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World Energy Projection System Plus (WEPS+): 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 EIA used to produce the industrial sector projections published in the *International Energy Outlook 2019* (IEO2019). WIM is 1 of 13 components of the WEPS+ energy modeling system, but the industrial model can also be run as a separate, individual model. 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 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.

Model Summary

The WEPS+ projects energy use in the manufacturing, agricultural, construction and mining sectors for 18 energy sources in each of the 16 WEPS+ regions for every year through 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 EIA to model changes in energy efficiency over time. Exogenously-specified energy prices affect both the mechanisms of the stock-flow process and the fuel switching projections over time.

Model Archival Citation

This documentation refers to the WEPS+ World Industrial Model as archived for the *International Energy Outlook 2019* (IEO2019).

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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 WIM model to 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.

2. Model Purpose

Model Objectives

The WIM generates annual projections of industrial energy use for 2017 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. Multi-country regions (e.g., OECD Europe) are listed in Appendix A.

Table 1. Regional coverage of the WEPS+ model

OECD Regions and index	Non-OECD Regions
United States	Russia
Canada	Non-OECD Europe and Eurasia
Mexico/Chile	China
OECD Europe	India
Japan	Other non-OECD Asia
Australia/New Zealand	Middle East
South Korea	Africa
	Brazil
	Non-OECD Americas

Models Inputs and Outputs

Inputs

WIM uses macroeconomic and industrial price projections imported from the WEPS+ restart file. These inputs have been previously projected by the Macroeconomic Model and the transformation and supply models (Table 2).

Table 2. WEPS+ Models that provide input to the World Industrial Model (WIM)

WIM Input	Source
Gross domestic product	Macroeconomic Model
Outputs of specific industries	Macroeconomic Model
Industrial retail prices	
Energy source	
motor gasoline	Global Hydrocarbon Supply Model
distillate	Global Hydrocarbon Supply Model
residual fuel	Global Hydrocarbon Supply Model
LPG (ethane, propane, butane, natural gasoline)	Global Hydrocarbon Supply Model
other petroleum	Global Hydrocarbon Supply Model
natural gas	Global Hydrocarbon Supply Model
coal	Coal Model
electricity	International Electricity Markets Model
district heat	District Heat Model

The data series listed in Table 3 are also imported into the WIM from the WIMInput.csv file.

Table 3. Major exogenous World Industrial Model (WIM) input data series

Source Input File	WIM Input
WIMInput.csv	Capacity retirement rates by industry and region
	Capacity retirement rate elasticities by industry and region
	Relative Energy Intensity (REI) coefficients by industry and region
	Technology Possibility Curve (TPC) growth rates for existing and new capacity by industry and region
	Technology Possibility Curve (TPC) price elasticities for existing and new capacity by industry and region

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 output and the WEPS+ models that use them

WIM Output	Destination
Petroleum consumption	Global Hydrocarbon Supply Model
motor gasoline	
distillate	
residual fuel	
LPG (ethane, propane, butane, natural gasoline)	
petroleum coke	
sequestered petroleum	
other petroleum	
crude oil (direct use)	
Natural gas consumption	Global Hydrocarbon Supply Model
Coal consumption	Coal Model
Electricity consumption	International Electricity Markets Model
Heat consumption	District Heat Model
Waste consumption	Reporting
Biomass consumption	Reporting
Geothermal consumption	Reporting
Solar consumption	Reporting
Other renewable consumption	Reporting

Relationship to Other Models

WIM is an integral component of the WEPS+ system and depends on 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 on for their key inputs. A summary description of the models, flows, and mechanics of the WEPS+ system used for the *IEO2019* report is available in a separate *Overview*.

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. 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 stand-alone model. In stand-alone mode, WIM inputs macroeconomic and price projections from the WEPS+ system *restart* file as created in a previous full-system run.

3. Model Rationale

Theoretical Approach

The 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). WIM projects industrial consumption for 18 energy sources in each of the 16 WEPS regions through the year 2050. WIM is a structured, industry-level, stock/flow model that uses gross output from the Macroeconomic Model and historical energy consumption as its primary drivers. These drivers are available to the WIM from the WEPS+ transformation and supply models through the shared restart file.

WIM projects energy consumption in eight energy-intensive (EI) industries, or distinctive with respect to energy consumption, three non-energy intensive (NEI), and five non-manufacturing (NM) industries. Table 5 shows these 16 industries.

