World Energy Projection System Plus: Industrial Module

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1. Introduction

Purpose of this Report
The World Industrial Model of the World Energy Projection System Plus (WEPS+) is an energy demand modeling system that projects industrial end-use sector energy consumption for 16 international regions. This report describes the version of the World Industrial Model (WIM) that was used to produce the industrial sector projections published in the International Energy Outlook 2017 (IEO2017). WIM is one of 13 components of WEPS+ energy modeling system, but the industrial model can also be run as a separate, individual model. The WEPS+ is a modular system, consisting of separate energy models that communicate and work together through the overall system model. These models are each developed independently, but are designed with well-defined protocols for system communication and interactivity. The WEPS+ modeling system uses a shared database (the “restart” file) that allows all the models to communicate with each other when they are run in sequence over a number of iterations. The overall WEPS+ system uses an iterative solution technique that allows for simultaneous convergence of consumption and price to simulate market equilibrium.

This report documents the objectives, analytical approach and development of the WIM. The report catalogues and describes critical assumptions, computational methodology, parameter estimation techniques, and model source code. This document serves three purposes. First, it is a reference document providing a detailed description for model analysts, users, and the public. Second, it meets the legal requirement of the U.S. Energy Information Administration (EIA) to provide adequate documentation in support of its models (Public Law 93-275, section 57.b.1). Third, it facilitates continuity in model development by providing documentation from which energy analysts can undertake and analyze their own model enhancements, data updates, and parameter refinements for future projects.

Model Summary
The World Industrial Model of the World Energy Projection System Plus (WEPS+) projects energy use in the manufacturing, agricultural, construction and mining sectors for 18 energy sources in each of the 16 WEPS+ regions on an annual basis to 2050. The model primarily employs a stock-flow accounting framework that uses exogenously-specified output of specific industries as a proxy for productive capacity. In WIM, old capacity is assumed to be retired over time to make way for new capacity. This framework allows for the modeling of changes in energy efficiency over time. Exogenously-specified energy prices impact both the mechanisms of the stock-flow process and fuel switching projections over time.

Model Archival Citation
This documentation refers to the WEPS+ World Industrial Model, as archived for the International Energy Outlook 2016 (IEO2016).
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Organization of This Report
Chapter 2 of this report discusses the purpose of WIM, the objectives and the analytical issues it addresses, the general types of activities and relationships it embodies, the primary input and output variables, and the relationship of the model to the other models in the WEPS+ system. Chapter 3 of the report describes the rationale behind the WIM, providing insights into further assumptions used in the model. Chapter 4 describes the model structure in more detail, including flowcharts, variables, and equations.
2. Model Purpose

Model Objectives

The primary objective of the WIM is to generate annual projections of industrial energy use for 2013 through 2050 for each of the 16 WEPS+ international regions. Projections are further broken out by fuel type, industry, and capacity vintage. As an integral component of the WEPS+ system, WIM provides consumption inputs to the various transformation and supply models of WEPS+ and contributes to the simulation of the overall energy supply and demand balance. The consumption inputs are also used by the Greenhouse Gases Model to calculate energy-related carbon dioxide emissions.

As part of the WEPS+ system, WIM operates at the level of the 16 WEPS+ world regions shown in Table 1. These regions consist of countries and country groupings within the broad divide of the Organization of Economic Cooperation and Development (OECD) membership. Multicountry regions (e.g. OECD Europe) are enumerated in Appendix A.

Table 1. Regional Coverage of the World Energy Projection System Plus Model

<table>
<thead>
<tr>
<th>OECD Regions and index</th>
<th>Non-OECD Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 United States</td>
<td>8 Russia</td>
</tr>
<tr>
<td>2 Canada</td>
<td>9 Non-OECD Europe and Eurasia</td>
</tr>
<tr>
<td>3 Mexico/Chile</td>
<td>10 China</td>
</tr>
<tr>
<td>4 OECD Europe</td>
<td>11 India</td>
</tr>
<tr>
<td>5 Japan</td>
<td>12 Other Non-OECD Asia</td>
</tr>
<tr>
<td>6 Australia/New Zealand</td>
<td>13 Middle East</td>
</tr>
<tr>
<td>7 South Korea</td>
<td>14 Africa</td>
</tr>
<tr>
<td></td>
<td>15 Brazil</td>
</tr>
<tr>
<td></td>
<td>16 Non-OECD Americas</td>
</tr>
</tbody>
</table>

Models Inputs and Outputs

Inputs

WIM uses macroeconomic and industrial price projections that are imported from the WEPS+ restart file. These inputs have been previously projected by the Macroeconomic Model and the transformation and supply models (Table 2). The macro index is not always the same as the industrial index in table 5. The following is the list of the industrial index first from 1 to 16 and the macro index second: 1 1; 2 2; 3 3; 4 4; 5 5; 6 6; 7 7; 8 8; 9 9; 10 10; 11 17; 12 18; 13 19; 14 20; 15; 21; and 16 12.
Table 2. WEPS+ Models that Provide Input to the World Industrial Model

<table>
<thead>
<tr>
<th>World Industrial Model Input</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross domestic product</td>
<td>Macroeconomic Model</td>
</tr>
<tr>
<td>Outputs of specific industries</td>
<td>Macroeconomic Model</td>
</tr>
<tr>
<td>Industrial retail prices</td>
<td></td>
</tr>
<tr>
<td>Energy Source Index number and name</td>
<td></td>
</tr>
<tr>
<td>1 Motor gasoline</td>
<td>Refinery Model</td>
</tr>
<tr>
<td>2 Distillate</td>
<td>Refinery Model</td>
</tr>
<tr>
<td>3 Residual fuel</td>
<td>Refinery Model</td>
</tr>
<tr>
<td>4 Kerosene</td>
<td>Refinery Model</td>
</tr>
<tr>
<td>5 Liquid Petroleum Gas (LPG)</td>
<td>Refinery Model</td>
</tr>
<tr>
<td>8 Other petroleum</td>
<td>Refinery Model</td>
</tr>
<tr>
<td>9 Natural Gas</td>
<td>Natural Gas Model</td>
</tr>
<tr>
<td>10 Coal</td>
<td>Coal Model</td>
</tr>
<tr>
<td>11 Electricity</td>
<td>World Electricity Model</td>
</tr>
<tr>
<td>12 District heat</td>
<td>District Heat Model</td>
</tr>
</tbody>
</table>

The data series listed in Table 3 are also imported into the World Industrial Model from the WIMInput.xml file.

Table 3. Major Exogenous World Industrial Model Input Data Series

<table>
<thead>
<tr>
<th>Source Input File</th>
<th>World Industrial Model Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIMInput.xml</td>
<td>Capacity retirement rates by industry and region</td>
</tr>
<tr>
<td></td>
<td>Capacity retirement rate elasticities by industry and region</td>
</tr>
<tr>
<td></td>
<td>Relative Energy Intensity (REI) coefficients by industry and region</td>
</tr>
<tr>
<td></td>
<td>Technology Possibility Curve (TPC) growth rates for existing and new capacity by industry and region</td>
</tr>
<tr>
<td></td>
<td>Technology Possibility Curve (TPC) price elasticities for existing and new capacity by industry and region</td>
</tr>
</tbody>
</table>

**Outputs**

WIM projects annual energy consumption by fuel and region. Upon completion of a model run, the projections are exported into the WEPS+ restart file for use by other models (Table 4).
### Table 4. WIM Model Output and the WEPS+ Models that Use Them

<table>
<thead>
<tr>
<th>World Industrial Model Output</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum consumption</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Motor gasoline</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Distillate</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Residual fuel</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Kerosene</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>LPG</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Petroleum coke</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Sequestered petroleum</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Other petroleum</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Crude oil (direct use)</td>
<td>Petroleum and Refinery Model</td>
</tr>
<tr>
<td>Natural gas consumption</td>
<td>Natural Gas Model</td>
</tr>
<tr>
<td>Coal consumption</td>
<td>Coal Model</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>World Electricity Model</td>
</tr>
<tr>
<td>Heat consumption</td>
<td>District Heat Model</td>
</tr>
<tr>
<td>Waste consumption</td>
<td>Reporting</td>
</tr>
<tr>
<td>Biomass consumption</td>
<td>Reporting</td>
</tr>
<tr>
<td>Geothermal consumption</td>
<td>Reporting</td>
</tr>
<tr>
<td>Solar consumption</td>
<td>Reporting</td>
</tr>
<tr>
<td>Other renewable consumption</td>
<td>Reporting</td>
</tr>
</tbody>
</table>
**Relationship to Other Models**

WIM is an integral component of the WEPS+ system and depends upon other models in the system for some of its key inputs. In turn, the WIM provides projections of energy consumption that other models in the system depend upon for their key inputs (Figure 1). A summary description of the models, flows, and mechanics of the WEPS+ system used for the *IEO2016* report is available in a separate *Overview* documentation.
Through the system, WIM receives gross domestic product (GDP) projections and gross output projections for specific industries from the Macroeconomic Model (also called the Global Activity Model) and receives a variety of price projections from various supply and transformation models (Figure 2). In
turn, WIM provides consumption projections through the system back to the supply and transformation models.

