2010: Distributional implications of alternative US greenhouse gas control measures. *The BE Journal of Economic Analysis and Policy*, 10(2).

Rosenthal, E.R., 2012: *GAMS - A user's guide.* Washington, DC, USA: GAMS Development Corporation.

Rubin, E. and H. de Coninck, 2005: *IPCC special report on carbon dioxide capture and storage.* Prepared by working group III of the intergovernmental panel on climate change, Intergovernmental Panel on Climate Change, Cambridge, UK.

Rutherford, T.F., 1995: Extension of GAMS for complementarity problems arising in applied economic analysis. *Journal of Economic Dynamics and Control*, 19(8), 1299–1324.

Rutherford, T.F., 1999: Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax. *Computational Economics,* 14(1-2), 1–46.

Rutherford, T.F., 2010: *GTAP7inGAMS*. Center for Energy Policy and Economics, Department of Management, Technology and Economics, ETH Zurich.

Sala-i-Martin, X.X., 1996: Regional cohesion: evidence and theories of regional growth and convergence. *European Economic Review,* 40(6), 1325–1352. doi: http://dx.doi.org/10.1016/0014-2921(95)00029-1

Schmalensee, R., T.M. Stoker and R.A. Judson, 1998: World carbon dioxide emissions: 1950–2050. *Review of Economics and Statistics,* 80(1), 15–27.

Sue Wing, I., 2004: Computable general equilibrium models and their use in economy-wide policy analysis. Technical Note, Joint Program on the Science and Policy of Global Change, MIT.

Sue Wing, I. and R.S. Eckaus, 2007: The implications of the historical decline in US energy intensity for long-run $CO_2$ emission projections. *Energy Policy*, 35(11), 5267–5286.

United Nations, 2012: *World population prospects, the 2012 revision.* New York: Population Division, Department of Economic and Social Affairs.

Webster, M.D., M.H. Babiker, M. Mayer, J.M. Reilly, J. Harnisch, R. Hyman, M.C. Sarofim and C. Wang, 2002: Uncertainty in emissions projections for climate models. *Atmospheric Environment,* 36(22), 3659–3670.

Webster, M.D., S. Paltsev, J.E. Parsons, J.M. Reilly and H.D. Jacoby, 2008: Uncertainty in greenhouse emissions and costs of atmospheric stabilization. MIT JPSPGC *Report 165*, November, 81 p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt180.pdf).

Webster, M., A.P. Sokolov, J.M. Reilly, C.E. Forest, S. Paltsev, A. Schlosser, C. Wang, D. Kicklighter, M. Sarofim, J. Melillo, R.G. Prinn and H.D. Jacoby, 2009: Analysis of climate policy targets under uncertainty. MITJPSPGC *Report 180*, September, 53 p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt180.pdf).

William, D.N., 1979: *The Efficent Use of Energy Resources.* New Haven: Yale University Press.

Wu, C.Z., X.L. Yin, Z.H. Yuan, Z.Q. Zhou and X.S. Zhuang, 2010: The development of bioenergy technology in China*. Energy,* 35(11), 4445–4450.

## REPORT SERIES of the MIT Joint Program on the Science and Policy of Global Change

FOR THE COMPLETE LIST OF JOINT PROGRAM REPORTS: http://globalchange.mit.edu/pubs/all-reports.php

**221. Green Growth and the Efficient Use of Natural Resources** *Reilly* June 2012

**222. Modeling Water Withdrawal and Consumption for Electricity Generation in the United States** *Strzepek et al.* June 2012

**223. An Integrated Assessment Framework for Uncertainty Studies in Global and Regional Climate Change: *The MIT IGSM*** *Monier et al.* June 2012

**224. Cap-and-Trade Climate Policies with Price-Regulated Industries: *How Costly are Free Allowances?*** *Lanz and Rausch* July 2012

**225. Distributional and Efficiency Impacts of Clean and Renewable Energy Standards for Electricity** *Rausch and Mowers* July 2012

**226. The Economic, Energy, and GHG Emissions Impacts of Proposed 2017–2025 Vehicle Fuel Economy Standards in the United States** *Karplus and Paltsev* July 2012

**227. Impacts of Land-Use and Biofuels Policy on Climate: *Temperature and Localized Impacts*** *Hallgren et al.* August 2012

