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# World Energy Projection System Plus: Electricity Module

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## 1. Introduction

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### Purpose of this report

The World Electricity Model (WEM) of the World Energy Projection System Plus (WEPS+) is a computer-based energy transformation model of the world electricity generation sector. This report describes the version of WEM that was used to produce the electricity generation projections published in the *International Energy Outlook 2016* (IEO2016). The WEPS+ is a modular system, consisting of separate energy models that are joined together through the overall system model in order to communicate and work with each other. These models are developed independently but are designed with well-defined protocols for system communication and interactivity. The WEPS+ modeling system uses a common and shared database (the “restart” file) that allows all the models to communicate with each other when they are run in sequence over multiple iterations. The system uses an iterative solution technique that allows for convergence of consumption and price to a simultaneous equilibrium solution.

This report documents the objectives, analytical approach, and development of the World Electricity Model. It also 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

WEM projects the amount of electricity generated to satisfy the electricity demands of the end-use demand models. Specifically, WEM projects the consumption of fossil, renewable, and nuclear fuels or fuel equivalents for the generation of electricity, based on both policy and least cost. The model projects annual electricity generation and electric power generating capacity, by technology, for 13 energy sources in each of the 16 international regions, through 2035. In addition, it projects end-use electricity prices for each of four demand sectors, by region.

WEM is a technology-based, least-cost model that uses a logit function to estimate levelized cost for new generation technology in three load segments. It then uses the levelized costs to project market shares for each technology. The model accounts for a slate of available new technologies along with their corresponding characteristics. These technology characteristics vary by region and include heat rates (efficiency), capital cost (per kilowatthour), fixed operating cost, variable operating cost, availability factor, and more. For each fuel type, the model features different technology representations, including carbon capture and storage (CCS) technologies.

The WEPS+ restart file provides WEM with macroeconomic, consumption, and price projections. These projections are determined beforehand by the Global Activity Model and the demand and supply models. Outputs from WEM include projections of the amounts of fuel consumed for electricity generation (by fuel), of electricity generation, and of electricity retail prices (by sector). These outputs are exported to the restart file for use by the other WEPS+ models.

## Model archival citation

This documentation refers to the WEPS+ World Electricity 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 the World Electricity Model, 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 WEM design, 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 World Electricity Model (WEM) has three primary objectives:

- To generate projections: The model generates projections of fuel consumed in the electric utility sector for 2013 through 2040 by fuel, region, and technology type. It also projects retail electricity prices, electricity generation, electricity capacity, and other details about technologies across vintage categories.
- To serve as an analytical tool: The model is used to assess the impact of policies and other changes on electricity generation through generation technologies, load slices, and equipment vintages.
- To provide data to other WEPS+ models: As an integral component of the WEPS+ system, WEM outputs consumption to the supply models of WEPS+ and electricity prices to the demand models of WEPS+ and contributes to the calculation of the overall energy supply and demand balance. The consumption outputs are also used by the Greenhouse Gases Model to calculate energy-related carbon dioxide emissions.

As part of the WEPS+ system, WEM provides projections for the 16 WEPS+ world regions (see Table 1). These regions consist of countries and country groupings within the broad divide of Organization of Economic Cooperation and Development (OECD) membership.

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

OECD Regions	Non-OECD Regions
United States	Russia
Canada	Other 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
	Other Central and South America

WEM projects the amount of electricity that must be generated in order to satisfy the electricity demands from the end-use demand models. Model projections include consumption for fossil fuels, renewable energy sources, and nuclear technologies for the purpose of generating electricity, based on both policy and least cost. WEM also projects electricity generation and generating capacity by technology, for 13 energy sources over the projection horizon. End-use electricity prices for each of four end-use demand sectors are also projected by region.



To create these projections, WEM tracks the availability of existing technologies with a stock-flow model and simulates the building of new capacity as needed in various load segments to satisfy electricity demands. Nuclear and renewables generation are largely policy driven, while fossil fuel generation is based on a least-cost market-share formulation using a logit algorithm to solve for new technology market shares in various load segments.

## Model inputs and outputs

### *Inputs*

As part of the WEPS+ system, WEM uses electricity demand and fuel price projections that it reads from the WEPS+ restart file. These have been previously projected by the demand and supply models (Table 2).

**Table 2. Restart file values used by the World Electricity Model**

<b>Model Input</b>	<b>Source</b>
Residential electricity consumption	Residential Model
Commercial electricity consumption	Commercial Model
Industrial electricity consumption	World industrial Model
Transportation electricity consumption	International Transportation Model
Electricity generation distillate retail price	Refinery Model
Electricity generation residual retail price	Refinery Model
Electricity generation natural gas retail price	Natural Gas Model
Electricity generation coal retail price	Coal Model

WEM also uses a large set of inputs that it reads from exogenous data files. The input files and the major inputs are shown in Table 3.

**Table 3. World electricity model input files**

Source Input File	Model Input
	Technology names, keywords, fuel categories, whether CCS, etc.
	Reference (U.S.) new technology characteristics – efficiency, capital cost, fixed operation and maintenance (O&M), variable O&M, availability factor, etc.
<b>PGTechFile.txt</b>	Regional new technology characteristic multipliers – capital cost, fixed O&M, efficiency (over time)
	Regional existing technology characteristics – efficiency, fixed O&M, variable O&M, availability factor, retirement rate, etc.
	Learning function coefficients
	Discount rates, logit coefficients, price deflators
	Transmission and distribution (T&D) loss factors
	Reserve margins
<b>PGMiscInput.xml</b>	Price markups
	Switch for price expectations, effectiveness of CCS, calibration factors, etc.
<b>PGLoadShape.xml</b>	Load shape parameters by region, sector, and segment
<b>PGExogIn.xml</b>	Projection of nuclear capacity and generation by region
	Renewable capacity factors by technology and region
<b>PGRenewables.xml</b>	Planned and expected renewable capacity by technology and region
<b>PGCapacityTargets.xml</b>	Renewable capacity targets by technology and region
<b>PGRenewableCeiling.xml</b>	Selected maximum renewable capacity limits by technology and region

### *Outputs*

For 13 energy sources, WEM estimates energy consumption for the purpose of electricity generation and stores the estimates in the WEPS+ restart file for use by the other models, as shown in Table 4. WEM also projects electricity generation, electricity generating capacity, and retail prices by demand sector and exports the projections to the restart file (see Appendix B. Input Data and Variable Descriptions).

**Table 4. World electricity model outputs**

<b>World Electricity Model Output</b>	<b>Destination</b>
Distillate consumption	Petroleum and Refinery Models
Residual consumption	Petroleum and Refinery Models
Crude oil consumption	Petroleum and Refinery Models
Natural gas consumption	Natural Gas Model
Coal consumption	Coal Model
Waste consumption	Reporting
Biomass consumption	Reporting
Hydroelectric consumption	Reporting
Geothermal consumption	Reporting
Solar consumption	Reporting
Wind consumption	Reporting
Other renewable consumption	Reporting
Nuclear consumption	Reporting
Residential electricity retail price	Residential Model
Commercial electricity retail price	Commercial Model
Industrial electricity retail price	World Industrial Model
Transportation electricity retail price	International Transportation Model

In the course of computing the electricity generation projections, WEM projects additional detailed information about technologies and vintages by region. These outputs include capacity, generation, and consumption, and they are divided by region, technology, load segment, and technology vintage.

### Relationship to other models

The World Electricity Model is an integral component of the WEPS+ system, and depends on the supply and demand models for some of its key inputs (Figure 1). WEM also projects fuel consumption and electricity price outputs, which those models depend on for their key inputs (Figure 2). A summary description of the models, flows, and mechanics of the WEPS+ system used for the IEO2016 is available in a separate *Overview* documentation.

Figure 1. World Energy Projection System Plus (WEPS+) Model Sequence

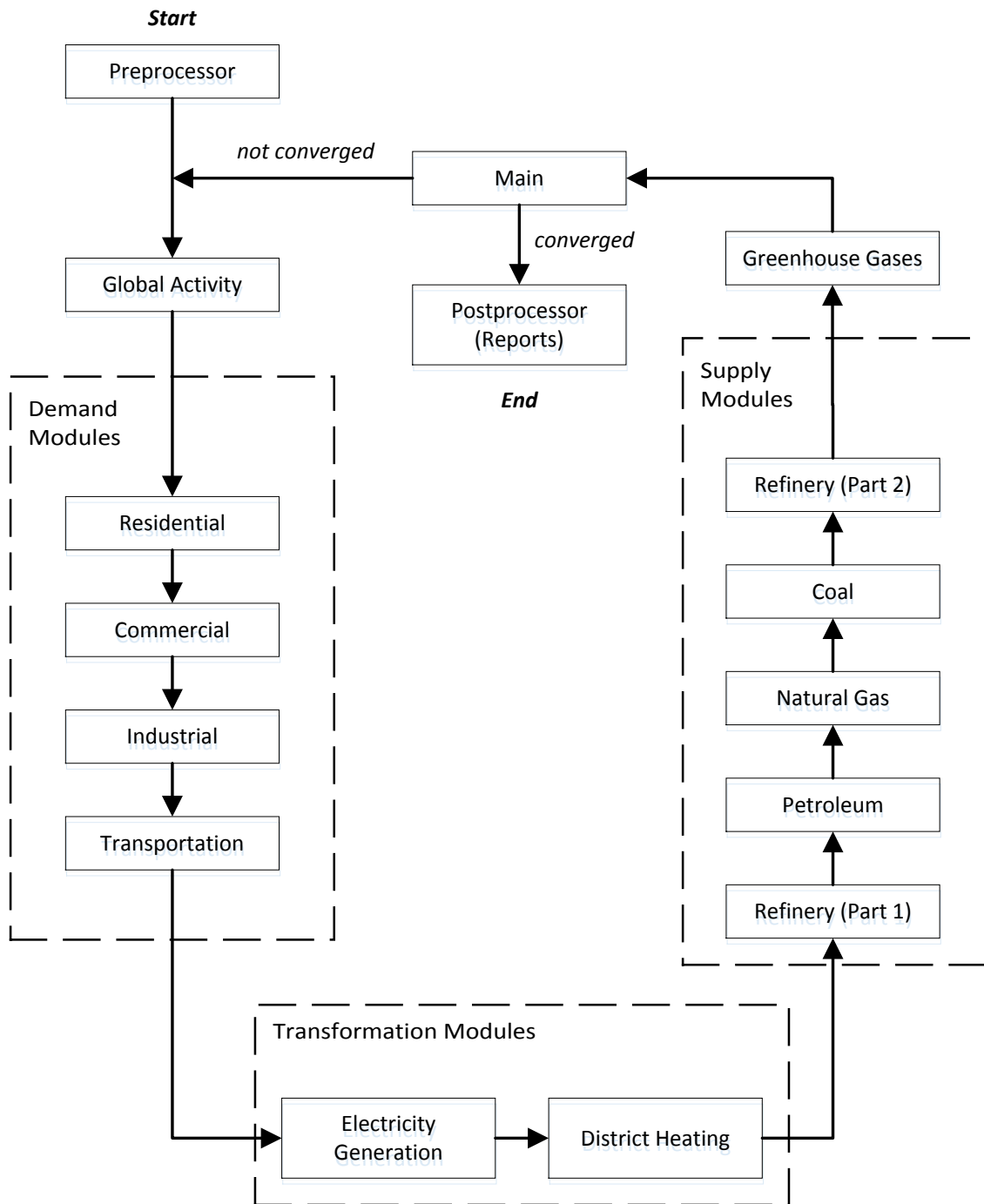
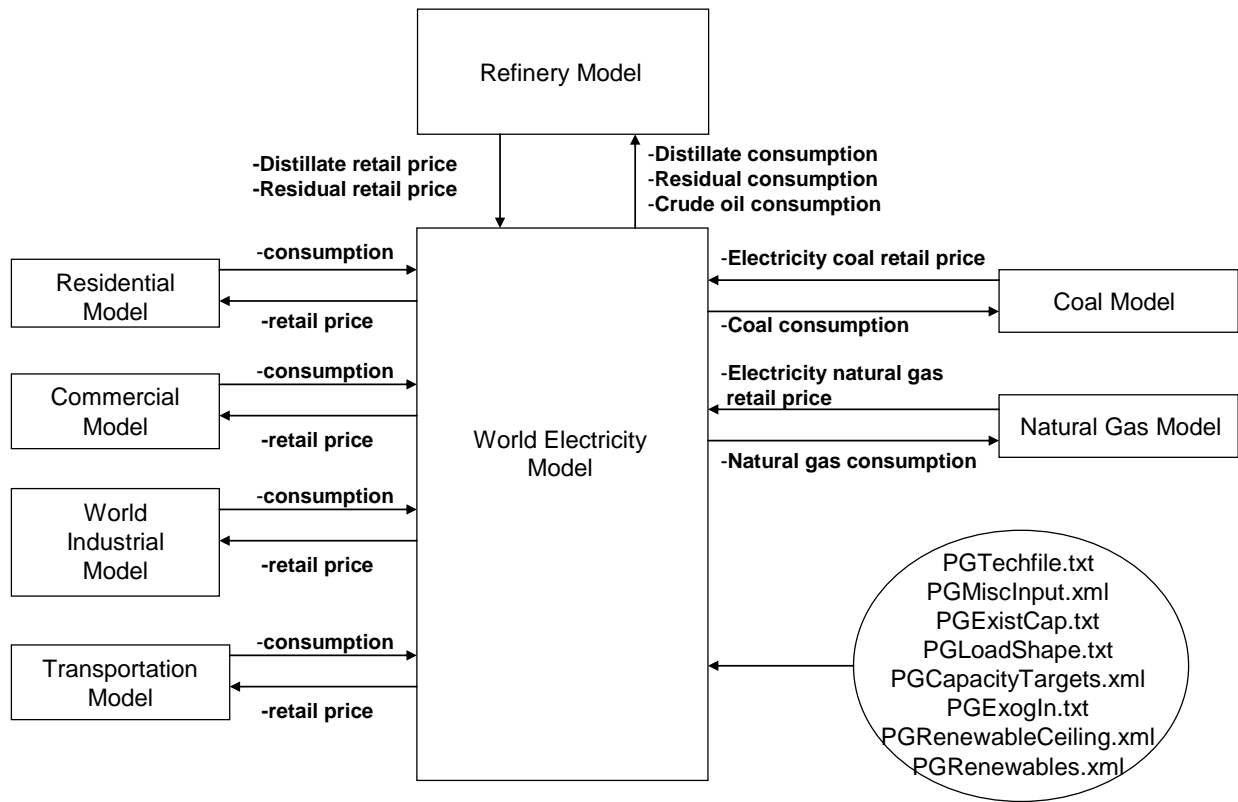


Figure 2. WEM Relationship to Other WEPS+ Models



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## 3. Model Rationale

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### Theoretical approach

WEM is a technology-based, least-cost model that uses a logit function to estimate levelized cost for new generation technology in three load segments. It then uses the levelized costs to project market shares for each technology. The model addresses a slate of available new technologies, along with the corresponding characteristics for each of those technologies. These technology characteristics include heat rates (efficiency), capital costs (per kilowatt), fixed operating costs, variable operating costs, and availability factors. Many of the technology characteristics used by the model vary by region. For each fuel type, the model features different technology representations, including carbon capture and storage (CCS) technologies.

Initially, WEM determines the total amount of generation that is required in each region by adding up the electricity demand from each sector and then accounting for losses from transmission and distribution. These generation requirements are allocated to seasons and load segments, based on overall system load curves. The model builds the system load curves based on the load curves for each sector and region and the relative weight of demand in each sector and region. Existing capacity is retired as necessary, and the amount of total capacity available for generation in each load segment and season is determined.

Both nuclear capacity and renewable capacity are determined outside of the economic competition used for fossil fuels. The total amount of nuclear capacity is generally policy driven and is exogenous to the model. The amount of renewable capacity, however, is determined by both policies and total generation demand. For each renewable and nuclear technology, the model determines the amount of new capacity added in a given year by looking at the difference between the total capacity for the current year and the remaining capacity from the previous year.

WEM then uses a load dispatch algorithm to determine how the remaining fossil-fuel capacity, along with the new nuclear and renewable capacity, is used to generate electricity. This algorithm first determines the amount of generation currently available. The generation available is compared to the generation requirements to determine how much new fossil generation is required. The new fossil generation is determined in a capacity planning algorithm that calculates levelized cost for each new technology that is available in the slate. The technology costs are then competed against each other in a logit-based, market share algorithm that gives more market share to lower cost technologies. (A logit coefficient determines the market share.) For each load segment, WEM runs the load dispatch and capacity planning algorithms. Because of the different generation requirements in each load segment, the algorithms select technologies with the costs and capacity factors that suit each load segment.

The amount of fuel consumed by each technology is determined by capacity planning choices, capacity dispatch choices, and the heat rates (efficiencies) of the chosen technologies.

WEM sums the consumption estimates across technologies within fuel categories and stores the results in the restart file. The model then calculates retail electricity prices based on the estimated fuel consumption and costs, along with fixed markups from wholesale to sectoral (e.g., residential, commercial) prices.

To keep track of the age of existing and new technologies, WEM uses a simple vintaging structure for all the capacity, generation, and consumption decisions. The “Key Computations and Equations” section of this report describes the four categories of the vintaging structure.

## Model assumptions

Numerous assumptions are made in WEM, covering areas such as technology characteristics, transmission and distribution losses, and load shapes. Assumptions are also made about how different technologies compete, how existing technologies are retired, and how new technologies are added by load segment. Some specific examples of the key assumptions made by WEM include the following:

- Within each region, electricity generation requirements are equal to the sum of electricity demand in the residential, commercial, industrial, and transportation end-use sectors and transmission and distribution losses (due to these losses, more electricity must be generated than consumed). In some regions these losses are substantial, but they are projected to lessen over the projection horizon. Electricity imports and exports are not modeled.
- Thirty-nine technologies, divided into 13 fuel groups, are available for electricity generation. These technologies have characteristics related to their efficiency (heat rate); capital cost; variable operating and maintenance cost; fixed operating and maintenance cost; availability factor; retirement rate; and more. These characteristics may differ across technologies, vintage categories, and years.
- Existing capacity for each electricity generation technology is retired in each year, based on an assumed retirement rate.
- Choices for dispatching existing capacity and for planning new capacity in each year are made for three different load requirements: base load, intermediate, and peak. The overall system load requirement (or shape) is determined by the underlying load shapes in each demand sector and their relative load requirements. Additional load requirements are added in the peak segment as a reserve margin.
- New generation requirements in each year are equal to the difference between the current available generation (with the current capacity) and the total generation requirements from the end-use demand sectors.
- Choices for nuclear technology capacity and generation are policy decisions and are exogenous to the choice decisions in the World Electricity Model. Nuclear capacity is added as base load.
- Choices for renewable technology capacity are input either as policy decisions or as percentages of total generation, depending on the time period. Renewable capacity is added mostly as base load, with some added as intermediate load.

- Choices for fossil technology capacity are based on the assumed characteristics of new technologies. These choices are determined by a least-cost market-share logit algorithm that takes into account the price of the fuel consumed, the technology efficiency, the capital, and other O&M costs. The choices are also made within the context of load segments and seasons and are constrained by technology limitations, such as maximum capacity factors.
- Total fuel consumption for electricity generation within each load segment is computed as a sum across technologies and vintage categories.