Although WIM is an integral part of the WEPS+ system, it can also be easily run as a standalone model. In standalone mode, WIM inputs macroeconomic and price projections from the WEPS+ system “restart” file as created in a previous full-system run.

**Figure 2. The World Industrial Model Relationship to Other WEPS+ Models**
3. Model Rationale

Theoretical Approach
The World Industrial Model (WIM) projects energy use that is directly consumed as a fuel or as a feedstock by industrial processes and activities. WIM includes manufacturing industries along with non-manufacturing industries such as construction, agriculture, and extraction (mining). The model is used to project industrial consumption for 18 energy sources in each of the 16 WEPS regions to the year 2050. WIM is a structured, industry-level, stock/flow model that uses gross output from the Macroeconomic Model as its primary driver. The model also uses retail energy prices for 12 energy sources. These drivers are available to the World Industrial Model from the WEPS+ transformation and supply models through the shared restart file.

WIM projects energy consumption in eight separate industries that are considered energy intensive or distinctive with respect to energy consumption. Other Chemicals and Other Manufacturing are non-energy intensive. Table 5 shows the 12 industries.
### Table 5. Industrial Sector Industries

<table>
<thead>
<tr>
<th>WIM Industry Number</th>
<th>Industry</th>
<th>Representative Industries</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Food</td>
<td>Food, beverage, and tobacco product manufacturing.</td>
</tr>
<tr>
<td>2</td>
<td>Paper</td>
<td>Paper manufacturing, printing and related support activities.</td>
</tr>
<tr>
<td>3</td>
<td>Basic Chemicals</td>
<td>Inorganic chemicals, organic chemicals (e.g. ethylene, propylene), resins, and agricultural chemicals. Includes chemical feedstock.</td>
</tr>
<tr>
<td>4</td>
<td>Refining</td>
<td>Petroleum refineries and coal products manufacturing to include coal and natural gas used as feedstock.</td>
</tr>
<tr>
<td>5</td>
<td>Iron and Steel</td>
<td>Iron and steel manufacturing, including coke ovens.</td>
</tr>
<tr>
<td>6</td>
<td>Non-Ferrous Metals</td>
<td>Primarily aluminum and other non-ferrous metals such as copper, zinc, and tin.</td>
</tr>
<tr>
<td>7</td>
<td>Non-Metallic Minerals</td>
<td>Primarily cement and other nonmetallic minerals such as glass, lime, gypsum, and clay products.</td>
</tr>
<tr>
<td>8</td>
<td>Other</td>
<td>All other manufacturing.</td>
</tr>
<tr>
<td>9</td>
<td>Other Chemicals</td>
<td>Pharmaceuticals, medicinal and botanical, paint and coatings, adhesives, detergents, and other miscellaneous chemical products. Includes chemical feedstock.</td>
</tr>
<tr>
<td>10</td>
<td>Agriculture</td>
<td>Agriculture, forestry, and fishing.</td>
</tr>
<tr>
<td>11</td>
<td>Oil Extraction</td>
<td>Oil and gas extraction</td>
</tr>
<tr>
<td>13</td>
<td>Other Extraction</td>
<td>Metallic and non-metallic mining such as gold and lithium.</td>
</tr>
<tr>
<td>14</td>
<td>Motor Vehicles</td>
<td>Transportation equipment - motor vehicles and aircraft - manufacturing.</td>
</tr>
<tr>
<td>15</td>
<td>OMBD</td>
<td>Other metal based durables manufacturing, computer and electronic products, machinery, and electrical equipment appliances and components.</td>
</tr>
<tr>
<td>16</td>
<td>Construction</td>
<td>Buildings (residential and commercial) construction, heavy and civil engineering construction, industrial construction, and specialty trade contractors.</td>
</tr>
</tbody>
</table>

WIM uses a stock/flow approach to estimate productive capacity needed to satisfy demand. It uses an existing stock of productive capacity for each industry in the base year. In subsequent projection years, the model estimates additional productive capacity needed to satisfy demand. The model calculates the change in productive capacity for three vintage categories:

**Remaining Original Capacity (Existing Vintage).** The model uses a retirement rate to determine how much of the original existing capacity remains (was not retired). The “original existing capacity” is simply the historical base year industrial capacity (the base year was 2012 for the IEO2016), which is based on
industrial output. The base year industrial energy intensity is computed from the original existing capacity.

*Added Capacity (New Vintage)* includes two types:

- Previously Added Capacity. The model projects changes in energy intensity (largely due to “housekeeping”) and changes in the fuel mix for the cumulative amount of previously added capacity. “Previously added capacity” is the amount of capacity added between the base year up to the current model year.

- New Capacity. For the current model year, the model determines the amount of new capacity added by subtracting the previously available capacity (original plus previously added) from the total required capacity, given the projected growth in gross output for the industry. The model projects the energy intensity for this new capacity, which is generally much better than that for the overall stock. A new fuel mix for the new capacity is also determined.

Total energy consumption in each vintage category is computed as gross output multiplied by energy intensity. Consumption of each fuel in each vintage category is computed as total energy consumption multiplied by the vintage-category fuel share. As discussed below, these fuel shares can be fixed or allowed to vary depending on consumption trends and price changes. The overall total industry consumption by fuel is calculated as the sum of consumption over the vintage categories. This approach takes into account the growth in output by industry and the rate at which new, typically more efficient, capacity is added. Over time, in rapidly growing industries, the new added capacity becomes a much more important determinant of energy consumption than in slowly growing industries. A simplified representation of the stock/flow approach is shown in Figure 3.

*Figure 3. Illustration of Stock/Flow Industrial Capacity Changes Over Time*
WIM requires a significant amount of initial data along with a number of projection coefficients. The data used to project industrial sector consumption is drawn from the International Energy Agency’s *Energy Statistics and Balances of OECD and non-OECD Countries* and calibrated for consistency with historical international energy data available from the Energy Information Administration. The coefficients for the *IEO2016* were based on comparisons of existing industrial energy intensities among world regions, taking into account the efficiency discrepancies between the more industrialized regions and the developing regions. Analysts used these comparisons, along with expert judgment, to estimate parameters such as regional energy intensities, capacity retirement rates, rates of change in intensity for remaining and added capacity, and fuel price elasticities.

**Model Assumptions**

WIM projects industrial energy consumption based upon numerous assumptions. The assumptions most critical to the projections include the following:

- Economic output is a suitable proxy for productive capacity, i.e., utilized capacity.\(^1\)
- Energy intensity of economic output is assumed to be inversely related to energy efficiency.
- Energy efficiency of new productive capacity will be better than energy efficiency of old productive capacity.
- Energy efficiency of economic output improves over time.
- Energy prices impact the retirement rate of capital, the rate of efficiency change, and the choice of fuels. Fuel switching is considered by region with variations by region.

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\(^1\) The model does not explicitly consider capacity utilization. However, if there is a decline in industrial output, followed by a subsequent increase, then the model will logically assume that the capacity “lost” during the downturn was just idled, and that this idled capacity is to brought back “on line” first before adding new (more energy efficient) capacity when industrial output starts to ramp up again.
4. Model Structure

Structural Overview
The main purpose of the World Industrial Model is to project annual industrial sector energy consumption, by region and fuel type, for 2015 through 2050. The industrial energy consumption calculations incorporate inputs that reflect analysts’ expectations of the state of technology in each region. Consumption is estimated for each of the 16 WEPS+ regions for 18 energy sources (motor gasoline, distillate fuel, residual fuel, kerosene, liquefied petroleum gas including feedstocks, petroleum coke, sequestered petroleum, other petroleum use including feedstocks, direct use crude oil, natural gas including feedstocks, coal including coking coal, electricity, heat, waste, biomass, geothermal, solar, and other renewables).

The basic structure of the World Industrial Model is illustrated in Figure 4. A call from the WEPS+ model interface to the WIM begins the import of information from the restart file and the other WEPS+ models needed to complete the projection calculations.

Next, a call from the main Industrial Model initiates the Ind subroutine (Figure 6), which uses data from the WIMInput.xml file to complete its calculations. To read in this information, the Ind subroutine calls the ReadXML subroutine (Figure 7), which assigns values from the WIMInput.xml file to local variables in the model. This file contains analyst-developed inputs for fuel switching fractions, price elasticities, technology possibility curve growth rates, and relative energy intensity coefficients.

