Independent Statistics & Analysis
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# World Energy Projection System Plus (WEPS+): Electricity Module

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# 1. Introduction

The International Electricity Market Model (IEMM) projects the following key quantities:

- Electricity generating capacity, including additions and retirements
- Electricity generation
- Electricity added and removed from storage
- Electricity sold and purchased
- Electricity delivered to consumers
- Fuel consumed in electricity generation
- Carbon dioxide emissions
- Electricity prices

The model projects these quantities for each of the 16 WEPS+ regions by year and *time-slice*. A time-slice is a time period, specified by EIA analysts, as a period of the day during a particular month or season (e.g., January from 7:00 p.m. to 9:00 p.m.). In some cases, some of the quantities listed above are also broken out by other characteristics such as the type of technology used to generate the electricity.

The module projects these quantities by minimizing an objective function subject to several constraints. The objective function represents the total cost to electricity suppliers of meeting all of the electricity demands, by year and time-slice, as projected by the WEPS+ demand modules. Examples of constraints include limits on fuel-specific electricity generating equipment, policy constraints (e.g., renewable portfolio standards), and emissions caps. The IEMM uses linear programming to perform the constrained optimization.

# 2. Objective Function

To minimize the total system cost of meeting electricity demands projected by WEPS+ demand modules, the IEMM breaks the cost into several components:

- *Capital costs* for investment in new electricity generating capacity–these costs are annualized over the generating unit's economic life, at either the system discount rate or a technology-specific discount rate estimated by EIA analysts,
- Fixed and variable annual *Operation and Maintenance (O&M)* costs of electricity generating equipment,
- Costs for *fuel* consumed, including purchases at regional fuel prices and any *delivery costs* identified by EIA analysts
- Projected *taxes* and *subsidies* minus the *salvage value* of generators with remaining economic life

In some cases, the IEMM includes additional costs in the analysis. Other possible costs include:

- *Decommissioning costs* (e.g., capital expenditures and/or annual operation and maintenance costs) for equipment that incurs costs for dismantling at the end of its useful life,
- *Damage costs* from pollutant emissions (e.g., from acid rain or health impacts), and
- *Welfare loss/gain* resulting from changes in quantity of electricity demanded.

The additional costs are included when we configure the IEMM to allow the quantity of electricity demanded in each region to be affected by price changes rather than fixed at the value received from the main WEPS+ system. In this case, the minimization of system costs, including welfare gains/losses, is equivalent to maximizing total consumer plus producer surplus.[1]

# 3. Key Constraints

## 3.1 Summary of Key Constraints

The cost minimization is subject to constraints that impose physical, operational, and policy restrictions on the electricity supply costs. These constraints account for:

- Retrofits and retirements of electricity generating equipment, based on equipment age
- Fuel-specific equipment efficiencies and fuel shares for fuel-flexible generating units
- Equipment availability
- Reserve capacity requirements, which require suppliers to maintain sufficient generating capacity to exceed peak demand by a specified amount
- Commodity balance and demand satisfaction
- Projected policy constraints, including renewable portfolio requirements, emissions limits, and minimum and maximum addition and operation of generating units by type

## 3.2 Discussion of Key Constraints

This section provides more information on the first five constraints listed above.

- **Equipment retrofits and retirements.** When computing the available capacity for a certain time period, the module accounts for the capacity resulting from all investments up to that period. Some of these capacity investments may have been made before the initial period but the equipment is still in operating condition and other capacity investments may have been projected at or after the initial period, up to and including the period in question. Investments in a particular technology increase its projected installed capacity for the duration of the technical life of the technology. When the technology is retired, the projected capacity for this technology decreases.
- **Equipment efficiencies and fuel shares.** These constraints specify that the amount of electricity produced (output) is in fixed proportion to the sum of the fuels used in electricity generation (inputs). For example, we may have a fuel-flexible power plant that can burn different combinations of fuels, but the total amount of electricity generated must be proportional to the sum of the quantities of fuel used.
- **Use of available capacity.** For each time period, the model may project the use of some or all of the installed electricity generating capacity, according to the technology-specific *availability factor*, which defines a maximum capacity usage.
- **Reserve capacity requirements.** This constraint requires that the total capacity of all processes producing electricity in each year, region, and time-slice must exceed the average demand in the time-slice where peak demand occurs (e.g., a daytime hour in summer), by a certain percentage.