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## 4. Model Structure

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### Structural overview

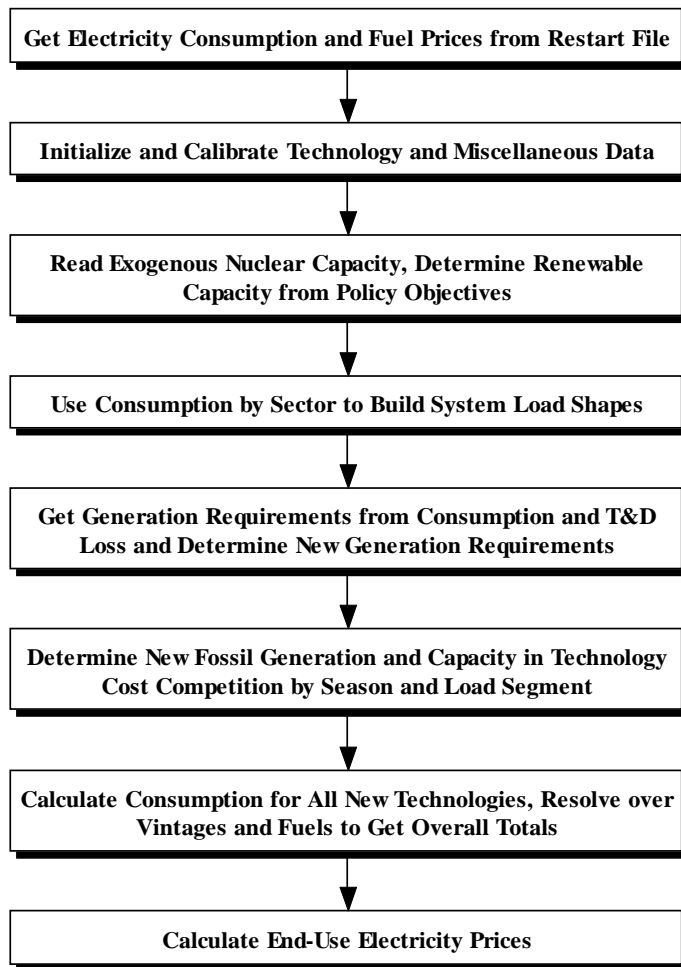
The World Electricity Model (WEM) used in the *IEO2016* projects the amount of electricity that must be generated to satisfy the electricity demands of the end-use demand sectors (residential, commercial, industrial, and transportation) in each region. For the years 2013 through 2040 the model projects annual fuel consumed, electricity generated, and generation capacity in each of the 16 WEPS+ international regions for the following 13 energy sources:

- Distillate
- Residual Fuel
- Crude Oil (used directly)
- Natural Gas
- Coal
- Waste
- Biomass
- Hydroelectric
- Geothermal
- Solar
- Wind
- Other Renewables
- Nuclear (Uranium)

The model also projects end-use electricity prices for four end-use sectors (residential, commercial, industrial, and transportation) in each of the 16 international regions over the projection horizon. WEM uses fuel prices from the supply models for five of the energy sources: crude oil, distillate, residual, natural gas, and coal.

Based on both policy and least cost, WEM projects how 39 fossil, renewable, and nuclear technologies are used to generate electricity. WEM is a technology-based least-cost model that uses levelized costs in a logit formulation to estimate new technology market shares in various load segments. It addresses a slate of available new technologies, taking into account characteristics such as heat rates (efficiency), capital cost (per kilowatthour), fixed operating cost, variable operating cost, and availability. The technology characteristics are allowed to vary by region. For each fuel type, the model has different technology representations with different characteristics. It also represents certain carbon capture and storage (CCS) technologies.

The flowchart in Figure 3 shows the major activities in the model. These will be discussed in more detail in the subsequent text.

**Figure 3. Flowchart for the World Electricity Model****Basic Flows for the World Electricity Model (WEM)****Key computations and equations**

To keep track of the age of existing and new technologies, WEM uses a simple four category vintaging structure (Table 5) for capacity, generation, and consumption:

**Table 5. WEM basic vintaging structure**

Vintages	Description
Existing	Capacity built before the last historical year (2012) that still remains (after retirements) in the current projection year.
New	Capacity added in the current projection year.
Added	Cumulative new capacity added since the last historical year, in the current projection year. (Includes the new capacity from the current year).
Total	Total capacity in the current projection year. This is the sum of “existing” and “added” in the current year.

The model computes estimates by vintage category for all 39 technologies considered. It then aggregates the estimates within fuels (13 fuel categories) at a coarser 5-fuel level (petroleum, natural gas, coal, renewable, and nuclear), and computes overall totals. The names of the electricity generation variables, at the different levels of aggregation, are shown in Table 6. (There are corresponding variables for consumption and capacity.)

**Table 6. Key technology data vintage formulations**

Variable Name	Description
<b>Full Level of Technology Detail</b>	
ETecGen(f,r,y)	Generation from existing capacity that has not been retired, by technology, region, and year
NTecGen(f,r,y)	New generation by technology, region, and year
ATecGen(f,r,y)	Cumulative generation added since last historical year, by technology, region, and year
TTecGen(f,r,y)	Total Generation (sum of ETecGen and ATecGen), by technology, region, and year
<b>13-Fuel Database Level</b>	
EFdbGen(d,r,y)	Generation from existing capacity that has not been retired, by 13-fuel categories, region, and year
NFdbGen(d,r,y)	New generation, by 13-fuel, region, and year
AFdbGen(d,r,y)	Cumulative generation added since last historical year, by 13-fuel categories, region, and year
TFdbGen(d,r,y)	Total Generation (sum of EFdbGen and AFdbGen), by 13-fuel categories, region, and year
<b>5-Fuel Level</b>	
EFulGen(f,r,y)	Generation from existing capacity that has not been retired, by 5-fuel categories, region, and year
NFulGen(f,r,y)	New generation, by 5-fuel, region, and year
AFulGen(f,r,y)	Cumulative generation added since last historical year, by 5-fuel categories, region, and year

**Table 6. Key technology data vintage formulations (cont.)**

Variable Name	Description
TFulGen(f,r,y)	Total Generation (sum ERulGen and AFulGen, by 5-fuel categories, region, and year)
<b>Overall Total Fuel Level</b>	
ETotGen(f,r,y)	Generation from existing capacity that has not been retired, by region and year
NTotGen(f,r,y)	New generation, by region and year
ATotGen(f,r,y)	Cumulative generation added since last historical year, by region and year
TotcGen(f,r,y)	Total Generation (sum of ETitGen and ATotGen), by region and year

WEM comprises many major subroutines, most of which are coded in Fortran. Table 7 lists the major subroutines that are called from the main routine, showing the sequence of operations in the model. In the text that follows, these subroutines will be sequentially described in more detail, along with the key data, algorithms, and equations.

**Table 7. Key model subroutines in sequence**

Subroutine/Function	Description
InitData	Read in initial data. Acquire and process consumption and price data from the restart file.
TechData	Read in new and existing technology characteristics and learning function coefficients. Process and manipulate the data as necessary.
GetExogs	Read in nuclear projections and initial renewable capacity and generation. Call renewable routines which read in renewable database and policies and make renewable capacity and generation projections.
TechCalb	Read in historical and planned capacity by technology. Calibrate existing capacity by technology to historical values by fuel. Calculate initial generation by technology and initial consumption by technology. Align nuclear and renewable capacity and generation.
LoadData2	Read in load shapes by sector, build system load shapes using end-use sector consumption projections.
SumUp	Sum up all the various capacity, generation, and consumption variables for history over vintages and by various technology and fuel categories.
do ym=FMYr LMYr	Go through a do-loop over the projection years (2013 through 2040).
do rm=1, 16	Go through a do-loop over the 16 WEPS+ regions.
heatrate_learning	Calculate the heat rate learning factors based on cumulative capacity additions.
CalcPrc	Create fuel price expectations for the next 30 years, in each projection year.
use_heatrate_learning	Implement the heat rate and cost learning factors based on cumulative capacity additions.
UseLearn	
CapDisp	Determine generation requirements. Retire existing technologies. Dispatch existing technologies and near-term planned builds. Determine the new generation requirements. Add nuclear and renewable first, leaving new fossil generation requirements.

**Table 7. Key model subroutines in sequence (cont.)**

<b>Subroutine/Function</b>	<b>Description</b>
CapPlan	Calculate leveled costs for generation technologies by season and load segment. Make new fossil technology choices using a least-cost market-share logit algorithm in each season and load segment. Determine new capacity factors and new capacity, generation and consumption by technology.
end do	End of region do-loop.
cost_learning	Calculate the cost learning factors based on cumulative capacity additions.
end do	End of projection years do-loop.
FinishUp	Make any adjustments or overwrites that are needed. Sum up all the various capacity, generation and consumption variables over the projection horizon over vintages and by various technology and fuel categories. Calculate amount of consumption using CCS technologies.
SysOut	Share petroleum to distillate, residual and crude oil. Determine share of combined heat and power (CHP) generation and amount of heat generated. Put variables into the restart file.
EUPrice	Calculate end-use retail electricity prices using fixed markups and put into the restart file.

## Data initialization

### Subroutine InitData

#### *Read Miscellaneous Inputs*

Subroutine InitData reads initial data and processes them for use in the model. It first reads the variables listed in Table 8 from the miscellaneous input file (named PGMiscInput.xml). The price deflator is imported from Common\_Inputs.xml, an input file shared by all WEPS+ models.

**Table 8. Miscellaneous input data**

Variable	Description
DRate(r)	Discount rate by region for the levelized cost calculations
Lamda(r)	Logit coefficient by region for the levelized cost calculations
BPMyop, CPMMyop	Switches indicating how to do price expectations, separate for the “base” price and for the carbon price if used
CCSFac(r,y)	Percent of total carbon dioxide captured by carbon capture and storage technologies, by region and year
EUPrcAdd(s,r), EUPrcFac(s,t)	End-use electricity price additive and multiplicative adjustment factors by sector and region
pricedeflator2011(y)	Price deflators for the levelized cost calculations
TDFac(r,y)	Transmission and distribution loss factors by region and year
RMarg(r,y)	Reserve margins by region and year
PrcFac(f,r,y)	User factor to adjust fossil fuel prices by region and year
FBsCoef, NFulFbs(f,r,y)	New technology fuel calibration coefficients by fuel, region and year
DoExElas(f), RFosPrc(r,y), ExElas(f,r,y)	Switch and coefficients for calculating changes in renewable and nuclear capacity and generation by fuel, region and year

### *Prices*

The InitData subroutine imports electricity demand projections by end-use sector from the WEPS+ restart file. The subroutine then imports fuel prices from the WEPS+ restart file and computes the overall oil price by averaging the distillate, residual and crude oil prices. It next imports the “base” price (calculated in the supply models) along with the carbon price (this is zero except in scenarios that assume a carbon emissions trading system or a carbon tax). Total price is calculated from the sum of these two prices. The model also uses the variable for the CCS effectiveness to calculate a partial carbon price to be used later for CCS technologies.

## Technology data initialization

### *Subroutine TechData*

This subroutine reads the technology characteristics for the new and existing power generation technologies from an input file named PGTechFile.txt. The subroutine also imports planned additions of fossil-fuel power plants from another input file.

### *Technology names, keywords, and groupings*

TechData first reads a list of all the technologies included in the model from the input file. The list includes the following information for each technology:

1. a long descriptive name
2. a short acronym keyword
3. index indicating the fuel type for each technology at the five fuel category level
4. index indicating the fuel type for each technology at the more detailed 13 fuel category level
5. an index indicating whether the technology is a carbon capture and storage technology
6. a value for the minimum capacity factor allowed (for some technologies)

Table 9 gives the set of technologies and indices that were used for the *IEO2016*.

**Table 9. List of all technologies**

<b>Technology Name (1)</b>	<b>Key (2)</b>	<b>MapFul (3)</b>	<b>MapFdb (4)</b>	<b>CCS (5)</b>	<b>MinCF (6)</b>
Oil CHP	PTCHP	1	1	0	0.00
Oil Combined Cycle	PTECA	1	1	0	0.00
Oil Internal Combustion	PTICA	1	1	0	0.00
Oil Steam Boiler	PTSBA	1	1	0	0.00
Oil Combustion Turbine	PTCTA	1	1	0	0.00
Oil Conventional Steam	PTOLS	1	1	0	0.00
Oil Generic DG for Base	PTGDN	1	1	0	0.00
Oil Generic DG for Peak	PTGDP	1	1	0	0.00
Oil Conv. CC	PTCCC	1	1	0	0.00
Oil Adv. CC	PTCCA	1	1	0	0.00
Oil Conv. Turbine	PTTRC	1	1	0	0.00
Oil Adv. Turbine	PTTRA	1	1	0	0.00
Gas CHP	NGCHP	2	3	0	0.00
Gas Combined Cycle	NGCCA	2	3	0	0.00
Gas Combustion Turbine	NGCTA	2	3	0	0.00
Gas Steam Boiler	NGSBA	2	3	0	0.00
Gas Fuel Cell	NGFCA	2	3	0	0.00
Gas Steam	NGAGS	2	3	0	0.00
Gas Fuel Cell	NGAFC	2	3	0	0.00
Gas CC with Sequestration	NGACS	2	3	1	0.00
Gas Conv. CC	GOCCC	2	3	0	0.00
Gas Adv. CC	GOCCA	2	3	0	0.00
Coal CHP	CLCHP	3	4	0	0.70
Coal Existing Standard	CLESA	3	4	0	0.70
Coal Fluidized Bed	CLFBA	3	4	0	0.70

**Table 9. List of all technologies (cont.)**

<b>Technology Name (1)</b>	<b>Key (2)</b>	<b>MapFul (3)</b>	<b>MapFdb (4)</b>	<b>CCS (5)</b>	<b>MinCF (6)</b>
Coal IGCC	COABA	3	4	0	0.70
Coal Pulverized Boiler	CLPBA	3	4	0	0.70
Scrubbed Coal	CLPCC	3	4	0	0.70
Integrated Coal IGCC	COABA	3	4	0	0.70
Coal IGCC with Sequestration	COASA	3	4	1	0.70
Nuclear	NUCVA	4	12	0	0.80
Waste	WSCVA	5	5	0	0.00
Biomass	BMCVA	5	6	0	0.00
Hydroelectric	HECVA	5	7	0	0.60
Geothermal	GTCVA	5	8	0	0.00
Solar	SLCVA	5	9	0	0.00
Wind	WNCVA	5	10	0	0.00

This list includes all technologies, both new and existing, that may be used in the model. There is some redundancy because new and existing technologies, even if they are essentially the same technology, are input with separate keys.

### *New Technology Characteristics*

The subroutine then reads the new technology characteristics (costs in year 2009 dollars) from the technology input file, using the “key” variable (in Table 9) to match the data to the technologies represented in the model. It stores only data on the new, potential technologies listed in Table 9. The technology characteristics are for the U.S., which is used as the “reference region,” and they are taken from EIA’s National Energy Modeling System (NEMS). The values used for the IEO2016, shown in Table 10, are updated from those used for the IEO2015.



**Table 10. New technology characteristics**

costs in year 2011 dollars

Technology Name	Key	Efficiency	Capital Cost	Fixed O&M	Variable O&M	Avail. Factor
			(\$/kW)	(mills/kWh)	(\$/kW)	
Oil Conventional Steam	PTOLS	0.323	2364	29.37	4.90	0.30
Oil Generic DG for Base	PTGDN	0.378	1465	17.14	7.62	0.30
Oil Generic DG for Peak	PTGDP	0.345	1759	17.14	7.62	0.06
Oil Conv. CC	PTCCC	0.484	901	12.94	3.54	0.30
Oil Adv. CC	PTCCA	0.531	1006	15.10	3.21	0.30
Oil Conv. Turbine	PTTRC	0.314	956	7.21	15.18	0.06
Oil Adv. Turbine	PTTRA	0.350	664	6.92	10.19	0.06
Gas Steam	NGAGS	0.359	2364	29.37	4.90	0.85
Gas Fuel Cell	NGAFC	0.359	6982	357.47	0.00	0.85
Gas CC w/Sequestration	NGACS	0.453	2059	31.23	6.66	0.87
Gas Conv. CC	GOCCC	0.484	901	12.94	3.54	0.87
Gas Adv. CC	GOCCA	0.531	1006	15.10	3.21	0.87
Gas Conv. Turbine	GOTRC	0.314	956	7.21	15.18	0.06
Gas Adv. Turbine	GOTRA	0.350	664	6.92	10.19	0.06
Scrubbed Coal	CLPCC	0.388	2883	30.64	4.39	0.85
Integrated Coal IGCC	COABA	0.392	3718	50.49	7.09	0.85
Coal IGCC w/Seq.	COASA	0.284	5138	65.31	4.37	0.85
Nuclear	NUCVA	0.326	5429	91.65	2.10	0.90
Waste	WSCVA	0.250	8408	381.74	8.51	0.83
Biomass	BMCVA	0.253	4041	103.79	5.17	0.83
Hydroelectric	HECVA	0.350	2397	14.57	2.60	0.51
Geothermal	GTCVA	0.350	2567	110.94	0.00	0.90
Solar	SLCVA	0.350	4979	66.09	0.00	0.22
Wind	WNCVA	0.350	2175	38.86	0.00	0.34
Other Renewable	ORCVA	0.350	2175	38.86	0.00	0.45

For each new technology on the list, TechData reads the descriptive name and key (columns 1 and 2 in Table 10) along with the following characteristics:

- efficiency (column 2), defined as the ratio of the energy out to the energy in, which is an inverse function of the heat rate (heat rate is equal to 3412 divided by the efficiency)
- capital cost, fixed cost, and variable operating and maintenance costs (columns 3 through 5)
- availability factor for the technology (column 6)

(The input data file also provides information on technology lifetime, size, and lead time, but these are not used in the model.)

Most of the renewable and nuclear technology characteristics shown in Table 10 are not used in the current version of WEM, because the renewable and nuclear generation and capacity values are exogenous. The current input file provides only one set of characteristics for each renewable technology and one for nuclear, but future versions of WEM may accommodate multiple entries for each technology type (e.g., there could be separate entries for onshore wind and offshore wind).

The model also reads a separate set of regional factors from the input file. It computes regional technology efficiency, capital cost, and fixed operation and maintenance (O&M) estimates by applying these regional factors to the corresponding reference (U.S.) values. The factors are specified for 2013 and for 2040; the model interpolates for the years between 2013 and 2040. The same set of new technologies is used in each of the 16 WEPS+ regions. The characteristics for each technology are allowed to vary by region and year.

For each technology  $t$ , region  $r$ , and year  $y$ ,

$$NtTecCCst(t, r, y) = NTecCCst(t, r = reference, y) * MultC(t, r, y);$$

$$NTecFOM(t, r, y) = NTecFOM(t, r = reference, y) * MultF(t, r, y); \text{ and}$$

$$NTecEff(t, r, y) = NTecEff(t, r = reference, y) * MultEff(t, r, y),$$

where

$$NtTecCCst(t, r, y) = \text{new technology capital cost};$$

$$NTecFOM(t, r, y) = \text{new technology fixed O\&M cost};$$

$$NTecEff(t, r, y) = \text{new technology efficiency};$$

$$MultC(t, r, y) = \text{regional factor for capital cost};$$

$$MultF(t, r, y) = \text{regional factor for fixed O\&M cost}; \text{ and}$$

$$MultEff(t, r, y) = \text{regional factor for efficiency}.$$

### *Existing Technology Characteristics*

The TechData subroutine then reads the existing technology characteristics (costs in year 2000 dollars) from the technology input file. These are also matched to the master list in Table 9 through the use of the “key” variable. For existing technologies, there is a separate set of characteristics in the input file for each of the 16 WEPS+ regions. To illustrate, the technology characteristics for China are shown in Table 11.