After the ReadXML subroutine executes, the Ind subroutine begins to compute industrial capacity and consumption projections by industry, fuel, and region. First, GDP and industrial price indices are computed across the projection period, by region and fuel, and adjusted for a high world oil price case scenario. Next, an overall industrial quantity index is calculated as the product of the historical consumption of fuels and the GDP and industrial price indices using benchmark factors for each region and industry.

The main Industrial Model then calls the GetGO subroutine (Figure 8) to read in macroeconomic data from an input file and compute the economic growth rate. After calculating the projected growth over the projection period, this subroutine relates overall economic growth of consumption to growth of GDP. It uses a dollar-to-physical-unit growth rate to convert dollars of output to industrial gross output, accounting for inflation and technological advancements over time. This information is then written into an output file. Next, the InitCalc subroutine is called to set up the initial gross outputs, consumption vintages, and intensity vintages. Finally, a weighted average price for each industry is calculated, which is related to historical price indices.

The bulk of the calculations in the Ind subroutine are made in the CalcMan subroutine (Figure 9). CalcMan uses the data in the WIMInput.xml subroutine to estimate the amount of existing, added, new, and total capacities for each fuel, industry, and region. First, consumption growth for each fuel is calculated by region and industry using a formula that assumes a continuous growth rate. Then, a switching fraction and price elasticity determines how much fuel is switched because of price changes throughout the projection period. The totals for each fuel are then calibrated to agree with the
projected total fuel usage in each region and industry through 2050. Then, the AddUp subroutine is called to aggregate the quantities calculated in the previous subroutines and export reports. Several output files are generated and returned to the main World Industrial Model routine. After the Ind subroutine has executed, the WriteRestart subroutine is called to send the output from the WIM to the restart file that will be used in future iterations of WEPS+.

Flow Diagrams
Figure 4 is the flow chart for subroutines, input files, and output files called by the industrial model. Figure 5 through Figure 9 are flow charts that provide more specific details. Figure 4 three subroutines noted with (not IND) are called but are high level subroutines not in the industrial model. The code names for the output and input file write and read statements are listed below:

- IN-Debug.txt (10)
- AllOut.txt (8)
- IN-QtyPrc.txt (31)
- IN-GOOutA.txt (30)
- IN-GOOutB.txt (31)
- IN-RptInit.txt (30)
- IN-MoreDetail.txt (60)
- IN-Detail.txt (25)
- IN-Detail.csv (26)
- ChinaSngleo2015.xml (IndSNG)
- IndInput-2010_07_25_JH.xml (indXML)
- WIMInput.xml (WIMXML)
- Ind_subsector_con.txt (IndHist)
Figure 4. Flow Chart for the Industrial Model Subroutines

ind_run
ReadCntl (not IND)
ReadRestart (not IND)
IndInitialize
Ind
WriteRestart (not IND)
IndInput

AllOut.txt
IN-QtyPrc.txt
IN-Debug.txt from almost all subroutines

IN-GOOutA.txt
IN-GOOutB.txt
IN-RptInit.txt
IN-MoreDetail.txt
IN-Detail.txt
IN-Detail.csv

IndInput-2010_07_25_JH.xml
ChinaSngleo2015.xml
WIMInput.xml
Ind_subsector_con.txt

XML Read Subroutines
XML Read Subroutines
HistRead
GetGO
InitCalc
CalcMan
AddUp
Figure 5. Flowchart for the Industrial Model

Start Main Routine

Call ReadRestart

Call Ind

Call WriteRestart

Return
Figure 6. Flowchart for the Ind Subroutine

Start

Call main model

Restart file data

WIMinput.xml

Call ReadXML

Calculate crude share of crude oil + residual add crude to residual value

Loop by region and year (2005-2007)

Adjust prices to account for any carbon allowance price

Loop by region, year, and fuel

Calculate price elasticities?

Y

N

Modify prices

Recalculate price indices

Loop by region and year

Do feedstocks?

Y

N

Loop by year, region, fuel

Adjust historical data to calculate feedstocks

Call GetGO

Call InitCalc

Call CalcMan

Call AddUp

Loop by region and industry

Do gas adjustment?

Y

N

Loop by region

Adjust historical data to account for LNG and GTL

Loop by fuel, region, and STEO year

Benchmark to STEO (using petroleum product consumption only)

Return

Loop by year, region, fuel

Calculate GDP indices
Figure 7. Flowchart for the ReadXML Subroutine

1. Start
   - Call Ind routine

2. Import WIMInput.xml
   - Import reporting option settings, region labels, etc.

3. Import growth rates of dollars to physical units, retirement rates, retirement rate elasticities, relative energy intensity of new capacity, technology possibility curve (TPC) growth rates for new and remaining capacity, and TPC elasticities for added and remaining capacity

4. Import remaining fuel share natural growth rate, switching fraction, and switching elasticity

5. Import initial relative fuel share factor, new/added fuel share natural growth rate, switching fraction, and switching elasticity

6. Compute "dollars to physical unit" fraction

7. Expand growth rates, switching fractions, and switching elasticities from 6 fuels to 17 fuels

8. Return
Figure 8. Flowchart for the GetGO Subroutine

Start call IND routine

Aggregate gross output (GO) into seven industries used in the industrial model; calculate ‘other’ and ‘total’

Loop by region and year

Loop by year, region, and industry

Change dollars of GO to physical units of GO

Return
Figure 9. Flowchart for the CalcMan Subroutine

Start call IND routine

Calculate weighted average price for industry, "im", based on the price in (year - 1).

If the weighted average prices for current year and prior year are both greater than 0, recalculate the retirement rate.

Re-compute existing capacity with retirements

New required capacity = total - (existing + added_capacity_{year-1})

Idle capacity_{year} = idle capacity_{year-1} - new requirement

Y

N

Decrease new requirement by available idle capacity

New capacity = new requirements

N

Idle capacity_{year} = 0.0

New capacity = new requirements

Added capacity_{year} = added capacity_{year-1} + new capacity_{year}

Total capacity_{year} = existing capacity_{year} + added capacity_{year}

Calculate total energy consumption based on adjusted price elasticities given existing, new, added, and total capacity

Share out total energy consumption for existing, new, and added capacity by fuel type

Loop by fuel

Do chemical feedstocks?

N

Y

Return

Calculate GO index and price index

Calculate feedstock fuel consumed for LPG, "other" petroleum, and crude oil based on data from last historic year and indices
Key Computations

Gross Output
The baseline for the World Industrial Model projections consists of set of gross output projections for specific industries through 2050 for each of the 16 regions from the restart file. These values are generated by the macroeconomic model for specific industries, some of which are aggregates of others. For the WIM there are aggregates to the twelve industry categories that are used in the model:

1. Food
2. Paper
3. Basic Chemicals
4. Refining
5. Iron and Steel
6. Non-Ferrous Metals (primarily aluminum)
7. Non-Metallic Minerals (primarily cement)
8. Other Manufacturing
9. Other Chemicals
10. Agriculture
11. Oil Extraction
12. Coal Extraction
13. Oth Extraction (other mining)
14. Motor Vehicles (transportation equipment motor vehicles and aircraft)
15. OMBD (Other Metal Based Durables)
16. Construction

Vintaging of Gross Output as a Proxy for Capacity
WIM is a stock/flow model that keeps track of simple vintaging of the capacity for each industry and in each region as illustrated in Figure 3. Since there is no direct measure of capacity or a measure of physical output, the model uses the dollar value of gross output as a proxy for capacity. In WIM, gross output is exogenously specified.

To estimate change in output across the projection period the model adds output from new capacity, and subtracts output from existing capacity that is being retired. The “added gross output” is then computed as the sum of gross output from newly installed capacity and the amount of gross output from capacity added in the previous projection year. Finally, the existing/remaining gross output is added to the “added gross output” to calculate the projected “total gross output.” The WIM does not have an exogenously supplied “new gross output” projection series. As a result, it is necessary to indirectly account for the new output for each projection year.

