

**Model Documentation**  
**Renewable Fuels Module**  
**of the National Energy Modeling System**

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# 1. Renewable Fuels Module Introduction

## Purpose of This Report

This report documents the objectives, analytical approach, and design of the National Energy Modeling System (NEMS) Renewable Fuels Module (RFM) as it relates to the production of the *Annual Energy Outlook 2006 (AEO2006)* forecasts. The report catalogues and describes modeling assumptions, computational methodologies, data inputs, and parameter estimation techniques. A number of offline analyses used in lieu of RFM modeling components are also described.

This documentation report serves three purposes. First, it is a reference document for model analysts, model users, and the public interested in the construction and application of the RFM. Second, it meets the legal requirement of the Energy Information Administration (EIA) to provide adequate documentation in support of its models (Public Law 93-275, Federal Energy Administration Act of 1974, Section 57(b)(1)). Finally, such documentation facilitates continuity in EIA model development by providing information sufficient to perform model enhancements and data updates as part of EIA's ongoing mission to provide analytical and forecasting information systems.

## Renewable Fuels Module Summary

The RFM consists of six analytic submodules that represent major renewable energy resources-biomass, landfill gas (LFG), solar (thermal and photovoltaic), wind, geothermal, and conventional hydroelectricity energy.

The purpose of the RFM is to define the technology, cost, performance, and renewable resource supply for renewable energy technologies. They are provided to the Electricity Market Module (EMM) for grid-connected central station electricity capacity planning and dispatch decisions. The characteristics include available generating capacity, location, unit size, capital cost, fixed operating cost, variable operating cost, capacity factor, heat rate, construction lead time, and fuel price. Because of the extensive interaction between the RFM and EMM, these two modules must be run together.

Renewable energy technology cost and performance characteristics which are common to all electricity generating technologies are input directly to the EMM via the input file ECPDAT. For characteristics that are unique to specific renewable energy technologies, specific files and subroutines are used, such as for renewable resource values for regional, seasonal, and hourly time segments of intermittent renewables.

Other renewables modeled elsewhere in NEMS include biomass in the industrial sector, ethanol in the Petroleum Market Module (PMM), wood in the residential sector, geothermal heat pumps and distributed (grid-connected) solar photovoltaics in the residential and

commercial sectors, and solar hot water heating in the residential sector. In addition, there are several areas, primarily nonelectric and off-grid electric applications, that are not represented in NEMS. They include direct applications of geothermal heat, several types of solar thermal use, and off-grid photovoltaics. For the most part, the expected contributions from these sources are confined to niche markets; however, as these markets develop in importance they will be considered for representation in NEMS.

The number and purpose of the associated technology and cost characteristics vary from one RFM submodule to another depending on the modeling context. For example, renewable resources such as solar, wind, and geothermal energy are not fuels; rather, they are inputs to electricity or heat conversion processes. Consequently, the Solar, Wind, and Geothermal Submodules do not provide fuel product prices.

EIA's Office of Integrated Analysis and Forecasting determines initial cost and performance values for renewable energy technologies based on examination of available information. Several sources for the cost and performance characterizations were examined for use in this version of the RFM. These sources provide values for capital costs (excluding the construction financing and process and project contingency components, since these are provided in the EMM), fixed and variable operation & maintenance (O&M) costs, capacity factors, and construction lead times. All cost values are converted to 1987 dollars.

Provided below are summaries of the six RFM submodules that are used for producing the *AEO2006* forecasts: the Landfill Gas Submodule (LFG), the Wind Energy Submodule (WES), the Solar Energy Submodule (SOLES), the Biomass Submodule, the Geothermal Energy Submodule (GES), and the Conventional Hydroelectricity Submodule. Each chapter concludes with information on the RFM archival package and EIA point of contact.

### **Landfill Gas Submodule (LFG)**

The Landfill Gas Submodule provides annual projections of energy produced from estimates of U.S. landfill gas capacity. The Submodule calculates the quantity of LFG produced (derived from an econometric equation that uses Gross Domestic Product and U.S. population as the principal forecast drivers). The landfill gas capacity is estimated based on reported waste and gas production data and judgement about future trends in recycling. The amount of new landfill gas-to-electricity capacity available in each projection period competes with other technologies by use of LFG supplies (curves) that are based on the amount of high, low, and very low methane producing landfills located in each Electricity Market Module Region.

## Wind Energy Submodule (WES)

The Wind Energy Submodule (WES) projects the availability of wind resources. Undeveloped wind resource availability, expressed as megawatts of capacity in each region, is passed to the EMM so that wind turbines can be built and dispatched in competition with other electricity generating technologies. The wind turbine data are expressed in the form of energy supply curves. The supply curves provide the maximum amount of turbine generating capacity that could be installed, given the available land area, average wind speed, and capacity factor. These variables are passed to EMM in the form of nine time segments that are matched to electricity load curves within EMM.<sup>1</sup>

## Solar Submodule (SOLAR)

Two solar technologies are represented in the Renewable Fuels Module (RFM), a 5 megawatt fixed-flat plate grid-connected central station photovoltaic (PV) unit without energy storage, and a 100-megawatt central receiver (power tower) solar thermal (ST) unit with a few hours energy storage. Both technologies are grid-connected and provided by electric utilities, small power producers, or independent power producers.

PV and ST cost and performance characteristics which are defined consistent with fossil and other characteristics reside in ECPDAT. Performance characteristics unique to these technologies (such as season and region-dependent capacity factors), however, are passed to the EMM via the solar submodule SOLAR.

## Biomass Submodule

The Biomass Submodule furnishes biomass resource and technology cost and performance characteristics for a biomass burning electricity generating technology to the EMM. It also provides biomass resources used in producing cellulosic ethanol to the PMM. The technology modeled for the *AEO2004* is Integrated Gasification Combined Cycle (IGCC). The submodule utilizes a regional biomass supply schedule from which the biomass fuel price is determined. Fuel prices are added to variable operating costs since there are no fuel costs in the structure of NEMS for renewable fuels. The biomass supply schedule is based on the accessibility of wood resources by the consuming sectors from existing wood and wood residues, crop residues, and energy crops.

## Geothermal Energy Submodule (GES)

The Geothermal Energy Submodule (GES) model current and future regional supply, capital cost, and operation and maintenance costs of electric generating facilities using hydrothermal resources (hot water and steam). Economically accessible geothermal resources are limited to the three western EMM regions. The data are assembled from 51

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<sup>1</sup> The nine time segments are derived from three 8-hour segments of the day for three seasons, winter, summer and off-peak (spring/fall averaged). The data represent average capacities based on empirical analysis.



known sites, each represented by information which reflects the specific resource conditions of that location. The GES generates a three-part geothermal resource supply curve for geothermal capacity for each region in each forecast year, for competition with fossil-fueled and other generating technologies. It truncates the supply curve based on the avoided cost for the construction and operation of new regional capacity and passes average cost and performance values of the truncated supply curve to the EMM.

### **Conventional Hydroelectricity Submodule (CHS)**

The Conventional Hydroelectricity Submodule (CHS) models the supply (megawatts), capital cost, and operation and maintenance costs of additional conventional hydroelectric power available from adding new hydro generating capacity in increments 1 megawatt or greater to (a) new sites without dams, (b) sites with existing dams but without hydroelectricity, and (c) existing hydroelectricity sites able to accommodate additional capacity. The CHS uses the Idaho Hydropower Resource Economics Database (IHRED). The CHS does not account for pumped storage capacity, increments of capacity less than 1 megawatt, potential available from refurbishing and upgrading existing hydro capacity, or capacity available from new in-stream, off-shore, or ocean technologies. Within each NEMS region, for each NEMS cycle, the CHS first identifies additional hydro capacity available at or below an avoided cost specified by the Electricity Market Module, then segments the available capacity into three least, mid, and highest cost supplies, and finally submits to the EMM the megawatts of available capacity in each of the three segments expressed in their capacity-weighted average capital and operation and maintenance costs and capacity factors. After making capacity decisions, the EMM informs the CHS of required decrements to potential available for selection in the next NEMS cycle.

## Capacity Credit for Intermittent Generation

Within the EMM, each region must have enough generating capacity installed to satisfy peak load requirements plus a regional reserve margin factor. For operator dispatched capacity types, the full summer-rated capacity for each generator unit is used to determine the contribution provided to the reserve margin requirement. However, non-dispatched, intermittently available generating capacity, such as wind turbines or solar electric facilities, will not reliably generate during peak demand periods, and thus cannot contribute its full rated capacity to satisfy the reserve margin requirement.

However, because there is a significant probability that at least some intermittent generators will be available during peak demand periods, as well as a significant probability that some portion of operator dispatched capacity will not be available during this time, intermittent generators can contribute some fraction of their rated capacity to the reserve margin. This fraction, referred to as the capacity credit, is a function of the correlation between the temporal generation pattern of the resource and the peak load periods, as well as the fraction of intermittent generation compared to total regional output. That is, a wind turbine in a region where the wind typically blows strong during the peak load period will contribute more to meeting peak-load system reliability than a wind turbine in a region with typically light peak-load winds. However, as wind or solar constitutes more of the system capacity, the variability of its peak-load operation will have a decreasingly beneficial effect on system reliability.

The capacity credit for intermittent generators is determined in NEMS as a function of the estimated average contribution that all units of that type (wind or solar) will provide to meeting an assumed system reliability goal of 99.999% availability (that is, the system should have enough generation capacity installed to be able to meet full load requirements 99.999% of the time, sometimes approximated as achieving 1 hour of load shortage in 10 years or 87,600 hours of operation). This contribution is, in turn, largely determined by the average, peak-load period capacity factor for the intermittent capacity, the standard deviation about that average, the degree to which the output at each individual site in a region is correlated with the output at other sites, and the reliability characteristics of the operator-dispatched (conventional) capacity in the region.

The peak-load period capacity factor for each intermittent generator is determined as described in the Wind and Solar Module chapters of this report. The normalized standard deviations for wind and solar plants are exogenously determined. The inter-site output correlation factors are also exogenously determined on a regional basis. The standard deviation for each conventional capacity type is calculated from the user-specified forced-outage rates, based on a binomial distribution:

$$S = C \times \sqrt{\frac{P \times (1 - P)}{N}}$$

Where C is the installed capacity of a specified type as calculated for that year, P is the

forced outage rate from UPFORT in ECPDAT, and N is the number of units for the specified plant type as calculated for that year.

The standard deviation of total capacity of all conventional types is:

$$S_{Conventional} = \sqrt{S_1^2 + S_2^2 \dots + S_n^2}$$

Where  $S_n$  is the standard deviation for the  $n^{\text{th}}$  capacity type.

The standard deviation for all intermittent units of a specified type (wind, solar thermal, or photovoltaic) is determined as:

$$S_{Intermittent} = C \times \sqrt{N * s^2 + (N^2 - N) * R * s^2}$$

Where  $s$  is the technology-specific normalized standard deviation from the INTSTDDV variable in the WESAREA file, N and C are as above (for intermittent rather than conventional capacity types), and R is the regional correlation factor from the INTREGCRL variable in the WESAREA file.

The total standard deviation of all generation (conventional and intermittent) is then calculated as:

$$S_{Total} = \sqrt{S_1^2 + S_2^2 \dots + S_n^2 + S_{Intermittent}^2}$$

Where  $S_n$  is as above, and  $S_{Intermittent}$  is the total standard deviations for intermittent capacity type being evaluated (wind, solar thermal, or photovoltaic).