**Table 11. Existing technology characteristics for China**

costs in year 2000 dollars

Technology Name	Key	Efficiency	Fixed O&M	Variable O&M	Avail. Factor	Retirement
						Rate
Oil CHP	PTCHP	0.370	4.36	2.57	0.85	0.010
Oil Combined Cycle	PTECA	0.367	13.46	2.24	0.90	0.010
Oil Internal Combustion	PTICA	0.295	14.58	3.36	0.85	0.010
Oil Steam Boiler	PTSBA	0.317	14.58	3.36	0.85	0.010
Gas CHP	NGCHP	0.400	5.47	3.40	0.85	0.010
Gas Combined Cycle	NGCCA	0.505	6.73	2.24	0.90	0.010
Gas Combustion Turbine	NGCTA	0.363	3.36	3.36	0.85	0.010
Gas Steam Boiler	NGSBA	0.367	14.58	3.36	0.85	0.010
Coal CHP	CLCHP	0.357	15.63	1.95	0.85	0.008
Coal Existing Standard	CLESA	0.282	14.58	1.68	0.85	0.008
Coal Fluidized Bed	CLFBA	0.262	14.58	3.36	0.90	0.008
Coal IGCC	CLICA	0.000	14.58	3.36	0.85	0.008
Nuclear	NUCVA	0.338	102.05	0.00	0.90	0.002
Waste	WSCVA	0.396	15.99	5.53	0.85	0.010
Biomass	BMCVA	0.396	15.99	5.53	0.85	0.010
Hydroelectric	HECVA	0.330	18.84	3.97	0.90	0.002
Geothermal	GTCVA	0.164	18.84	5.61	0.90	0.005
Solar	SLCVA	0.396	18.84	2.98	0.50	0.010
Wind	WNCVA	0.396	19.39	2.86	0.45	0.008
Renewable Other	ORCVA	0.396	19.39	2.86	0.45	0.010

The subroutine reads the descriptions, key values, and characteristics for all existing technologies included in the model. The categories of characteristics are the same as those read for new technologies (described above) except that they include a retirement rate (last column of Table 11) and exclude the “capital cost,” which the model uses only for the new technologies. Although the model’s data structure allows these variables to change over time, the model assigns constant default values for all years in the projection period. To accommodate the exogenous technologies, Table 11 includes only one entry for each renewable technology and one for nuclear.

Finally, the subroutine imports planned fossil-fuel power plant additions. These plants include facilities under construction at the time of the *IEO2016* publication that are expected to become operational no later than 2015 and are not otherwise represented by WEM’s economic model.

After the technologies have been imported, the subroutine verifies that there are no zeros for efficiency in the existing technologies. If there is a zero, the value is replaced by the corresponding value from the U.S. The model also sets the evaluation period for new technologies (for the technology competition) to 30 years.

## Nuclear and renewable initialization and projections

### Subroutine GetExogs

This subroutine reads in the exogenous capacity and generation projections for nuclear technology and renewable technology capacity factor multipliers. The input file is named PGExogIn.xml. The model also calls a subroutine that creates renewable projections based on renewable policies and generation requirements.

#### *Read exogenous nuclear projections and renewable capacity factor multipliers*

The GetExogs subroutine reads an input file containing exogenous projections of nuclear capacity and generation. The nuclear values cover all WEPS+ regions for the period 2013 through 2040. The input file also contains capacity factor multipliers for every renewable technology in each of the WEPS+ regions. These factors are applied to the “reference region” (i.e., U.S.) availability factors for new renewable technologies that were read in from the technology input file. They are used to differentiate regions that have abundant renewables resources (*e.g.*, strong wind, consistent sunlight) from regions with scarce resources. In most cases these factors are set to a value of 1.

#### *Create renewable projections*

The subroutine calls another subroutine named “renewable projection,” which creates the renewable projections for each region and technology, over the projection horizon. The projections are based on regional policies, such as mandates for fixed amounts of renewable capacity. The actual projection process is described in more detail in Projections for Renewable Technologies, which appears later in this documentation. Once this subroutine finishes processing, the cumulative capacity and generation projections for each fuel, region, and year are copied into two variables.

$RenewCap(f, r, y)$  and  $RenewGen(f, r, y)$  represent the total amounts of capacity and generation in year  $y$  (as opposed to the amounts newly added in year  $y$ ) for each renewable technology  $f$  in each region  $r$  from the renewable projection subroutine.

#### *Nuclear calibration*

Next, the values for nuclear capacity and generation are calibrated to ensure that their total 2012 values are equal to the values in the restart file that were derived from historical EIA data.

#### *Option for nuclear and renewable elasticity*

Earlier in the program, WEM read in a set of indicator variables and elasticities from the miscellaneous input file for each renewable and nuclear technology ( $DoExElas(f)$ ). These provide the option to use elasticities to calculate new levels for generation and capacity. If the indicator variable is equal to one for a technology, the model recalculates the capacity and generation for that technology. This option was not used for the *IEO2016*, and is generally available for use in carbon dioxide emissions analyses. The model estimates the elasticity based on changes in the overall weighted average fossil fuel price relative to a previously set base price. To determine the new level of capacity or generation, the model uses the elasticity calculated from this price ratio and a capacity or generation ratio representing change relative to a base level. The equation used (with generation as the example) for each renewable or nuclear technology is

$$GenElas(t, r, y) = \frac{\ln\left(\frac{NewGen(t, r, y)}{BaseGen(t, r, y)}\right)}{\ln\left(\frac{NewPrc(t, r, y)}{BasePrc(t, r, y)}\right)}$$

where, for technology  $t$ , region  $r$ , and year  $y$ ,

$NewGen(t, r, y)$  and  $BaseGen(t, r, y)$  are the new (resulting) and base generation levels, respectively;

$NewPrc(t, r, y)$  and  $BasePrc(t, r, y)$  are the new (changed) and base weighted average fossil fuel prices, respectively; and

$GenElas(t, r, y)$  is the estimated price elasticity.

## Projections for renewable technologies

### Subroutine renewable projection

The renewable projection subroutine, which is called from the GetExogs subroutine, projects cumulative electricity capacity for renewable technologies, based on regional policies.

#### Overview

This subroutine provides a semi-endogenous renewable electricity projection for WEM. It incorporates the effects of government policies, the primary driver of renewable electricity growth, into the projections. This section describes the components of the subroutine, explains why this particular model was used for the IEO2016, and details the steps the module uses to project renewable electricity.

This subroutine uses different methodologies for three periods, which vary by region, covering the projection period:

1. Planned Additions (2013-2022)
2. Renewable Policy Targets and Goals (2013-2040)
3. Renewable Generation Floor (2013-2040)

The projection period is split up into three phases to best incorporate the currently available data concerning renewable electricity projects, policies, and trends.

#### Phase I – Planned Additions (2013-2022)

For the early years of the projection period, the model uses data on planned additions. Collected from trade press, company announcements, and other industry reports, planned additions represent renewable energy projects (e.g., wind farms, solar farms, and hydroelectric dams) that were under construction during the IEO2016's writing or that have a high probability of beginning construction before 2023. The probabilities of construction are estimated based on available financing, government policies, the technology type, and the time horizon. These probabilities are incorporated into a MySQL database of planned additions.

### ***Phase II – Renewable Policy Targets and Goals (2013-2040)***

For the middle years of the projection period, the model relies on government renewable policy targets and goals. Collected from the IEA Policy database, government announcements, and other government reports, renewable targets and goals are primarily capacity targets for particular years. For example, China has declared a wind capacity target of 100 gigawatts by 2020. The expected values of these policies (calculated as the capacity target times the estimated probability of success) are incorporated into the model for the year of their end date. The probability of a country successfully achieving a particular renewable goal is estimated based on financial capability, available government incentives for that goal, the country's success rate with previous renewable targets, and the time horizon of the goal compared to the country's current renewable capacity growth rate. The policies and probabilities are stored in a MySQL database.

### ***Phase III – Renewable Generation Floor (2013-2040)***

For the final years of the projection period, the model relies on a renewable generation floor. After the renewable policy targets and goals expire, countries are assumed to maintain the same percentage of renewable generation over the remainder of the projection period. This assumption reflects EIA's "business as usual" modeling policy: After a government policy expires, it is unlikely that a country that achieved a renewable target would suddenly stop building renewable power plants, even if they are not as economical as fossil fuel-fired plants.

## **Subroutine details**

### ***Steps before WEPS+ Runs***

Renewable projects and renewable capacity targets are stored in two tables in the MySQL database "weps\_renewables." Using a Python script, the projects's capacities are aggregated from a country level to the 16 WEPS+ regions and summed by technology type and expected completion year. Government capacity targets are also aggregated by region, technology type, and expected completion year. The Python script exports the results as two CSV files ("PGRenewables" and "PGCapacityTargets") for import into WEM.

### ***Phase I – Planned Additions (2013-2022)***

WEM imports "PGRenewables" and stores the values in an array. These planned capacity data are then added to the historical renewable capacity data already in WEPS+ to generate a preliminary renewable electricity capacity projection.

### ***Phase II – Renewable Policy Targets and Goals (2013-2040)***

WEM imports "PGCapacityTargets" and stores the values in an array. The capacity target is spread out over a three-year period, beginning with the expected completion year, to account for late implementation of the targets and goals.

The capacity targets are then inserted into the projected series if the targets are greater than the values calculated in the preliminary projections.

WEM uses a linear growth algorithm to evenly spread capacity additions between any multi-year gaps. For example, if there are capacity additions in 2009 and 2010 and then no capacity additions until 2018, the algorithm will calculate a linear growth rate between 2010 and 2018. This growth rate is then used in the projection to prevent sudden jumps in projected capacity that can occur when a government target is expected to be met.

At this point, the renewable electricity projection in WEM includes planned capacity additions and government targets and policies. This projection is valid for regions with modeled targets and policies through 2020-2040, depending on the region.

### ***Phase III – Renewable Generation Floor (2013-2040)***

To extend the projections to 2040, the model calculates the renewable generation floor. Because WEM generates the electricity projection by matching electricity supply to electricity demand (as calculated by the demand modules), the renewable module first calculates total electricity demand for each year in the projection period. Electricity demand in WEPS+ is expressed in terms of trillion Btu and must first be converted to billion kilowatthours using a conversion factor:

$$Demand\_BKWh(r, y) = Demand\_TBtu(r, y) * 3.412,$$

where, for region  $r$ , and year  $y$ ,

$$Demand\_BKWh(r, y) = \text{demand in billion kilowatthours; and}$$

$$Demand\_TBtu(r, y) = \text{demand in trillion Btu.}$$

After accounting for transmission and distribution losses, the calculated generation requirements can be compared to the renewable generation projection currently in WEPS+. The module uses expected capacity factors, which represent the proportion of renewable capacity actually used, to estimate the annual generation (BKWh per year) from the projected capacity additions. It multiplies the capacity factors by the capacity (BKW, or terawatts in SI units) and the number of hours in a year (8,760):

$$Generation = Capacity * Capacity\_Factor * 8760$$

Adding the generation from capacity additions to the generation from historical capacity data provides total generation projections. For each year of the projection period, the module divides the total renewable generation by the generation requirements to calculate the percent of total generation that comes from renewable sources in that year.

The subroutine identifies the last year in which a renewable target or goal exists in a region, stores that year in an array, and uses it as the year to switch from the government policy model to the renewable generation floor model. It then calculates the percentage of renewable generation for each technology (i.e., the module calculates a different percentage for hydroelectricity, wind power, solar power, etc.) by dividing the renewable generation for each technology by the total renewable generation for each year of the projection period.

From the year the model switches to the renewable generation floor assumption to the last year of the projection period, the model holds the percentage of generation from each renewable technology constant. Using the equation above that relates generation to capacity (through the capacity factors) the model calculates final capacity additions over the entire projection period from the final generation projection.

If at any point in the projection period the projected total capacity for any renewable technology reaches the resource ceiling (predefined in “PGRenewableCeiling.xml”), total capacity growth stops at the ceiling. Generation is then recalculated using the ceiling capacity.

## Technology initialization and calibration

### Subroutine TechCalb

This subroutine reads in the preliminary historical and planned capacity by technology. It then imports the overall historical capacity and other values from the initial database in the restart file. It uses these values to calibrate the existing capacity by technology to the more aggregate historical values. It then calculates the initial generation and consumption by technology.

#### *Input capacity by technology*

The TechCalb subroutine first reads preliminary capacity estimates by technology from an input file named pg\_udi.xml. The preliminary estimates must still be calibrated to the actual values from the historical database.

#### *Capacity, generation, electricity consumption and heat at 13-fuel level from restart file*

In the next step, WEM imports historical capacity, generation, consumption, and district heat data from the WEPS+ restart file. WEM calibrates the preliminary capacity estimates to agree with these historical data, which are provided at the 13-fuel level. These historical data are available for capacity, generation and consumption in electricity-only plants and in combined heat and power (CHP) plants. For CHP generation, the data on electricity generated is stored separately from the data on heat generated. The data categories in each region in the initial year are as follows:

- For fuel  $f$ , region  $r$ , and year  $y$ , historical data include the following estimates for Electricity Only Plants (indicated by “1” in the second subscript)
  - Capacity by Fuel –  $RFCap(f,1,r,y)$
  - Generation of Electricity by Fuel –  $RFGen(f,1,r,y)$
  - Consumption by Fuel –  $RFCon(f,1,r,y)$



- For fuel  $f$ , region  $r$ , and year  $y$ , historical data include the following estimates for CHP Plants (indicated by “2” in the second subscript)
  - Capacity by Fuel –  $RF\text{Cap}(f,2,r,y)$
  - Generation of Electricity by Fuel –  $RF\text{Gen}(f,2,r,y)$
  - Consumption by Fuel –  $RF\text{Con}(f,2,r,y)$

### *Calibration/calculation of generation by technology*

The calculation and calibration of generation by technology for existing capacity in the historical period is a two step process. The first step is to calculate a capacity factor for each fuel at the 13-fuel level from the historical capacity and generation data from the restart file. A capacity factor reflects the proportion of generating capacity that is actually used. It is defined as the number of kilowatt hours of electricity generated per year divided by the product of the corresponding capacity value and the number of hours per year (8,760). In the equation below, generation is divided by 1000 to convert billion kilowatt hours to gigawatt hours, the unit that corresponds with the provided capacity (gigawatts). For each technology  $t$  that uses fuel type  $f$ , the capacity factor is given by

$$ETecCF(f, t, r, y = 2012) = \frac{RF\text{Gen}(f, 3, r, y = 2012)}{RF\text{Cap}(f, 3, r, y = 2012 * 8.760)}$$

where for fuel  $f$ , in region  $r$ , and year  $y$ ,

$ETecCF(f, t, r, y = 2012)$  = capacity factor for technology  $t$  using fuel  $f$  (assumed constant across technologies);

$RF\text{Gen}(f, 3, r, y)$  = total generation from the restart file; and

$RF\text{Cap}(f, 3, r, y)$  = total capacity from the restart file.

In the second step, these capacity factors for each fuel  $f$  are applied to the capacity estimates for each technology  $t$  using fuel  $f$  to calculate a calibrated level of generation for each technology. The values for the last historical year are used for the future years that contain planned additions.

$$ETecGen(f, t, r, y = 2012) = ETecCap(f, t, r, y = 2012) * (ETecCF(f, t, r, y = 2012) * 8.760)$$

where for technology  $t$  using fuel  $f$ , in region  $r$ ,

$ETecCap(f, t, r, y = 2012)$  = capacity (calculated as described above)

$ETecCF(f, t, r, y = 2012)$  = capacity factor

$ETecGen(f, t, r, y = 2012)$  = generation

### Calculation of consumption by technology

After determining the existing level of capacity and generation by technology, the subroutine uses efficiency and generation estimates to calculate the consumption of fuels by technology. The computation for 2012 is

$$ETecCon(f, t, r, y = 2012) = \frac{ETecGen(f, t, r, y = 2012) * 3.412}{ETecEff(f, t, r, y = 2012)},$$

where for technology  $t$  using fuel  $f$ , in region  $r$ ,

$ETecCon(f, t, r, y = 2012)$  = consumption of fuel  $f$  for technology  $t$ ;

$ETecGen(f, t, r, y = 2012)$  = generation (calculated as described above); and

$ETecEff(f, t, r, y = 2012)$  = efficiency for technology  $t$  using fuel  $f$  (from the input file).

(The unit conversion factor 3.412 is the number of billion KWh per trillion Btu.) Because the sum of the consumption estimates for the technologies within each fuel type may not equal the consumption estimate for the fuel type that was read from the restart file, the subroutine calibrates the consumption estimates to ensure consistency:

$$ETecCon'(f, t, r, y = 2012) * \left( \frac{RFCon(f, 3, r, y = 2012)}{\sum_{t \in f} ETecCon(f, t, r, y = 2012)} \right),$$

where, for region  $r$ ,

$RFCon(f, 3, r, y = 2012)$  = consumption of fuel  $f$  for technology  $t$ , from the restart file;

$ETecCon(f, t, r, y = 2012)$  = consumption of fuel  $f$  for technology  $t$ , estimated as described above; and

$ETecCon'(f, t, r, y = 2012)$  = calibrated estimate of consumption of fuel  $f$  for technology  $t$ .

However, after the consumption estimates have been recalibrated, the efficiencies by technology may no longer be consistent. So the final part of this step is to recalibrate the efficiencies to preserve the relationship between the generation and the newly calibrated consumption.

$$ETecEff'(f, t, r, y = 2012) = \frac{ETecGen(f, t, r, y = 2012) * 3.412}{ETecCon'(f, t, r, y = 2012)},$$

where  $ETecEff'(f, t, r, y = 2012)$  is the calibrated estimate of efficiency for technology  $t$  using fuel  $f$  in region  $r$

### *Substitution of renewable capacity and generation*

From an input file, the model reads initial historical capacity and generation values for renewable fuels and substitutes these for the values in the technology-level data. Since a capacity factor should be calculated for each technology, these historical capacity and generation values have to be substituted for matching renewable technologies. To make the substitution straightforward, the model uses only one technology for each of the individual renewable fuel. These values are given by

$$ETecCap(f, t, y, y = 2012) = RenewCap(t = f, r, y = 2012);$$

$$ETecGen(f, t, y, y = 2012) = RenewGen(t = f, r, y = 2012).$$

After this substitution is made, a capacity factor at the technology level is also calculated:

$$ETecCF(t, r, y = 2012) = \frac{RenewGen(t = f, r, y = 2012)}{RenewCap(t = f, r, y = 2012) * 3.412}.$$

A consumption estimate for each technology is then calculated, using the value for the technology-level efficiency:

$$ETecCon(t, r, y = 2012) = \frac{RenewGen(t = f, r, y = 2012) * 3.412}{ETecEff(t, r, y = 2012)}.$$

### *Substitution of nuclear capacity and generation*

The model reads exogenous values for nuclear capacity and generation from an input file and substitutes them for the values in the technology-level data. This includes not only the values over the projection horizon, but also the historical values through 2012 (which were also calibrated earlier). To make the substitution straightforward, the model includes only one technology for nuclear (nuclear is treated as a fuel category.) These values are given by

$$ETecCap(t, r, y = 2012) = NukeCap(t = f, r, y = 2012);$$

$$ETecGen(t, r, y = 2012) = NukeGen(t = f, r, y = 2012).$$

After the substitution is made, a capacity factor at the technology (and fuel) level is calculated:

$$ETecCF(t, r, y = 2012) = \frac{NukeGen(t = f, r, y = 2012)}{Nukecap(t = f, r, y = 2012) * 8.760}.$$

Fuel consumption for the nuclear technology is then estimated using the value for the technology-level efficiency:

$$ETecCon(t, r, y = 2012) = \frac{NukeGen(t = f, r, y = 2012) * 3.412}{ETecEff(t, r, y = 2012)}.$$

*Extend existing technology efficiencies and capacity factors*

Throughout the projection period, the efficiencies and capacity factors for existing technologies that are either read from an input file or calculated as described above are applied for the remaining capacities of existing technologies. They are not used, however, for new technologies that may be added during the projection period.