**228. Carbon Tax Revenue and the Budget Deficit: *A Win-Win-Win Solution?*** *Sebastian Rausch and John Reilly* August 2012

**229. CLM-AG: An Agriculture Module for the Community Land Model version 3.5** *Gueneau et al.* September 2012

**230. Quantifying Regional Economic Impacts of $CO_2$ Intensity Targets in China** *Zhang et al.* September 2012

**231. The Future Energy and GHG Emissions Impact of Alternative Personal Transportation Pathways in China** *Kishimoto et al.* September 2012

**232. Will Economic Restructuring in China Reduce Trade Embodied $CO_2$ Emissions?** *Qi et al.* October 2012

**233. Climate Co-benefits of Tighter $SO_2$ and $NO_x$ Regulations in China** *Nam et al.* October 2012

**234. Shale Gas Production: *Potential versus Actual GHG Emissions*** *O'Sullivan and Paltsev* November 2012

**235. Non-Nuclear, Low-Carbon, or Both? *The Case of Taiwan*** *Chen* December 2012

**236. Modeling Water Resource Systems under Climate Change: *IGSM-WRS*** *Strzepek et al.* December 2012

**237. Analyzing the Regional Impact of a Fossil Energy Cap in China** *Zhang et al.* January 2013

**238. Market Cost of Renewable Jet Fuel Adoption in the United States** *Winchester et al.* January 2013

**239. Analysis of U.S. Water Resources under Climate Change** *Blanc et al.* February 2013

**240. Protection of Coastal Infrastructure under Rising Flood Risk** *Lickley et al.* March 2013

**241. Consumption-Based Adjustment of China's Emissions-Intensity Targets: *An Analysis of its Potential Economic Effects*** *Springmann et al.* March 2013

**242. The Energy and $CO_2$ Emissions Impact of Renewable Energy Development in China** *Zhang et al.* April 2013

**243. Integrated Economic and Climate Projections for Impact Assessment** *Paltsev et al.* May 2013

**244. A Framework for Modeling Uncertainty in Regional Climate Change** *Monier et al.* May 2013

**245. Climate Change Impacts on Extreme Events in the United States: An Uncertainty Analysis** *Monier and Gao* May 2013

**246. Probabilistic Projections of 21$^{st}$ Century Climate Change over Northern Eurasia** *Monier et al.* July 2013

**247. What GHG Concentration Targets are Reachable in this Century?** *Paltsev et al.* July 2013

**248. The Energy and Economic Impacts of Expanding International Emissions Trading** *Qi et al.* August 2013

**249. Limited Sectoral Trading between the EU ETS and China** *Gavard et al.* August 2013

**250. The Association of Large-Scale Climate Variability and Teleconnections on Wind Resource over Europe and its Intermittency** *Kriesche and Schlosser* September 2013

**251. Regulatory Control of Vehicle and Power Plant Emissions: *How Effective and at What Cost?*** *Paltsev et al.* October 2013

**252. Synergy between Pollution and Carbon Emissions Control: *Comparing China and the U.S.*** *Nam et al.* October 2013

**253. An Analogue Approach to Identify Extreme Precipitation Events: *Evaluation and Application to CMIP5 Climate Models in the United States*** *Gao et al.* November 2013

**254. The Future of Global Water Stress: *An Integrated Assessment*** *Schlosser et al.* January 2014

**255. The Mercury Game: *Evaluating a Negotiation Simulation that Teaches Students about Science–Policy Interactions*** *Stokes and Selin* January 2014

**256. The Potential Wind Power Resource in Australia: *A New Perspective*** *Hallgren et al.* February 2014

**257. Equity and Emissions Trading in China** *Zhang et al.* February 2014

**258. Characterization of the Wind Power Resource in Europe and its Intermittency** *Cosseron et al.* March 2014

**259. A Self-Consistent Method to Assess Air Quality Co-Benefits from US Climate Policies** *Saari et al.* April 2014

**260. Electricity Generation and Emissions Reduction Decisions under Policy Uncertainty: *A General Equilibrium Analysis*** *Morris et al.* April 2014

**261. An Integrated Assessment of China's Wind Energy Potential** *Zhang et al.* April 2014

**262. The China-in-Global Energy Model** *Qi et al.* May 2014

Contact the Joint Program Office to request a copy. The Report Series is distributed at no charge.