The reliable capacity is then calculated excluding the intermittent capacity, then again including all capacity types using:

$$C_{reliable} = (\sum C_{ave,n}) - Z * S$$

Where  $C_{ave,n}$  is the total annual average capacity for each of the  $n^{\text{th}}$  capacity types, and is evaluated for conventional-only capacity types and then again for conventional plus intermittent capacity types. For conventional resources, average capacity is the installed summer capacity times one minus the forced outage rate and for intermittent resources it is the installed capacity times the peak-load period capacity factor. Z is the statistical parameter for the number of standard deviations in a distribution that are needed to account for a specified fraction of the area under the normal distribution curve, specified as variable UPINTZ in the ECPDAT file<sup>2</sup>, and S is as calculated above for  $S_{conventional}$  or  $S_{Total}$  as appropriate for the conventional-only or the total reliable capacity calculation.

Finally, the capacity credit (U) for the intermittent resource is calculated as:

$$U_{Intermittent} = \frac{C_{reliable,Total} - C_{reliable,Conventional}}{C_{installed,Intermittent}}$$

Where  $C_{reliable}$  is as above for total and conventional-only generation and  $C_{installed,Intermittent}$  is the installed, nameplate capacity of the intermittent resource being evaluated (wind,

<sup>2</sup>For AEO2004, the default Z value of 3.19 is used to represent 99.93% of the area under the Gaussian normal distribution. The use of 99.93% to represent 99.999% reliability is explained in Appendix 1-A.

solar thermal, or PV). Note that the capacity credit for each intermittent resource is evaluated separately. As a given intermittent resource is calculated, the other two are included in the “conventional capacity” calculations, using the capacity credit from the previous model iteration to determine availability.

The resulting capacity credit is the average value for all intermittent units of the specified type in that region in the current year. This value is used by the EMM to determine total intermittent capacity to count toward the regional reserve margin. Because of the intra-regional power output correlation factor for the intermittent resources, the marginal capacity credit (that is, the contribution to reserve margin of the last unit built) actually declines, thus reducing the average capacity credit with increasing penetration. For purposes of capacity planning in NEMS, however, the intermittent plant vintage does not affect the calculation, and each plant (the first through the last built) receives the average capacity credit for that resource type.

Also, because the capacity credit is only calculated for the current year’s installed capacity, it is not prospective, and the same number is evaluated within the EMM regardless of the amount of capacity ultimately constructed in the following year(s). While this approximation is reasonable if the annual capacity additions for the resource are small, it can significantly over-estimate the capacity credit in scenarios that result in the rapid build-up of intermittent renewable resources. Therefore, the maximum limit on the regional fraction of intermittent generation is allowed to increase by 5 percentage points per year, but cannot exceed 40% nor fall below 20%. That is, NEMS computes the maximum historical fraction of intermittent generation and then adds 0.05. If this value exceeds 0.40 (as specified by the UPINTBND in ECPDAT), it is set to 0.40. If this value falls below 0.20 (actually specified as one half of the ultimate upper bound on intermittent generation or UPINTBND/2), it is set to 0.20. This expanding limit serves to ensure that capacity credit impacts are reasonably accounted for and to simulate the time needed for regional system operators to adjust operating procedures to accommodate large amounts of intermittent generation. The final regional limit of 40% intermittent generation accounts for the uncertain system costs to accommodate such large amounts of non-dispatched generation.

The statistical approximations used to describe the variance in output from both conventional and intermittent resources are reasonable over a wide range of capacity configurations. However, with extreme levels of intermittent capacity, it is possible for the algorithm to produce a negative capacity credit for intermittent resources. Since the instantaneous or long-term output of real-world intermittent resources cannot fall below zero, these resources cannot have a capacity credit less than zero. Therefore, the capacity credit is constrained to be greater than zero.

An additional impact of intermittent generation on reliable grid operations is the potential for excessive generation during off-peak periods. Since solar resources do not operate during the lowest-load hours (which are typically at night), the treatment of this impact in NEMS is described in the chapter of the report on the Wind module.

## **Appendix 1-A: Background Information on Deriving the Capacity Credit for Intermittent Generation**

The algorithm used to represent the capacity credit for intermittent resources is revised from the AEO2003 algorithm. Examination of the literature for developing the AEO2003 algorithm indicated that the initial wind plants introduced into a power coordination region (or control area) could contribute to reliable capacity needs roughly in proportion to its peak-load capacity factor. However, as grid penetration increases, the capacity credit for the wind plants decreases, approaching a zero marginal capacity credit at sufficient penetration levels. Viewed another way, the introduction of wind capacity can increase the effective load carrying capacity of a system, but eventually reaches a “saturation” level at which addition of new wind capacity does not increase the effective load carrying capacity of the region.

The AEO2003 algorithm modeled an exogenously determined decay function for capacity credit based strictly on fraction of regional generation. To improve the representation of this saturation effect, a statistical model of capacity adequacy for generation reliability was developed. This model has provided the basis for the revised algorithm to calculate the capacity credit assigned to intermittent generation in the current version of NEMS.

Understanding the fundamental issue of assuring capacity adequacy with large amounts of non-dispatched power with a significant random component can be accomplished with a greatly simplified statistical representation of the generating resources on a grid. While confirmation of the results of this analysis with more detailed reliability models would be useful in refining the parameters developed, the approximations developed from this model provide a significant improvement over the AEO2003 method of estimating intermittent capacity credit used in NEMS.

Establishing the statistical foundation for such a model requires closer examination of the statistical properties of each component of the system. In this case, we are concerned with two basic types of components: 1) conventional, dispatchable generation capacity including steam plants (using nuclear, biomass, coal, or other fossil fuels), combustion turbines (simple and combined cycle), and hydroelectric power (primarily those with seasonal water storage, as “run-of-river” plants have a significant intermittent component) and 2) intermittent generation, with wind being the primary resource of interest.

In understanding how an uncontrollable, and to large extent uncertain resource like wind can contribute at all to regional reliability reserves, it is important to remember that no single generation resource is perfectly reliable. In addition to planned outages for maintenance, which can be scheduled to coincide with periods of low demand, every plant experiences forced outages. Thus there is some significant probability that the wind generation will be “available” (that is, the wind blowing) at the same time some

fraction of dispatched capacity is unexpectedly offline. Forced outage rates vary from plant to plant and are a function of technology type, plant vintage, and maintenance regime. Although some equipment failure (or other reliability incident) may result in a partial outage or capacity derating, the statistical model developed in this appendix makes the simplifying assumption that a conventional plant outage is a Bernoulli trial: that is, there is a chance that plant is either fully operational or fully out-of-service, but not in some intermediate state (such as operable at a derated capacity level). Note that is not important to calculating generation adequacy that the plant actually operate at full capacity (or even operate at all), but simply that its full capacity is (or is not) available if needed.

Although a typical conventional plant may have a forced outage rate of 5% (or conversely an availability rate of 95%), it is assumed here that utilities want to achieve an overall system availability rate of 99.999% (“five nines of reliability” or “one hour of outage in 10 years”). Obviously, it is not possible to achieve more than 95% system reliability if you are using a single typical plant. What’s the reliability if the system gets two completely redundant units (each capable of providing 100% load at 95% availability)? This is the probability that both units are operating ( $0.95 \times 0.95=0.9025$ ) plus the probability that unit B is operating while unit A is out ( $0.95 \times 0.05=0.0475$ ) plus the probability that unit A is out while unit B is operating (also 0.0475). The two-generator system achieves 99.75% availability to serve load equal in size to the single generator. Note that simply doubling the capacity of the single unit would not improve system reliability, as there would still only be a 95% chance of maintaining load (average capacity improves the same in both cases, but system reliability only improves when the number of generators is increased).

Building a contingency table to calculate the probabilities of all possible on/off states of each generator in a system of more than a handful of units would be quite time consuming. However, because of the Bernoulli nature of the probabilities, the statistical behavior of the system is already fairly well described. Specifically, if we can assume individual units of equal size and availability, then we can assume an average availability for total capacity of 95% (or whatever the common availability is). The 99.999% availability level is then the mean available capacity minus 4.265 standard deviations (that is, 99.999% of the area under a standardized normal “bell” curve is within 4.265 standard deviations of the mean). For a collection of Bernoulli trials, the normalized standard error of a sample N (in this case, number of plants within a region of interest) with probability P (in this case, representing the availability) is from the binomial distribution:

$$\text{Eq. 1) } S = \sqrt{\frac{P * \bar{P}}{N}}$$

With a sufficiently large number of trials (each representing a generator unit), the binomial distribution approaches the Gaussian normal distribution, and the standard

error can be used for the Gaussian standard deviation. Multiplying by the average capacity converts the normalized standard deviation to the capacity standard deviation.

Of course, we need to account for multiple generators of varying capacity and reliability. The overall standard deviation of a multi-plant system is as follows:

$$\text{Eq. 2) } S_T = \sqrt{S_1^2 + S_2^2 \dots + S_n^2}$$

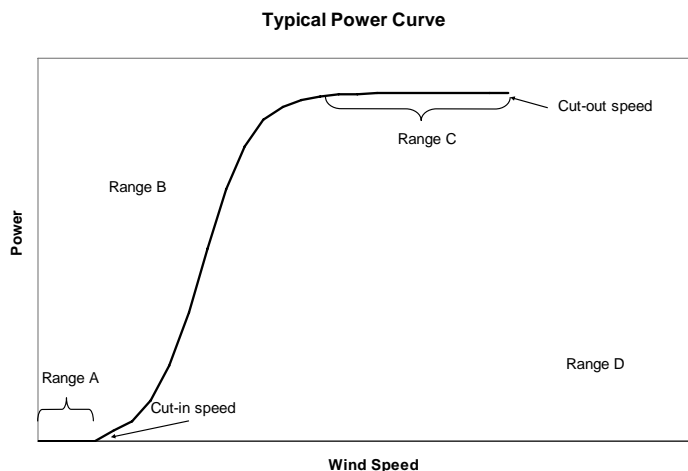
Where  $S_n$  is the standard deviation of the  $n^{\text{th}}$  term.

For a binomial distribution, the system reliability is inversely proportional to the square root of the number of units. Thus reliability is improved by adding more redundancy (that is, more units) into the generation mix, as indicated in the simple example at the beginning of this appendix. Adding the same amount of capacity with a single, large unit improves reliability somewhat less than adding the same amount of capacity with several smaller units.

The 99.999% reliability requirement is for the entire year, 24 hours a day, 7 days a week.

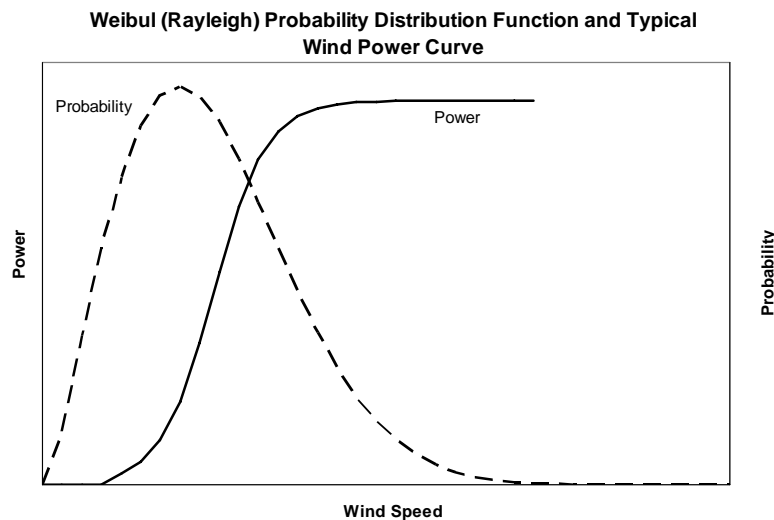
In general, utilities are most concerned with having enough reliable capacity on-hand to meet peak load requirements (with the working assumption that if you have enough capacity to meet peak requirements, you should have more than enough to meet off-peak requirements). Peak load periods, as modeled in NEMS, account for about 1.56% of all hours in a year. If it is assumed that the “1 hour in 10 years” of outage in a “five-nines” system occurs during the 1.56% of peak hours (the top 137 hours of load), then the system operator needs to maintain 1 hour in 10 years-of-peak-load-periods reliability, or 1 hour in 1370 operating hours (137 hours per year for a 10 year period). Thus a targeted reliability of 99.93% for peak-load should be sufficient to maintain “five-nines” of reliability for all load hours – assuming that there will be abundant excess off-peak capacity to cover both forced outages and planned maintenance.