**Calculate system load shapes****Subroutine LoadData2**

The LoadData2 subroutine reads load shapes by sector for each region from an input file. It uses these sectoral load shapes, along with the end-use sector consumption projections to build system load shapes for each region.

*Input load shapes by sector*

To determine the overall system load shape, WEM uses load shapes for each region and each end-use electricity-consuming sector, which it reads from the input file PGLoadShape.xml. This file provides separate load shapes for each of the 16 WEPS+ regions and for each of five end-use sectors: residential, commercial, industrial, transportation, and agriculture. (In WEM, the agriculture sector is considered part of the industrial sector and is not broken out explicitly; therefore WEM does not currently use the agriculture load shape.) Each load shape describes how much of the annual load is consumed within specified periods of time in three seasons: the summer (S), the winter (W), and for the intermediate (I) or shoulder months. The periods of time are specified as fractions of the year and the amounts of the load are specified as fractions of the load. Although load shapes vary by region, the following time periods (specified as fractions of a year) are used for all three seasons and for all regions:

Seasonal Base: 0.247 (fraction of a year)

Seasonal Mid-period: 0.080 (fraction of a year)

Seasonal Peak: 0.007 (fraction of a year)

For each of the 16 WEPS+ regions, Table 12 shows the load proportions for each time period.

Table 12. Load shape coefficients by region

Proportion of Annual Load for Region United States									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.206	0.104	0.010	0.270	0.100	0.009	0.207	0.086	0.007
Comm	0.185	0.137	0.015	0.192	0.139	0.014	0.170	0.134	0.015
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.226	0.101	0.007	0.227	0.098	0.007	0.229	0.100	0.006
Proportion of Annual Load for Region Canada									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.223	0.092	0.007	0.270	0.091	0.007	0.223	0.081	0.006
Comm	0.223	0.092	0.007	0.270	0.091	0.007	0.223	0.081	0.006
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.247	0.080	0.007	0.243	0.078	0.011	0.246	0.077	0.011
Proportion of Annual Load for Region Mexico/Chile									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.205	0.097	0.011	0.231	0.115	0.014	0.210	0.105	0.013
Comm	0.194	0.110	0.009	0.223	0.119	0.010	0.213	0.113	0.010
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.248	0.080	0.006	0.247	0.074	0.011	0.247	0.079	0.008
Proportion of Annual Load for Region OECD Europe									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.188	0.083	0.009	0.285	0.106	0.011	0.219	0.124	0.010
Comm	0.158	0.118	0.011	0.240	0.132	0.012	0.197	0.124	0.010
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.228	0.092	0.014	0.216	0.104	0.011	0.222	0.099	0.015
Proportion of Annual Load for Region Japan									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.203	0.094	0.009	0.276	0.103	0.009	0.212	0.087	0.007
Comm	0.172	0.127	0.013	0.212	0.140	0.014	0.178	0.130	0.014
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.229	0.098	0.008	0.225	0.098	0.008	0.229	0.100	0.006
Proportion of Annual Load for Region Australia/New Zealand									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.223	0.092	0.007	0.270	0.091	0.007	0.223	0.081	0.006
Comm	0.197	0.091	0.008	0.283	0.102	0.010	0.214	0.088	0.007
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.230	0.098	0.007	0.226	0.098	0.008	0.229	0.099	0.006

Table 12. Load shape coefficients by region (cont.)

Proportion of Annual Load for Region South Korea									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.223	0.092	0.007	0.270	0.091	0.007	0.223	0.081	0.006
Comm	0.160	0.116	0.0014	0.223	0.146	0.015	0.182	0.131	0.015
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.230	0.100	0.005	0.230	0.096	0.006	0.231	0.098	0.005
Proportion of Annual Load for Region Russia									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.160	0.062	0.007	0.328	0.120	0.013	0.208	0.091	0.011
Comm	0.164	0.106	0.010	0.253	0.125	0.010	0.205	0.118	0.010
Ind	0.247	0.080	0.007	0.253	0.125	0.010	0.205	0.118	0.010
Tran	0.217	0.102	0.013	0.205	0.112	0.015	0.214	0.106	0.015
Proportion of Annual Load for Region Non-OECD Europe and Eurasia									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.190	0.086	0.009	0.272	0.114	0.013	0.213	0.095	0.012
Comm	0.162	0.115	0.010	0.226	0.139	0.012	0.198	0.127	0.011
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.232	0.088	0.014	0.224	0.094	0.014	0.223	0.097	0.015
Proportion of Annual Load for Region China									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.200	0.086	0.011	0.258	0.107	0.014	0.218	0.094	0.013
Comm	0.185	0.114	0.009	0.218	0.130	0.010	0.205	0.120	0.010
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.242	0.082	0.010	0.229	0.091	0.012	0.235	0.088	0.012
Proportion of Annual Load for Region India									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.201	0.087	0.008	0.259	0.101	0.013	0.231	0.087	0.012
Comm	0.193	0.121	0.013	0.205	0.134	0.010	0.184	0.131	0.009
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.240	0.086	0.007	0.234	0.084	0.015	0.236	0.087	0.012
Proportion of Annual Load for Region Other Non-OECD Asia									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.191	0.093	0.011	0.247	0.121	0.014	0.206	0.105	0.013
Comm	0.194	0.106	0.009	0.236	0.114	0.010	0.216	0.108	0.009
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.247	0.080	0.007	0.243	0.078	0.011	0.246	0.077	0.011

Table 12. Load shape coefficients by region (cont.)

Proportion of Annual Load for Region Middle East									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.211	0.110	0.012	0.221	0.116	0.013	0.201	0.104	0.012
Comm	0.205	0.108	0.010	0.224	0.114	0.010	0.210	0.110	0.009
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.305	0.027	0.002	0.304	0.025	0.003	0.304	0.026	0.003
Proportion of Annual Load for Region Africa									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.213	0.098	0.008	0.235	0.100	0.010	0.230	0.097	0.009
Comm	0.213	0.098	0.008	0.235	0.100	0.010	0.230	0.097	0.009
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.257	0.070	0.006	0.248	0.073	0.011	0.251	0.072	0.012
Proportion of Annual Load for Region Brazil									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.223	0.092	0.007	0.270	0.091	0.007	0.223	0.081	0.006
Comm	0.223	0.092	0.007	0.270	0.091	0.007	0.223	0.081	0.006
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.276	0.055	0.004	0.268	0.058	0.006	0.272	0.059	0.004
Proportion of Annual Load for Region Other Central and South America									
	S-Base	S-Mid	S-Peak	W-Base	W-Mid	W-Peak	I-Base	I-Mid	I-Peak
Resd	0.199	0.096	0.012	0.243	0.113	0.014	0.209	0.102	0.013
Comm	0.190	0.108	0.009	0.218	0.129	0.011	0.208	0.119	0.009
Ind	0.247	0.080	0.007	0.245	0.080	0.007	0.247	0.080	0.007
Tran	0.281	0.049	0.004	0.277	0.048	0.007	0.284	0.044	0.007

The annual load proportions are ultimately multiplied by the actual annual load in kilowatthours (or in Btu) to compute the actual load in each time segment. Similarly, the proportion of annual time is multiplied by the total hours in the year (8,760) to compute the actual number of hours in each time segment. These values can then be used together to represent a load duration curve, where the height of the curve (capacity) at each point is the number of kilowatthours per hour, which simplifies to kilowatts.

### *Calculate system load shape by region*

WEM calculates system load shape for each region as a weighted average of the load shapes in the five sectors. The model weights each sector's proportional load by the total annual consumption in the sector within each region. (Because the agriculture sector is part of the industrial sector and is not broken out explicitly in the current system, WEM does not currently use the agriculture load shape.) For each segment *seg* (base, intermediate, or peak) within each season *sea* (summer, winter, or shoulder), the weighted average proportional load for region *r* in year *y* is given by

$$SysPctLoad(sea, seg, r, y) = \frac{\sum_s [QtyDem(s, r, y) * PctLoad(s, sea, seg, r)]}{\sum_s QtyDem(s, r, y)},$$

where  $QtyDem(s, r, y)$  = annual demand for sector  $s$ , in region  $r$  and year  $y$ ;

$PctLoad(s, sea, seg, r)$  = imported proportion of load for sector  $s$  in segment  $seg$  of season  $sea$  in region  $r$ ; and

$SysPctLoad(sea, seg, r, y)$  = system (weighted average) proportion of load for segment  $seg$  in season  $sea$  in region  $r$  and year  $y$ .

For each segment, the proportion of load is divided by the proportion of hours within the segment to get the height or capacity for the segment:

$$SysHgtLoad(sea, seg, r, y) = \frac{SysPctLoad(sea, seg, r, y)}{PctTime(seg)},$$

where  $SysHgtLoad(sea, seg, r, y)$  = system height or capacity of load for season  $sea$ , segment  $seg$ , region  $r$  and year  $y$ ; and

$PctTime(seg)$  = proportion of hours in segment  $seg$  (constant across sectors, seasons, regions, and years).

Although the system load shapes in the current version are represented for three seasons and for three segments within each season, the seasonal data have been added together in the following graphs to illustrate the use of the load shapes.

Two examples of the resulting load shapes are shown in the two graphs below, as load duration curves for the U.S. and China. (The x-axis in each graph represents the hours of the year and the y-axis represents the generation capacity requirements over that period as a proportion of average capacity requirements. The average height in each graph is 1.0.) Each graph shows the system load shapes in an early year, based on the mix of sector consumption in that year, and the system load shapes in 2035, based on the changed mix of sector consumption in 2035. A key detail to notice is that the load shape for the U.S. has a greater peak than the load shape for China. This is largely a consequence of the mix of sectoral consumption in each of the regions. In the U.S. the residential and commercial sectors make up a large part of the electricity consumption. In China, the great majority of the electricity consumption is in the industrial sector. The residential and commercial sectors typically have load shapes with greater peaks than the industrial sector. As a consequence, China has a much greater need for baseload generating technologies, while the U.S. must have more peaking generating technologies.



Figure 4. Load Shapes in USA, 2005 and 2035

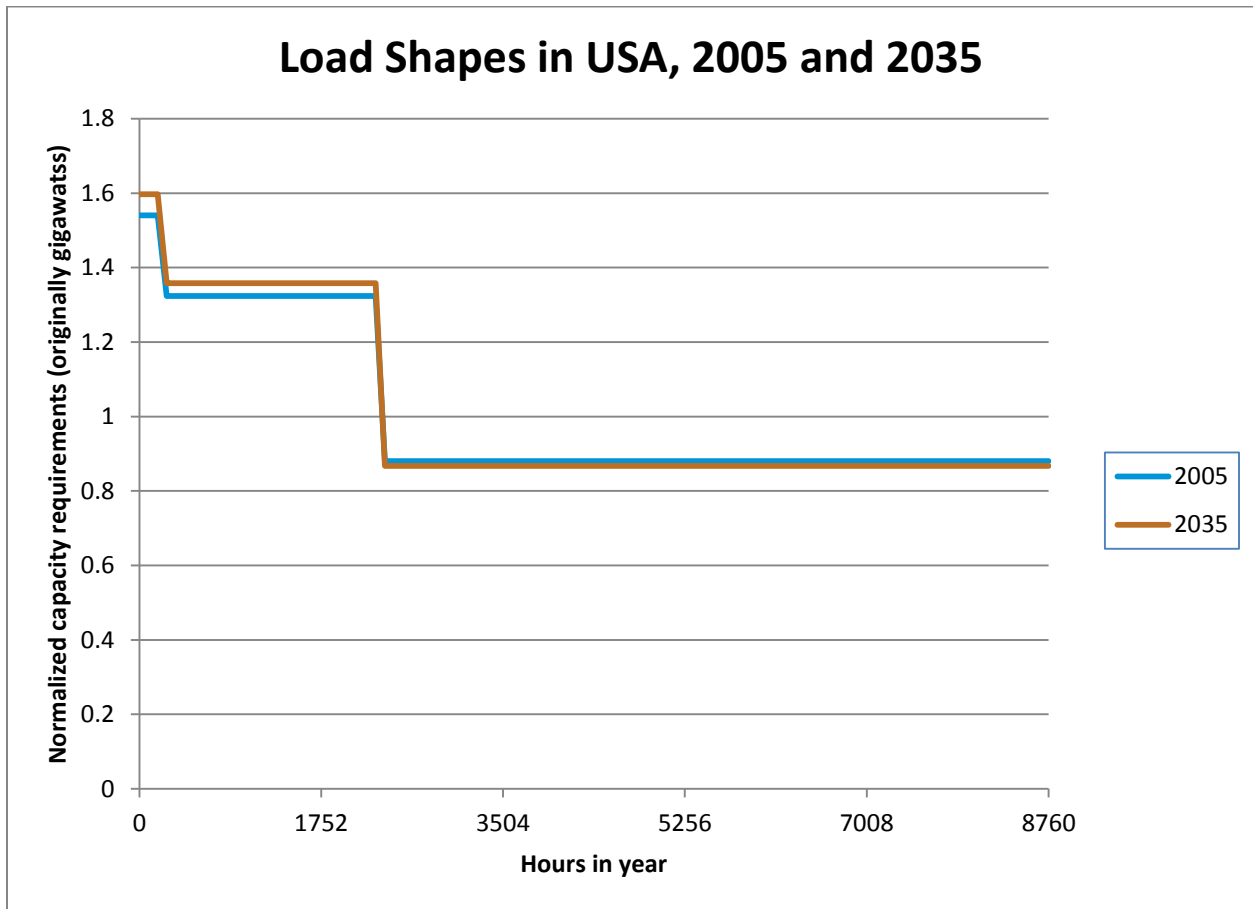
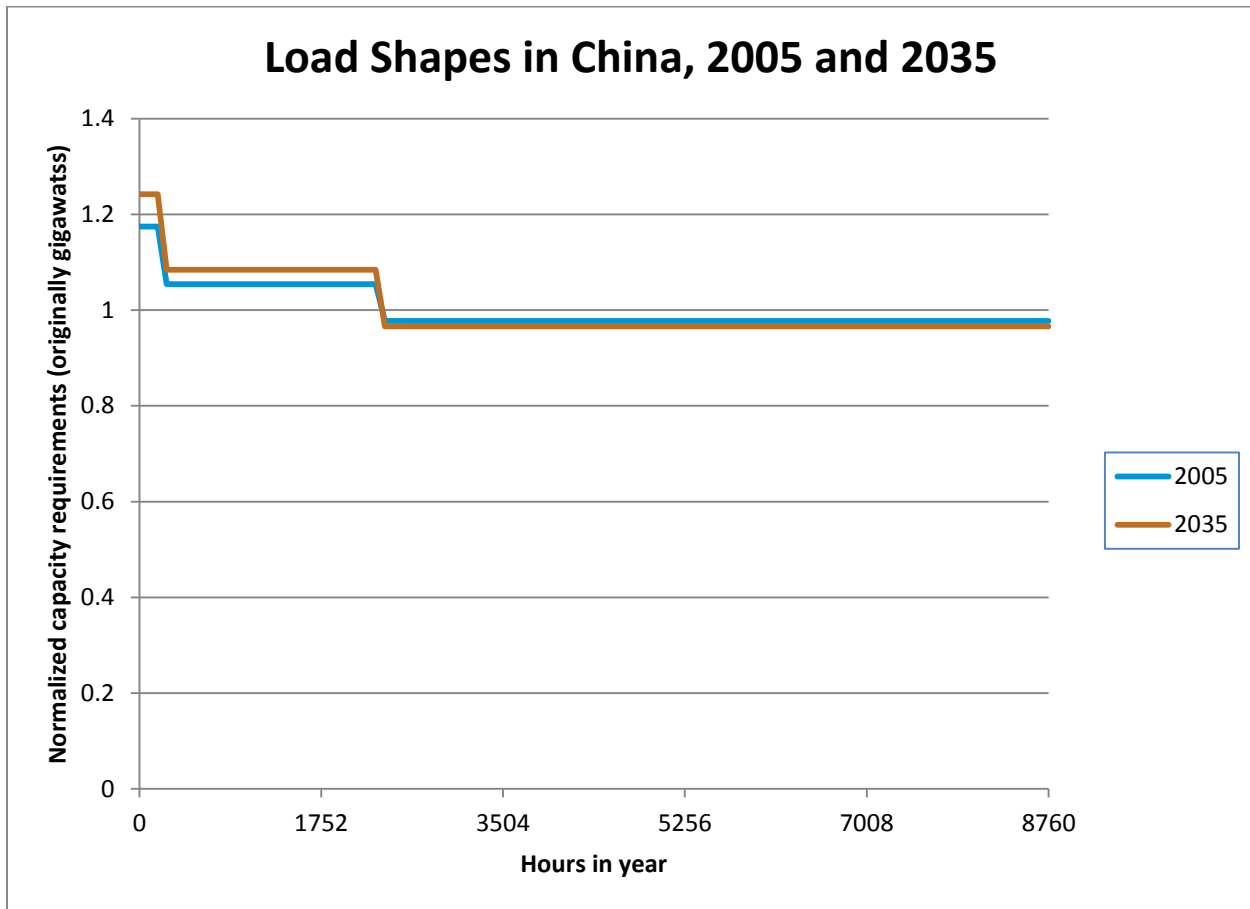


Figure 5. Load Shapes in China, 2005 and 2035



### *Percent of load and time in each season*

The next step in this subroutine is to calculate the overall proportion of load and time that is in each season (over the three segments within the season). For the load, this is the sum of the proportions of load for the segments within the season:

$$SeaPctLoad(sea, r, y) = \sum_{seg} SysPctLoad(sea, seg, r, y),$$

where, for season  $sea$  in region  $r$  and year  $y$ ,

$SysPctLoad(sea, seg, r, y)$  = system proportion of load; and

$SeaPctLoad(sea, r, y)$  = system proportion of load for segment  $seg$ .

The time within each season is the percent of time, by seasons and segments, summed over the segments:

$$SeaPctTime(sea) = \sum_{seg} PctTime(sea, seg),$$

where  $PctTime(sea)$  = proportion of time assigned to season  $sea$  (=1/3 for all seasons, sectors, regions, and years); and

$SeaPctTime(sea)$  = proportion of time for segment  $seg$  in season  $sea$ .

### ***Percent of time and load for each segment in each season***

The next step in this subroutine is to calculate the percent of load and time that is in each segment within each season. This is given by

$$SeasSegPctTime(sea, seg) = \frac{PctTime(sea, seg)}{\sum_{seg} PctTime(sea, seg)},$$

where, for segment  $seg$  in season  $sea$  and region  $r$ ,

$SeasSysPctLoad(sea, seg, r, y)$  = load for segment  $seg$  as a proportion of the load in season  $sea$  in year  $y$ ;

$SegPctLoad(sea, seg, r, y)$  = load for segment  $seg$  as a proportion of load in year  $y$ ;

$PctTime(sea, seg)$  = Imported time in segment  $seg$  as a proportion of time in year  $y$  (same for all sectors and regions); and

$SeasSegPctTime(sea, seg)$  = time in segment  $seg$  as a proportion of time in season  $sea$  in year  $y$ .