Table 5. Industrial sector industries

Industry Classification	Industry Category	Representative Industries
EI	Food	Food, beverage, and tobacco product manufacturing
EI	Paper	Paper manufacturing, printing, and related support activities
EI	Basic chemicals	Inorganic chemicals, organic chemicals (e.g., ethylene, propylene), resins, and agricultural chemicals, including chemical feedstocks
EI	Refining	Petroleum refineries and coal products manufacturing, including coal and natural gas used as feedstock
EI	Iron and steel	Iron and steel manufacturing, including coke ovens
EI	Non-ferrous Metals	Primarily aluminum and other non-ferrous metals such as copper, zinc, and tin, including carbon anode production for primary aluminum smelting
EI	Non-metallic Minerals	Primarily cement and other non-metallic minerals such as glass, lime, gypsum, and clay products
NEI	Other industrial	All other manufacturing
EI	Other chemicals	Pharmaceuticals, medicinal and botanical, paint and coatings, adhesives, detergents, and other miscellaneous chemical products, including chemical feedstocks
NM	Agriculture	Agriculture, forestry, and fishing
NM	Oil extraction	Oil and natural gas extraction
NM	Coal extraction	Coal extraction
NM	Other extraction	Metallic and non-metallic minerals mining such as bauxite, iron, lithium, sand, or gold
NEI	Motor vehicles	Transportation equipment—motor vehicles and aircraft—manufacturing.
NEI	Other metal-based durables	Other metal based durables (OMBD) manufacturing, computer and electronic products, machinery, and electrical equipment appliances and components
NM	construction	Buildings (residential and commercial) construction, heavy and civil engineering construction, industrial construction, and specialty trade contractors

WIM uses a stock/flow approach to estimate the 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 industrial capacity for the historical base year (the base year is 2016 for the *IEO2019*), which is based on industrial output. The base year industrial energy intensity is computed from the original existing capacity.

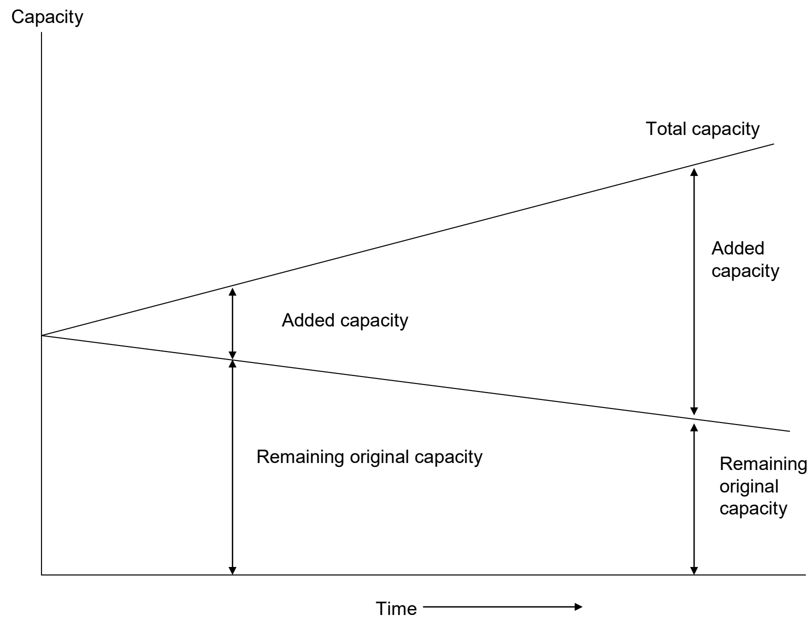
Added capacity (New Vintage) includes two types:

- **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 and 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 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 1.

Figure 1. Illustration of stock/flow industrial capacity changes over time



WIM requires significant initial data along with a number of projection coefficients. The data used to project industrial sector consumption are 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 EIA. The coefficients for the *IEO2019* were based on comparisons of existing industrial energy intensities among world regions, taking into account the efficiency discrepancies between industrialized regions and 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

- 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.

[1] The model does not explicitly consider capacity utilization. However, if industrial output declines, 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.

- Energy prices affect 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.

4. Model Structure

Structural Overview

The WIM projects annual industrial sector energy consumption, by region and fuel type, for 2017 through 2050. The industrial energy consumption calculations incorporate inputs that reflect EIA 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).

A call from the WEPS+ model interface to the WIM begins the import of information from the restart file and the other WEPS+ models it needs to complete the projection calculations.

Key Computations

Gross Output

The baseline for the WIM projections consists 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 16 industry categories used in the model:

- Food
- Paper
- Basic chemicals
- Refining
- Iron and steel
- Non-ferrous metals (primarily aluminum)
- Non-metallic minerals (primarily cement)
- Other manufacturing
- Other chemicals
- Agriculture
- Oil extraction
- Coal extraction
- Other extraction (metallic and non-metallic minerals mining)
- Motor vehicles (transportation equipment motor vehicles and aircraft)
- OMBD (other metal-based durables)
- 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. Because 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, EIA must indirectly account for the new output for each projection year.