Although conventional generators do have occasional partial outages, modeling single-unit availability as a Bernoulli trial is a reasonable approximation of actual operations. The availability of wind generation to the grid, however, can not reasonably be modeled as an all-or-nothing event. The power output from a typical wind turbine as a function of ambient wind speed is shown below.



below. A wind turbine may have zero output for maybe 10 or 20% of the time, when the wind is either too light to move the blades (common, shown as range “A”) or too strong to allow the mechanism to operate without damage (rare, shown as range “D”). However, the rest of the time (that is 80 to 90% of the time)

its output fluctuates more-or-less continuously as a non-linear function of the wind speed.



Wind speeds are not evenly distributed at a given site. Although the exact distribution of wind speeds varies from location to location, even within a “wind resource class”, the Weibul distribution with a “shape” parameter of around 2 is frequently cited as a typical form. The figure at left shows a Weibul probability density function with a shape parameter of 2 (also known as a Rayleigh distribution)

overlaid on the previous power curve example. The resulting distribution of wind power output (that is, the average of the wind power curve as weighted by the Weibul probabilities at each wind speed) is not characteristic of a binomial, Weibul, or other common probability distribution. However, with sufficient numbers of wind plants, one would expect the aggregate statistical distribution of the output to assume an increasingly Gaussian form.

Since the standard deviation of power output for a wind turbine or wind plant cannot be determined analytically, it is determined through simulated output of a typical wind turbine power curve<sup>3</sup> in a Class 6 wind resource. The simulated statistical parameters for the single turbine are directly scaled-up to represent the full site (assuming that, over the timeframe of interest, hourly-to-daily, there is perfect correlation among all turbines in a relatively compact 50 MW site). The simulation indicates an average standard deviation in output of 38% of the nameplate capacity. So for a 50 MW site, average hourly output would have a standard deviation of 19 MW. For solar resources, a normalized standard deviation of 10% of nameplate capacity is assumed.

Of course, any significant penetration of wind in a larger system is going to consist of more than one wind plant. One way to model larger increments of wind capacity would be simply to scale the single-plant model to a larger composite size. Scaling the single plant implies that each individual turbine in the composite plant is subject to essentially the same wind regime (that is, simultaneous sampling from the same distribution) as

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<sup>3</sup>Turbine power curve used in the simulation is a normalized approximation of the Vestas V-47 wind turbine. This turbine was selected because of availability of independently verified data through the DOE/EPRI Turbine Verification Program and the substantial installed capacity base of that model in the U.S. The use of the characteristics of this turbine is not an endorsement or statement of technological preference on the part of EIA.



shown here:

$$\text{Eq. 3) } S_T = \sqrt{(N * S)^2}$$

Where N is the number of wind farms, each with the same annual average capacity factor and standard deviation (S). While this is a reasonable assumption when scaling a single turbine to a 50 MW wind farm spread over 325 sq. km of land (about 18 km by 18 km), for a region with multiple wind farms separated by hundreds of miles, it seems more reasonable to assume that the output of each farm is not perfectly correlated with the output of the other farms, at least over a time period of interest to grid reliability (one hour to one day).

In the limiting case of multiple wind farms with uncorrelated output, we can use Equation 2 to determine the overall standard deviation of the system, using the statistical parameters for each wind plant. To simplify the math, we could further assume that for wind farms of equal size, we have equal capacity factors and standard deviations. That is, we are sampling from different populations with the same statistical parameters (mean and variance). The standard deviation of the thus simplified Equation 2 is:

$$\text{Eq. 4) } S_T = \sqrt{N * S^2}$$

So for highly correlated wind units (such as the output of a single wind plant scaled to higher levels of assumed wind capacity), the standard deviation is directly proportional to the total number of installed units. For completely uncorrelated wind units (such as individual wind plants placed in entirely different climate zones), the standard deviation is proportional to the square-root of the number of units. Conceptually, this is the same result as we had for the conventional units: multiple smaller units provided better reliability than a single unit of equivalent capacity. However, in the case of the conventional units, we had an implicit (and reasonable) assumption of independence for the availability of each unit (that is, an outage of one unit would not correlate with the probability of an outage from any other unit).

Equation 3 assumes perfect correlation among all wind sites. Equation 4 assumes no correlation among any wind site. In the real world, there is likely some correlation among sites, but not perfect correlation. Partial correlation between two populations (populations 1 and 2) is statistically described by the population standard deviations and two additional parameters: the correlation coefficient ( $R_{1,2}$ ) and the covariance ( $C_{1,2}$ ), which are related as follows:

$$\text{Eq. 5) } C_{1,2} = R_{1,2} * S_1 * S_2$$

Where S is the standard deviation for the indicated population. The total standard deviation of two partially correlated populations is:

$$\text{Eq. 6) } S_T = \sqrt{S_1^2 + S_2^2 + 2 * R_{1,2} * S_1 * S_2}$$

Generalizing to a system with N windy sites, each site equally correlated with each other site, and otherwise drawn from different populations with the same population parameters (That is,  $S_1=S_2=S_N$ , per our previous simplifying assumption), we get:

$$\text{Eq. 7) } S_T = \sqrt{N * S^2 + 2 * \binom{N}{2} * R * S^2}$$

Where  $\binom{N}{2}$  (“N choose 2”) represents the number of combinations of 2 items (pairs) that can be formed from a sample of N items.

The “N choose 2” term of Equation 7 is a non-linear term that increases about half as fast as the quadratic term from Equation 3, or more precisely,  $\binom{N}{2} = \frac{N^2 - N}{2}$ , so when R is 1, Equation 7 reduces to Equation 3. Thus, as might be expected, partial correlation provides for non-linear growth in the standard deviation of the system, approaching the growth observed for perfect correlation as R approaches 1 (where 1 is perfect correlation), and approaching perfect independence as R approaches 0 (when R is 0, Equation 7 reduces to Equation 4).

With the assumption of normal probability distributions for large aggregations of both conventional and intermittent capacity, Equation 2 can be extended to modeling of a highly diverse generating stock that includes conventional units of different size and reliability, as well as intermittent units:

$$\text{Eq. 8) } S_T = \sqrt{S_1^2 + \dots + S_N^2}$$

Where each  $S_N$  represents a class of units with substantially similar statistical characteristics. Examples of such unit classes could include all simple combustion turbines, all wind farms within a particular geographic range, coal steam units with common technology, and so forth.

In NEMS, each electric generation technology is assigned a class-typical forced outage rate. Although over 50 technology types are represented, over half of these are variations on coal-steam plants with different combinations of emission control technologies. The statistical outage properties for each dispatchable technology can be characterized by Equation 1. Table 1 shows for the availability parameters needed for each major capacity type grouping in the EMM.

Table 1A, Forced Outage Rate by Major Group of NEMS Capacity Type

| Plant Type            | Forced Outage Rate<br>(fraction of annual<br>hours) |
|-----------------------|---|
| Combined Cycle        | 0.055   |
| Coal                  | 0.066   |
| Nuclear               | 0.070   |
| Combustion Turbine    | 0.036   |
| Hydro                 | 0.036   |
| Municipal Solid Waste | 0.066   |
| Other Steam           | 0.071   |
| Biomass               | 0.066   |
| Geothermal            | 0.066   |
| Intermittent*         | 0.036   |

\* - Not used in this calculation, intermittent capacity credit is calculated as described in text, not based on forced outage rate.

To derive the capacity credit for wind, the standard deviation for each conventional capacity type is then determined through Equation 2, using only the operator-dispatched capacity. The derived capacity group standard deviations are then used in Equation 8 to determine the total standard deviation for all conventional capacity ( $S_{conventional}$ ).

Peak-load system reliability without intermittent capacity is determined from the reliable load carrying capacity of the conventional units at the 99.93% confidence level:

$$\text{Eq. 9) } C_{99.93\%} = C_{ave} - 3.19 * S_{conventional}$$

Where  $C_{ave}$  is the average available capacity (sum of nameplate times availability for each unit type).

Using the conventional capacity standard deviation from above, the total system standard deviation,  $S_{total}$ , is determined based on the wind correlation assumption and the assumed standard deviation for each wind plant:

$$\text{Eq. 10) } S_{total} = \sqrt{S_{conventional}^2 + (N^2 + 2 * \begin{bmatrix} N \\ 2 \end{bmatrix} * R) * S_{wind}^2}$$

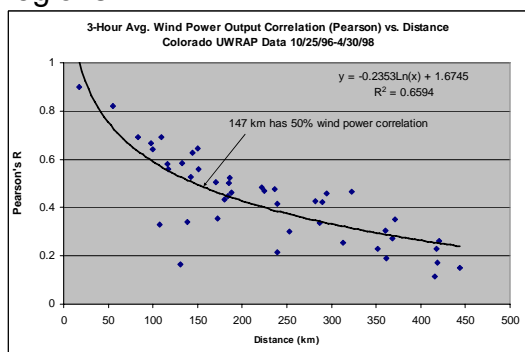
The reliable load carry capacity of the total system (with intermittent resources) is then calculated from Equation 9, substituting the total standard deviation ( $S_{total}$ ) for the conventional standard deviation and using the total system average available capacity. Note that the contribution to average available capacity for intermittent resources is the

sum of the nameplate capacities times the peak-load period capacity factor. The average capacity credit for wind or other intermittent resource ( $U_{wind}$ ) is then the incremental improvement in system capacity from the intermittent resources divided by the total installed intermittent resource:

$$\text{Eq. 11) } U_{wind} = \frac{C_{reliable,total} - C_{reliable,conventional}}{C_{installed,wind}}$$

Where  $C_{reliable}$  is the reliable load carrying capacity for operator-dispatched capacity (conventional) and all capacity including intermittents (total) and  $C_{installed,wind}$  is the nameplate wind capacity installed.

The regional wind power output correlation factor (R in the above system of equations) is determined using data from the Utility Wind Interest Group's Utility Wind Resource Assessment Program (UWRAP). The UWRAP data represent almost 1 year's worth of simultaneously sampled, 1 hour resolution wind speed data from 10 sites across the state of Colorado<sup>4</sup>. Analysis of this data indicates that significant correlation on wind power output (averaged over 3 hours) between site pairs drops off significantly within 150 km or so of separation, but residual correlation remains even beyond 400 km of separation. A logarithmic regression curve, detailed in the figure below, is fitted to the UWRAP data under the assumption that even sites separated by great distances will have potential for some wind speed correlation because of the large geographic scope of the synoptic scale phenomena that dominate hourly-to-daily weather (that is, a storm front can extend for hundreds of miles, or a "ridge" of high-pressure can cover a substantial portion of the country on any given day). Although such a curve doesn't intercept the zero distance point (at zero distance, correlation must be 1), for this application it is less important to accurately describe the close proximity sites than to reasonably describe correlation at distances corresponding to the size of the EMM regions.