### ***Cumulative time, height or capacity, and the marginal load***

The subroutine then assigns a cumulative time and a marginal load to each of the load segments (peak, intermediate, and base).

In Figure 4 and Figure 5 it can be seen that the peak capacity is used only during the peak segment. During the peak segment, the height of the curve indicates the relative amount of capacity needed, while the area under the curve is the total amount of generation (or load) that is needed. The marginal load (or generation) is the area under the curve for the peak segment that lies above the intermediate capacity height, i.e., the extra generation needed due to the peak demand (as compared to the demand observed at the intermediate level).

The intermediate capacity is used during both the peak segment and the intermediate segment. Again, the height of the curve in the intermediate segment indicates the amount of capacity needed, while the area under the curve is the total amount of generation (or load) that is needed. The marginal load (or generation) is the area under the curve for the intermediate segment that lies above the height of the curve for the baseload segment.

The baseload capacity is used over the entire year. The height of the curve indicates the amount of capacity needed, while the area under the curve is the total amount of generation (or load) that is needed. The marginal load (or generation) for this segment is the same as the total load, i.e., the area under the curve.

The model calculates the height, total load, and marginal load for each season, segment, region, and year. It uses these quantities in future steps to determine the new capacity added in each load segment. The height for each segment within each season, region, and year is given by

$$SegHgtLoad(sea, seg, r, y) = \frac{SegPctLoad(sea, seg, r, y)}{SegPctTime(sea, seg)}.$$

A cumulative time variable is also calculated for the segments within each season. The cumulative time for the peak segment is its (marginal) proportion of time. The cumulative time for the intermediate segment is the sum of the (marginal) percentage of time for the peak plus the intermediate. The cumulative time for the baseload segment is the sum of the (marginal) percentage of time for the peak, plus the intermediate, plus the baseload. The cumulative time for the baseload segment should be 1 (or 100 percent), since baseload generation is always online by definition. For a general number of segments  $n$  per season, the cumulative time for segment  $i \in \{1, \dots, n\}$  is given by

$$SegCumTime(sea, seg = i) = \sum_{j=1}^i SegPctTime(sea, seg = j).$$

(The current implementation of the model sets  $n = 3$ , but the program allows for a general number of segments.) The subroutine then calculates a marginal load for each segment within each season. For example, for the intermediate marginal load the calculation involves multiplying the cumulative time for the intermediate segment by the capacity that lies below the peak but above the baseload. The marginal load for segment  $i \in \{2, \dots, n\}$  in region  $r$  and year  $y$  is

$$\begin{aligned} SegMarLoad(sea, seg = i, r, y) \\ &= [SegHgtLoad(sea, seg = i, r, y) - SegHgtLoad(sea, seg = i - 1, r, y)] \\ &\quad * SegCumTime(sea, seg = i) \end{aligned}$$

### ***Reserve margin***

For the peak segment, a reserve margin is added to the capacity to guarantee sufficient generating capacity in peak periods. For each region and year, the model reads the reserve margin,  $RMarg(r, y)$ , expressed as a proportion, from an input file. The model calculates a reserve load based on the proportion and then adds the reserve load to the peak load previously calculated. For the general case of  $n$  segments (where segment  $n$  is the peak segment),

$$\begin{aligned} ResLoad(sea, seg = n, r, y) \\ &= SegHgtLoad(sea, seg = n, r, y) * RMarg(r, y) * SegPctTime(sea, seg = n); \end{aligned}$$

$$SegMarLoad'(sea, seg = n, r, y) = SegMarLoad(sea, seg = n, r, y) + ResLoad(sea, seg = n, r, y),$$

where, for season  $sea$  in region  $r$  and year  $y$ ,

$RMarg(r, y)$  = reserve margin (proportion read from an input file);

$ResLoad(sea, seg = n, r, y)$  = additional reserve load required for the peak segment;

$SegMarLoad(sea, seg = n, r, y)$  = previously calculated marginal load (defined above);  
and

$SegMarLoad'(sea, seg = n, r, y)$  = newly calculated marginal load, including the reserve load.

In the current model implementation,  $n = 3$ .

### *Alternative variables subsequently used in WEM*

Some WEM subroutines use alternative names for some of the variables described above. These are shown below. The region and year dimensions are added to the segment time variables, even though the original variables do not need these dimensions (the original time proportions are constant across regions and years). The uses of these variables are further explained in the documentation for other subroutines.

$$SHFac(sea, seg, r, y) = SegCumTime(sea, seg)$$

$$SLFac(sea, seg, r, y) = SeaMarLoad(sea, seg, r, y)$$

$$SeaHPct(sea, r, y) = SeaPctTime(sea)$$

$$SeaLPct(sea, r, y) = SeaPctLoad(sea, r, y)$$

## Sum up initial data into vintage categories

### Subroutine SumUp

This subroutine sums the historical capacity, generation and consumption variables over vintages and provides aggregates by technology and fuel type at various levels of detail. In previous subroutines, the model has calculated all the variables at the individual technology level (within fuel type), and these detailed data are now aggregated to the coarser fuel and total levels. For all the capacity, generation, and consumption decisions, WEM uses a simple vintaging structure to keep track of the age of existing and new technologies. This vintaging structure consists of four categories, described in Table 13 for capacity:

**Table 13. WEM basic vintaging structure**

<b>Vintage Type</b>	<b>Description</b>
Existing	Capacity built before the last historical year that still remains (after retirements) in the current projection year
New	Capacity added in the current projection year
Added	Cumulative new capacity added since the last historical year, in the current projection year. (Includes the new capacity from the current year.)
Total	Total capacity in the current projection year. This is the sum of “existing” and “added” in the current year.

The model calculates capacity, generation, and consumption by vintage for each of the 39 technologies addressed. The model aggregates the technology vintage data into three coarser levels of detail. The four levels of detail are as follows:

- 1) the full 39-technology/fuel level
- 2) the 13-fuel level
- 3) the 5-fuel level (petroleum, natural gas, coal, renewable, and nuclear), and
- 4) an overall total.

The variables for electricity generation are illustrated in Table 14 (there are corresponding variables for consumption and capacity).

**Table 14. Key technology data vintage formulations**

Variable Name	Description
<b>Full Level of Technology Detail</b>	
ETecGen( $t,r,y$ )	Generation from existing capacity that has not been retired, in year $y$
NTecGen( $t,r,y$ )	New generation added in year $y$ from new capacity
ATecGen( $t,r,y$ )	Cumulative generation added since last historical year, in year $y$
TTecGen( $t,r,y$ )	Total Generation (sum of ETecGen and ATecGen)
<b>13-Fuel Database Level</b>	
EFdbGen( $d,r,y$ )	Generation from existing capacity that has not been retired, in year $y$ , in region $r$ , by 13-fuel categories
NFdbGen( $d,r,y$ )	New generation added in year $y$ , in region $r$ , by 13-fuel categories
AFdbGen( $d,r,y$ )	Cumulative generation added since last historical year, in year $y$ , in region $r$ , by 13-fuel categories
TFdbGen( $d,r,y$ )	Total Generation (sum of EFdbGen and AFdbGen) in year $y$ , in region $r$ , by 13-fuel categories
<b>5-Fuel Level</b>	
EFulGen( $f,r,y$ )	Generation from existing capacity that has not been retired, in year $y$ , in region $r$ , by 5-fuel categories
NFulGen( $f,r,y$ )	New generation added in year $y$ , in region $r$ , by 5-fuel categories
AFulGen( $f,r,y$ )	Cumulative generation added since last historical year, in year $y$ , in region $r$ , by 5-fuel categories
TFulGen( $f,r,y$ )	Total Generation (sum EFulGen and AFulGen) in year $y$ , region $r$ , by 5-fuel categories
<b>Overall Total Fuel Level</b>	
ETotGen( $r,y$ )	Generation from existing capacity that has not been retired, in year $y$
NTotGen( $r,y$ )	New generation added in year $y$
ATotGen( $r,y$ )	Cumulative generation added since last historical year, in year $y$
TTotGen( $r,y$ )	Total Generation (sum of ETotGen and ATotGen)

## Create fuel price expectations

### Subroutine CalcPrc

For each projection year, the CalcPrc subroutine computes fuel price expectations for all years in the projection period. WEM uses these expected prices to simulate cost competition between various technologies.

In the model's computer code, the CalcPrc subroutine is called in the middle of a do-loop for years – from the first model year to the last model year – and for the 16 WEPS+ regions. The region loop is inside the year loop. The year index is  $ym$  and the region index is  $rm$ . In the equations given here, these indexes are used in place of  $y$  and  $r$  to indicate calculations performed within this particular pair of nested loops.

The WEPS+ restart file provides two main types of fuel prices to the power generation model: “base” prices and “carbon” prices. The base price is the regular retail price for the fuel, while the carbon price is a carbon allowance or tax that the model adds to the base price when the model is simulating a carbon tax or “cap-and-trade” scenario. The model incorporates two variations of the carbon price: a full carbon price, and a partial carbon price for use with carbon capture and storage (CCS) technologies (based on the CCS effectiveness). Partial carbon prices are calculated exogenously.

The model calculates the base and carbon prices separately, and the projection method for each is determined by the value of a “switch” (indicator) variable. The estimation option for the base price is given by the switch *BPMyp* and the option for the carbon price is given by the switch *CPMyop*.

The first option (switch equals 0), called “myopic foresight formulation” holds the prices constant over the 50-year price projection period, at the level in the current projection year.

The second option (switch equals 1), called “limited foresight formulation,” lets the prices grow over the 50-year period as they have over the past five years before the current projection year, subject to some constraints and exceptions. For the first four years of the projection period, the model grows the expected prices at 1.5% per year (1.0% for carbon prices), because there is no previous five-year period of projections. Also, the model imposes a maximum annual price growth rate of 3.0% and a minimum growth rate of 0%. That is, if prices have been falling during the previous five-year period, the expected prices are held constant.

The third option (switch equals 2), called “perfect foresight formulation,” uses the projected prices from the WEPS+ restart file for all years for which these prices are available. For years after 2035, the restart file prices are not available, and the model reverts back to the second option described above, using the growth rate for the previous five-year period.

In a typical run (and for the *IEO2016*), the model calculates the base price expectations using the first option (constant prices in a myopic foresight formulation) and calculates the carbon price expectations using the third option (perfect foresight). It is assumed that planners know little about how the base prices will change but do know about any carbon tax that is to be implemented.

For consistency with the costs in the technology data, the resulting expected price projections are converted from 2013 to 2011 dollars. As noted above, the carbon price may be either the CCS carbon price or the full (non-CCS) carbon price. All fuel prices are represented as dollars per million Btu. For fuel *f* and vintage year *v*, the model calculates the base and carbon prices adjusted to 2011 dollars:

$$PGBPr50(f, v) = PGBPr50(f, v) * pricedeflator_{2011};$$

$$PGCPr50(f, v) = PGCPr50(f, v) * pricedeflator_{2011};$$

$$PGDPr50(f, v) = PGDPr50(f, v) * pricedeflator_{2011},$$

where  $pricedeflator_{2011}$  = price deflator for 2013 to 2011 dollars;

$$PGBPr50(f, v) = \text{base expected price};$$



$PGCPr50(f, v)$  = full carbon expected price;

$PGDPr50(f, v)$  = carbon CCS expected price and

The final expected price projection is the sum of the base price and the carbon price.

$$PGPr50(f, v) = PGBPr50(f, v) + PGCpr50(f, v);$$

$$PGPr50CCS(f, v) = PGBPr50(f, v) + PGDpr50(f, v),$$

where, for fuel  $f$  in vintage  $v$ ,

$PGPr50(f, v)$  = standard overall expected price;

$PGPr50CCS(f, v)$  = CCS overall expected price.

The standard overall price is used for all non-CCS technologies and the separate CCS overall price is used for technologies that use carbon capture and storage. (Carbon prices are assumed to be zero unless a carbon tax or “cap and trade” scenario is being simulated.)

## Calculate technology learning

### Subroutines `heatrate_learning_cost_learning`, `UseLearn`, and `use_heatrate_learning`

WEM has four subroutines that are used to calculate and represent technology learning, i.e., the cost reductions and efficiency improvements that are expected to result from the experience gained through use of a technology. The first two, `heatrate_learning` and `cost_learning`, calculate the learning factors based on cumulative capacity for technology components. The third and fourth, `UseLearn` and `use_heatrate_learning`, use the learning factors to adjust the cost and efficiency variables for new technologies. These subroutines were enabled for the first time for *IEO2016*.

The learning subroutines are called from within nested year loops. The subroutines operate outside of the region loop because the subroutines estimate learning factors based on worldwide, not regional, cumulative capacity.

#### *Calculate learning factors*

The learning coefficients are read in earlier from the technology file. The model simulates the effects of technology learning by adjusting heat rates and capital costs associated with the components that compose the technologies. Each new technology learning is divided into one to four major components. Each component is classified as *revolutionary*, *evolutionary* or *conventional*.

Different learning rates may be assumed for each component. Similar components are assumed to “learn” at the same rate, even if they are associated with multiple technologies. For example, it is assumed that the underlying turbine generator for a combustion turbine, combined cycle and integrated coal-gasification combined cycle unit is basically the same. Therefore construction of any of these technologies would contribute to cost reductions associated with technology learning for the turbine

component. The rate of learning defined by the exogenous learning coefficient provides a non-linear reduction in costs or heat rate for every doubling of cumulative world capacity. A learning rate is calculated for each component within a technology, and a learning factor for the technology is then calculated as a weighted average of the component-level learning rates.

### *Implement learning factors*

The subroutines UseLearn and use\_heatrate\_learning implement the learning factors. For costs, the current model new-technology cost variable is multiplied by two learning factors. For efficiency, the learning subroutine calculates a new heat rate value that is converted to an efficiency and written to the new technology efficiency variable.

## Generation requirements, capacity dispatch

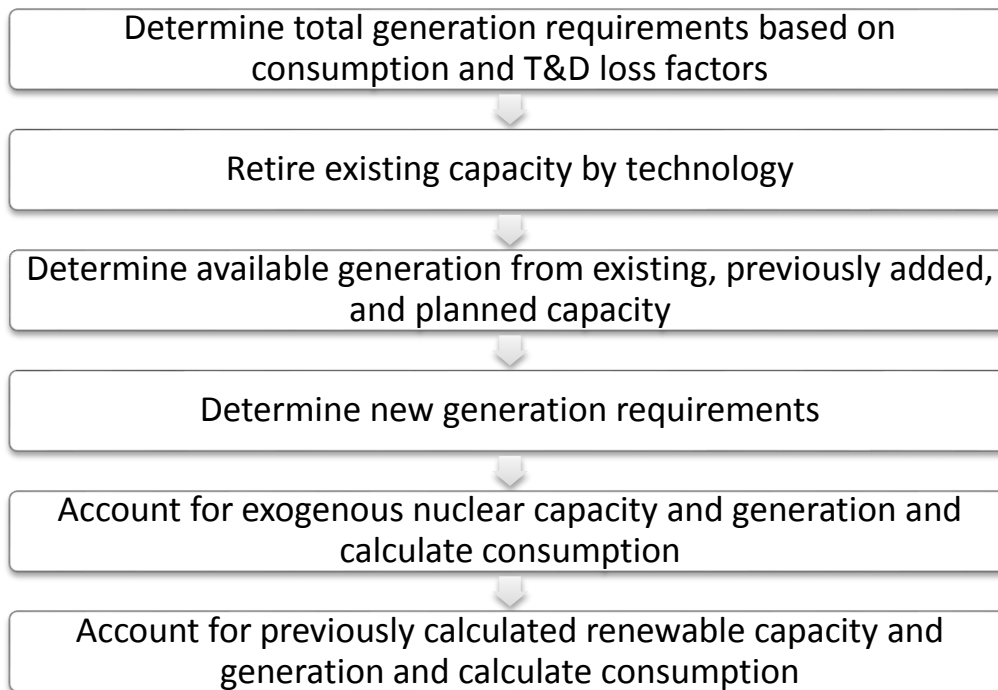
### Subroutine CapDisp

The CapDisp subroutine first determines the overall generation requirements based on the end-use sector electricity demand. It then retires some of the capacity for the existing technologies and uses remaining capacity and planned capacity, along with the overall generation requirements, to determine the new generation requirements. To simulate fulfillment of the new generation requirements, it adds capacity for new nuclear and renewable technologies first, leaving new fossil generation requirements for a subsequent step.

The subroutine is called from within a pair of nested loops for projection year and WEPS+ regions. The region loop is nested within the year loop. The documentation uses the subscripts  $ym$  and  $rm$  for year and region, respectively, to indicate that the calculations are performed within the nested loops.

The flowchart in Figure 6 shows the basic steps in this subroutine.

Figure 6. Basic Flows in the CapDisp Subroutine



### *Generation requirements*

The model adds the electricity consumption projections (expressed in trillions of Btu) for four end-use sectors to calculate the total generation requirements for each region and year. It uses a conversion factor (0.003412) to convert the consumption projections from trillions of Btu to billions of Kwh:

$$TDemKwh(rm, ym) = \frac{ResQty(rm, ym) + ComQty(rm, ym) + IndQty(rm, ym) + TrnQty(rm, ym)}{0.003412}$$

where, for region  $rm$  in year  $ym$ ,

$ResQty(rm, ym)$  = residential consumption (in trillion Btu);

$ComQty(rm, ym)$  = commercial consumption (in trillion Btu);

$IndQty(rm, ym)$  = industrial consumption (in trillion Btu);

$TrnQty(rm, ym)$  = transportation consumption (in trillion Btu); and

$TDemKwh(rm, ym)$  = total demand in billion Kwh.

The total generation requirement in the current region is the total amount of the electricity consumption in kilowatthours divided by the transmission and distribution (T&D) loss factor that was previously read into the model from an input file. The T&D loss factor is given as the fraction of the electricity that is not lost. For example, a value of 0.93 signifies a 7% loss. Because of the T&D loss, the amount of generation required is a bit more than the actual electricity consumed.

$$TGenReq(rm, ym) = \frac{TDemKwh(rm, ym)}{TDFac(rm, ym)},$$

where, for region  $rm$  in year  $ym$ ,

$TDFac(rm, ym)$  = T&D loss factor; and

$TGenReq(rm, ym)$  = total generation requirement.

### ***Retire existing capacity***

In each projection year, the model estimates the capacity that is remaining from the original base year, 2012. Some of this remaining capacity is retired in each year, based on a technology-specific retirement rate, which is read from the technology input file. For each technology  $t$  and region  $rm$ , the retirement rate is converted to an adjustment factor that represents the survival rate of the original base year capacity:

$$ETecSuv(t, rm) = 1 - RetRate(t, rm).$$

This survival rate is applied to the existing capacity from year  $ym - 1$  to determine the remaining capacity for year  $ym$ :

$$EtecCap(t, rm, ym) = EtecCap(t, rm, ym - 1) * ETecSuv(t, rm),$$

where, for existing technology  $t$  in region  $rm$ ,

$ETecSuv(t, rm)$  = survival rate; and

$EtecCap(t, rm, ym)$  = existing base year capacity remaining in year  $ym$ .

In addition to capacity, the model estimates the levels of generation and consumption from the remaining base year (2012) capacity, using the existing technology capacity factor and the existing technology efficiency:

$$ETecGen(t, rm, ym) = [EtecCap(t, rm, ym) * 8.760] * ETecCF(t, rm, ym),$$

$$ETecCon(t, rm, ym) = \frac{EtecCap(t, rm, ym) * 3.412}{ETecEff(t, rm, ym)},$$

where, for existing technology  $t$  in region  $rm$  and year  $ym$ ,

$ETecCF(t, rm, ym)$  = capacity factor of base year power plants at the beginning of year  $ym$ ;

$ETecEff(t, rm, ym)$  = efficiency of base year power plants at the beginning of year  $ym$ ;

$ETecGen(t, rm, ym)$  = generation from remaining base year capacity at the beginning of year  $ym$ ; and

$ETecCon(t, rm, ym)$  = consumption from remaining base year capacity.