First, the model imports the estimated amount of total gross output, \( TGrOut(x, y, r) \), for each industry \( x \), forecast year \( y \), and region \( r \). Total gross output is the sum of existing gross output for the current year and added gross output for the current year. Existing gross output for this year is equal to last year’s existing gross output adjusted by a retirement rate:

\[
TGrOut(x, r, y) = EGrOut(x, r, y) + AGrOut(x, r, y)
\]

\[
EGrOut(x, r, y) = EGrOut(x, r, y - 1) \times (1.0 - RetRate(x, r, y)),
\]

(1)

(2)
where

\[ TGrOut(x, r, y) = \text{total gross output for industry } x, \text{ region } r, \text{ and year } y \]

\[ EGrOut(x, r, y) = \text{existing gross output for industry } x, \text{ region } r, \text{ and year } y \]

\[ AGrOut(x, r, y) = \text{added gross output for industry } x, \text{ region } r, \text{ and year } y \]

\[ RetRate(x, r, y) = \text{capacity retirement rate for industry } x, \text{ region } r, \text{ and year } y \]

The model then calculates the new gross output added in year \( y \) by subtracting the total gross output for \( y - 1 \) from the total gross output for year \( y \).

\[ NGrOut(x, r, y) = TGrOut(x, r, y) - TGrOut(x, r, y - 1) \]  

\[ = TGrOut(x, r, y) - [EGrOut(x, r, y - 1) + AGrOut(x, r, y - 1)], \]  

where

\[ NGrOut(x, r, y) = \text{new gross output for industry } x, \text{ region } r, \text{ and year } y \]

Finally, the added gross output for the current projection year is calculated as the sum of the added gross output from the previous year plus the new gross output:

\[ AGrOut(x, r, y) = AGrOut(x, r, y - 1) + NGrOut(x, r, y) \]  

**Retirement Rate Adjustment**

The retirement rate is adjusted over time based on the change in the weighted average energy price \( WaPrc(x, r, y) \) and the exogenous retirement price elasticity for that industry and region. The relationship between the change in the retirement rate and prices is given by

\[ \ln \left( \frac{RetRate(x, r, y)}{RetRate(x, r, y - 1)} \right) = RetElas(x, r) \times \ln \left( \frac{WaPrc(x, r, y)}{WaPrc(x, r, y - 1)} \right) \]  

where

\[ RetRate(x, r, y) = \text{retirement rate for industry } x, \text{ region } r, \text{ and year } y \]

\[ RetElas(x, r) = \text{exogenous retirement elasticity with respect to changes in price for industry } x, \text{ region } r, \text{ and year } y, \text{ which is read in from the WIMInput.xml file} \]

\[ WaPrc(x, r, y) = \text{weighted average prices, weighted by fuel, for industry } x, \text{ region } r, \text{ and year } y \]
**Energy Intensity and Consumption by Vintage**

The industrial model projects the energy intensity (of consumption) for each stock/flow vintage of gross output for each industry and each region. Intensity is defined as the total amount of energy consumption for a specific industry in a specific region divided by the corresponding gross output. The intensity in each vintage category is the total consumption for that category divided by its gross output. The model estimates intensity in order to estimate consumption – it does not use consumption estimates to calculate intensity.

**Initial Energy Intensity for the Existing Vintage**

The model begins with the total consumption and the initial total gross output for each industry and region in the most recent historical year for which data are available. It uses the historical consumption and output data to calculate the energy intensity in the last historical year or initial year ($y_i = 2012$) for each industry in each region. This is the starting point for the energy intensity that changes over the projection period.

\[
EFmIntF(x, r, y) = \frac{EFmQty(x, r, y_i)}{EGrOut(x, r, y_i)}
\]

where

- \(EFmIntF(x, r, y_i)\) = energy intensity for industry \(x\), region \(r\), and initial year \(y_i\)
- \(EFmQtyF(x, r, y_i)\) = quantity of energy consumed for industry \(x\), region \(r\), and initial year \(y_i\)
- \(EGrOut(x, r, y_i)\) = gross output of industry \(x\), region \(r\), and initial year \(y_i\)

**Energy Intensity by Vintage**

The energy intensities for the existing and new vintage change over time for reasons such as technology upgrades, process changes, fuel substitution. For each industry and region, this process is represented by a coefficient that provides a growth rate trend factor, which is exogenous.

**Existing Vintage**

The energy intensities for the existing vintage changes over time for reasons such as technology upgrades, process changes, fuel substitution. For each industry and region, this process is represented by a coefficient that provides a growth rate trend factor, which is exogenous. The change in energy intensity for each year is given by

\[
EFmIntF\_1(x, r, y) = EFmIntF\_1(x, r, y - 1) \times (1 + TPCRemGR(x, r))
\]

where:

- \(EFmIntF\_1(x, r, y)\) = unadjusted measure of intensity by industry \(x\), region \(r\), and year \(y\) for the existing vintage
- \(TPCRemGR(x, r)\) = Technology Possibility Curve (TPC) growth rate for all fuels by industry \(x\) and region \(r\) for the existing vintage
Changing energy prices may also affect energy intensity. WIM models this process using a simple price elasticity:

\[
PERFac(x, r, y) = \exp \left[ TPCRemElas(x, r) \times \ln \left( \frac{WaPrc(x, r, y)}{WaPrc(x, r, y - 1)} \right) \right] \quad (9)
\]

where

\[PERFac(x, r, y)\] = TPC adjustment factor with respect to price for industry \(x\), region \(r\), and year \(y\) for the existing vintage

\[TPCRemElas(x, r)\] = elasticity of the TPC with respect to price, for industry \(x\) and region \(r\), which is exogenous and read in from the WIMI Input file

\[WaPrc(x, r, y)\] = weighted average fuel price, for industry \(x\), region \(r\), and year \(y\), summed across all fuels

Multiplying the TPC adjustment factor by unadjusted energy intensity yields adjusted energy intensity for the existing vintage, and energy intensity is multiplied by existing gross output to yield energy consumption for the existing vintage:

\[EFmIntF(x, r, y) = PERFac(x, r, y) \times EFmIntF_{-1}(x, r, y) \quad (10)\]

\[EFmQtyF(x, r, y) = EGrOut(x, r, y) \times EFmIntF(x, r, y). \quad (11)\]

where

\[EFmIntF(x, r, y)\] = adjusted energy intensity for industry \(x\), region \(r\), and year \(y\) for the existing vintage

\[EFmQtyF(x, r, y)\] = total energy consumption for industry \(x\), region \(r\), and year \(y\) for the existing vintage

**New Vintage**

Over the course of the projection period, the model calculates the intensity for new capacity by multiplying the previous measure of intensity by a Relative Energy Intensity (REI) coefficient. The REI coefficient, \(REINew(x, r)\), is exogenously specified for each industry \(x\) and region \(r\). Energy Intensity for the initial year first year \(y_i\) is as follows:

\[NFmIntF(x, r, y_i) = EFmIntF(x, r, y_i) \times REINew(x, r) \quad (12)\]

where

\[NFmIntF(x, r, y_i)\] = energy intensity for industry \(x\) in year \(y_i\) and region \(r\) for the new vintage

\[EFmIntF(x, r, y_i)\] = energy intensity for industry \(x\), region \(r\), and initial year \(y_i\)
Energy intensity for industry $x$ and region $r$ of new vintage equipment relative to existing vintage, which is read in from WIMInput.xml:

$$REINew(x,r) = \text{energy intensity for industry } x \text{ and region } r \text{ of new vintage}$$

The energy intensities for the new capacity change over time for reasons such as technology upgrades, process changes, and fuel substitution. For each industry and region, this process is represented by a coefficient that provides a growth rate trend factor, which is exogenous. Energy intensity for years after the initial year $y_i$ are as follows:

$$NFmIntF(x,r,y) = NFmIntF(x,r,y - 1) \times (1 + TPCNewGR(x,r)) \quad (13)$$

$$NFmQtyF(x,r,y) = NGrOut(x,r,y)^* NFmIntF(x,r,y) \quad (14)$$

where

$NFmIntF(x,r,y)$ = energy intensity for industry $x$ in year $y > y_i$ and region $r$ for the new vintage

$TPCNewGR(x,r) =$ TPC growth rate for all fuels by industry $x$ and region $r$ for the new vintage

$NFmQtyF(x,r,y)$ = total energy consumption industry $x$, region $r$, and year $y > y_i$ for the new vintage;

$NGrOut(x,r,y)$ is as defined on page 24.

Energy consumption for the new vintage is the energy consumption of total added capacity, which is the sum of energy consumption of previously added capacity and new capacity. In subsequent years, energy consumption for added capacity is adjusted by a TPC adjustment parameter similar to $PERFac(x,r,y)$:

$$AFmQtyF_{-1}(x,r,y) = AFmQtyF(x,r,y - 1) + NFmQtyF(x,r,y) \quad (15)$$

$$AFmQty(x,r,y) = PEAFac(x,r,y) * AFmQtyF_{-1}(x,r,y) \quad (16)$$

where

$AFmQtyF(x,r,y)$ = adjusted total energy consumption for industry $x$, region $r$, and year $y$ for the new vintage

$AFmQtyF_{-1}(x,r,y)$ = unadjusted total energy consumption industry $x$, region $r$, and year $y$ for the new vintage

$NFmQtyF(x,r,y)$ = energy consumption of new capacity for industry $x$, region $r$, and year $y$

$PEAFac(x,r,y)$ = $\exp \left[ TPCAddElas(x,r) \times \ln \left( \frac{WaPrce(x,r,y)}{WaPrce(x,r,y-1)} \right) \right]$ 

TPC adjustment parameter with respect to price for industry $x$, region
The intensity and consumption forecast for the overall total capacity are determined through summing total energy use for added and existing capacity and dividing by total gross output:

\[ TFmQtyF(x, r, y) = EFmQtyF(x, y, r) + AFmQtyF(x, y, r) \]  