To account for the impact of regional size site separation on correlation, the area of each EMM region is calculated. The radius of a circle of area equal to half of the region's area is then evaluated in the regression curve ( $R = -0.2353 \cdot \ln(D) + 1.6745$ , where R is the

<sup>4</sup> See <http://www.uwig.org/uwrapprotocols.htm>. Note data was utilized from the period of October 1996 through April 1998, analyzing the 8347 hours with data collected for all 10 sites.

correlation coefficient and D is the calculated average distance between any two windy sites) to determine the correlation factor for that region. Although this approach does not fully account for the complex geometry of each region (that is, no regions are circles, but are in a wide variety of outlines), it provides a simple approximation of the average distance between any two windy sites within the region. Only half the area of the region is used to account for the concentration of windy sites within each region. Because of this concentration effect, the average distance between any two windy sites within the region will be significantly less than the average distance between any two sites-at-random within the region. Table 2 indicates the correlation factors used for each region for wind and solar technologies (solar thermal power and photovoltaic). Note that for the solar technologies, it is assumed that regional correlation is relatively high, given the strong diurnal solar cycle that is consistent across regions of the size considered.

Table 2, Regional Power Correlation Factor

|       | Wind | Solar |
|-------|------|-------|
| ECAR  | 0.33 | 0.7   |
| ERCOT | 0.33 | 0.7   |
| MAAC  | 0.50 | 0.7   |
| MAIN  | 0.40 | 0.7   |
| MAPP  | 0.25 | 0.7   |
| NY    | 0.50 | 0.7   |
| NE    | 0.50 | 0.7   |
| FL    | 0.25 | 0.7   |
| STV   | 0.25 | 0.7   |
| SPP   | 0.30 | 0.7   |
| NWP   | 0.20 | 0.7   |
| RA    | 0.30 | 0.7   |
| CNV   | 0.35 | 0.7   |

While assuming a constant correlation between all sites within a region provides a simple, tractable model of these effects, it is important to note that actual inter-site correlation is likely variable across space and time. Sites that are physically closer to each other will have more highly correlated outputs over shorter time spans. Sites that are more distant from each other will have lower correlation, which may only become evident over extended periods of time (seasons or years). Furthermore, this correlation is also a function of resource development. If few available wind resource have been developed, a new plant can easily be sited in a location more distant (and hence less correlated) from existing plants. But as development increases, plants will eventually be built closer together, thus increasing the correlation.

## **Representation of Depreciation for Renewables Fueled Generating Technologies**

For most central station electricity generating technologies, NEMS assumes a 20 year tax life over which the capital is depreciated. However, nuclear technologies are assigned a 15 year tax life. Renewables fueled central station electricity generating technologies, including biomass, geothermal, hydroelectric, landfill gas, solar (photovoltaic and thermal) and wind, are assigned 5 tax lives and 5 year double declining balance depreciation in NEMS. The basis for, biomass, geothermal, solar, and wind enjoying 5 year double declining balance depreciation is a consequence of the Economic Recovery Tax Act of 1982 (ERTA, P.L. 97-34); see Internal Revenue Code, subtitle A, Chapter 1, Subchapter B, Part VI, Section 168 (e)(3)(vi)(1994) – accelerated cost recovery.

## **Archival Media**

The RFM is archived as part of the National Energy Modeling System production runs.

## **Model Contact**

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## Report Organization

Subsequent chapters of this report provide detailed documentation of each of the RFM's five working submodules. Each chapter contains the following sections:

- **Model Purpose** —a summary of the submodule's objectives, detailing input and output quantities, and the relationship of the submodule to other NEMS modules
- **Model Rationale** —a discussion of the submodule's design rationale, including insights into assumptions utilized in the model development process, and alternative modeling methodologies considered during submodule development phase
- **Model Structure**—an outline of the model structure, using text and graphics to illustrate the major model data flows and key computations
- **Appendices**—supporting documentation for input data and parameter files currently residing on the EIA mainframe computer. Appendix A in each RFM submodule chapter lists and defines the input data used to generate parameters and endogenous forecasts. Appendix B contains a mathematical description of the computation algorithms, including model equations and variable transformations. Appendix C is a bibliography of reference materials used in the model development process. Appendix D consists of a model abstract. Appendix E discusses data quality and estimation methods.



## **2. Landfill Gas (LFG) Submodule**

### **Model Purpose**

The main purpose of the Landfill Gas (LFG) Submodule is to provide EMM with annual projections of electric power capacity of landfill-gas-to-energy plants. The submodule uses the quantity of municipal solid waste (MSW) that is produced, the proportion of MSW that will be recycled, and the emission characteristics of three types of landfills, to produce forecasts of the future electric power capacity from landfill gas.

It is assumed that no new mass burn waste-to-energy facilities will be built and operated during the forecast period in the US. It is also assumed that mass burn waste-to-energy facilities that are already operational will continue to operate and retire as planned throughout the forecast period.

### **Relationship of the LFG Submodule to Other Models**

The LFG submodule passes capacity estimates, cost, and performance characteristics of landfill-gas-to-electricity technology to the EMM for capacity planning decisions. LFG cost and performance characteristics reside in RFM's input file MSWDAT.

The amount of new landfill-gas-to-electricity capacity during the projection period competes with other technologies using supply curves that are based on the amount of high, low, and very low methane producing landfills located in each electricity market module region.

The only interfaces from other NEMS modules are: (1) annual real Gross Domestic Product (GDP) and (2) the total U.S. population projection, both of which come from the NEMS Macroeconomic Activity Module (MAM).

# Modeling Rationale

## Theoretical Approach

The modeling approach involves calculation of a three-step supply curve that is based on the amount of high, low, and very low methane producing landfills located in each electricity market module region. An average cost of electricity production for each type of landfill is calculated using gas collection system and electricity generator costs and characteristics developed by EPA's Energy Project Landfill Gas Utilization Software (E-PLUS)<sup>5</sup>.

## Fundamental Assumptions

### MSW Quantity Projections

The amount of methane available is calculated by first estimating the amount of total methane-producing waste generated excluding composting and incineration, for the years 1999 through 2030 and applying assumptions regarding the amount of waste that is recycled against this waste stream.

The definition of MSW for the regression in the LFG Submodule is consistent with that used by the Environmental Protection Agency (EPA) and defined in Subtitle D of the Resource Conservation and Recovery Act. In this definition, municipal solid waste includes discarded durable goods, nondurable goods, containers and packaging, food wastes, and yard trimmings from the residential, commercial, institutional, and industrial sectors. The EPA definition of MSW does not include everything that might be landfilled in Subtitle D landfills or burned, such as municipal sludge, nonhazardous industrial wastes, construction and demolition wastes, urban wood waste and tires. These wastes are often disposed alongside those wastes formally defined as MSW. To capture these other materials as part of the projections, the EPA estimates (Franklin 1994) were compared to the higher quantities reported in the annual Biocycle survey (Biocycle, 1993). The average difference between the EPA and Biocycle values for historical years was used as a multiplicative adjustment factor applied to the regression results. In effect it represents the difference between a calculated value and the more empirical value presented by the survey. These same values for total MSW are also used in estimating landfill gas use, discussed later in this section.

### Estimation of Recycling Quantity

It is assumed that recycling will account for 35 percent of the total waste stream by 2005 and will linearly increase to 50 percent by 2010. The recycling portion is held constant at 50 percent from 2010 through 2025. This is consistent with EPA's goals of nationwide recycling targets. This is considered to be an ambitious but achievable goal since some communities in the US are already recycling at 50 percent levels.

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<sup>5</sup> U.S. Environmental Protection Agency, Atmospheric Pollution Prevention Division, *Energy Project Landfill Gas Utilization Software (E-PLUS) Version 1.0*, EPA-430-B-97-006, Washington DC, January 1997.

## Projected Quantity of Methane Generation

The quantity of waste that will be landfilled from 1999 through 2025, is used as supply inputs for a slightly modified EMCON Methane Generation Model<sup>6</sup>. The EMCON model characterizes waste into three categories: readily, moderately, and slowly decomposable material – based on the emission characteristics of each type of waste. It then calculates methane emissions over the decomposition cycle associated with each type. The model and emission parameters are the same as those used in calculating historical methane emissions in EIA's *Emissions of Greenhouse Gases in the United States 2003*<sup>7,8</sup>.

The ratio of high, low, and very low methane production sites to total methane production is calculated by applying the ratios of high, low, and very low methane yielding sites as calculated from data obtained for 156 operating landfills contained in the Governmental Advisory Associate's METH2000 database<sup>9</sup>.

## Constructing the Supply Curve

The production cost of electricity for high, low, and very low methane-yielding sites was calculated by constructing a model of a representative 100-acre by 50-foot deep landfill site and by applying methane emission factors for high, low, and very low methane emitting wastes (Table 2-1).

Table 2-2 shows the cost-of-electricity for the three landfill types and the regional distribution of landfill capacity. In order to construct Table 2-2 the Governmental Advisory Associate's METH2000 database was used. This database has data on 156 operating landfills from which ratios of high, low, and very low methane yielding sites for each state can be calculated. The state level ratios of the different types of sites are then mapped to NERC regions allocating capacities to the different NERC regions on the basis of their shares of State areas. Annual methane production for a hypothetical site differs with each yield assumption. Therefore, each landfill type has associated differences in terms of generator size, number of wells, cost of gas cleanup, piping, and other gas collection and generating requirements. These variations lead to different production costs of electricity due to increases in material cost as well as economies of scale. In general, high methane yield sites produce electricity at a lower cost per kilowatt-hour than lower yielding sites. The cost of electricity and the available supply of methane at each yield assumption for each region is shown in Table 2-2.

**Table 2-1. Methane Production Parameters for High, Low, and Very Low Yield Sites**

|  |             |
|--|-------------|
|  | <b>Very</b> |
|--|-------------|

<sup>6</sup> D. Augenstein, "The Greenhouse Effect and U.S. Landfill Methane", Global Environmental Change, December 1992, pp. 311-328.

<sup>7</sup> Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2003*, DOE/EIA-0573(2003), Washington DC, December 2004.

<sup>8</sup> Energy Information Administration, Documentation for *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0638(2002), Washington, DC, January 2004, pp.79-84.

<sup>9</sup> Governmental Advisory Associates, Inc., METH2000 Database, Westport CT, January 25, 2000.

| <b>Methane Yield Parameters</b>  | <b>High Yield</b> | <b>Low Yield</b> | <b>Low Yield</b> |
|--|-------------------|------------------|------------------|
| Fraction readily decomposable  | 0.040             | 0.040            | 0.040            |
| Fraction moderately decomposable   | 0.450             | 0.450            | 0.450            |
| Fraction slowly decomposable   | 0.052             | 0.052            | 0.052            |
| Rate of methane yield – readily decomposable (ft <sup>3</sup> /pound)    | 4.50              | 2.75             | 1.38             |
| Rate of methane yield – moderately decomposable (ft <sup>3</sup> /pound) | 3.55              | 1.95             | 0.98             |
| Rate of methane yield – slowly decomposable (ft <sup>3</sup> /pound)     | 0.50              | 0.29             | 0.16             |
| Lag for methane generation from readily decomposable waste (years)       | 0                 | 0                | 0                |
| Lag for methane generation from moderately decomposable waste (years)    | 2                 | 2                | 2                |
| Lag for methane generation from slowly decomposable waste (years)        | 5                 | 5                | 5                |
| Production limit for readily decomposable waste (years)                  | 3                 | 4                | 4                |
| Production limit for moderately decomposable waste (years)               | 10                | 20               | 20               |
| Production limit for slowly decomposable waste (years)                   | 20                | 40               | 40               |

Sources: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2003*, DOE/EIA-0573(2003), Washington, DC, December 2004.

Energy Information Administration, Documentation for *Emissions of Greenhouse Gases in the United States 2002*, DOE/EIA-0638(2002), Washington, DC, January 2004, pp.79-84.

Parameters for very low yield site assumed to be 50 percent of low yield site values.