(The factor 8.760 converts gigawatts to billion KWh, while the factor 3.1412 converts billion KWh to trillion Btu.) The generation and consumption estimates are then aggregated to the 13-fuel level, the 5-fuel level, and overall totals (across all technologies and fuels). The variable names for the capacity, generation, and consumption totals are  $ETotCap$ ,  $ETotGen$ , and  $ETotCon$ , respectively.

#### *Determine generation and consumption from planned additions*

The model also estimates the levels of generation and consumption from planned capacity additions, using the new technology capacity factor and the new technology efficiency. Planned capacity additions include facilities under construction at the time of the *IEO2016* publication that are expected to become operational no later than 2018 and are not otherwise represented by WEM's economic model.

The equations are identical to the ones cited above for  $ETecGen$  and  $ETecCon$ , except the new technology factors are used instead of existing technology factors.

The model adds planned capacity, generation, and consumption to existing capacity, generation, and consumption before it determines available generation.

#### *Determine available and new generation*

At the beginning of the current projection year, the total amount of available generation (over all technologies) in each region is the generation available from the existing technologies remaining from the base year 2012 (those not retired as described above) *plus* the generation from technologies that have been added since the base year. The model aggregates the data for the existing remaining technologies as described above. Data for technologies added in prior projection years (up to year  $ym - 1$ ) have also been incorporated. The total amount of available generation (based on capacity) for projection year  $ym$  is given by

$$AvailGen(rm, ym) = ETotGen(rm, ym) + ATotGen(rm, ym - 1),$$

where, for region  $rm$  and year  $ym$ ,

$AvailGen(rm, ym)$  = total amount of generation available at the beginning of year  $ym$

$ETotGen(rm, ym)$  = total amount of generation available from existing technologies at  
the beginning of year  $ym$

$ATotGen(rm, ym - 1)$  = total amount of generation available from technologies added  
between the base year and year  $ym - 1$

At this point the model has estimated the required generation for the current projection year  $ym$  and the generation available from the capacity existing in year  $ym - 1$  (i.e., at the beginning of year  $ym$ ). The difference between these two is the amount of new generation that must be added in the current year, given by

$$NTotGen(rm, ym) = \begin{cases} TGenReq(rm, ym) - AvailGen(rm, ym), & \text{if } TGenReq(rm, ym) > AvailGen(rm, ym); \\ 0, & \text{otherwise,} \end{cases}$$

where, for region  $rm$  and year  $ym$ ,

$$NTotGen(rm, ym) = \text{total new generation required.}$$

The model adds the required new generation for year  $ym$  to the cumulative generation added between the base year and year  $ym - 1$ . It then adds the generation from the remaining base year capacity to obtain the total generation for year  $ym$ :

$$ATotGen(rm, ym) = ATotGen(rm, ym - 1) + NTotGen(rm, ym),$$

$$TTotGen(rm, ym) = ETotGen(rm, ym) + ATotGen(rm, ym),$$

where, for region  $rm$  and year  $ym$ ,

$ATotGen(rm, ym)$  = total amount of generation from capacity added by the end of the year  $ym$ ; and

$TTotGen(rm, ym)$  = sum of generation from remaining 2012 capacity and generation from capacity added between 2012 and the end of year  $ym$ .

The calculations above can be simplified by noting that, for year  $ym$  in region  $rm$ , the model sets the total generation equal to the required generation:

$$TTotGen(rm, ym) = TGenReq(rm, ym).$$

Then the generation from capacity added during year  $ym$  is equal to total generation (above) less generation from capacity existing at the beginning of year  $ym$ :

$$ATotGen(rm, ym) + TGenReq(rm, ym) - ETotGen(rm, ym).$$

### ***Exogenous nuclear capacity, generation and consumption***

Nuclear capacity and generation are exogenous to WEM. At this point in the run, the model has determined the total amount of new generation required in the current projection year. This generation may come from nuclear, renewable, and/or fossil technologies. Because the nuclear projections are exogenous, the model first determines how much new nuclear generation is available (based on capacity) in the current year and allocates this amount of the total new generation requirements to the nuclear technology. The remainder of the total generation requirement is subsequently allocated to renewable and fossil generation.

The model has already read in the total amount (stock) of exogenous nuclear generation and capacity for each year. Therefore, in order to determine how much new nuclear generation is available in year  $ym$ , it uses the same type of accounting as described above. (Some of the existing generation has already been retired.) The new nuclear generation added in year  $ym$  is estimated as

$$NTecGen(nuc, rm, ym) \\ = NukeGen(rm, ym) - [ETecGen(nuc, rm, ym) + ATecGen(nuc, rm, ym - 1)],$$

where, for region  $rm$  and year  $ym$ ,

$NukeGen(rm, ym)$  = total amount (stock) of nuclear generation (calculated exogenously and read from an input file);

$ETecGen(nuc, rm, ym)$  = nuclear generation remaining from the base year capacity;

$ATecGen(nuc, rm, ym - 1)$  = nuclear generation from capacity added between the base year and year  $ym - 1$ ; and

$NTecGen(nuc, rm, ym)$  = new nuclear generation to be added in year  $ym$

The model ascertains that the new nuclear generation is not less than zero and not greater than the total amount of new generation requirements calculated above.

The model then performs the accounting to calculate the added and total nuclear generation:

$$ATecGen(nuc, rm, ym) = ATecGen(nuc, rm, ym - 1) + NTecGen(nuc, rm, ym);$$

$$ATotGen(nuc, rm, ym) = ETecGen(nuc, rm, ym) + ATecGen(nuc, rm, ym).$$

The model then calculates the nuclear capacity in the same fashion that it calculates generation. The model calculates the consumption based on the generation and the technology efficiencies:

$$NTecCon(nuc, rm, ym) = \frac{NTecGen(nuc, rm, ym) * 3.412}{NTecEff(nuc, rm, ym)},$$

where  $NTecEff(nuc, rm, ym)$  = new technology efficiency for nuclear technology in region  $rm$  and year  $ym$

The model then calculates the added and total consumption based on the relationships illustrated directly above. The existing consumption has already been calculated (above) after accounting for a certain amount of retirement of an existing technology during given year  $ym$ .

### ***Exogenous renewable capacity, generation and consumption***

Renewable capacity and generation for several technologies have already been calculated by WEM. At this point, the model has determined the total amount of new generation required in this year and subtracted the amount allocated to new nuclear generation. The remaining amount may come from renewable and/or fossil technologies. Since the renewable generation is already calculated, the model determines how much new renewable generation is available from each technology in the current year and allocates the amount to each renewable technology, subtracting it from the total new generation requirements. The total remaining generation is then allocated to fossil technologies. The allocation among fossil technology types is subsequently determined through a simulated cost competition.

The model has already determined the total amount (stock) of exogenous renewable generation and capacity for several renewable technologies for each year. In order to determine how much new renewable generation is available in the current year, it employs the same type of accounting as described above. (Some of the existing generation has already been retired.) In the equations below,  $t = ren$  represents any of several renewable technologies.

$$NtecGen(ren, rm, ym) = RenewGen(rm, ym) - [ETecGen(ren, rm, ym) + ATecGen(ren, rm, ym - 1)],$$

where, for renewable technology  $ren$  in region  $rm$  and year  $ym$ ,

$RenewGen(rm, ym)$  = total amount (stock) of generation calculated earlier;

$ETecGen(ren, rm, ym)$  = generation from the remaining base year capacity;

$ATecGen(ren, rm, ym - 1)$  = generation from capacity added between the base year and year  $ym - 1$ ; and

$NtecGen(ren, rm, ym)$  = new generation to be added in year  $ym$ .

The model checks to ensure that the new renewable generation is not less than zero. The model then calculates the converted (in Kwh) total added renewable generation for year  $ym$ .

$$NTecCon(ren, rm, ym) = \frac{NtecGen(ren, rm, ym) * 3.412}{NTecEff(ren, rm, ym)},$$

where  $NTecEff(ren, rm, ym)$  = new technology efficiency for renewable technology  $ren$  in region  $rm$  and year  $ym$ .

The model then calculates the added consumption and total consumption for year  $ym$ , based on the relationships illustrated directly above. The existing consumption is calculated (above) before the existing capacity is retired.

#### ***Verify new nuclear and renewable versus total new generation requirements***

The model then verifies that the sum of the exogenous nuclear and renewable new generation is not greater than the total required new generation. If this imbalance occurs, then the model retains the nuclear generation (considers it fixed) and reduces the amount of the renewable generation as necessary. This imbalance occurs occasionally for some regions where renewable capacity is growing quickly. If the renewable generation must be reduced, the model keeps track of the amount by which it is reduced and tries to add the amount to the renewable generation projections for subsequent years.



## Least-cost, market-share technology competition

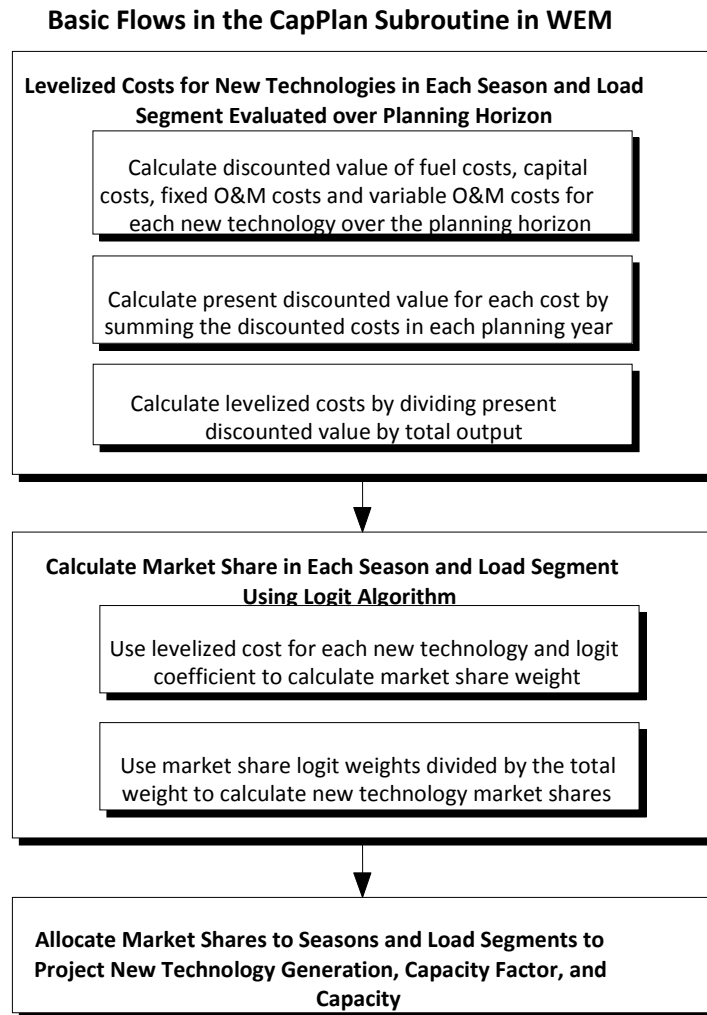
### Subroutine CapPlan

The CapPlan subroutine calculates levelized costs for electricity generation technologies by season and load segment. It then simulates new fossil technology choices using a least-cost market-share logit algorithm for each season and load segment. It calculates the total generation and capacity (using capacity factors based on how the capacity is used) over all load segments and years. The subroutine projects the total overall new capacity factors and new capacity, generation, and consumption by technology.

The CapPlan subroutine is called from within a pair of nested loops over the 16 WEPS+ regions and over all projection years. The region loop is nested within the year loop. The documentation uses the subscripts *ym* for projection year and *rm* for WEPS+ region to indicate that the calculations are performed within this pair of nested loops.

The flowchart in Figure 7 shows the basic steps in the CapPlan subroutine.

Figure 7. Basic Flows in the CapPlan Subroutine



### Overview

The power generation model projects the technologies that will be used to provide the new generation requirements. The model has already projected the required new generation and the amount of new generation that will come from exogenous nuclear and renewable. To project new capacity for the fossil fuel technologies, it considers the cost of building new capacity for each technology within a set of seasons and load segments (time periods within seasons). The cost of building new capacity differs across technologies. Because new capacity can be used to generate electricity almost continuously (i.e., baseload capacity) or used to generate only occasionally (e.g., during peak usage periods), the model considers total costs, including operating costs which depend on usage, within each of several load segments.

The model uses a technology-based least-cost function based on levelized costs and a logit algorithm that allocates market shares to technologies. There are two options for the logit algorithm. The first competes all the technologies against each other in a straight logit, and the second uses a nested logit structure to compete technologies within smaller groups first and then compete the groups against each other.

### *Levelized costs for new technologies in each season and load segment*

The current power generation model simulates technology-level competition only for fossil fuel technologies, since nuclear generation is exogenous and generation from renewable technologies is calculated elsewhere. To simulate the cost competition, the model must first calculate present discounted value of costs and revenue. The model then levelizes the costs across the various technologies and incorporates any necessary calibration effects. Levelized cost is measured in dollars per kilowatt hour.

Only technologies available in the current projection year are included. This is to account for technologies that become available or become unavailable during the projection period. Many of the technology characteristics can change over time, and the model structure accommodates the changes by incorporating a time series for each characteristic.

The fixed costs for the technologies are expressed in dollars per kilowatt of capacity, while the variable costs are in terms of dollars per kilowatt hour generated. The total cost for a technology depends on the number of hours it is in use. The cost evaluations are made over the various seasons and load segments.

The model considers natural gas and oil technologies that are basically the same but can use either fuel. A previous version of the model allowed oil technologies to gain market share when the oil price was only slightly higher than the gas price. Because it was determined that such a gain was unlikely, the current model incorporates an algorithm that removes this potential market share advantage for oil technologies. If the price of oil is greater than the price of gas, the model computes the following factor based on the relative prices and applies it to the logit share for oil technologies:

$$PetLCFac(rm, ym) = \left( \frac{PGPrc(oil, rm, ym)}{PCPrc(gas, rm, ym)} \right)^4$$

where, for fuel  $f \in \{oil, gas\}$  in region  $rm$  and year  $ym$ ,

$PGPrc(f, rm, ym)$  = standard overall price of fuel  $f$ ; and

$PetLCFac(rm, ym)$  = oil and gas ratio price factor.

(If the price of oil is less than or equal to the price of gas, the factor is set to 1). The model starts a do-loop over the three seasons (indexed by  $sea$ ) and, nested within the season loop, a loop for load segments (indexed by  $seg$ ). Until otherwise noted in the text, all the calculations below are performed for each season and segment within season. For a cleaner notation, we suppress the subscripts  $sea$  (season) and  $seg$  (segment) in some equations.

The calculations then enter a third do-loop over all new technologies with the technology index  $t$ .

If the technology is a carbon capture and storage technology (CCS), then the carbon price used is reduced in proportion to the effectiveness of the CCS technology, e.g., a 100% effective CCS technology has a carbon price of zero.

$$ActPrc(f, t, \psi, rm, ym) = \begin{cases} PGPr50CCS(f, t, \psi, rm, ym), & \text{if } t \text{ is CCS;} \\ PGPr50(f, t, \psi, rm, ym), & \text{otherwise.} \end{cases}$$

where  $\psi = \text{evaluation year (years of evaluation period, 1..30)}$  e.g.,  $\psi = 1$  indicates that the evaluation year is the projection year.

Capital cost, expressed in dollars per KW, represents the one-time expenses incurred to build a power plant. When estimating levelized cost, capital cost must be divided by a power plant's availability factor because different generation technologies are able to operate for different portions of the year (e.g., the availability of solar and wind technologies is weather dependent). In the model, the loan rate is assumed to be equal to the discount rate, also making the present value of capital cost equal to the financing cost, if the plant's capital costs were financed.

$$PVCCst(t, rm, ym) = \frac{NTecCCst(t, rm, ym)}{NTecAF(t, rm, ym)},$$

where, for technology  $t$  in region  $rm$  and year  $ym$ ,

$PVCCst(t, rm, ym)$  = value of the capital cost, adjusted for availability;

$NTecCCst(t, rm, ym)$  = technology capital cost; and

$NTecAF(t, rm, ym)$  = technology availability factor.

Each load segment that is evaluated has a different number of hours of use. The annual number of hours in use (the somewhat misnamed "annual output") is computed by multiplying the fraction of annual hours in the load segment by the number of hours in a year. The total output over the evaluation period is computed by multiplying the annual output by the number of years in the evaluation period (typically set to 30).

$$AnnOut(t, sea, seg, rm, ym) = SHFac(sea, seg, rm, ym) * 8760;$$

$$TotOut(t, sea, seg, rm, ym) = AnnOut(t, sea, seg, rm, ym) * NTecLE(t, rm, ym),$$

where, for technology  $t$  in season  $sea$ , segment  $seg$ , region  $rm$ , and year  $ym$ ,

$SHFac(sea, seg, rm, ym)$  = fraction of annual hours in segment  $seg$  of the particular season  $sea$ ;

$AnnOut(t, sea, seg, rm, ym)$  = total hours in a year that the technology will operate;

$NTecLE(t, rm, ym)$  = number of years in the evaluation period for the cost competition; and

$TotOut(t, sea, seg, rm, ym)$  = total hours that the technology will operate in the evaluation period.

Note that the variables defined above are constant across all technologies  $t$ .

At this point the calculations enter another do-loop over all years of the evaluation period (the number of years is given by the variable  $NTecLE(t, rm, ym)$  above). The index  $v$  indicates the number of years between the evaluation year and the current projection year  $ym$ , e.g.,  $v = 1$  indicates that the evaluation year is the projection year. The other costs are discounted over the technology evaluation period, with their discounted values added together over the evaluation years in order to determine the total present value (in projection year  $ym$ ) of the future streams of the cost.

The discount factor used for each evaluation year is given by

$$DFac(v, rm) = [DRate(rm)]^{\psi-1}$$

where

$DFac(\psi, rm)$  = discount factor for evaluation year  $\psi$  in region  $rm$ ; and

$DRate(rm)$  = discount rate for region  $rm$ .

The model uses a series of steps to calculate the discounted fuel cost for each evaluation year, accounting for regional discount rates, annual output, fuel costs, and the efficiency of each technology in each year. The efficiency is first converted to a heat rate:

$$HeatRate(t, rm, ym) = \left[ \frac{3412}{NTecEff(t, rm, ym)} \right]$$

where, for technology  $t$  in region  $rm$  and year  $ym$ ,

$HeatRate(t, rm, ym)$  = heat rate

$NTecEff(t, rm, ym)$  = efficiency

The heat rate is then used in the discounted fuel cost calculation for the evaluation years:

$$DFCst(\psi, t, rm, ym) = \frac{DFac(\psi, t, rm, ym) * AnnOut(t, rm, ym) * HeatRate(t, rm, ym) * ActPrc(\psi, t, rm, ym)}{1,000,000}$$

where  $DFCst(\psi, t, rm, ym)$  = discounted fuel cost for technology  $t$  in evaluation year  $\psi$  region  $rm$ , and projection year  $ym$ .

The result is divided by 1,000,000 to convert dollars per million btu to dollars per btu, which corresponds to the heat rate units.