[1] See Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. *Documentation for the TIMES Model Part I*, Energy Technology Systems Analysis Programme, https://www.iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf, Section 3.2.3.2, for an explanation of the equivalence.

- **Commodity balance and demand satisfaction.** In each year and time-slice, the production of electricity within each region, plus any imports from other regions, must balance the amount of electricity consumed in the region and exported to other regions.

## 3.3 Optional Constraints

In addition to the core constraints discussed above, EIA analysts may add *bounds* to model variables. This section describes the major additional bounds and constraints that we added to IEMM.

A bound is an upper, lower, or fixed limit on a single model variable. For example, bounds can be imposed on:

- Capacity, investment, generation, fuel consumption, or emissions from any technology (e.g., to project the effects of operational or policy limits on technology investment and behavior in each region)
- Total production, consumption, or net level of any commodity (e.g., to set emissions caps)

EIA analysts may include constraints specifying more complex relationships between variables. Common applications of such constraints include:

- Imposing bounds on selected technologies/commodities for a group of regions (e.g., a common emission cap on a group of regions that are allowed to trade)
- Imposing renewable portfolio, clean energy standards, carbon emissions intensity, and other policies based on relationships between fractions of generation by different plant types or between emissions and generation
- Creating banking schemes for cap and trade programs
- Imposing build-rate penalties (e.g., any capacity created beyond ***x*** GW per year will cost an additional $***y*** / GW)

Constraints that relate variables across periods or time-slices can be used to

- Impose a limit on the rate of growth (or decay) in capacity/activity of a new technology type from one period to the next
- Limit the ramping rate—the percentage increase or decrease in the utilization level of a thermal power plant from one time-slice to the next

## 3.4 Renewables Penetration Limits

IEMM uses the bound and constraint facilities to construct two sets of limitations to the penetration of variable renewable (VRE) generation. The need for these limits arises because VRE has inherently granular temporal and spatial dependencies. No matter how detailed the time and space resolution of a global model such as IEMM, it will always be insufficient to capture these dependencies fully. Specifically, we wish to address two challenges:

- Limiting the use of country-level wind and solar penetration in large, possibly multi-country regions
- Limiting the ability of variable resources to meet average loads in model time-slices

IEMM contains country-level wind and solar potentials, but it projects demand at a regional level. In multi-country regions, as well as in large countries, resources may not be located near loads and transmission capacity may not exist from resources to load. We do not want the module to satisfy an unrealistic portion of regional load with renewables that may be located in a small, and potentially distant, portion of the region.

To provide a generic structure to control the penetration of these technologies, IEMM allows each *country* to produce a maximum level of generation from wind-plus-solar before it has to incur a grid extension cost. To allow generation beyond that limit, we provided three levels of *grid extension* investment—notionally representing short distance, medium distance, and long distance transmission—each with assumed bounds and investment costs.

The bounds for the initial maximum generation and the three levels of grid extension are initially driven by projected country-level electricity demand, which is based on a logistic curve fitted to minimize the sum of squared errors of per capita consumption from historical values and population projections. EIA analysts may add similar constraints to prevent the IEMM from projecting over utilization of hydroelectric resources in countries with large hydroelectric potential that don't have the corresponding electricity transmission investment.

IEMM time-slices are designed to capture two important types of temporal variation in load and generation: season and time-of-day. They do not capture day-to-day variation within seasons; rather, they average over such variation. When penetrations of VRE sources become large relative to total load, such averaging may run the risk of implicitly assuming free storage between days, or even hours, within the same time-slice.