(17)

\[ TFmIntF(x, r, y) = \frac{TFmQty(x, r, y)}{TGrOut(x, r, y)} \]  

(18)

where

- \( TFmQtyF(x, r, y) \) = total energy consumption for industry \( x \), region \( r \), and year \( y \)
- \( TFmIntF(x, r, y) \) = energy intensity for industry \( x \), region \( r \), and year \( y \) for the new vintage
- \( TGrOut(x, r, y) \) = total gross output for industry \( x \), region \( r \), and year \( y \)

### Consumption by Fuel

The WIM first computes total energy consumption by industry and region for each vintage category, as described above. Then it allocates the total consumption projections to the fuels used in the industrial sector. Although there are 17 fuel types represented in the WIM, the allocation algorithm is applied using six broad fuel categories. This is done to facilitate share specification. The share coefficients for percent fuel for these six fuel categories are later used for all of the subcategories. The six fuel categories are as follows:

- Petroleum (the sum of eight petroleum products)
- Natural Gas
- Coal
- Electricity
- District Heating
- Renewable (the sum of five renewable categories)

The ability to switch fuels is considered to be limited within these 6 groups. The switching on one petroleum fuel for another (say diesel for gasoline) would in most cases not make sense given that a) their prices are positively correlated, therefore savings possibilities are limited; and b) any savings does not justify the investment cost of switching, for example, from a diesel generator to one that runs on gasoline. The fuel sharing estimation methodology is also applied at the vintage category level, because, while the existing/remaining fuel shares are fairly fixed, the added fuel shares can differ as new capacity is installed.
**Fuel Shares and Consumption by Fuel for the Existing Vintage**

The existing vintage fuel shares \((EFS_hr)\) are first set to their values in the initial projection year and then updated for subsequent years, based on relative energy consumption changes in each industry. Shares are calculated for each fuel:

\[
EFS_hr(f, x, r, y) = \frac{EFmQty(f, x, r, y - 1)}{EFmQtyF(x, r, y - 1)}
\]

\[
EFmQty_1(f, x, r, y) = EFS_hr(f, x, r, y) \times EFmQtyF(x, r, y)
\]

where

\(EFS_hr(f, x, r, y)\) = fuel share for fuel \(f\), industry \(x\), region \(r\), and year \(y\) for the existing vintage

\(EFmQty(f, x, r, y)\) = adjusted quantity consumed of fuel \(f\) for industry \(x\), region \(r\), and year \(y\) for the existing vintage

\(EFmQtyF(x, r, y)\) = total energy consumption for industry \(x\), region \(r\), and year \(y\) for the existing vintage

\(EFmQty_1(f, x, r, y)\) = unadjusted quantity consumed of fuel \(f\) for industry \(x\), region \(r\), and year \(y\) for the existing vintage

As each individual share is updated, the sum of the shares may deviate from 1, making it necessary to renormalize the shares. The changes in shares may differ from the changes in actual consumption volume. For example, even though a fuel has a positive growth rate, its normalized share might decrease because other fuels have higher growth rates. Also, fuels with larger initial shares are rising from a larger base value, so minor changes in their shares may represent large consumption changes.

Fuel shares are also affected by fuel substitution in response to changes in relative prices. This is represented through a fuel switching algorithm that uses industrial sector fuel substitution elasticities. First, the relative price changes from the previous model year to the current model year are computed for all fuels \(f \in F = \{c \text{ (coal)}, g \text{ (natural gas)}, o \text{ (oil)}, e \text{ (electricity)}\}\). (All liquid fuels are grouped into the “oil” category). The elasticity \(\eta_{f,l}\) represents the price elasticity of fuel \(f\) with respect to the price of fuel \(l \in F\). Elasticities for each region are obtained or estimated directly from the 2009 World Bank report on interfuel substitution. The equation below computes the relative changes in the fuel mix. The fuel levels are then normalized so that the pre-switching and post-switching total “switchable” fuel consumed (all liquids + natural gas + coal + electricity) are the same.

\[
deltaqty(f) = \sum_{l \in F} \eta_{f,l} \left( \frac{\Delta p_l}{p_l} \right)
\]

The fuel mix change is used to adjust energy consumption by fuel

\[
EFmQty(f, x, r, y) = EFmQty_1(f, x, r, y) \times (1 + \deltaqty(f))
\]

where
\[ \text{deltaqty}(f) = \text{percent change in consumption of fuel } f \]
\[ \eta_{f,l} = \text{price elasticity of fuel } f \text{ with respect to fuel } l \in F \]
\[ p_l = \text{price of fuel } l \in F \]

**Fuel Shares and Consumption for the New Vintage**

Like the fuel shares for existing capacity, the added fuel shares are initialized at the first projection year and then updated to account for trends and substitution due to changes in relative prices. The updates are computed by the same method described above for existing vintage, as shown starting on page 29.

**High World Oil Price Fuel Substitution**

In the High World Oil Price (HWOP) case, the level of petroleum consumption declines significantly. In the model formulation shown above, however, there are no cross-price elasticities, so there is no fuel substitution. This was not considered a particular problem for the original Reference case, because the model was “calibrated” through user judgment for each of the individual fuels. However, because high oil prices cause a lot of movement out of petroleum fuels, it was recognized that some of this change is a behavioral change in which less energy is consumed, but some change is a structural change where other fuels have been substituted for petroleum. A simple algorithm was built into the model to represent this fuel substitution.

In the HWOP case, a portion of the decline in petroleum consumption from the level in the Reference case is replaced by an increase in consumption of other fuels. In order to determine how much petroleum consumption has declined from the Reference case, it is first necessary to read in some data that specify the level of petroleum consumption in the Reference case. These data are read in along with some other data that provide the fractional increment of the petroleum that will be assumed to be replaced by other fuels. In the input file, the fractional increment is set to be 0.5 for all regions, meaning that 50 percent of the petroleum decrease in the HWOP case will be replaced by an increase in consumption of other fuels. The model projects the substitution over the years 2015 to 2050 and modifies the fractional increment so that it starts at 0 in 2015 and ramps up to its full value in 2019, then remains the same to 2050, after which the model solves as it does in the Reference case.

Once the model determines how much petroleum substitution to project, it allocates the amounts to natural gas, coal, and electricity based upon the current relative shares of each of these fuels. For example, if 100 trillion Btu requires a substitution, and the respective shares of natural gas, coal, and electricity are 0.4, 0.0, and 0.6, then projected natural gas consumption will increase by 40 trillion Btu, coal consumption will be unchanged, and electricity consumption will increase by 60 trillion Btu.

**STEO Calibration**

The U.S. Energy Information Administration’s Short-Term Energy Outlook (STEO) projects worldwide liquid fuels consumption to 2013. Outside of the World Industrial Model but within the WEPS+, the Main Model reads the STEO data in each iteration. Based upon the results from the current iteration, the Main Model shares the total petroleum consumption to some sub-regions and to all the detail in the end use sectors. The exception to this step is the electric power sector, where liquids-fired generation is not included because electricity generation is a small liquids-consuming sector. The amount of liquids...
consumption is allocated to the sectors based upon the share of liquids consumption. These quantities are then exported to the restart file so that they are available to each of the WEPS+ models for calibration to STEO. It is worth noting that these sector shares are performed in the Main Model for each WEPS+ iteration so that the actual amounts adapt to the changing shares of projected sector consumption as the model moves towards the equilibrium solution.

**Process Flow Models for China**

Calculating output by process for steel

Heretofore, all the industries in the World Industrial Model are structurally the same. In any given industry, there are two energy intensities \(NEFmIntF\) or \(tF\), which dictate energy consumption for each industry. In particular, no allowance exists for individual processes within a given industry, some of which might have very different energy intensities. For example, in the iron & steel industry, crude steel is generally produced either by recycling scrap steel or by reducing iron ore into iron. Both processes lead to the same steel products but have very different energy requirements.

Allowing for a distinction between processes in the model allows the model to determine the energy use based on factors such as recycling rates. In the World Industrial Model for China, there are now process flow models for the steel and the aluminum portions of the non-ferrous metal industries. Following the method for the NEMS Industrial Demand Model (IDM)\(^2\), the WIM now employs a simpler form of the PRODFLOW matrix similar to that in the IDM, but uses fewer processes than the IDM.

The steel category industry in the IEO contains NACE codes 24.1, 24.2, and 24.3, which include basic steel production as well as hot-rolled and cold-rolled finished products. Steel products from purchased steel is included in the IEO “other” industrial gross output category.