The discounted fixed operation and maintenance calculation in each evaluation year is simply the discount factor times the input fixed O&M cost.

$$DFOM(\psi, t, rm, ym) = DFac(\psi, rm) * NTecFOM(t, rm, ym)$$

where  $DFAC(\psi, rm)$  = discount factor in evaluation year  $\psi$ , region  $rm$ ; and

$DFOM(\psi, t, rm, ym)$  = discounted fixed O&M cost for technology  $t$  in evaluation year  $\psi$ , region  $rm$ , and projection year  $ym$ ; and

$NTecFOM(t, rm, ym)$  = fixed O&M cost for technology  $t$ , region  $rm$ , and projection year  $ym$ .

The discounted variable operation and maintenance cost in each evaluation year is computed by multiplying the imported variable O&M cost by the discount factor and the annual hours of operation. The units for the variable O&M cost are also converted from dollars per mWh to dollars per kWh by dividing by 1,000:

$$DVOM(\psi, t, rm, ym) = DFac(\psi, rm) * \frac{NTecVOM(t, rm, ym)}{1000} * AnnOut(t, rm, ym),$$

where, for region  $rm$  in year  $ym$ ,

$AnnOut(t, rm, ym)$  = annual hours of operation for technology  $t$ ;

$DVOM(\psi, t, rm, ym)$  = discounted variable O&M cost for technology  $t$  in evaluation year  $\psi$ ; and

$NTecVOM(t, rm, ym)$  = variable O&M cost for technology  $t$ .

The subroutine now sums the discounted values over the evaluation years. It calculates the total present value (in each projection year) for each technology and region as the sum of the discounted fuel costs over all the evaluation years:

$$PVFCst(t, rm, ym) = \sum_{\psi} DFCst(\psi, t, rm, ym).$$

Similarly, the present value of the fixed O&M cost is the sum of the discounted costs over all the evaluation years:

$$PVFOM(t, rm, ym) = \sum_{\psi} DFOM(\psi, t, rm, ym).$$

The present value of variable O&M cost is the sum of the discounted costs over all the evaluation years:

$$PVVOM(t, rm, ym) = \sum_{\psi} DVOM(\psi, t, rm, ym)$$

Finally, the subroutine exits the evaluation year ( $v$ ) loop and aggregates the four cost variables:

$$\begin{aligned} PVTot(t, rm, ym) \\ &= PVCCst(t, rm, ym) + PVFCst(t, rm, ym) + PVFOM(t, rm, ym) \\ &+ PVVOM(t, rm, ym) \end{aligned}$$

The total value of the levelized cost,  $LVCst(t, rm, ym)$ , for technology  $t$  in region  $rm$  and projection year  $ym$ , is computed by dividing the total cost by the total output of the technology:

$$LVCst(t, rm, ym) = \frac{PVTot(t, rm, ym)}{TotOut(t, rm, ym)}$$

This levelized cost for each technology then is used in a subsequent logit algorithm for each load segment to calculate market shares for the technologies in each load segment within each season. However, the model does allow for a “shadow cost” to be added to the levelized cost to adjust for effects that the model may not otherwise capture. This “shadow cost” is added to the calculated levelized cost and used in place of the levelized cost in the market share competition (for any other calculations the original base levelized cost is maintained).

The model allows for two such costs. Currently only one cost, specified by fuel, is used to account for a tendency, in some regions, to use one fuel rather than another. This tendency is not likely to be fully captured through the model’s subroutines, due to data limitations and the complexity of the regulated industries present in some regions. Also, the oil/gas competition factor calculated earlier,  $PetLCFac$ , is added at this point.

After calculating the levelized costs for all the new technologies (within the loops for one season and for one load segment), the model exits the new technology loop. The costs are used to calculate market share for each new technology.

### *Technology choice using a logit algorithm*

The logit algorithm considers the levelized cost for each of the technologies in each of the load segments and allocates market share to each technology. The technology with the lowest cost receives the largest market share, while other technologies with costs that are almost as low receive smaller market shares. The lowest cost technology does not receive the entire market share if other technologies have comparable costs. The model uses a logit coefficient, currently specified by the user, to allocate market share to the technologies. (The user-defined coefficients may vary by region but are held constant across years within a region.) A smaller logit coefficient causes market share to be allocated more evenly across technologies, while a larger coefficient causes market share to be more concentrated on the lower cost technologies. A very large coefficient provides a result that is similar to simple least-cost choice (i.e., all market share is allocated to the lowest cost technology).

The logit algorithm first assigns each technology an “inverse cost weight” based on its levelized cost and the logit coefficient,  $Lambda(rm)$ .

$$TecWt(t, rm, ym) = LVCst(t, rm, ym)^{-Lambda(rm)},$$

where  $Lambda(rm)$  = user specified logit coefficient for region  $rm$ ; and

$TecWt(t, rm, ym)$  = weight assigned to technology  $t$  and year  $ym$  for region  $rm$ .

For each technology, the model assigns a market share proportional to its share of the total inverse cost weight, summed across all technologies:

$$TotWt(rm, ym) = \sum_t TecWt(t, rm, ym)$$

$$TecShr(t, rm, ym) = \frac{TecWt(t, rm, ym)}{TotWt(rm, ym)}$$

The model performs the allocation within the nested loops over seasons and load segments. Thus the market share for each technology is allowed to vary by year, region, season, and load segment.

### *Nested logit option*

One of the limitations of the logit algorithm described above is that it tends to allocate larger total market shares to fuels that have a large number of associated technologies. The model therefore provides the option of using a nested logit algorithm in place of the straight technology-level algorithm. The nested logit performs the allocation in two steps: first by fuel and then by technology within each fuel. (The algorithm also allows other groupings of the technologies.)

The current set of technology groups are fuel groups; the technologies are grouped into those that use petroleum, natural gas, coal, nuclear, and renewable. The technologies in each of these groups are competed among themselves to get a set of market shares for the technologies within each group. The results in each group are then used to calculate a weighted average cost for each group. Then the five groups are competed against each other, using the group’s average cost, to get a market share for each of the five groups. Finally, the market share for each technology is calculated as the product of the market share for the group times and the market share for the technology within the group.

For the fossil-only competition that the model performs at this point, the nested logit results are not significantly different from the straight logit results. For this reason, the straight logit was used for the *IEO2016*.

### *Generation for each new fossil technology*

At this point the model exits the do-loops for season and for load segments. It saves the new technology shares for fossil fuels, as well as other information, for each of the seasons and load segments.



The model has previously stored the estimates of new electricity generation from nuclear and renewable sources. If additional fossil generation is needed to fulfill the projected demand requirements, the model estimates generation for new fossil technologies. First, it calculates the total new generation required in each season and load segment:

$$TNewGen(sea, seg, rm, ym) = NTotGen(rm, ym) * SLFac(sea, seg, rm, ym) * SeaLPct(sea, rm, ym),$$

where, for year  $ym$  in region  $rm$ ,

$NTotGen(rm, ym)$  = new generation required;

$TNewGen(sea, seg, rm, ym)$  = new generation required in segment  $seg$  of season  $sea$ ;

$SLFac(sea, seg, rm, ym)$  = fraction (previously calculated) of new generation for segment  $seg$  of season  $sea$ ; and

$SeaLPct(sea, rm, ym)$  = fraction (previously calculated) of new generation in season  $sea$  within year  $ym$ .

Next, the total new renewable and new nuclear generation in each of the seasons and load segments must be determined in order to calculate how much fossil fuel generation is needed in each load segment. The renewable and nuclear generation is allocated to load segments as follows:

- All new nuclear is in the baseload load segment.
- All waste, biomass, hydroelectric, and geothermal are in the baseload load segment.
- Half of solar, wind and other renewables are in the baseload load segment.
- Half of solar, wind and other renewables are in the intermediate load segment.

For each season and load segment, the estimates of new nuclear and renewable generation are subtracted from the total estimated new required generation. The resulting difference is the amount of new fossil generation to be added:

$$FNewGen(sea, seg, rm, ym) = TNewGen(sea, seg, rm, ym) - XNewGen(sea, seg, rm, ym),$$

where  $FNewGen(sea, seg, rm, ym)$  = new fossil generation required; and

$XNewGen(sea, seg, rm, ym)$  = new nuclear and renewable new generation.

The model then allocates the new fossil generation to the fossil technologies by applying the technology share in each season and segment to the new fossil generation total. It then calculates an annual total for each technology by adding the generation amounts across seasons and segments:

$$NTecGen(t, rm, ym) = \sum_{sea} \left[ \sum_{seg} [FNewGen(sea, seg, rm, ym) * TecShr(sea, seg, t)] \right]$$

where  $NTecGen(t, rm, ym)$  = new fossil generation by technology  $t$  in region  $rm$  and year  $ym$

$TecShr(sea, seg, t)$  = new technology market share

The overall new technology shares for nuclear and renewable technologies are also calculated by aggregating the season and segment shares.

### *New capacity factors*

Capacity factors indicate the proportion of a technology's capacity that is actually used for generation. The model calculates overall capacity factors for the new technologies as weighted averages of the capacity factors for the load segments and the seasons. Within each load segment and season, the capacity factors are based on the average fraction of the year in which the technologies are generating. However, each of the seasons and each of the load segments represents a certain proportion of the total load, so the overall capacity factor for each technology is a weighted average of the segment-level factors.

For each segment  $seg$  in each season  $sea$ , the subroutine first calculates a load share for technology  $t$  in region  $rm$  and year  $ym$ :

$$XTot(sea, seg, t, rm, ym) = TecShr(sea, seg, t) * SLFac(sea, seg, rm, ym) * SeaLPct(sea, rm, ym)$$

where  $SLFac(sea, seg, rm, ym)$  = fraction (previously calculated) of new generation for segment  $seg$  of season  $sea$ ; and

$SeaLPct(sea, rm, ym) = SeaLPct(sea, rm, ym)$  = fraction (previously calculated) of new generation in season  $sea$  within year  $ym$ .

It then aggregates the segment-level shares these within each season and uses the totals to compute proportionate load weights for the segments:

$$PSeg(sea, seg, t, rm, ym) = \frac{XTot(sea, seg, t, rm, ym)}{\sum_{seg} XTot(sea, seg, t, rm, ym)}$$

Next the model computes each technology's share of the load within each season and load segment:

$$XTTot(sea, seg, t, rm, ym) = SHFac(sea, seg, rm, ym) * SeaHPct(sea, rm, ym) * PSeg(sea, seg, t, rm, ym).$$

The capacity factor for the technology is the sum of its shares, aggregated over seasons and load segments:

$$XCapFac(t, rm, ym) = \sum_{sea} \left[ \sum_{seg} XTTot(sea, seg, r, rm, ym) \right].$$

The model ensures that the capacity factor to be used in the projections does not exceed the technology availability factor originally imported:

$$NTecCF(t, rm, ym) = \begin{cases} XCapFac(t, rm, ym), & \text{if } XCapFac(t, rm, ym) \leq NTecAF(t, rm, ym); \\ NTecAF(t, rm, ym), & \text{otherwise,} \end{cases}$$

where, for technology  $t$  in region  $rm$  and year  $ym$ ,

$NTecAF(t, rm, ym)$  = imported technology availability factor; and

$NTecCF(t, rm, ym)$  = capacity factor to be used in WEM projections.

### *Capacity for each new technology*

Using the new generation for each technology and the new capacity factor calculated above, the model calculates the capacity for each new technology:

$$NTecCap(t, rm, ym) = \frac{NTecGen(t, rm, ym)}{NTecCF(t, rm, ym) * 8.760}.$$

### *Fuel consumption for each new technology*

The total amount of fuel consumed by each new technology is calculated by using the new generation for each technology and the efficiency for each technology:

$$NtecCon(t, rm, ym) = \frac{NTecGen(t, rm, ym) * 3.412}{NTecEff(t, rm, ym)}.$$

### *Miscellaneous calculations*

The total levelized cost of each new technology is a weighted average of the levelized cost over the seasons and load segments. This is calculated by the model but is not currently used.

Finally, the model calculates a generation share for each technology:

$$TotTec(rm, ym) = \sum_t NTecGen(t, rm, ym);$$

$$NTecShr(t, rm, ym) = \frac{NTecGen(t, rm, ym)}{TotTec(rm, ym)}.$$

The CapPlan subroutine ends and the model exits the do-loops for projection years ( $ym$ ) and regions ( $rm$ ).

## Summing up and final accounting

### Subroutine FinishUp

The FinishUp subroutine aggregates all the capacity, generation and consumption variables over the projection years, vintages, technologies and fuel levels. It also performs any necessary adjustments and overwrites to the estimates and calculates electricity consumption from carbon capture and storage (CCS) technologies.

#### *Overwrites*

The FinishUp subroutine first calls another subroutine named “OverWrite,” which makes any user-specified adjustments or overwrites in the calculated estimates. No overwrites occurred for *IEO2016*.

#### *Vintage accounting*

For each region, technology, and projection year, the model adds the estimated new electricity generation for the projection year  $y$  to the estimated generation added between the base year and year  $y - 1$ :

$$ATecGen(t, r, y) = ATecGen(t, r, y - 1) + NTecGen(t, r, y),$$

where, for technology  $t$  in region  $r$ ,

$ATecGen(t, r, y)$  = generation added between the base year (2012) and year  $y$ ; and

$NTecGen(t, r, y)$  = new generation added during year  $y$ .

To estimate total generation for year  $y$ , the model then adds the generation remaining from the base year capacity:

$$TTecGen(t, r, y) = ETecGen(t, r, y) + ATecGen(t, r, y),$$

where, for technology  $t$  in region  $r$  and year  $y$ ,

$ETecGen(t, r, y)$  = generation remaining from 2012 capacity; and

$TTecGen(t, r, y)$  = total generation (original plus added).

The model performs analogous calculations for capacity and consumption.

#### *Technology/fuel/total level accounting*

The model now aggregates all of the vintage categories from the technology level up to the corresponding categories at the 13-fuel, 5-fuel, and overall total levels. This is the same basic accounting that was discussed earlier for initialization in the subroutine “SumUp.” The result is capacity, generation, and consumption aggregated at the 13-fuel level, at the 5-fuel level, and for totals.

### *Consumption for carbon capture and sequestration technologies*

The WEM estimates electricity consumption from carbon capture and sequestration (CCS) technologies and passes this information to the WEPS+ system for use in estimating carbon emissions. The model takes into account the effectiveness of the CCS technologies. The total effective amount of a fuel  $f$  consumed in region  $r$  and year  $y$  for which CCS technologies captured and sequestered carbon is given by

$$ConCCS(f, r, y) = \sum_{t \in f} [TTecCon(f, t, r, y) * CCSFac(r, y)],$$

where:  $ConCCS(f, r, y)$  = effective fuel consumption of CCS technologies;

$TTecCon(f, t, r, y)$  = total fuel consumption for CCS technology  $t$  using fuel  $f$ ; and

$CCSFac(r, y)$  = effectiveness factor for CCS technologies in region  $r$  and year  $y$ , assumed constant across technologies and fuels.

## Fill in variables for the restart file

### Subroutine SysOut

The subroutine SysOut prepares various variables for export to the WEPS+ system and writes them to the restart file. It allocates the petroleum consumption to three categories: distillate, residual and crude oil. It also allocates generation, consumption, and capacity to CHP and electricity-only plants and estimates the amounts of heat generated by CHP plants.

### *Petroleum consumption categories*

The model projects petroleum consumption for specific technologies and aggregates these to compute an overall total. Because the petroleum can be from distillate, residual or crude oil consumed directly, the WEM allocates petroleum consumption to these three fuel categories. The allocation is performed by region and is based on the 2012 consumption shares for the three fuels.

### *CHP*

WEM initially imports historical data on consumption, generation and capacity for electricity-only plants and for CHP plants. WEM also imports historical data on the amount of heat generated by CHP plants. WEM projects electricity generation without distinguishing generation from CHP and electricity-only plants. As a final step, however, it allocates generation to the two categories of plants, based on the shares reflected in the 2012 data. Similarly, it allocates consumption and capacity based on the 2012 shares. For the CHP plants, the model uses the 2012 shares (assumed fixed over time) to estimate the amounts of electricity and heat generated over the projection horizon.

### *Restart file*

WEM writes the electricity projections and other estimates to the WEPS+ restart file for use by other models and for the final reports. The estimates include the end-use retail electricity prices by sector, region and year; fuel consumption (at the 13-fuel level) by region and year; and consumption, generation, and capacity by plant type (electricity only and CHP).

## Calculate end-use electricity prices

### Subroutine EUPrice

This subroutine calculates end-use retail electricity prices using fixed markups and writes them to the WEPS+ restart file.

The WEM estimates end-use retail electricity prices for each sector and for each region based on market assumptions and general economic relationships. The estimation method represents an effort to provide a connection between the prices of fuels consumed for electricity generation and the final end-use electricity prices. Due to data limitations, however, the quality of the end-use price estimates varies considerably across WEPS+ regions. For some regions, there is very limited information on even the actual historical end-use electricity prices. The current process informs the end-use models with prices that probably reflect the correct patterns of change over time and approximate the correct levels for many regions.

To calculate the end-use prices, the model starts with the overall weighted average of the cost of the fuels consumed to generate electricity in each region. This cost includes both the base fuel price and the carbon fuel price (in the case of a carbon price scenario). The calculation assumes that the nuclear fuel price can be approximated by the coal price and that the cost of all the renewable fuels is zero.

In addition to the weighted average cost of fuels to the WEM model, the model uses two historical data inputs to calculate the end-use prices:

- 1) Additive factors for the U.S. market that indicate the amount that is added to the fuel cost to get the final end-use prices in each sector. The additive amounts are considered to be additional costs for capital, transmission and distribution, as well as taxes and subsidies.
- 2) Multiplicative factors for each end-use sector in each region, which indicate the level of end-use prices in that region *relative to* the level in the United States.

The price estimation algorithm first imports the U.S. end-use prices from historical data. It then assigns the U.S. prices to regions and sectors by applying the sectoral additive and multiplicative factors. Once this is done for the historical period, the model determines a set of additive factors by sector for all regions, using the same methodology applied to the U.S. data. Finally, for each projection year, the model estimates the overall fuel cost for each region and applies the region's additive factors to obtain the end-use retail prices in each sector and region.

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## Appendix A. Model Abstract

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***Model name:***

World Electricity Model

***Model acronym:***

WEM

***Model description:***

The World Electricity Model (WEM) of the World Energy Projection System Plus (WEPS+) is a computer-based energy transformation model of the world electricity generation sector, designed to provide regional-level projections. WEM for *IEO2016* projects the amount of electricity generated to satisfy the electricity demands of the end-use demand models for each of the 16 WEPS+ regions. It projects how 39 fossil, renewable, and nuclear technologies are used to generate electricity, based on both policy and least cost. The model also projects fuel consumed, electricity generated, and generation capacity by each technology represented, for 13 energy sources in each of the 16 international regions over the projection horizon to 2040. WEM also projects end-use electricity prices for each of four demand sectors in each of the 16 international regions.

WEM is a technology-based, least-cost model that uses levelized costs in a logit formulation to estimate levelized cost for new generation technology market shares in three load segments. It then uses the levelized costs to project market shares for each technology. The model accounts for a slate of available new technologies along with their corresponding characteristics. These technology characteristics vary by region and include heat rates (efficiency), capital cost (per kilowatthour), fixed operating cost, variable operating cost, availability factor, and more. For each fuel type, the model features different technology representations with different characteristics. It also includes certain carbon capture and storage (CCS) technologies.