To avoid such an outcome, EIA implemented constraints that limit the maximum projected share of total electricity production in each region and time-slice from VRE sources. Output from storage technologies is included in the denominator of the constraint, resulting in a requirement for storage investment and operation when VRE penetrations become very high. The maximum VRE share is currently set at 65%.

# 4. Interaction with Other WEPS+ Modules

The IEMM receives regional annual sectoral electricity demands and power sector fuel prices from other WEPS+ modules. IEMM also receives nuclear capacity and generation projections from the WEPS+ nuclear module. For each of the four WEPS+ end-use sectors (residential, commercial, industrial, and transportation), the IEMM provides to other WEPS+ modules the projections for

- Regional electricity capacity and generation by fuel and technology
- Power sector fuel consumption
- Wholesale and retail prices.

IEMM provides an economic projection of global electricity generating capacity and dispatch. IEMM tracks existing equipment by region and age (or *vintage*), along with analyst-specified planned capacity builds, and evaluates options to build new capacity and retire existing capacity. At the same time, it optimizes the dispatch, subject to technology- and region-specific dispatch limitations and policy requirements. It also tracks existing inter-regional transmission capacity and can project new transmission capacity. The IEMM projects electricity demand by end-use sector and time-slice using sector-specific data provided by other WEPS+ modules. The module uses a linear programming approach to find the lowest cost capacity-plus-dispatch solution.

# 5. Energy System Structure

The IEMM energy system structure within each WEPS+ region is depicted in Figure 1, along with the *information flows* between IEMM and other WEPS+ modules.

**Stepped fuel supply curves**: IEMM receives regional delivered power sector fuel prices for coal, natural gas, and oil products from the WEPS+ fuel modules. It also retains a delivered quantity from a previous run of the WEPS+ system. IEMM constructs a stepped supply curve, shaped by analyst-provided elasticities, around these initial points. These supply curves allow some supply-price adjustment to help speed convergence of the WEPS+ system. IEMM also receives projected fuel-based emissions factors from the WEPS+ emissions module.

**Renewable potential and cost**: The IEMM knowledgebase contains detailed country-level potentials for onshore and offshore wind, photovoltaic, and hydroelectric capacity. Wind potentials are segmented by resource class, distance from transmission, and, for offshore wind, depth. Each country-level segment has its own cost, resulting in a detailed global wind supply curve. PV potential is similarly segmented by resource class within each country. Hydroelectric capacity is specified by a three-step cost supply curve.

EIA developed hourly wind and solar generation profiles for each country using geospatial solar and wind speed data. The hourly data are aggregated into model time-slices. Country-level availability factors constrain hydroelectricity production at the annual and seasonal levels, based on historical seasonal generation, where available, or seasonal precipitation data. Moderate (20%) additional seasonal flexibility is provided to represent the capacity for reservoirs to allow seasonal shifting of production.