Following the PRODFLOW methodology in the NEMS IDM model, the “process flow” vector \(z\), represents physical output for a particular year. The vector \(z\) can be computed from the multiplication of a formula that includes and input output PRODFLOW and a demand vector, \(d\), which is denominated in dollars. Only the first element of \(d\) is nonzero (year subscripts are suppressed for simplicity):

\[
z = (I - PRODFLOW)^{-1}d
\]

This matrix equation yields this system of equations (see Appendix E for the derivation):

\[
q_{\text{demand}} = (\text{total steel shipments})
\]

\[
q_{\text{EAF}} = P_{\text{EAF}} (\text{total steel shipments})
\]

\[
q_{\text{BOF}} = P_{\text{BOF}} (\text{total steel shipments})
\]

\[
q_{\text{DRI}} = P_{\text{EAF}}X_{\text{DRI}} (\text{total steel shipments})
\]

---


\[ coke = P_{BOF} X_{\text{metcoal}} (\text{total\_steel\_shipments}) \]  \hspace{1cm} (28)

where

- \(q_{\text{demand}}\) = steel production in tons
- \(total\_\text{steel\_shipments}\) = gross output of steel in tons, calculated from the macro model gross output in constant dollars and converted into physical units using an historical price parameter based on the dollar value of shipments in the steel sector and the physical quantity of steel produced
- \(q_{\text{EAF}}\) = electric arc furnace steel output in tons
- \(P_{\text{EAF}}\) = share of steel output produced in an electric arc furnace
- \(q_{\text{BOF}}\) = basic oxygen furnace output in tons
- \(P_{\text{BOF}}\) = share of steel output produced in a basic oxygen furnace \(P_{\text{EAF}} + P_{\text{BOF}} \equiv 1\)
- \(q_{\text{DRI}}\) = electric arc furnace output in tons
- \(X_{\text{DRI}}\) = fraction of input into electric arc furnace that is direct reduced iron
- \(coke\) = coke production in tons
- \(X_{\text{metcoal}}\) = the amount of metallurgical coal needed to produce a certain amount of coke. This element is currently zero, because metallurgical coal is not accounted for separately

In principle, these parameters can be obtained for every country from the data sources cited above, although some work will be required to compute regional parameters for WEPS+ regions. (The historical parameters \(P_{\text{EAF}}, P_{\text{BOF}}, \) and \(X_{\text{DRI}}\) will thus vary depending on the region, e.g., China has a different \(P_{\text{EAF}}\) than does India. So in principle there would be 16 different PRODFLOW matrices if the process flow model methodology were to be implemented for all regions). Note that all three of these parameters will be between (or equal to) 0 and 1, and thus the matrix \((I - \text{PRODFLOW})\) is never singular.

An important point to note is that these parameters \(P_{\text{EAF}}, P_{\text{BOF}}, \) and \(X_{\text{DRI}}\) are time dependent. (\(X_{\text{metcoal}}\) equals 0 since in the IEO2016 metallurgical coal is not accounted for separately.) Thus, if there is reason to believe that the relative fraction of electric arc furnaces will evolve over time, then it can be modified accordingly. This evolution could be a temporal trend from history or can be described using econometric-based drivers such as coal and electricity prices. For the IEO2016 a simple linear trend that represented change in China’s steel production from basic oxygen furnaces to electric arc furnaces was implemented.
Calculating fuel consumption for steel

To compute fuel consumption values \( \hat{C}_\gamma \), the resulting demand vector (the left side of the above equation) is used with an energy intensity matrix to compute actual fuel consumption values. Let fuel \( \gamma \in \{MG, DS, RS, KS, LG, PC, SP, OP, NG, CL, EL, HT, WS, BM, GT, SL, OR\} \) denote a fuel (as shown in Table 7), and let \( C_\gamma \) denote consumption of fuel \( \gamma \). Then \( C_\gamma \) is estimated as

\[
\hat{C}_\gamma = (E_{EAF}^\gamma)(q_{EAF}) + (E_{BOF}^\gamma)(q_{BOF}) + (E_{DRI}^\gamma)(q_{DRI}).
\]  \hfill (29)

Here, for example, \( E_{EAF}^\gamma \) represents the energy intensity of fuels used in EAF production (in trillion Btu/tons of steel).

In general, the energy intensities \( E_I^j \) in many cases can be estimated using data from the U.S. Energy Information Administration’s Manufacturing Energy Consumption Survey (MECS) or from third party data. Some examples for specific fuels are provided. However, many of the intensities are zero: for example, \( E_{CL}^EAF = 0 \), i.e., no coal is used in the electric arc furnace process. If the region has no DRI (or it is known that all the direct reduced iron in the country (like Iran) is made from natural gas), then it can be assumed that all coal is used in the BOF process. Note that energy intensity term \( E_{CL}^{BOF} \) in the above equation will also incorporate the coal used in coke ovens, which is why coke is not specifically part of the fuel list.

Once the energy intensities have been estimated based on existing data, they must be normalized so that the initial energy consumption for each fuel in the steel industry equals the base year fuel consumption coming from the WEPS+ input data (which is derived from the IEA and IES data). So, for example, if the electricity consumption in steel in the base year is \( C_{EL} \), then

\[
C_{EL} = N_{EL} \left[ E_{EAF}^E_{EL} (q_{EAF}) + E_{BOF}^E_{EL} (q_{BOF}) + E_{DRI}^E_{EL} (q_{DRI}) \right]
\]  \hfill (30)

The normalization factor \( N_{EL} \) is used to ensure that the above equation is an equality, and \( N_{EL} \) may be equal to 1. Each intensity is then re-scaled via the same normalization constant for that fuel:

\[
SE_{EAF}^E_{EL} = N_{EL} E_{EAF}^E_{EL}
\]  \hfill (31)

\[
SE_{BOF}^E_{EL} = N_{EL} E_{BOF}^E_{EL}
\]  \hfill (32)

\[
SE_{DRI}^E_{EL} = N_{EL} E_{DRI}^E_{EL}
\]  \hfill (33)

where \( SE_{\gamma}^p \) = Scaled energy intensity for process \( p \) and fuel \( \gamma \).

Over the projection period the projected fuel consumption will change as the \( P_{EAF}, P_{BOF}, \) and \( X_{DRI} \) parameters are allowed to vary over time, e.g., China is assumed to move away from BOF production towards more EAF production eventually. Each \( E_I^j \) is a first cut and can be allowed to evolve via the Technology Possibility Curve (TPC) that is already in place for the steel industry (used for all fuels).

(Note: coke production, whether it is merchant or captive (i.e., within the steel producing facility), in terms of energy use is associated with the steel industry in the IEO. This association of coke production
with the steel industry is not completely accurate since merchant coke production (i.e., coke made in a location other than where the blast furnace is located) is associated with NACE code 19 (coke and refined petroleum products). There is no way to split captive and merchant coke production apart given the aggregations the WEPS+ model has regarding industrial classifications. Thus there is an inconsistency (merchant coke oven energy consumption accounted for in steel, but merchant coke gross output accounted for in coke, refining and petroleum products) but the ultimate effect on energy consumption should be relatively small.

Calculating output for Non-Ferrous metals
This process flow methodology was also used for China’s aluminum industry (the major component of the “non-ferrous metals” industry category). Non-ferrous metals other than aluminum are split out from aluminum based on United States Geological Service reports, which have data for Chinese production of aluminum and other non-ferrous metals detailed separately. The methodology is primarily the same as with the steel sector process flow model.

Refinery Fuel Use
For the IEO2016, refinery fuel use was explicitly computed in the WEPS+ Refinery Model. This is in contrast to previous reports where projected gross output shipments from the macro model were used to determine refinery fuel consumption. Because the refinery fuel consumption is directly correlated with overall liquids demand, for the IEO2016, liquids demand from all demand sectors (industrial, transportation, commercial, and residential) for all liquid fuels was used by the WEPS+ Refinery model to calculate the requisite fuel consumption for refinery processing. See the WEPS+ Refinery model documentation for more details.

Additional Calibrations
As noted, the base year 2012 for the IEO2016 is also the last historical year, meaning that all subsequent years are projection years, including 2013 and 2014. One of the largest calibrations performed for the IEO2016 was the inclusion of an “unspecified sector” in the demand modeling, which represented an adjustment for liquid fuel consumption. This adjustment was based on the apparent historical discrepancy between the data used from the IEO’s traditional data sources (i.e., EIA’s International Energy Statistics (IES) consumption data and the IEA’s historical disaggregated consumption data) and “bottom-up” analysis based on historical industrial production/gross output shipment levels. This adjustment for historical liquids fuel consumption was most pronounced for China, where implied diesel fuel intensities based on construction and mining shipments seemed much too low. Also, petroleum coke use (in the form of catalytic coke) in the refining sector in China is not accounted for by the IEA or IES, and thus an adjustment for this historical data point had to be made as well. More detail on the broader methodology and rationale for implementing this “unspecified sector” in the IEO2016 can be found in the publication itself.