**Table 2-2. Landfill Gas to Energy Supply and Cost of Electricity Production by Region**

| MW equivalent                                | ECAR         | ERCOT       | MAAC        | MAIN         | MAPP        | NY          | NE          | FL          | STV          | SPP         | NWP         | RA          | CNV          | US            |
|--|--------------|-------------|-------------|--------------|-------------|-------------|-------------|-------------|--------------|-------------|-------------|-------------|--------------|---------------|
| High yield                                   | 72           | 12          | 93          | 83           | 43          | 54          | 62          | 14          | 68           | 5           | 17          | -           | 131          | 653           |
| Low yield                                    | 30           | 26          | 22          | 92           | 22          | 27          | 6           | 26          | 22           | -           | 58          | -           | 250          | 581           |
| Very low yield                               | 539          | 316         | 311         | 495          | 150         | 142         | 51          | 158         | 447          | 185         | 185         | 91          | 749          | 3,819         |
| <b>Total</b>                                 | <b>641</b>   | <b>354</b>  | <b>427</b>  | <b>670</b>   | <b>214</b>  | <b>222</b>  | <b>119</b>  | <b>198</b>  | <b>537</b>   | <b>191</b>  | <b>260</b>  | <b>91</b>   | <b>1,130</b> | <b>5,053</b>  |
| Percent of national capacity                 |              |             |             |              |             |             |             |             |              |             |             |             |              |               |
| High yield                                   | 1.43         | 0.23        | 1.84        | 1.64         | 0.85        | 1.06        | 1.23        | 0.28        | 1.35         | 0.11        | 0.33        | 0.00        | 2.59         | 12.93         |
| Low yield                                    | 0.60         | 0.51        | 0.44        | 1.82         | 0.43        | 0.53        | 0.12        | 0.52        | 0.43         | 0.00        | 1.16        | 0.00        | 4.95         | 11.50         |
| Very low yield                               | 10.66        | 6.26        | 6.16        | 9.79         | 2.96        | 2.81        | 1.00        | 3.12        | 8.85         | 3.66        | 3.65        | 1.80        | 14.83        | 75.57         |
| <b>Total</b>                                 | <b>12.69</b> | <b>7.01</b> | <b>8.44</b> | <b>13.26</b> | <b>4.23</b> | <b>4.39</b> | <b>2.36</b> | <b>3.92</b> | <b>10.63</b> | <b>3.77</b> | <b>5.14</b> | <b>1.80</b> | <b>22.36</b> | <b>100.00</b> |
| Electricity price (1998 cents/kilowatt-hour) |              |             |             |              |             |             |             |             |              |             |             |             |              |               |
| High yield                                   |              |             |             |              |             |             |             |             |              |             |             |             |              | 3.20          |
| Low yield                                    |              |             |             |              |             |             |             |             |              |             |             |             |              | 4.10          |
| Very low yield                               |              |             |             |              |             |             |             |             |              |             |             |             |              | 6.45          |

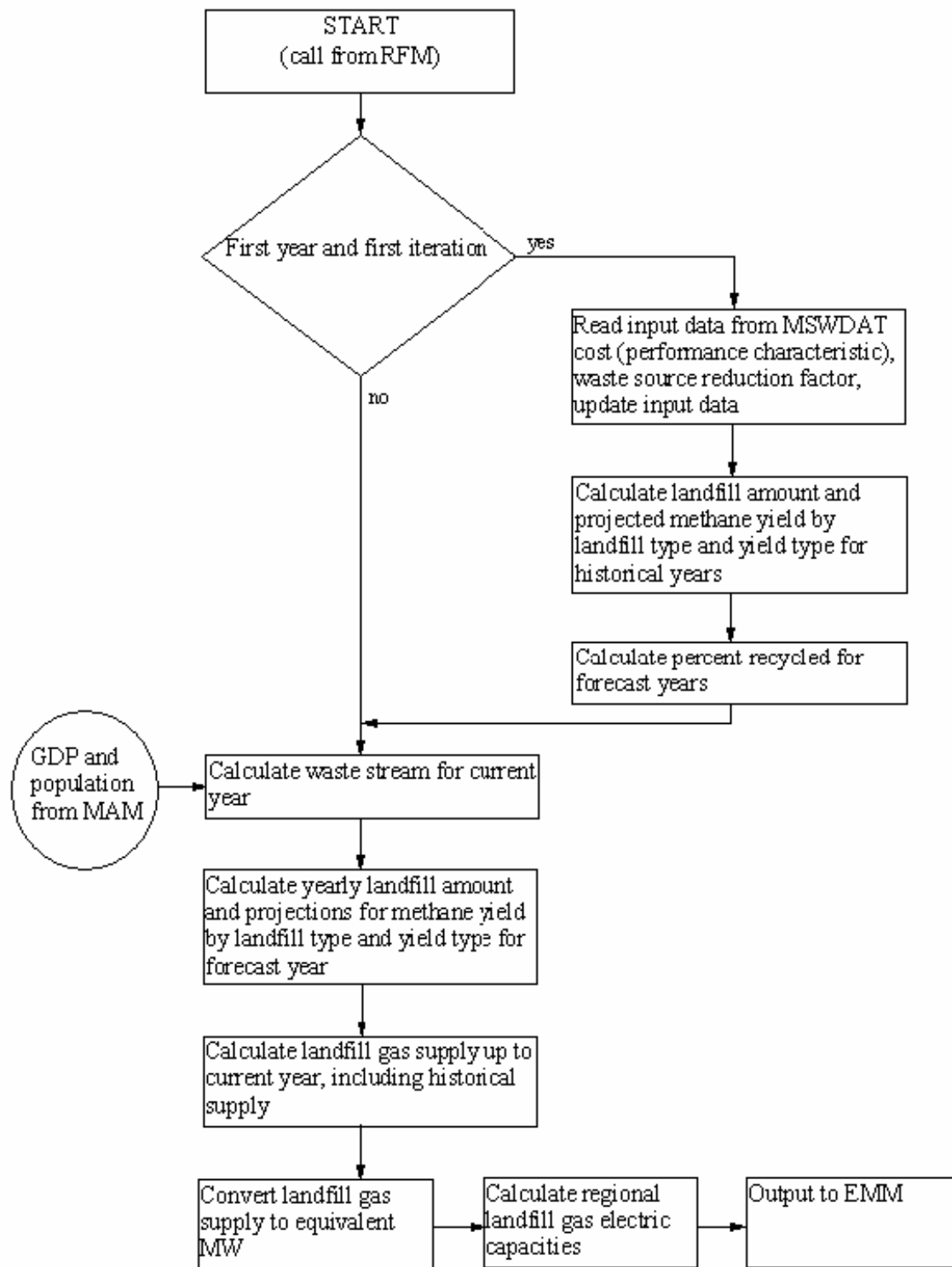
Source: Energy Information Administration, Office of Integrated Analysis and Forecasting

# LFG Submodule Structure

## Submodule Flow Diagram

This section presents a flow diagram (Figure 1) of the LFG Submodule that shows the Submodule's main computational steps and data relationships.

Figure 1. Landfill Gas Submodule Flowchart



## Key Computations and Equations

The LFG Submodule calculates a three-step supply curve that is based on the amount of high, low, and very low yield methane producing landfills located in each electricity market module region. An average cost of electricity generation for each type of landfill is calculated using gas collection system and electricity generation costs and characteristics.

The amount of methane available is calculated by first determining the amount of total waste available excluding composting and incineration for 1999 through 2030 and applying assumptions regarding the amount of waste that is recycled against this waste stream. It is assumed that recycling will account for 35 percent of the total waste stream by 2005 and will linearly increase to 50 percent by 2010. The recycling portion is held constant at 50 percent from 2010 through 2030.

The quantity of waste that will be landfilled from 1999 through 2030 is used as supply input for the methane generation model. The model calculates methane emissions over the decomposition cycle associated with each type of waste (readily, moderately, and slowly decomposable material).

The cost of electricity generation for high, low, and very low methane yielding sites is calculated by constructing a model of a representative 100-acre by 50-foot deep landfill site and by applying methane emission factors for high, low, and very low methane emitting wastes.

Formulae for some of these calculations are presented in Appendix 2B: Mathematical Description.

## Appendix 2-A: Inventory of Variables, Data, and Parameters

This Appendix describes the variables and data inputs associated with the LFG Submodule. Table 2A-1 provides a tabular listing of model variables, input data, and parameters. The table contains columns with information on item definitions, modeling dimensions, data sources, measurement units, and documentation page references.

The remainder of Appendix 2A consists of detailed descriptions of data inputs and variables, including discussions on supporting data assumptions and transformations.

**Table 2A-1. NEMS Landfill Gas Submodule Inputs and Outputs**

| Model Variable       | Definition and Dimensions  | Source                                      | Units                                      |
|----------------------|--|---|--|
| <b>INPUT DATA</b>    |  |   |  |
| <i>WHC</i>           | MSW heat content values in Census division <i>r</i> in year <i>y</i> | U.S. EPA                                    | Btu/lb of MSW                              |
| <i>UPHTRT*</i>       | LFG heat rate for electricity production                             | Government Advisory Associates<br>Oak Ridge | Btu/kWh                                    |
| <i>UPMCF*</i>        | Capacity factor of a LFG plant                                       | EPRI TAG                                    | unitless                                   |
| <i>UPOVR*</i>        | Capital cost for a LFG plant   | EPRI TAG                                    | \$/KW                                      |
| <i>UPFOM*</i>        | Fixed O&M cost for a LFG plant                                       | EPRI TAG                                    | mills/kWh                                  |
| <i>WVC</i>           | Variable O&M cost for a LFG plant                                    | EPRI TAG                                    | mills/kWh                                  |
| <i>SR</i>            | Annual source reduction factor                                       | EIA staff                                   | Percentage                                 |
| <i>a<sub>1</sub></i> | Regression coeff. representing GDP dependency                        | Regressed by EIA                            | 10 <sup>6</sup> ton/10 <sup>9</sup> \$     |
| <i>a<sub>2</sub></i> | Regression coeff. representing population dependency                 | Regressed by EIA                            | 10 <sup>6</sup> ton/10 <sup>6</sup> capita |
| <i>α</i>             | waste stream adjustment factor                                       | Determined by EIA                           | unitless                                   |



**Table 2A-1. NEMS Landfill Gas Submodule Inputs and Outputs (Continued)**

| Model Variable              | Definition and Dimensions   | Source            | Units                 |
|-----------------------------|---|-------------------|-----------------------|
| <b>CALCULATED VARIABLES</b> |   |                   |                       |
| <i>MC_GDP92C</i>            | Real gross domestic product for year <i>y</i>   | Determined in MAM | Billion \$            |
| <i>MC_N</i>                 | U.S. Population incl. Overseas armed forces   | Determined in MAM | 10 <sup>6</sup>       |
| <i>Q</i>                    | Quantity of energy from municipal solid waste for generation of electric power in EMM region <i>n</i>                   |                   | MMBtu per year        |
| <i>WASTE_STREAM</i>         | Quantity of municipal solid waste produced in the U.S.  |                   | million tons per year |
| <i>WCAMSEL</i>              | MSW electric capacity for utilities in EMM region <i>n</i> in year <i>y</i>   |                   | Megawatts             |
| <i>WVCMSEL</i>              | Variable O&M cost of MSW electric generating capacity in EMM region <i>n</i> in year <i>y</i> adjusted for tipping fees |                   | mills/kWh             |

\*Assigned in EMM input file ECPDAT.

**MODEL INPUT:**     *WHC*

**DEFINITION:**     Heat content in year *y*

Heat content values, measured in Btu per pound of MSW. Heat contents are national data, and are assumed to be the same for each EMM region. The historical and projected percent composition of MSW was obtained from Franklin Associates for each of the main components of MSW. The main components of MSW include: paper and paper board, glass, metals, plastics, rubber and leather, textiles, wood, food waste, yard waste, other organics, and other inorganics. The Btu content was obtained for each material from the U.S. EPA. The percentages and Btu contents were combined to provide an overall heat content per pound of MSW. Values for the years through 2000 were based on an assumed continuation of the historical trend. Beyond 2000, it was assumed that *WHC* remains level for the duration of the forecast horizon.