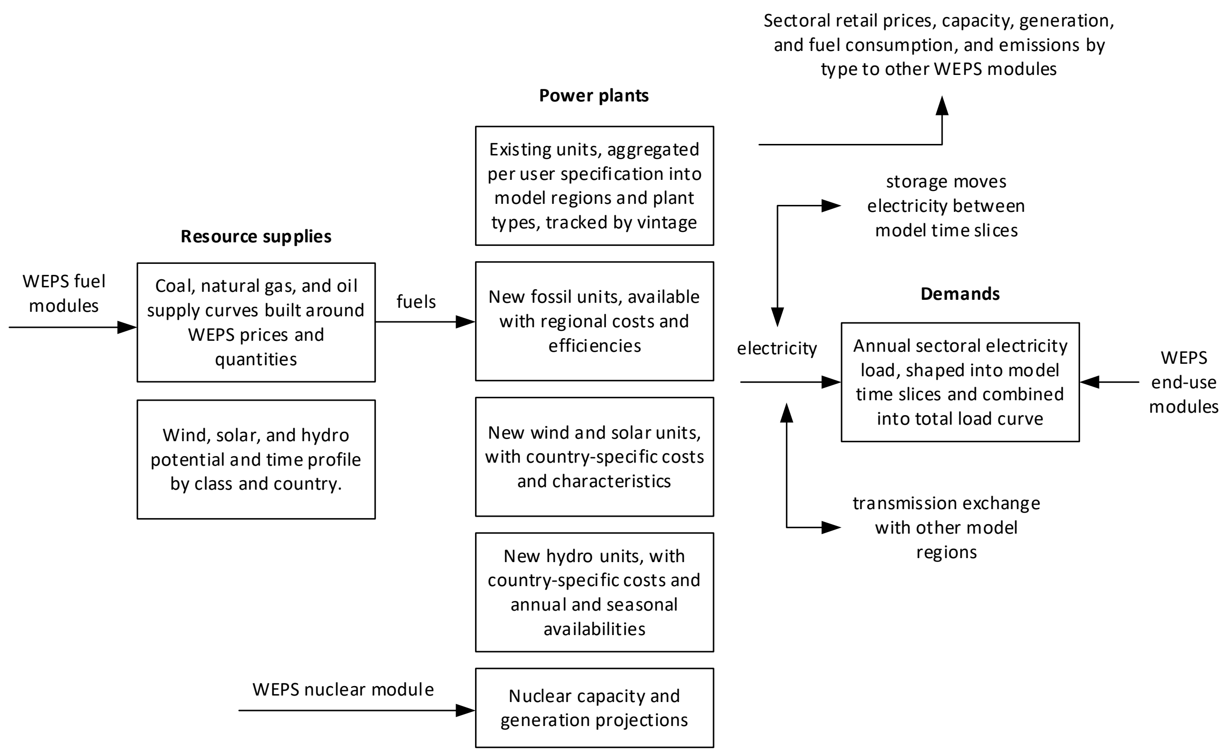


**Figure 1. Energy system structure and WEPS+ linkages for each model region**

# 6. Shadow Prices and Cost-of-Service Regimes

IEMM sends capacity, generation, and fuel consumption projections to the main WEPS+ system for each region and technology type. In addition to these outputs, IEMM produces

- Marginal prices (shadow prices) of generation by region and time-slice
- Average cost of electricity generation by region
- The shadow price on meeting reserve capacity requirements by region

The WEPS+ system uses these inputs to produce electricity generation prices under cost-of-service and competitive pricing regulatory regimes.

Under cost-of-service regimes, the generation price is calculated as the average cost of generation, which is simply the sum of all system costs (including capital, operating, fuel, and policy compliance costs) divided by total generation. Under competitive pricing regimes, the retail price is the sum of an energy component based on the marginal price of generation and a capacity component based on the shadow price on the reserve requirement constraint. EIA analysts specify the ratio of cost-of-service and competitive pricing, along with end-use sector markups representing transmission and distribution adders, taxes, and subsidies.

# 7. Model Data Sources

## 7.1 Existing generation stock

The Platts UDI World Electric Power Plants Database (WEPP) is used for existing and under-construction capacity by country and state. Planned builds may be adjusted by EIA analysts to reflect the most recent information on national plans.

## 7.2 Operating and maintenance costs

Country-level O&M costs are based on the 2010 and 2015 IEA Generation Cost studies[2], which provide national O&M cost estimates for new units. Because of incomplete coverage, EIA divided countries into five reporting peer groups, and we used data from the Bureau of Labor Statistics on international wage differentials to establish which countries were most closely aligned in labor costs. On this basis, we assigned non-reporting countries to a peer group paired with countries that did report. Calculations based on the two capacity factor scenarios IEA reported were used to distinguish fixed and variable O&M. We used data from EIA's recently commissioned Sargent & Lundy study on operating costs of U.S. generation to develop ratios for large versus small units. This ratio was applied to the base costs for all countries.