***Model purpose:***

As a component of the WEPS+ integrated modeling system, WEM generates long-term projections of energy consumed in the electricity generation sector, along with retail electricity prices. As part of the system, the model provides consumption and price inputs for the other models. The model provides a tool for analysis of international electricity generation and capacity within the WEPS+ system and can also be run independently as a standalone model.

***Most recent model update:***

November 2015

***Part of another model:***

World Energy Projection System Plus (WEPS+)

***Model interfaces:***

The World Electricity Model receives inputs from and provides outputs to other models in the WEPS+ system, through the common, shared interface file of th WEPS+.

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***Documentation:***

U.S. Energy Information Administration, U.S. Department of Energy, *World Energy Projection System Plus Model Documentation 2016: World Electricity Model*, DOE/EIA-M073(2016) (Washington, DC, July 2011).

***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 electricity generation sector capacity, generation, and energy consumption.

***Coverage:***

***Geographic:*** Sixteen 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 Central and South America.

***Structure:*** Technology-based stock/flow least-cost market-share structure.

***Time Unit/Frequency:*** Annual, 2013 through 2040.

***Modeling features:***

The World Electricity Model provides an accounting framework that considers international electricity generation, capacity, consumption and prices. It projects the generation of electricity to satisfy the electricity demands from the end-use demand models. WEM also projects how 39 fossil, renewable, and nuclear technologies are used to generate electricity, based on both policy and least cost. WEM is a technology-based, least-cost model that uses levelized costs in a logit formulation to solve for new technology market shares in various load segments. The model takes into account the vintage of equipment, maintaining a structure that looks at differing technology characteristics and uses existing/remaining, new, and added capacity vintages. The model considers a slate of available new technologies along with their corresponding characteristics.



***DOE input sources:***

U.S. Energy Information Administration, International Energy Statistics Database, web site [www.eia.doe.gov/emeu/international](http://www.eia.doe.gov/emeu/international) (as of July 1, 2015).

U.S. Energy Information Administration, *Short Term Energy Outlook* (STEO), Washington, D.C., March 2015.

Electricity Market Model of the National Energy Modeling System for the *Annual Energy Outlook 2015* new technology characteristics.

***Non-DOE input sources:***

International Energy Agency (IEA), *Energy Balances of OECD Countries*, Paris, 2015.

International Energy Agency (IEA), *Energy Balances of Non-OECD Countries*, Paris, 2015.

International Energy Agency (IEA), *World Energy Outlook*, Paris, 2015.

International load shapes by sector and region developed by OnLocation, Inc.

Utility Data Institute (UDI) World Electric Power Plants Database, Platts/McGraw-Hill, New York, 2015.

***Independent expert reviews:***

None

***Computing environment:***

*Hardware/Operating System:* Basic PC with Windows XP (or other Windows OS).

*Language/Software Used:* Fortran 90/95 (Currently using Compaq Visual Fortran), not required at runtime. Python used for data import.

*Run Time/Storage:* Standalone model with one iteration runs in about 6-7 seconds, CPU memory is minimal, inputs/executable/outputs require less than 20MB storage.

*Special Features:* None.

## Appendix B. Input Data and Variable Descriptions

In the variables defined in this appendix may rely on the following indices: region ( $r$  or  $rm$ ), year ( $y$ ), sector ( $s$ ), technology number ( $NumTec$ ), technology ( $t$ ), plant type ( $x$ ), fuel at the 5-fuel level ( $f$ ), fuel at the 13-fuel level ( $d$ ), season ( $sea$ ), and segment ( $seg$ ).

The following variables represent data input from the file PGMiscInput.xml.

Classification: Input variable.

$DRate(r)$ :	Discount rate, by region
$Lamda(r)$ :	Logit coefficient, by region
$BPMycop$ :	Choice for base price expectations
$CPMyop$ :	Choice for carbon price expectations
$CCSFac(r,y)$ :	Effectiveness of CCS, by region and year
$EUPrcAdd(s,1)$ :	End-use electricity price additive for USA, by sector
$EUPrcFac(s,r)$ :	End-use electricity price factors relative to USA, by sector and region
$TDFac(r,y)$ :	Transmission and distribution loss factors for the projection, by region and year (this variable is equal to $(1-T\&D$ losses))
$RMarg(r,y)$ :	Reserve margin, by region and year
$PrcFac(f,r,y)$ :	Retail price factors, by fuel, region, and year
$FBsCoef$ :	Fuel calibration coefficient
$XFBS$ :	Coal calibration coefficient
$DoExElas(f)$ :	Elasticity switch, by fuel
$RFosPrc(r,y)$ :	Reference case weighted average fossil fuel price, by region and year
$ExElas(f,r,y)$ :	Elasticities for the exogenous renewable and nuclear inputs, by fuel, region and year

The following variables represent data input from the file PGTechFile.txt.

Classification: Input variable.

<i>TecName(NumTec):</i>	Power plant technology name, by technology number
<i>TecCode(NumTec):</i>	Power plant technology code, by technology number
<i>MapFul(NumTec):</i>	Power plant 5-fuel group, by technology number
<i>MapFdb(NumTec):</i>	Power plant 13-fuel group, by technology number
<i>MapCCS(NumTec):</i>	Power plant carbon capture and storage availability, by technology number
<i>MinCF(NumTec):</i>	Power plant minimum capacity factor, by technology number
<i>NTecFYr(t,r,y):</i>	New power plant first year of availability, by technology number, region, and year
<i>NTecLYr(t,r,y):</i>	New power plant last year of availability, by technology number, region, and year
<i>NTecEff(t,r,y):</i>	New power plant thermal efficiency (assumed for renewables), by technology number, region, and year
<i>NTecCCst(t,r,y):</i>	New power plant capital costs (year 2000 \$), by technology number, region, and year
<i>NTecFOM(t,r,y):</i>	New power plant fixed operations and maintenance costs (year 2000 \$), by technology number, region, and year
<i>NTecVOM(t,r,y):</i>	New power plant variable operations and maintenance costs (year 2000 \$), by technology number, region, and year
<i>NTecAF(t,r,y):</i>	New power plant availability factor, by technology number, region, and year
<i>NTecLT(t,r,y):</i>	New power plant lifetime, by technology number, region, and year (this variable is overwritten by the economic lifetime variable)
<i>ETecUse(t,r):</i>	Existing power plant availability, by technology number and region
<i>ETecEff(t,r,y):</i>	Existing power plant thermal efficiency (assumed for

	renewables), by technology number, region, and year
$ETecFOM(t,r,y)$ :	Existing power plant fixed operations and maintenance costs (year 2000 \$), by technology number, region, and year
$ETecVOM(t,r,y)$ :	Existing power plant variable operations and maintenance costs (year 2000 \$), by technology number, region, and year
$ETecAF(t,r,y)$ :	Existing power plant availability factor, by technology number, region, and year
$ETecLT(t,r,y)$ :	Existing power plant lifetime, by technology number, region, and year (this variable is overwritten by the economic lifetime variable)
$ETecSuv(t,r,y)$ :	Existing power plant survival rate, by technology number, region, and year (this variable is equal to $(1 - \text{retirement rate})$ )
$MultC(y,r,t)$ :	Capital cost regional multipliers, by year, region, and technology number
$MultF(y,r,t)$ :	Fixed operations and maintenance cost regional multipliers, by year, region, and technology number
$MultEff(y,r,t)$ :	Thermal efficiency regional multipliers, by year, region, and technology number

The following variables represent data input from the file PGExogIn.xml.

Classification: Input variable.

$NukeCap(r,y)$ :	Nuclear power plant capacity, by region and year
$NukeGen(r,y)$ :	Nuclear power plant generation, by region and year

The following variables represent data input from the file pg\_udi.xml.

Classification: Input variable.

$udi\_capacity\_cumulative(t,r,y)$ :	Capacity (gigawatts), by technology, region, and year (used for dividing fuel capacity into technology capacity)
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The following variables represent data input from the file PGLoadShape.txt.

Classification: Input variable.

<i>PctTime(s,sea,seg):</i>	Load shapes, by sector, season, and segment
<i>PctLoad(s,sea,seg,r):</i>	Load shapes, by sector, season, segment, and region

The following variables represent data input from the file PGRenewables.xml.

Classification: Input variable.

<i>RenewCapAdd(t,f,r,y):</i>	New renewable capacity (megawatts), by renewable technology ( $t=f$ ), region, and year
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The following variables represent data input from the file PGCapacityTargets.xml.

Classification: Input variable.

<i>xmlCapacity(t,f,r,y)</i>	Renewable capacity (megawatts) policy targets, by renewable technology ( $t=f$ ), region, and year
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The following variables represent data input from the file PGRenewableCeiling.xml.

Classification: Input variable.

<i>xmlCapacity(t,f,r,y)</i>	Maximum renewable capacity (gigawatts), by renewable technology ( $t=f$ ), region, and year.
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The following variables represent data input from the restart file.

Classification: Input variable from demand models.

<i>QELRS(r,y):</i>	Electricity consumption (in trillion BTU) over the projection period in the residential sector, by region and year
<i>QELCM(r,y):</i>	Electricity consumption (in trillion BTU) over the projection period in the commercial sector, by region and year
<i>QELIN(r,y):</i>	Electricity consumption (in trillion BTU) over the projection period in the industrial sector, by region and year
<i>QELTR(r,y):</i>	Electricity consumption (in trillion BTU) over the projection period in the transportation sector, by region and year

<i>SHUGNDS(x,r,y):</i>	Utility generation of distillate (in TWh) over the historical period, for plant type x (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNRS(x,r,y):</i>	Utility generation of residual (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNCD(x,r,y):</i>	Utility generation of crude oil (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNNG(x,r,y):</i>	Utility generation of natural gas (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNCL(x,r,y):</i>	Utility generation of coal (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNWS(x,r,y):</i>	Utility generation of waste (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNBM(x,r,y):</i>	Utility generation of biomass (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNHE(x,r,y):</i>	Utility generation of hydroelectricity (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNGT(x,r,y):</i>	Utility generation of geothermal (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNSL(x,r,y):</i>	Utility generation of solar (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNWN(x,r,y):</i>	Utility generation of wind (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNOR(x,r,y):</i>	Utility generation of other renewables (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUGNNU(x,r,y):</i>	Utility generation of nuclear (in TWh) over the historical period, by plant type (electricity only, CHP, heat from CHP), region, and year
<i>SHUCNDS(x,r,y):</i>	Utility consumption of distillate (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNRS(x,r,y):</i>	Utility consumption of residual (in trillion BTU) over the historical

	period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNCD(x,r,y):</i>	Utility consumption of crude oil (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNNG(x,r,y):</i>	Utility consumption of natural gas (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNCL(x,r,y):</i>	Utility consumption of coal (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNWS(x,r,y):</i>	Utility consumption of waste (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNBM(x,r,y):</i>	Utility consumption of biomass (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNHE(x,r,y):</i>	Utility consumption of hydroelectricity (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNGT(x,r,y):</i>	Utility consumption of geothermal (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNSL(x,r,y):</i>	Utility consumption of solar (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNWN(x,r,y):</i>	Utility consumption of wind (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNOR(x,r,y):</i>	Utility consumption of other renewables (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCNNU(x,r,y):</i>	Utility consumption of nuclear (in trillion BTU) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPDS(x,r,y):</i>	Utility capacity of distillate (in gigawatts) over the

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	historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPRS(x,r,y):</i>	Utility capacity of residual (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPCD(x,r,y):</i>	Utility capacity of crude oil (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPNG(x,r,y):</i>	Utility capacity of natural gas (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPCL(x,r,y):</i>	Utility capacity of coal (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPWS(x,r,y):</i>	Utility capacity of waste (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPBM(x,r,y):</i>	Utility capacity of biomass (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPHE(x,r,y):</i>	Utility capacity of hydroelectricity (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPGT(x,r,y):</i>	Utility capacity of geothermal (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPSL(x,r,y):</i>	Utility capacity of solar (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPWN(x,r,y):</i>	Utility capacity of wind (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>SHUCPOR(x,r,y):</i>	Utility capacity of other renewables (in gigawatts) over the historical period, by plant type (electricity only, CHP,



	total), region, and year
<i>SHUCPNU(x,r,y):</i>	Utility capacity of nuclear (in gigawatts) over the historical period, by plant type (electricity only, CHP, total), region, and year
<i>QHDSPG(r,y):</i>	Utility consumption of distillate (in trillion BTU) over the historical period, by region and year
<i>QHRSPG(r,y):</i>	Utility consumption of residual (in trillion BTU) over the historical period, by region and year
<i>QHCDPG(r,y):</i>	Utility consumption of crude oil (in trillion BTU) over the historical period, by region and year
<i>QHNGPG(r,y):</i>	Utility consumption of natural gas (in trillion BTU) over the historical period, by region and year
<i>QHCLPG(r,y):</i>	Utility consumption of coal (in trillion BTU) over the historical period, by region and year
<i>QHWSPG(r,y):</i>	Utility consumption of waste (in trillion BTU) over the historical period, by region and year
<i>QHBMPPG(r,y):</i>	Utility consumption of biomass (in trillion BTU) over the historical period, by region and year
<i>QHHEPG(r,y):</i>	Utility consumption of hydroelectricity (in trillion BTU) over the historical period, by region and year
<i>QHGTTPG(r,y):</i>	Utility consumption of geothermal (in trillion BTU) over the historical period, by region and year
<i>QHSLPG(r,y):</i>	Utility consumption of solar (in trillion BTU) over the historical period, by region and year
<i>QHWNPPG(r,y):</i>	Utility consumption of wind (in trillion BTU) over the historical period, by region and year
<i>QHORPPG(r,y):</i>	Utility consumption of other renewables (in trillion BTU) over the historical period, by region and year
<i>QHNUPG(r,y):</i>	Utility consumption of nuclear (in trillion BTU) over the historical period, by region and year

The following variables represent data calculated in the subroutine WEMMain.

Classification: Computed variable.

<i>NTecCap(t,rm,y):</i>	New (current year) capacity (KW), by technology, region, and year
<i>NTecGen(t,rm,y):</i>	New (current year) generation (TWh), by technology, region, and year
<i>NTecCon(t,rm,y):</i>	New (current year) consumption (trillion btu), by technology, region, and year
<i>ATecCap(t,rm,y):</i>	Added (since last historical year) capacity (KW), by technology, region, and year
<i>ATecGen(t,rm,y):</i>	Added (since last historical year) generation (TWh), by technology, region, and year
<i>ATecCon(t,rm,y):</i>	Added (since last historical year) consumption (trillion btu), by technology, region, and year
<i>ETecCap(t,rm,y):</i>	Existing (remaining from last historical year) capacity (KW), by technology, region, and year
<i>ETecGen(t,rm,y):</i>	Existing (remaining from last historical year) generation (TWh), by technology, region, and year
<i>ETecCon(t,rm,y):</i>	Existing (remaining from last historical year) consumption (trillion btu), by technology, region, and year
<i>TTecCap(t,rm,y):</i>	Total (existing plus added) capacity (KW), by technology, region, and year
<i>TTecGen(t,rm,y):</i>	Total (existing plus added) generation (TWh), by technology, region, and year
<i>TTecCon(t,rm,y):</i>	Total (existing plus added) consumption (trillion btu), by technology, region, and year
<i>NFulCap(f,rm,y):</i>	New (current year) capacity (KW), by 5-fuel type, region, and year
<i>NFulGen(f,rm,y):</i>	New (current year) generation (TWh), by 5-fuel type, region, and year

<i>NFulCon(f,rm,y):</i>	New (current year) consumption (trillion btu), by 5-fuel type, region, and year
<i>NFdbCap(d,rm,y):</i>	New (current year) capacity (KW), by 13-fuel type, region, and year
<i>NFdbGen(d,rm,y):</i>	New (current year) generation (TWh), by 13-fuel type, region, and year
<i>NFdbCon(d,rm,y):</i>	New (current year) consumption (trillion btu), by 13-fuel type, region, and year
<i>NTotCap(rm,y):</i>	New (current year) capacity (KW) total, by region and year
<i>NTotGen(rm,y):</i>	New (current year) generation (TWh) total, by region and year
<i>NTotCon(rm,y):</i>	New (current year) consumption (trillion btu) total, by region and year
<i>AFulCap(f,rm,y):</i>	Added (current year) capacity (KW), by 5-fuel type, region, and year
<i>AFulGen(f,rm,y):</i>	Added (current year) generation (TWh), by 5-fuel type, region, and year
<i>AFulCon(f,rm,y):</i>	Added (current year) consumption (trillion btu), by 5-fuel type, region, and year
<i>AFdbCap(d,rm,y):</i>	Added (current year) capacity (KW), by 13-fuel type, region, and year
<i>AFdbGen(d,rm,y):</i>	Added (current year) generation (TWh), by 13-fuel type, region, and year
<i>AFdbCon(d,rm,y):</i>	Added (current year) consumption (trillion btu), by 13-fuel type, region, and year
<i>ATotCap(rm,y):</i>	Added (current year) capacity (KW) total, by region and year
<i>ATotGen(rm,y):</i>	Added (current year) generation (TWh) total, by region and year
<i>ATotCon(rm,y):</i>	Added (current year) consumption (trillion btu) total, by region and year

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<i>TFulCap(f,rm,y):</i>	Total (existing plus added) capacity (KW), by 5-fuel type, region, and year
<i>TFulGen(f,rm,y):</i>	Total (existing plus added) generation (TWh), by 5-fuel type, region, and year
<i>TFulCon(f,rm,y):</i>	Total (existing plus added) consumption (trillion btu), by 5-fuel type, region, and year
<i>TFdbCap(d,rm,y):</i>	Total (existing plus added) capacity (KW), by 13-fuel type, region, and year
<i>TFdbGen(d,rm,y):</i>	Total (existing plus added) generation (TWh), by 13-fuel type, region, and year
<i>TFdbCon(d,rm,y):</i>	Total (existing plus added) consumption (trillion btu), by 13-fuel type, region, and year
<i>TTotCap(rm,y):</i>	Total (existing plus added) capacity (KW), by region and year
<i>TTotGen(rm,y):</i>	Total (existing plus added) generation (TWh), by region and year
<i>TTotCon(rm,y):</i>	Total (existing plus added) consumption (trillion btu), by region and year

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## Appendix C. References

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## Appendix D. Data Quality

### Introduction

The World Electricity Model (WEM) for *IEO2016* projects the amount of electricity generated to satisfy the electricity demands projected by the end-use demand models. It projects how 39 fossil, renewable, and nuclear technologies are used to generate electricity, based on both policy and least cost. The model also projects fuel consumed, electricity generated, and generation capacity by the represented technologies for 13 energy sources in each of the 16 international regions over the projection horizon to 2040. These projections are based on the data elements as detailed in Appendix B of this report. In Chapter 4: Model Structure, the documentation details transformations, estimation methodologies, and resulting inputs required to implement the model algorithms. The quality of the principal sources of input data is discussed in this appendix. Information regarding the quality of parameter estimates and user inputs is provided where available.

### Source and quality of input data

#### *Sources of input data*

- *International Statistics Database* – The U.S. Energy Information Administration provides historical data on international electricity capacity, generation, and consumption by fuel type from 1980 through 2012. These data are used as the historical basis for all regional projections that appear in the *IEO2011*. While the numbers are continually updated, WEPS+ used a “snapshot” of the database as it existed on April 1, 2011 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](http://www.iea.org). These data are benchmarked to the historical aggregate energy consumption data provided in the U.S. Energy Information Administration’s international statistical data base.
- *NEMS* – Many of the assumptions about technology characteristic and load shapes are based in a 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 on world electricity capacity, generation, and consumption, based on previous values, responses, and regional and technical knowledge;
- consistency checks; and
- technical edits to detect and correct errors, extreme variability.