**SOURCES:**

Franklin Associates, "Characterization of Municipal Solid Waste in the United States: 1997 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, May 1998.

**MODEL INPUT:**     *UPHTRT*

**DEFINITION:** Heat rate for LFG plants

The heat rate (Btu/kwh) is assumed to be constant for all EMM regions and years. For those plants that cogenerate electricity and steam, the heat rate is assumed to equal the heat rate of facilities that generate only electricity.

**SOURCE:** Electric Power Research Institute, *Technical Assessment Guide*. EPRI TR-1022765, Vol. 1: Rev. 7, Palo Alto, CA, June 1993.

**MODEL INPUT:** *UPMCF*

**DEFINITION:** Capacity factor for an LFG plant

**SOURCE:** Electric Power Research Institute, *Technical Assessment Guide*. EPRI TR-102276S, Vol. 1: Rev. 7, Palo Alto, CA, June 1993.

**MODEL INPUT:** *UPOVR*

**DEFINITION:** Capital cost of an LFG plant

**SOURCE:** Electric Power Research Institute, *Technical Assessment Guide*. EPRI TR-102276S, Vol. 1: Rev. 7, Palo Alto, CA, June 1993.

**MODEL INPUT:** *UPFOM*

**DEFINITION:** Fixed operation & maintenance (O&M) cost for an LFG plant

Data for calculating operating costs are obtained from the EPRI Technical Assessment Guide (TAG). Data are available for mass burn technology and refuse derived fuel. Information for the mass burn technology is used in the calculations, assuming a 78 percent capacity factor.

**SOURCES:** Electric Power Research Institute, *Technical Assessment Guide*. EPRI TR102276S, Vol. 1: Rev. 7, Palo Alto, CA, June 1993.

**MODEL INPUT:** *WVCMSEL*

**DEFINITION:** Variable O&M cost for an LFG plant in EMM region *n* and year *y* adjusted for tipping fees

Data for calculating the operating cost are obtained from the EPRI Technical Assessment Guide (TAG). Data are available for mass burn technology and refuse derived fuel. Information for the mass burn technology is used in the calculations. The variable operating cost is adjusted by subtracting the tipping fee, and assigning the operating cost value to the RFM common block variable, *WVCMSEL*.

**SOURCES:** Electric Power Research Institute, *Technical Assessment Guide*. EPRI TR102276S, Vol. 1: Rev. 7, Palo Alto, CA, June 1993.

**MODEL INPUT:** WVC

**DEFINITION:** Variable O&M cost for an LFG plant

Variable represents the unadjusted (excluding tipping fees) O&M cost for LFG plants.

**SOURCES:** Electric Power Research Institute, *Technical Assessment Guide*. EPRI TR102276S, Vol. 1: Rev. 7, Palo Alto, CA, June 1993.

**MODEL INPUT:** SR

**DEFINITION:** Annual source reduction factor, the amount of annual waste stream reduction achieved - percentage.

**SOURCE:**

EIA, Office of Integrated Analysis and Forecasting

**MODEL INPUT:**  $a_1$

**DEFINITION:** Regression coefficient representing the GDP dependency of the waste stream

**SOURCE:**

Franklin Associates, "Characterization of Municipal Solid Waste in the United States: 1997 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, May 1998.

**MODEL INPUT:**  $a_2$

**DEFINITION:** Regression coefficient representing the population dependency of the waste stream.

**SOURCE:**

Franklin Associates, "Characterization of Municipal Solid Waste in the United States: 1997 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, May 1998.

**MODEL INPUT:**      $\alpha$

**DEFINITION:**       Waste stream adjustment factor - expands the EPA-defined MSW quantity to account for empirical information on other disposed materials.

**SOURCES:**

Biocycle, "The State of Garbage in America," Annual series, (April 1988-April 1997).

Franklin Associates, "Characterization of Municipal Solid Waste in the United States: 1998 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, May 1998.

## Appendix 2-B: Mathematical Description

This Appendix provides the detailed mathematical specification of the LFG Submodule as presented in the RFM FORTRAN code execution sequence.

The LFG submodule first computes the annual amount of municipal solid waste as a bi-linear relation of the national population and the economic activity as represented by the GDP.

$$WASTE\_STREAM_y = a_1 * MC\_GDP92C_y + a_2 * MC\_N_y$$

Where:

|                   |   |   |
|-------------------|---|---|
| $WASTE\_STREAM_y$ | = | national annual waste stream in year $y$ , in [ $10^6$ ton]   |
| $a_1$             | = | regression coefficient representing the impact of change in GDP ( $a_1=0.02523713$ [ $10^6$ ton/ $10^9$ \$])    |
| $a_2$             | = | regression coef. representing the impact of change in population ( $a_2=0.159544$ [ $10^6$ ton/ $10^6$ capita]) |
| $MC\_GDP92C_y$    | = | gross domestic product in year $y$ , in [ $10^9$ \$] (chain weighted)   |
| $MC\_N_y$         | = | national population in year $y$ , in [ $10^6$ capita]   |

The waste stream is then adjusted to capture the efforts to reduce generation of MSW and to reflect definitional change. The relation is expressed as:

$$WASTE\_STREAM_y = WASTE\_STREAM_y * (1 - (y + 15) SR) * \alpha * 1000$$

Where:

|                   |   |  |
|-------------------|---|--|
| $WASTE\_STREAM_y$ | = | Adjusted national annual waste stream in year $y$ , in [ $10^6$ ton]   |
| $y$               | = | NEMS year  |
| $SR$              | = | source reduction factor <sup>10</sup>  |
| $\alpha$          | = | waste stream adjustment factor - expands the EPA-defined MSW quantity to account for empirical information on other disposed materials. The value is calculated as a simple average of the ratios of the EPA value to the total waste value from a State survey by <i>Biocycle</i> magazine. <sup>11</sup> |

<sup>10</sup> Allaway, David, "Does Source Reduction Work?", *Resource Recycling*, July 1992, pp. 52-61.

<sup>11</sup> "The State of Garbage in America" (repeated annually), *Biocycle*, April/May, 1989-1997.

## Source Reduction Factor

Projections of MSW generation quantities based on the above regression approach must be modified because of structural market changes that are occurring and are likely to occur in future years. Governments and businesses have adopted strategies to lessen the amount of waste generated without reducing economic output. The general term for these strategies is *source reduction*. An example of such a strategy is the local government trend toward unit-based disposal rates, which has brought about a reduction of generated waste where implemented. Source reduction goals can be met through a combination of source reduction and recycling. To the extent that source reduction strategies are successful, they will likely alter the basic relationship between GDP and MSW quantity.

In order to reflect anticipated annual reductions in the quantity of MSW generated on account of source reduction efforts, the quantity projected by the MSW supply equation will be reduced by an exogenously-determined source reduction multiplier. This multiplier, *SR*, will be based in part on legislation passed or proposed to promote source reduction. Currently, EIA uses expert judgment to derive the *SR* parameter that is used in the MSW supply equation.

## Waste Stream Adjustment Factor

As mentioned earlier, the basic regression to develop coefficients uses the EPA definition of MSW. However, this definition omits a notable segment of the waste stream that is likely to be burned or buried. Among omitted materials are tires, construction and demolition debris, and certain industrial materials. An adjustment is computed as a multiplier on the equation to represent the inclusion of these items. The value for it is the average of the incremental differences between the EPA value and one presented in an annual survey by *Biocycle* magazine. The same value applies to all regions.

## Appendix 2-C: Bibliography

Biocycle, "The State of Garbage in America," April and May issues, 1989-2003.

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Office of Technology Assessment, *Facing America's Trash: What Next for Municipal Solid Waste?*, Congress of the United States, U.S. Government Printing Office, Washington, DC, October 1989.

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SERI, "The Potential of Renewable Energy," an Interlaboratory White Paper, Solar Energy Research Institute and other laboratories, SERI/TP-260-3674, Golden Colorado, March 1990.

Klass, "The U.S. Biofuels Industry," *Energy from Biomass and Wastes XIV*, "Institute of Gas Technology," Chicago, IL, pg 1-46, 1990.

Waste Age, "The 1992 Municipal Waste Combustion Guide," November 1992.

## Appendix 2-D: Model Abstract

**Model Name:**

Landfill Gas Submodule

**Model Acronym:**

LFG

**Description:**

The submodule uses the quantity of municipal solid waste produced (derived econometrically), to produce forecasts of the production of electricity from landfill gas. Forecasts are disaggregated by region.

**Purpose of the Model:**

The LFG Submodule provides the NEMS Electricity Market Module with annual regional projections of energy produced from landfill gas. The submodule provides regional forecasts of electric capacity to be decremented from electric utility capacity requirements, as well as capital and operating costs for the calculation of electricity prices.

**Most Recent Model Update:**

March 2003.

**Part of Another Model?:**

The LFG submodule is a component of the Renewable Fuels Module (RFM) of the National Energy Modeling System (NEMS).

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**Documentation:**

*Model Documentation Report, Renewable Fuels Module of the National Energy Modeling System, June 2005.*

**Archive Media and Installation Manual(s):**

Archived as part of the NEMS production runs.

**Energy System Described:**

Energy production from the combustion of landfill gas.

**Coverage:**

- Geographic: Thirteen modified EMM regions.
- Time Unit/Frequency; Annual, 1990 through 2025
- Products: generating capacity
- Economic Sectors: electric utility sector



**Modeling Features:**

- Model Structure: Sequential calculation of forecasted landfill gas to electricity generation, followed by derivation of regional and sector energy shares based on estimates of the percentage of MSW combusted.
- Modeling Technique: Econometric estimation of municipal solid waste generation, coupled with an energy share allocation algorithm for deriving electric generation capacity and energy quantities by sector and region.
- Special Features: Allows for the modeling of regional and national resource recovery efforts.

**Non-DOE Input Sources:**

Franklin Associates, data prepared for the Environmental Protection Agency:

- National annual quantity of municipal solid waste generated
- Current annual percentages of municipal solid waste combusted and landfilled

Government Advisory Associates, *Resource Recovery Yearbook* and Resource Recovery Database:

- Plant-specific electricity generation, Btu energy content of MSW
- Plant locations and energy consuming sectors

Electric Power Research Institute, *TAG Technical Assessment Guide*:

- Capital cost; fixed and variable operation & maintenance costs
- Plant capacity factor

**DOE Input Sources:**

Source reduction factor

Waste stream adjustment factor

Landfill gas-fueled capacity

Projected shares of MSW combusted and landfilled

Heat content of MSW

Current capacities for MSW and landfill gas-fueled units

**Independent Expert Reviews Conducted:**

None.

**Status of Evaluation Efforts by Sponsor:**

None.

## Appendix 2-E: Data Quality and Estimation Processes

This Appendix discusses the quality of the principal sources of input data used in the LFG Submodule, along with a discussion of user-defined parameters and guidelines used to select them.

A principal driver of the LFG projection is the estimation of the projected waste stream. This is done in a stepwise fashion beginning with EPA data and supplemented with data from *Biocycle*. EPA data are based on in-depth analysis, but are defined narrowly. However, the data have the advantage of a lengthy series. The data were correlated to GDP and population data. Since considerable material outside that definition does and will be disposed in combusters and landfills, the EPA value was factored up to a level represented by *Biocycle's* survey data. The weakness of this data is that the individual States reporting would be using varying definitions of MSW, and the vintage of the data series varies somewhat. The source reduction value is estimated based on readings of MSW literature and although the precise level is judgmental, it is deemed important to include.