First, the model imports the estimated 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:

$$TGrOut(x,r,y) = EGrOut(x,r,y) + AGrOut(x,r,y) \tag{1}$$

$$EGrOut(x,r,y) = EGrOut(x,r,y-1) * \big(1.0 - RetRate(x,r,y)\big), \tag{2}$$

where

$TGrOut(x,r,y)$	= total gross output for industry x, region r, and year y
$EGrOut(x,r,y)$	= existing gross output for industry x, region r, and year y
$AGrOut(x,r,y)$	= added gross output for industry x, region r, and year y
$RetRate(x,r,y)$	= capacity retirement rate for industry x, region r, and year y

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

$$NGrOut(x,y,r) = TGrOut(x,r,y) - TGrOut(x,r,y-1) \tag{3}$$

$$= TGrOut(x,r,y) - [EGrOut(x,r,y-1) + AGrOut(x,r,y-1)], \tag{4}$$

where

$NGrOut(x,r,y)$	= new gross output for industry x, region r, 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:

$$AGrOut(x,r,y) = AGrOut(x,r,y-1) + NGrOut(x,r,y) \quad (5)$$

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

$$\ln\left(\frac{RetRate(x,r,y)}{RetRate(x,r,y-1)}\right) = RetElas(x,r) * \ln\left(\frac{WaPrc(x,r,y)}{WaPrc(x,r,y-1)}\right) \quad (6)$$

where

$RetRate(x,r,y)$	= retirement rate for industry x, region r, and year y
$RetElas(x,r)$	= exogenous retirement elasticity with respect to changes in price for industry x, region r, and year y, which is read in from the WIMInput.xml file
$WaPrc(x,r,y)$	= weighted average prices, weighted by fuel, for industry x, region r, 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 consumption for an industry in a 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 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 ($yi = 2016$) for each industry in each region. This calculation is the starting point for the energy intensity that changes over the projection period.

$$EFmIntF(x,r,yi) = \frac{EFmQty(x,r,yi)}{EGrOut(x,r,yi)} \quad (7)$$

where

$EFmIntF(x,r,yi)$	= energy intensity for industry x, region r, and initial year yi
$EFmQtyF(x,r,yi)$	= quantity of energy consumed for industry x, region r, and initial year yi

$EGrOut(x, r, yi)$	= gross output of industry x, region r, and initial year yi

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

$$EFmIntF\_1(x,r,y) \; = \; EFmIntF\_1(x,r,y-1) ^* \; (1 + TPCRemGR(x,r)) \qquad (8)$$

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:

$$PERFac(x,r,y) \; = \exp\left[TPCRemElas(x,r) * \ln\left(\frac{WaPrc(x,r,y)}{WaPrc(x,r,y-1)}\right)\right] \qquad (9)$$

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 WIMInput 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:

$$EFmIntF(x,r,y) = \; PERFac(x,r,y) * EFmIntF\_1(f,x,r,y) \qquad (10)$$

$$EFmQtyF(x,r,y) = \; EGrOut(x,r,y)^* \; EFmIntF(x,r,y). \qquad (11)$$

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 yi is as follows:

$$NFmIntF(x,r,yi) = EFmIntF(x,r,yi)^{*}\ REINew(x,r) \qquad (12)$$

where

$NFmIntF(x,r,yi)$	= energy intensity for industry x in year yi and region r for the new vintage
$EFmIntF(x,r,yi)$	= energy intensity for industry x, region r, and initial year yi
$REINew(x,r)$	= energy intensity for industry x and region r of new vintage equipment relative to existing vintage, which is read in from WIMInput.xml

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 yi are as follows:

$$NFmIntF(x,r,y) = \ NFmIntF(x,r,y-1)^{*}\ (1 + TPCNewGR(x,r)) \qquad (13)$$

$$NFmQtyF(x,r,y) = \ NGrOut(x,r,y)^{*}\ NFmIntF(x,r,y) \qquad (14)$$

where

$NFmIntF(x,r,y)$	= energy intensity for industry x in year $y > yi$ 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 $y > yi$ for the new vintage;

$NGrOut(x,r,y)$ = nominal gross output of industry x, region r, and year y

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

$PEAFac(x,r,y)$ = $\exp\left[TPCAddElas(x,r) * \ln\left(\frac{WaPrc(x,r,y)}{WaPrc(x,r,y-1)}\right)\right]$ TPC adjustment parameter with respect to price for industry x,region r, and year y for the new vintage, analogous to $PERFac(x,r,y)$.