## 7.3 Wind and solar potential

Wind resource data by country come from a resource assessment performed at the National Renewable Energy Laboratory (NREL), based on the National Center for Atmospheric Research's (NCAR) Climate Four Dimensional Data Assimilation (CFDDA) mesoscale climate database. Resources are defined by country and resource quality. We further differentiated onshore supply curves by distance to nearest large load or power plant and offshore supply curves by distance to shore and water depth. Resources are calculated from hourly wind velocity vectors at a 40 kilometer (km) grid at 90 meter hub heights. Output is derated for outages and wake losses to obtain the net capacity factor. Protected, urban, and high-elevation areas are fully excluded, and certain land cover types are fractionally excluded. Areas within 5 nautical miles of or farther than 100 nautical miles from shore are excluded. Protected marine areas are also excluded. Marine areas are assigned to countries based on exclusive economic zones; unassigned or disputed areas are excluded.

The estimated solar potential is obtained from NREL and represents an annual average of the daily total solar resource averaged over surface cells of 10 km resolution at the country level. The data are based on the State University of New York, Albany satellite radiation model, which uses several factors to calculate the hourly total insolation (sun and sky) falling on a horizontal surface output over a 12-year period (1998–2009):

- Hourly radiance images from geostationary weather satellites
- Daily snow cover data
- Monthly averages of atmospheric water vapor, trace gases, and the amount of aerosols in the atmosphere

[2] https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf

The values returned are the kilowatthours per square meter per day ($kWh/m^2/day$) available to fixed, flat plate systems titled toward the equator at an angle equal to the latitude. The total solar resources within each country are then organized by class, starting at 3 $kWh/m^2/day$ or less and increasing in 0.5 $kWh/m^2/day$ increments, with the highest solar class being 6 $kWh/m^2/day$ or more. Each solar class in each country is then converted into total potential solar energy available per year as a function of land area per solar class, conversion efficiency (10%), and number of days per year (365).

## 7.4 Hydro potential and generation profile

Hydropower potential and installed cost are based on an article published in Gernaat et al. (2017)[3] that only evaluated data for river power plants (or conventional hydropower). Currently, countries with specific cost and potential include

- Angola
- Argentina
- Australia
- Bolivia
- Brazil
- Cameroon
- Canada
- Central African Republic
- Chile
- China
- Colombia
- Congo (Brazzaville)
- Democratic Republic of Congo
- Egypt
- Ethiopia
- France
- Gabon
- India
- Indonesia
- Italy
- Japan
- Madagascar
- Malaysia
- Mexico
- Mozambique
- Myanmar
- Nepal
- New Zealand
- Pakistan
- Papua New Guinea
- Peru

[3] Gernaat, D. E. H. J., Bogaart, P. W., Van Vuuren, D. P., Biemans, H., and Niessink, R. "High-resolution assessment of global technical and economic hydropower potential," *Nature Energy*, Vol 2 (October 2017), p. 821-828.

- Russia
- Sudan
- Tanzania
- Turkey
- Uganda
- United States
- Venezuela
- Vietnam
- Zambia

Countries with no specific installed cost information use regional costs, which are based on data from the International Renewable Energy Agency (IRENA, Renewable Power Generation Costs in 2017) and Oak Ridge National Laboratory (ORNL).

The annual availability factor for hydropower generation for each country is an average capacity factor, calculated from historical (2000 to 2015) capacity and generation data from EIA International Energy Statistics. Monthly capacity factor is based on historical hydropower generation for

- OECD countries
- Argentina
- Brazil
- China
- Colombia
- India
- Russia
- Vietnam

For other countries with no historical hydro generation, monthly capacity factor is based loosely on monthly share of precipitation.

## 7.5 Inter-regional transmission capacity

Inter-country transmission capacity data is derived from ENTSO-E data (https://www.entsoe.eu/data/data-portal/exchange/Pages/default.aspx) for European countries. For other major electricity trading countries, historical trades are derived from the UN Comtrade database (https://comtrade.un.org/data/) and converted into an implied capacity.

## 7.6 Historical generation and consumption

We used the International Energy Agency's historical data on generation and fuel consumption by country, fuel, and major unit type and electricity consumption by sector for

- Calibration
- Derivation of sector load shapes
- Projecting country-level load to set renewable bounds