The portion of capacity that was projected from the landfilled share of the waste is estimated in the model. There is a somewhat similar stepwise process for deriving energy and hence, capacity for this share. The key is the formulae for computing gas yield from existing and future landfilled MSW over their lifetimes. These have been developed from EPA research reports and are assumed to remain valid throughout the forecast horizon. The conversion of the resulting gas energy to generate capacity is similar to the approach for combusters. A key assumption is the increase in the percent of gas captured from about 13 percent in 1995 to about 50 percent by 2010. This is consistent with the goals of an EPA program to reduce methane emissions.

### **3. Wind Energy Submodule (WES)**

#### **Model Purpose**

The Wind Energy Submodule (WES) contains information on U.S. regional wind energy resources and provides estimates of wind supplies by region and cost category to the Electricity Capacity Planning (ECP) component of the Electricity Market Module (EMM). WES quantifies regional wind supplies by differences in (1) average wind speed, and (2) distances from existing transmission lines. General technology values – such as overnight capital cost, fixed operations and maintenance costs, generation subsidies, construction profiles, and optimism and learning characteristics – are input directly from the ECPDAT file in the EMM. The RFM data file “rendat” contains the short- and long-term cost adjustment factors. The combination of wind supplies and technology costs yields regional wind technology cost supply information to the EMM.

All cost parameters assume construction of a 50 MW wind plant (or wind “farm”), notionally consisting of 50, 1 MW turbines. Although U.S. wind plants range in size from single-turbine 1 MW installations to large 300 MW turbine arrays, 50 MW remains typical of recent wind construction. While both plant size and turbine size may, in the future, increase as a way of reducing plant costs, such improvements are implicitly modeled through the learning-by-doing function contained within the EMM, and thus are not explicitly reflected in the assumptions of the WES. Customer-sited turbines or individual turbines and small turbine clusters connected directly to the distribution grid have significantly different cost, if not performance, characteristics than central-station facilities, and are thus not modeled.

After determining the new capacity builds for a given model year, the EMM provides the WES information on installed wind capacity. WES then subtracts new capacity from the resource supply to determine the remaining wind resources available for future installations.

#### **Relationship of the Wind Energy Submodule to Other Models**

As a submodule of the RFM, WES receives data from and provides its output through the RFM. WES is initiated by a call from the RFM. The RFM then provides input to and receives values from the EMM. The WES calculates values for two variable arrays, which are then passed to the EMM for further processing. The calculated arrays are (1) yearly available capacity per region, and (2) yearly capacity factors for each wind class, region, and subperiod (i.e., “slice” of the load duration curve). The first array is calculated from the available land area versus wind class (average speed “bins”), the power per area of wind resource, and the annual capacity factor for each wind class. The second array is calculated from the subperiod energy percentages and subperiod definitions. All other input data, such as economic life, tax life, construction profile, fixed operation and maintenance costs, the forced outage rate, and other values, are passed directly from ECPDAT to the EMM. The WES generates a wind capacity supply curve with a straightforward (deterministic) calculation from wind turbine performance projections. The uncertainties in the results are related to the technological cost and performance projections and the assumptions about the availability of wind.

# Modeling Rationale

## Theoretical Approach

Wind resources are not a uniform supply for use in electricity generation. Winds vary geographically and temporally (by hour of the day and by season of the year) and differ in distance from transmission lines. The purpose of the Wind Energy Submodule (WES) is to account for effects of these variables on wind supply by estimating the quantities (megawatts) of wind capacity available for new generating capacity in each region in each wind quality category.

The submodule begins with estimates of land area exhibiting specified ranges of average annual wind speed. It uses the end use exclusion scenario described in the National Renewable Energy Laboratory *Draft Final Report to EIA on Incorporation of Existing Validated Wind Data into NEMS* for 23 states, and a Pacific Northwest Laboratory study and a subsequent update for the remainder. This data set excludes lands assumed prohibited by other uses; it further differentiates the areas by average distances from transmission lines, and finally estimates the quantities of land resource available in each of 3 wind quality classes (Class 4 through 6, as defined by PNL). The WES uses this data to calculate generating capacity available in each forecast year for each wind quality-distance category after accounting for current installed capacity. For use in calculating efficiencies and costs, WES also differentiates and projects regional average capacity factors by EMM load periods.

Having estimated available megawatts regional capacity, the EMM uses general cost and performance values in ECPDAT and regional capacity factor values for the EMM load periods to calculate the net present value of the wind technology over its economic life and then competes wind technology with fossil and other alternatives in the capacity planning process.

U.S. commercial wind installations have existed since the early 1980's. Counts of these pre-existing installations are used to adjust estimates of available windy land at the beginning of the NEMS model run. The WES tracks the quantity of windy land remaining by wind class and zone that is available for future development after each run year by calculating the amount of resource required to provide a given amount of wind installed capacity and subtracting that amount from the total resource available. This assumes that the best economic resource (i.e. highest average wind speed and closest proximity to the electric grid) is used first. The amount of resource used is then subtracted from the previous year's available amount to yield the current year's available windy land. The wind resource depletion scheme uses the land area with the highest quality wind class in all zones beginning with the one closest to the transmission lines and then expanding to the more distant zones before using the next lower quality wind resource.

# Fundamental Assumptions

## WES Wind Capacity Projections

The EMM requires capacity, performance, and cost data by EMM region. Overall technology cost and performance assumptions, such as capital cost, construction profile, fixed operations and maintenance costs, subsidies (e.g. renewable energy production tax credit under EPACT), optimism and learning characteristics, and other assumptions applicable to all regions reside in the ECPDAT file of the EMM and not in the WES. Values which vary by region and contribute to differences in generating costs and performance, along with the steps necessary in calculating overall cost differences for capacity decisions in EMM are found in the WES. As in the EMM, values are provided for 13 EMM regions excluding Alaska and Hawaii. WES also contains 9 distinct capacity factors for each EMM region, covering three seasons (winter, summer, and spring/fall) and three time-of-day periods (early morning, morning and evening, and peak).

The WES submodule converts estimates of wind supply in each EMM region to estimates of available capacity by wind quality group in the following manner:

First, the WESTECH file in WES contains estimates of windy land area (square kilometers) in each EMM region by wind class, all estimated at a rotor hub height of 10 meters:

| <u>Average Annual Wind Speed</u> | <u>WES Wind Class</u> | <u>PNL Wind Class</u> |
|----------------------------------|-----------------------|-----------------------|
| Above 14.5 mph                   | Class 1               | 6+                    |
| 13.4 – 14.5 mph                  | Class 2               | 5                     |
| 12.4 – 13.4 mph                  | Class 3               | 4                     |

The land area available for wind plant development has been extracted from data produced in coordination with the National Renewable Energy Laboratory (NREL). In producing this data, NREL staff used consistently derived, validated windspeed maps for the 23 states available at the time the work was performed. For the remaining 25 states (Alaska and Hawaii are not interconnected with the continental U.S. and thus NEMS does not model their potential contribution of wind power), NREL used data originally developed by the Pacific Northwest National Laboratory. The WES input data excludes all environmentally protected lands (such as parks and wilderness areas), all lands with greater than 20 percent slope, all lands known to be reserved by State for Federal government for uses exclusive of wind power development (such as National Parks), all urban lands, all wetlands, all airports, areas within 3 kilometers of otherwise excluded lands (except wetlands), 50 percent of non-ridgecrest forested lands, and lands that do not have sufficient density of windy land to support utility-scale wind development (5 km<sup>2</sup> of windy land within a 100 km<sup>2</sup> area). Second, windy land areas are further disaggregated – or eliminated – by distance from existing 115kV or 230kV transmission lines:

| <u>Zone</u> | <u>Land Distance from Transmission Line (miles)</u> |
|-------------|---|
| 1           | 0 - 5 miles   |
| 2           | 5 – 10 miles  |
| 3           | 10 – 20 miles                                       |

In effect, corridors of 10, 20, and 40 miles are established centered with existing transmission lines.

As a result, eligible wind areas in each EMM region are distributed among 9 wind speed and distance categories. Because new transmission lines are assumed necessary connecting new generating capacity to the lines, WES imposes increasing costs for new capacity at greater distances, with assumed average distances from existing lines of 2.5, 7.5, and 15 miles.

The development and application of the land exclusion criteria and transmission line corridors within the data are discussed in the draft NREL report : *Incorporation of Existing Validated Wind Data into NEMS*, attached as an appendix to this chapter.

Additions to capital costs occur to account for interconnection itself and also for the increased interconnection distances unique to wind power.

All new technologies, including wind, are assigned an increment to capital cost to account for the cost of maintaining and expanding the transmission network. Because terrain, urbanization, and other factors affect costs, these costs are assigned in the EMM for each electric power region, as follows:

| <u>EMM Region</u> | <u>Transmission Cost per Kilowatt</u><br>(\$1987) |
|-------------------|---|
| 1 ECAR            | 124.4   |
| 2 ERCOT           | 133.1   |
| 3 MAAC            | 151.0   |
| 4 MAIN            | 123.1   |
| 5 MAPP            | 123.1   |
| 6 NY              | 151.0   |
| 7 NE              | 151.0   |
| 8 FL              | 129.2   |
| 9 STV             | 129.2   |
| 10 SPP            | 128.2   |
| 11 NWP            | 258.8   |
| 12 RA             | 226.4   |
| 13 CNV            | 323.9   |

Source: Energy Information Administration, Office of Integrated Analysis and Forecasting, input file ECPDAT

Further, wind technologies are assigned an additional interconnection cost as follows:

| Region | Wind Interconnection Costs (2002 \$ per kilowatt) |         |          |
|--------|---|---------|----------|
|        | <5 mi   | 5-10 mi | 10-20 mi |
| ECAR   | 5.3   | 7.4     | 9.1      |
| ERCOT  | 5.4   | 7.5     | 9.2      |
| MAAC   | 7.2   | 10.0    | 12.3     |
| MAIN   | 5.0   | 6.9     | 8.5      |
| MAPP   | 5.1   | 7.1     | 8.7      |
| NY     | 5.9   | 8.2     | 10.1     |
| NE     | 5.7   | 7.9     | 9.7      |
| FL     | 4.1   | 5.7     | 6.9      |
| STV    | 6.6   | 9.1     | 11.2     |
| SPP    | 6.4   | 8.8     | 10.9     |
| NWP    | 5.7   | 7.8     | 9.6      |
| RA     | 4.2   | 5.7     | 7.0      |
| CNV    | 7.1   | 9.8     | 12.1     |

Source: Energy Information Administration, Office of Integrated Analysis and Forecasting, input file WESAREA.

Third, WES subroutine CALMWA converts windy land areas (square kilometers) to estimates of wind energy (kilowatthours/square meter) by estimating the number of wind turbines to be placed per unit area <sup>12</sup>, and the energy capture of each turbine. For *AEO2005*, EIA assumes an array of turbines spaced 5 rotor diameters between turbines and 10 rotor diameters between turbine rows. This corresponds to the 6.5mw/km<sup>2</sup> power density factor used to calculate the decrement to windy lands.

Historical analysis of wind turbine performance for U.S. installations indicates a trend of improving capacity factors with each additional capacity increment. Detailed analysis of this apparent performance improvement is complicated by the wide variety of site-specific performance factors at each installation, but several factors could, in principal, contribute to the observed trend:

- Improvements in turbine reliability, thus ensuring that the turbines are available for generation when the wind is blowing;
- Increases in rotor size and turbine height, which are able to capture more consistent, higher quality winds at altitude; and
- Better micro-siting of turbines within wind farms to maximize resource capture and minimize aerodynamic interactions among turbines.

<sup>12</sup> This refers to the resource area eliminated from the wind resource base. The physical plant (turbine foundation, access roads, and associated power equipment) would occupy less than 5% of this land, and the remainder could still be useful for other activities such as agriculture or grazing.