Another calibration for China that was implemented for the IEO2016 was allowing for an explicit switch from diesel to liquefied natural gas (LNG) in heavy off-road equipment used in the mining and construction industries. Using a predetermined elasticity, the diesel – natural gas price differential at any given year in the projection period is compared to the price differential in the first projection year (2013). If the current differential is greater than the base year differential, then a portion of the
incremental diesel fuel demand for that year is assumed to be natural gas instead of diesel. The exact portion depends on the size of the price differential and the aforementioned predetermined elasticity.

Finally, a calibration for China’s chemical feedstock consumption was implemented. First, based on outside third party data from IHS, coal feedstock consumption levels were hardcoded inside the WIM itself through year 2018. Post 2018, incremental feedstock use in China was projected using a preset share amongst the following chemical feedstocks: LPG (10%), naphtha (30%), natural gas (30%), and coal (30%). For future IEO reports, these percentages can be modified based on relative prices and/or policy changes.
Appendix A. Model Abstract

Model Name:  
World Industrial Model of the World Energy Projection System Plus

Model Acronym:  
WIM

Model Description:  
The World Industrial Model of the World Energy Projection System Plus (WEPS+) is a computer-based energy demand modeling system of the world industrial sector at a regional level. The WEPS+ World Industrial Model for the IEO2016 projects energy use that is consumed in the manufacturing, agricultural, construction, and mining sectors. The model projects industrial sector consumption for 18 energy sources in each of the 16 WEPS+ regions on an annual basis to 2050.

Model Purpose:  
As a component of the World Energy Projection System Plus (WEPS+) integrated modeling system, WIM generates long-term projections of industrial sector energy consumption. As part of the system, the model provides consumption inputs for a variety of the other WEPS+ models. The model provides a tool for analysis of international industrial energy use within the WEPS+ system and can be run independently as a standalone model.

Most Recent Model Update:  
May 2016

Part of Another Model:  
World Energy Projection System Plus (WEPS+)

Model Interfaces:  
WIM receives inputs from and provides outputs to a variety of other models in the WEPS+ system, through the common, shared interface file of the WEPS+.

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Paul Otis  
Telephone: (202) 586-2306

Address:  
Energy Information Administration  
Office of Energy Analysis  
EI-32/Forrestal Building  
United States Department of Energy  
1000 Independence Avenue, SW  
Washington, D.C. 20585
**Documentation:**

**Archive Information:**
The model is archived as part of the World Energy Projection System Plus archive of the runs used to generate the *International Energy Outlook 2016*.

**Energy System Described:**
International industrial sector energy consumption.

**Coverage:**
**Geographic:** Sixteen WEPS+ regions: U.S., Canada, Mexico/Chile, OECD Europe, Japan, Australia/New Zealand, South Korea, Russia, Other non-OECD Europe and Eurasia, China, India, other non-OECD Asia, Middle East, Africa, Brazil, and other Non-OECD Americas. The following defines the multi-country regions:

- **OECD Europe:** This includes European Union and all of Europe except countries listed for Other non-OECD Europe and Eurasia. Israel is also included.
- **Other non-OECD Europe and Eurasia:** Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, FYROM (Macedonia), Georgia, Gibraltar, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Moldova, Romania, Serbia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
- **Non-OECD Asia:** This is all other Asia countries that are not specifically considered.
- **Middle East:** Bahrain, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates (UAE), Yemen
- **Africa:** All countries in the continent of Africa to include northern Africa countries such as Egypt.
- **Non-OECD Americas:** Central America, Caribbean and South America not elsewhere classified.

**Mode:** total industrial sector energy consumption.

**Time Unit/Frequency:** Annual, 20135 through 2050.

**Modeling Features:**
The World Industrial Model projects energy use in the manufacturing, agricultural, construction and mining sectors for 18 energy sources in each of the sixteen WEPS+ regions on an annual basis to 2050. The model primarily employs a stock-flow accounting framework that uses exogenously-specified output of specific industries as a proxy for productive capacity. In WIM, old capacity is retired over time to make way for new capacity. This framework allows for the modeling of changes in energy efficiency over time. Exogenously-specified energy prices impact both the mechanisms of the stock-flow process and fuel switching over time.

**DOE Input Sources:**

*Non-DOE Input Sources:*


*Independent Expert Reviews:*
None

*Computing Environment:*
Hardware/Operating System: PC with Windows OS.

Language/Software Used: Intel Fortran version 11.1, 64-bit.

Run Time/Storage: Standalone model with one iteration runs in about 3-4 seconds, CPU memory is minimal, inputs/executable/outputs require less than 20MB storage.

Special Features: None.
Appendix B. Input Data and Variable Descriptions

The WIM model variables with the definition, type, and units are listed in Table 6. The types are the following: Exogenous variables that are received from other models; Endogenous variables that are defined and used in the WIM model. Since prices are for different regions, they are defined based on region specific Purchasing Power Parity (PPP) to convert prices to 2013 USA dollars by million Btu (2013$PPP/mill Btu). There are also shipments that are by region specific PPP to convert prices to 2010 USA dollars (2010 US $ PPP). Energy use is by Trillion Btu (TBTu). Energy intensity is energy use divided by shipments (TBTu/billion 2010 US $ PPP). Several variables are unitless because they are ratios, region names, functions, or type indicators (e.g., fuel types).

Table 6. WIM Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Filename</th>
<th>Definition</th>
<th>Type</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACLIN</td>
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<td>Endogenous</td>
<td>TBTu/billion 2010 US $ PPP</td>
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<td>TBTu</td>
</tr>
<tr>
<td>AFQtyA</td>
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<td>Endogenous</td>
<td>TBTu</td>
</tr>
<tr>
<td>AFrInt</td>
<td></td>
<td>added since initial year intensity at fuel report detail level</td>
<td>Endogenous</td>
<td>TBTu/billion 2010 US $ PPP</td>
</tr>
<tr>
<td>AFrQty</td>
<td></td>
<td>added since initial year consumption at fuel report detail level</td>
<td>Endogenous</td>
<td>TBTu</td>
</tr>
<tr>
<td>AFShr</td>
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<td>added fuel share</td>
<td>Endogenous</td>
<td>Unitless</td>
</tr>
<tr>
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<td>TBTu</td>
</tr>
<tr>
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</tr>
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</tr>
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<tr>
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<td></td>
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</tr>
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<td>Definition</td>
<td>Type</td>
<td>Units</td>
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<tr>
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<td>TBTu</td>
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<td>Variable</td>
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<td>------------</td>
<td>------------------------</td>
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<td>TBtu</td>
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<td>OPFeed</td>
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<td>QHDSIN</td>
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<td>quantity of industrial use of electricity</td>
<td>Endogenous</td>
<td>TBtu</td>
<td></td>
</tr>
<tr>
<td>QHGTIN</td>
<td>quantity of industrial use of geothermal</td>
<td>Endogenous</td>
<td>TBtu</td>
<td></td>
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<td>quantity of industrial use of heat</td>
<td>Endogenous</td>
<td>TBtu</td>
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<td>Endogenous</td>
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<td>quantity of industrial use of LPG including feedstocks</td>
<td>Endogenous</td>
<td>TBtu</td>
<td></td>
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<td>quantity of industrial use of motor gasoline</td>
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<td>TBtu</td>
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<td>quantity of industrial use of natural gas including feedstocks</td>
<td>Endogenous</td>
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<td>quantity of industrial use of residual</td>
<td>Endogenous</td>
<td>TBtu</td>
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<td>TBtu</td>
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</tr>
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<td>QHW SIN</td>
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</tr>
<tr>
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<td>Definition</td>
<td>Type</td>
<td>Units</td>
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<td>TBtu</td>
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<td>Endogenous</td>
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<tr>
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<td>Endogenous</td>
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</tr>
<tr>
<td>ZGTIN</td>
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<td>Endogenous</td>
<td>TBtu</td>
</tr>
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<td>ZHTIN</td>
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<td>quantity of heat consumption over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
</tr>
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<td>ZKSIN</td>
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<td>quantity of industrial consumption of kerosene over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
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<td>Variable</td>
<td>Filename</td>
<td>Definition</td>
<td>Type</td>
<td>Units</td>
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<td>industrial coal gasification</td>
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<td>TBtu</td>
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<td>quantity of industrial consumption of motor gasoline over forecast period</td>
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<td>TBtu</td>
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<td>ZNGLPIN</td>
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<td>industrial natural gas feedstock consumption</td>
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<td>TBtu</td>
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<td>ZNGFDIN</td>
<td></td>
<td>quantity of industrial consumption of natural gas over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
</tr>
<tr>
<td>ZNGIN</td>
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<td>industrial natural gas lease and plant consumption</td>
<td>Endogenous</td>
<td>TBtu</td>
</tr>
<tr>
<td>ZOPFDIN</td>
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<td>industrial other petroleum feedstock consumption</td>
<td>Endogenous</td>
<td>TBtu</td>
</tr>
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<td>ZOPIN</td>
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<td>quantity of industrial consumption of other petroleum over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
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<tr>
<td>ZORIN</td>
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<td>Endogenous</td>
<td>TBtu</td>
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<td>quantity of industrial consumption of petroleum coke over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
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<td>ZRSIN</td>
<td></td>
<td>quantity of industrial consumption of residual over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
</tr>
<tr>
<td>ZSLIN</td>
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<td>quantity of industrial consumption of solar over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
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<tr>
<td>ZSPIN</td>
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<td>quantity of industrial consumption of sequestered petroleum over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
</tr>
<tr>
<td>ZWSIN</td>
<td></td>
<td>quantity of waste consumption over forecast period</td>
<td>Endogenous</td>
<td>TBtu</td>
</tr>
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**Table 7. Fuel Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Fuel Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG</td>
<td>Motor Gasoline</td>
</tr>
<tr>
<td>DS</td>
<td>Distillate</td>
</tr>
<tr>
<td>RS</td>
<td>Residual</td>
</tr>
<tr>
<td>KS</td>
<td>Kerosene</td>
</tr>
<tr>
<td>LG</td>
<td>Liquefied Petroleum Gas (LPG)</td>
</tr>
<tr>
<td>PC</td>
<td>Petroleum Coke</td>
</tr>
<tr>
<td>SP</td>
<td>Sequestered Petroleum</td>
</tr>
<tr>
<td>OP</td>
<td>Other Petroleum</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>CL</td>
<td>Coal</td>
</tr>
<tr>
<td>EL</td>
<td>Electricity</td>
</tr>
<tr>
<td>HT</td>
<td>Heat</td>
</tr>
<tr>
<td>WS</td>
<td>Waste</td>
</tr>
<tr>
<td>BM</td>
<td>Biomass</td>
</tr>
<tr>
<td>GT</td>
<td>Geothermal</td>
</tr>
<tr>
<td>SL</td>
<td>Solar</td>
</tr>
<tr>
<td>OR</td>
<td>Other Renewables</td>
</tr>
</tbody>
</table>
Appendix C. References