Total energy Consumption and Intensity

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:

$$TFmQtyF(x,y,r) = EFmQtyF(x,y,r) + AFmQtyF(x,y,r) \quad (17)$$

$$TFmIntF(x,r,y) = \frac{TFmQty(x,r,y)}{TGrOut(x,r,y)} \quad (18)$$

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 18 fuel types represented in the WIM, the allocation algorithm is applied using 6 broad fuel categories, which facilitates 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 include

- Petroleum (the sum of eight petroleum products)
- Natural gas
- Coal
- Electricity
- District heat
- Renewables (the sum of five renewable categories)

The ability to switch fuels is considered to be limited within these six groups. The switching from one petroleum fuel to another (say diesel to 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, although 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 ($EFShr$) 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:

$$EFShr(f,x,r,y) = \frac{EFmQty(f,x,r,y-1)}{EFmQtyF(x,r,y-1)} \qquad (19)$$

$$EFmQty\_1(f,x,r,y) = EFShr(f,x,r,y) * EFmQtyF(x,r,y) \qquad (20)$$

where

$EFShr(f,x,r,y)$	= 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 the individual shares are updated, the sum of the shares may deviate from one, 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 change 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 $f \in F = \{c\ (coal),\ g\ (natural\ gas), o\ (oil), e\ (electricity)\}$. (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.

$$deltaqty(f) = \sum_{l \in F} \eta_{f,l} \left(\frac{\Delta p_l}{p_l}\right) \qquad (21)$$

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

$$EFmQty(f,x,r,y) = EFmQty\_1(f,x,r,y) * (1 + deltaqty(f)) \qquad (22)$$

where

$deltaqty(f)$ = percentage change in consumption of fuel f

$\eta_{f,l}$ = price elasticity of fuel f with respect to fuel $l \in F$

p_l = 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 as a result of changes in relative prices. The updates are computed by the same method described above for existing vintage.

Refinery Fuel Use

For the *IEO2019,* refinery fuel use was explicitly computed in the WEPS+ Global Hydrocarbon Supply Model (GHySMo). Fuel use for coal-to-liquids (CTL), gas-to-liquids (GTL), and biomass-to-liquids (BTL) production is also computed by GHySMo. See GHySMo documentation for more details.

Oil and Natural Gas Extraction Fuel Use

Fuel use for liquefaction and regasification of LNG, as well as lease and plant fuel (fuel typically used at the extraction site), is computed in GHySMo.

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 (WIM) 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+ WIM for the *IEO2019* projects energy use that is consumed in 16 industries comprising the manufacturing, agricultural, construction, and mining sectors. The model projects industrial sector consumption for 18 energy sources in each of the 16 WEPS+ regions every year from 2017 through 2050.

Model Purpose:

As a component of the WEPS+ integrated modeling system, WIM generates long-term projections of industrial sector energy consumption. As part of the system, WIM provides consumption inputs for a variety of the other WEPS+ models. The model provides a tool for analyzing international industrial energy use within the WEPS+ system, and WIM can be run independently as a standalone model.

Most Recent Model Update:

October 2018

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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Documentation:

Energy Information Administration, U.S. Department of Energy, *World Industrial Model of the World Energy Projection System Plus: Model Documentation 2019*, DOE/EIA(2019)

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 2019*.

Energy System Described:
International industrial sector energy consumption

Coverage:
Geographic: 16 WEPS+ regions: United States, 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: The European Union, Israel, and all of Europe except countries listed for Other non-OECD Europe and Eurasia
- Other non-OECD Europe and Eurasia: Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Fyrom (Republic of North Macedonia), Georgia, Gibraltar, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Moldova, Romania, Serbia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
- Non-OECD Asia: 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 African continent, including northern Africa countries such as Egypt
- Non-OECD Americas: Central America and Caribbean and South America not elsewhere classified

Mode: total industrial sector energy consumption

Time Unit/Projection Period: Annual, 2019 through 2050

Modeling Features:
The WIM projects energy use in the manufacturing, agricultural, construction and mining sectors for 18 energy sources in each of the 16 WEPS+ regions annually through 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 affect both the mechanisms of the stock-flow process and fuel switching over time.

DOE Input Sources:
Energy Information Administration, International Energy Statistics Database, web site http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm# (as of January 2019).

Energy Information Administration, *Short Term Energy Outlook* (STEO), (March 2019 release).

Non-DOE Input Sources:
International Energy Agency (IEA), *World Energy Balances*, 2018.

Oxford Economics, *Global Economics Model and Global Industrial Model,* February 2019.

Appendix B. 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 Δ 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:

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