Appendix D. Data Quality

Introduction
For 16 regions of the world, WIM projects world industrial use of fuels (including motor gasoline, distillate fuel, residual fuel, kerosene, liquefied petroleum gas including feedstocks, petroleum coke, sequestered petroleum, other petroleum use including feedstocks, direct use crude oil, natural gas including feedstocks, coal including coking coal, electricity, heat, waste, biomass, geothermal, solar, and other renewables). The WIM projections are computed from the data elements listed in Appendix B. Chapter 4 (Model Structure) details the WIM estimation methods and the inputs required to implement the model algorithms. Here the principal sources of input data are described and information is provided, where available, about the quality of the imported parameter estimates.

Source and Quality of Input Data

Source of Input Data
• **STEO** – Short-term liquid fuel consumption from 2005 to 2013 are provided by region from EIA’s Short-Term Energy Outlook. The IEO2016 results are benchmarked to the STEO results.

• **International Statistics Database** – The Energy Information Administration provides historical data on international energy consumption by fuel type from 1980 through 2012. These data are used as the historical basis for all regional projections that appear in the IEO2016. While the numbers are continuously updated, WEPS+ used a “snap shot” of the database as it existed on April, 2015 as the source of its international data.

• **International Energy Agency** – The by-end-use-sector, by-product historical data are available from the OECD and non-OECD balances and statistics database by country on the subscription site www.iea.org. These data are benchmarked to the historical aggregate energy consumption data provided in the Energy Information Administration’s international statistical data base.

• **NEMS** – Many of the assumptions about price and economic elasticities are based in large part on those included in the National Energy Modeling System for the United States. Expert judgment has, in some cases, been used to alter assumptions based on analyst knowledge about specific regions in the WEPS+ model.

Data Quality Verification
As a part of the input and editing procedure, an extensive program of edits and verifications was used, including:

• Checks of projected values for world and U.S. industrial consumption of fuels, retail prices, and elasticities, based on historical data, previous projections, responses, knowledge of regional economics, and technical knowledge

• Consistency checks

• Technical edits to detect extreme values or variability and correct errors
Appendix E. Derivation of Matrix Terms for Steel

This Appendix describes the full derivation of the PRODFLOW matrix for steel into the equation system represented on Page 31. Following the PRODFLOW methodology in the NEMS IDM model, the “process flow” vector, represents physical output for a particular year. The vector \( z \) can be computed from the multiplication of a formula that includes and input output (I/O) matrix \( A \) and a demand vector, \( d \), which is denominated in dollars. Only the first element of \( d \) is nonzero (year subscripts are suppressed for simplicity):

\[
z = (I - \text{PRODFLOW})^{-1} d
\]

where \( I \) = identity matrix, \( A = \text{I/O matrix} \), and \( d = \text{demand vector} \). In matrix form this equation is:

\[
\begin{bmatrix}
q_{\text{demand}} \\
q_{\text{EAF}} \\
q_{\text{BOF}} \\
q_{\text{DRI}} \\
\text{coke}
\end{bmatrix} = 
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
-P_{\text{EAF}} & 1 & 0 & 0 & 0 \\
-P_{\text{BOF}} & 0 & 1 & 0 & 0 \\
0 & -X_{\text{DRI}} & 0 & 1 & 0 \\
0 & 0 & -X_{\text{metcoal}} & 0 & 1
\end{bmatrix}^{-1}
\begin{bmatrix}
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}}
\end{bmatrix}
\]

(34)

When the inverted matrix terms are explicitly represented,\(^3\)

\[
\begin{bmatrix}
q_{\text{demand}} \\
q_{\text{EAF}} \\
q_{\text{BOF}} \\
q_{\text{DRI}} \\
\text{coke}
\end{bmatrix} = 
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
P_{\text{EAF}} & 1 & 0 & 0 & 0 \\
P_{\text{BOF}} & 0 & 1 & 0 & 0 \\
P_{\text{EAF}}X_{\text{DRI}} & X_{\text{DRI}} & 0 & 1 & 0 \\
P_{\text{BOF}}X_{\text{metcoal}} & 0 & X_{\text{metcoal}} & 0 & 1
\end{bmatrix}
\begin{bmatrix}
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}} \\
total_{\text{steel}}_{\text{shipments}}
\end{bmatrix}
\]

(35)

which yields the system of equation as on page 31:

\[
q_{\text{demand}} = (\text{total}_{\text{steel}}_{\text{shipments}})
\]

\[
q_{\text{EAF}} = P_{\text{EAF}} (\text{total}_{\text{steel}}_{\text{shipments}})
\]

\[
q_{\text{BOF}} = P_{\text{BOF}} (\text{total}_{\text{steel}}_{\text{shipments}})
\]

\[
q_{\text{DRI}} = P_{\text{EAF}}X_{\text{DRI}} (\text{total}_{\text{steel}}_{\text{shipments}})
\]

\[
\text{coke} = P_{\text{BOF}}X_{\text{metcoal}} (\text{total}_{\text{steel}}_{\text{shipments}})
\]

---

\(^3\) Source: Matrix calculator: https://matrixcalc.org/en/#%7B%7B1,0,0,0%7D,%7B1,0,0,0%7D,%7B0,1,0,0%7D,%7B0,1,0,0%7D,%7B0,1,0,0%7D,0,1%7D%7D %5E%28-1%29
Appendix F. Derivation of Elasticities

Below is the derivation of the retire elasticity and energy intensity elasticity equations. By the standard definition of price elasticity we have

$$Elasticity = \frac{\Delta x / x}{\Delta P / P}$$

Where $x$ is usually the price sensitive (demand) quantity but here we define it as the retirement rate or energy intensity; $P$ of course represents the price. Allowing the finite differences to become differentials in the limit as $\Delta x \to 0$, i.e., letting $\Delta x \to dx$ and $\Delta P \to dP$ we have

$$Elasticity = \frac{dx / x}{dP / P}.$$ 

The natural log ($\ln x$) is defined as the integral of $1/t$ is, from 1 to $x$, i.e.,

$$\int_1^x \frac{dt}{t} \equiv \ln x$$

and so

$$\frac{dx}{x} = d[\ln x].$$

Approximating the differential on the right with a finite difference we have

$$\frac{dx}{x} \approx \Delta[\ln x].$$

If $\Delta$ is the difference operator for quantities representing adjacent time points (one year apart for the IEO2016 model), then

$$\Delta[\ln x] = \ln x(t) - \ln x(t - 1) = \ln \frac{x(t)}{x(t - 1)},$$

and similarly for approximating $dP / P$. Thus finally we have the desired result:

$$Elasticity = \frac{\ln[x(t)/x(t - 1)]}{\ln[P(t)/P(t - 1)].}$$