Although the “Betz” limit<sup>13</sup> constrains the theoretical ultimate efficiency of a wind turbine (that is, the amount of energy captured as a fraction of total wind energy passing through the rotor disc), there is no pre-determined physical limit on the capacity factor of a wind turbine. Because no such limit on capacity factor can be theoretically derived, the RFM allows the user to input a limiting capacity factor for each of the three wind classes modeled based on the user’s assessment of the economic trade-offs involved in turbine design and how these trade-offs are likely to be realized under future market conditions.

Typically, learning functions describe a decrease in cost as a function of cumulative units constructed or sold (sometimes in the functional form of a logarithmic decay, with each doubling of units resulting in some fractional decrease in cost). In the case of wind turbine performance, this typical functional form does not describe a process by which capacity factor increases (rather than decreases) toward some limiting level (absolutely limited to 100 percent, but likely limited to a significantly lower fraction) with increasing cumulative capacity additions.

Learning-induced improvement in wind turbine capacity factor are assumed to asymptotically approach the user-specified capacity factor limit according to:

$$C = C_U e^{-b/G}$$

Where C is the current capacity factor,

$C_U$  is the ultimate capacity factor for wind Class 6 (CFULT in the WESAREA input file),  
b is the decay factor, and

G is the current capacity (as passed to the RFM).

The user can specify the decay factor, b, by indicating an assumed Class 6 wind capacity factor at a specified level of capacity installation. The decay factor is calculated as follows:

$$b = G_I \ln\left(\frac{C_I}{C_U}\right)$$

Where  $G_I$  is the total installed wind capacity at some initial time, I (FIXEDX in the WESAREA input file),

$C_I$  is the assumed capacity factor for Class 6 wind turbine installations at time I (CFATX in the WESAREA input file), and

$C_U$  is as above, the ultimate achievable Class 6 capacity factor.

Because of the wide variation observed in the capacity factor of actual wind plant installations, and the uncertainty over the actual wind class each is constructed in, a reliable “initial conditions” measure of Class 6 capacity factor for any given year/level of installed capacity, cannot be constructed. Therefore, the user can specify the initial conditions based on the best available information/analysis.

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<sup>13</sup>See [www.windpower.org/en/tour/wres/betz.htm](http://www.windpower.org/en/tour/wres/betz.htm) for an explanation of the Betz limit.



The RFM directly calculates only the Class 6 capacity factor. Capacity factors for Class 5 and 4 wind resources are scaled to the Class 6 value, based on the ultimate capacity factors specified for each class (CFULT in the WESAREA input file).

The derivation of the capacity factor learning algorithm is detailed in the report “Modeling wind and intermittent generation in the National Energy Modeling System (NEMS).”<sup>14</sup>

Capacity factors for each of the 9 ECP load segments (3 seasons, each with 3 time-of-day periods, as detailed in the EMM documentation) are calculated based on the capacity factor of the best available wind class in each region, as adjusted to account for wind production curtailed to balance system demands during periods of high wind output and low demand. The file WESAREA provides a table of the fraction of annual hours and the fraction of total annual wind energy output in each load segment for each region. The time-specific capacity factor is calculated as follows:

$$C_t = C_T \frac{E_t}{H_t}$$

Where  $C_t$  is the capacity factor for load segment  $t$ ,  $C_T$  is the annual average capacity factor,  $E_t$  is the fraction of wind energy output for load segment  $t$ , and  $H_t$  is the fraction of annual hours in load segment  $t$ .

This surplus wind curtailment effect initially manifests itself when a high penetration of wind capacity produces above-average generation during times of low system demand. Because other units, typically steam units fired by coal or nuclear fuels, may already be committed to generation during these “baseload” hours, unexpected or especially large excess production from wind generators within a self-contained electricity supply region may require system operators to choose between cycling (turning down or off) of thermal plant or curtailing wind plants (that is, shutting down some significant portion of capacity, despite available wind resource).

To account for this curtailed wind energy, it is assumed that only nuclear and coal-steam plants are limited in ability to cycle to accommodate excess wind during low load. Furthermore, it is assumed that these plants may be cycled down to a user-specified “turn-down” ratio, currently 3:1 of nameplate capacity for coal and 2:1 for nuclear, before system operators would curtail wind production to avoid further cycling or unit shutdown. If any other units (gas-fired simple cycle or combined cycle turbines, for example) operate during affected load periods, it is assumed that they may be fully cycled (including shut-down) to accommodate excessive wind output without significant economic, safety, or other technical cost.

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<sup>14</sup> Namovicz, C. “Modeling wind and intermittent generation in the National Energy Modeling System (NEMS).” *Proceedings of WindPower 2003, Austin TX*. American Wind Energy Association. May 2003.

On average, wind units will contribute energy to meet segment-specific load based on the wind capacity factor for the given region and load segment. In the real world, to the extent that it does not create difficulties for other committed units, wind would be allowed to contribute to the extent the wind was blowing at any given time (that is, with near-zero running cost, it would always be the low-bid in the dispatch pool). However, there is a probability that local or regional high winds will increase the wind energy contribution at any given time. This probability, of course, increases with increasing wind capacity penetration in the regional power pool. There is also a probability that the wind will contribute less-than-average energy to the load segment, but other mechanisms within NEMS account for this effect (see capacity credit algorithm in Appendix 1-A of this report).

To determine the probability that the wind output will be in excess of operational limits, the user must specify a normalized standard deviation of output from a typical regional wind plant. Analyses of typical wind regimes and wind turbine power curves indicate that a reasonable approximation for this parameter is 38% of the average power output of a 50 MW wind farm (about 19 MW). Scaling this distribution to a large amount of capacity installed over a large region needs to account for the geographical diversity of the wind source. That is, the wind will be blowing at various speeds over a wide area, so the output of each turbine (or plant) will not be perfectly correlated with the output of the other turbines (plants) in the system. For partially correlated wind units, the total standard deviation of the system could be approximated by:

$$S_T = \sqrt{(N + (N^2 - N) * R * S^2)}$$

Where R is the user-specified correlation coefficient of the output at each site, assuming constant correlation among all sites as specified in the WESAREA input file (see Appendix 1-1A of this document for further derivation of this approximation and of the correlation factors used).

Current default correlations are as follow:

| Region    | Correlation |
|-----------|-------------|
| 1 - ECAR  | 0.33        |
| 2 - ERCOT | 0.33        |
| 3 - MAAC  | 0.50        |
| 4 - MAIN  | 0.40        |
| 5 - MAPP  | 0.25        |
| 6 - NY    | 0.50        |
| 7 - NE    | 0.50        |
| 8 - FL    | 0.25        |
| 9 - STV   | 0.25        |
| 10 - SPP  | 0.30        |
| 11 - NWP  | 0.20        |
| 12 - RA   | 0.30        |
| 13 - CNV  | 0.35        |

The installed wind standard deviation can be used to describe the standard deviation of a Gaussian normal distribution of wind power output for the region, where the mean equals the installed capacity times the annual average capacity factor. To determine the amount of wind that needs to be curtailed, the model next determines the point at which to evaluate the normal distribution: the critical wind output level where curtailment must occur to avoid the unplanned shut-down or excessive cycling of coal or nuclear plants. This critical point is as follows:

$$W_{Crit} = L_{g,t} - (D_{coal} * O_{coal} * C_{coal} + D_{nuclear} * O_{nuclear} * C_{nuclear})$$

Where  $W_{Crit}$  is the critical limit on wind output,  $L_{g,t}$  is load for Region g and Load time-slice t. D is the minimum operating fraction of nameplate capacity (inverse of turn-down ratio) for the specified plant type, O is the total (planned and forced) outage rate for the specified technology, and C is the regional installed capacity of each technology.

With the installed wind standard deviation and the critical limit, the necessary parameters are available to determine the probability of wind output greater than  $W_{Crit}$ . This is done by evaluating the cumulative distribution function of a normal distribution as follows:

$$P(W_{Crit}) = \frac{1}{\sqrt{2\pi} * S_T} * e^{-\frac{(W_{Crit} - W_{Ave})^2}{2S_T^2}}$$

Where  $P(W_{Crit})$  is the cumulative probability of wind output in excess of  $W_{Crit}$  and where  $W_{Ave}$  is the average output of regional installed wind capacity for the current slice of the regional load duration curve (time-slice specific capacity factor times installed nameplate capacity).

If no wind curtailment is assumed, total wind energy output in the current LDC slice would be:

$$E = F_t * W_{nameplate} * H_t$$

Where  $W_{nameplate}$  is the nameplate installed capacity for the region,  $H_t$  is the total number of hours in LDC slice t, and  $F_t$  is the capacity factor for wind during LDC slice t.

The energy curtailed is:

$$E_{curtail} = P(W_{Crit}) * W_{nameplate} * H_t$$

The adjusted total energy produced during slice t is the difference between the total wind energy output without curtailment and the curtailed output ( $E_{adjusted}=E-E_{curtail}$ ), and the adjusted capacity factor for wind during slice t is:

$$F_{t,adjusted} = \frac{E_{adjusted}}{W_{nameplate} * H_t}$$

After adjusting the capacity factors for each segment, the annual average capacity factor to be passed to the EMM is then re-calculated. However, in the next model iteration, the learning for capacity factor is applied to the baseline (non-adjusted) capacity factor value, and the curtailment adjustments are re-calculated again.

For the *AEO2005* reference case, the parameters for wind turbine capacity factor learning are as follows:

CFULT -

Class 6 ultimate capacity factor, 48%

Class 5 ultimate capacity factor, 44%

Class 4 ultimate capacity factor, 38%

FIXEDX and CFATX - An average Class 6 capacity factor of 38% is assumed at a total installed wind capacity base of 4.29 GW, roughly corresponding to the year 2001.

PWRDEN – Specified as 6.5 MW/km<sup>2</sup>, assuming 5 by 10 rotor diameter spacing.

After new wind generating capacity is selected in the EMM, WES decrements wind supplies to estimate remaining wind resources.

### **Projected Btu Value of Wind Energy**

Energy balance computations and report writing and consumption rates within NEMS require a heat rate, i.e., an equivalent fossil-fuel displacement for wind generated electricity. This is currently set at the heat rate for fossil-fueled steam-electric plants of 10,280 Btu per kilowatthour.

## **Cost Adjustment Factors**

Capital costs for wind technologies increase as a function of either short-term or resource constraint cost adjustment factors. The short-term factor accounts for short-term bottlenecks in production, siting, and construction costs and is reflected in additional capital costs incurred in a specific year for all new units of U.S. wind capacity beyond a defined threshold. This adjustment is applied in the ECP and is documented in the EMM documentation.

## Rationale

Capital costs for generating technologies using wind resources are assumed to increase as a function of exhaustion of most favorable resources. In general, capital costs are assumed to increase because of any or all of three broad conditions: (1) necessity of using less favorable natural resources, (2) increasing costs of upgrading existing distribution and transmission networks - separate from costs of building an interconnection, and (3) increasing costs in meeting environmental concerns.

As a result, for *AEO2006*, each EMM region's total wind resources are parceled among five broad ranges, including an initial resource share incurring no capital cost penalty, a second share for which capital costs are assumed to increase 15 to 20 percent, a third share imposing increases of 50 percent, a fourth at 75 to 100 percent, and a final share (all remaining resources) for which capital costs increase 100-200 percent over initial cost. Resource proportions vary by technology and region.

## Methodology

For wind, the resource-related cost adjustment factors account for the additional capital costs that are not reflected in the RFM cost characterizations. EIA benchmarked the estimates underlying the factors using regional renewable energy market and resource assessments of the Northwest Power Planning Council and the California Energy Commission.<sup>15</sup>

The cost-adjustment factors are applied on a regional basis as a function of the fraction of total resource for each relevant technology utilized in each of the 13 EMM regions. For each region/technology combination, the input file 'rendat' allows the user to specify the start-point resource fraction and multiplier for each of the five steps. For example, if the cost of using wind resources in Region 1 is assumed to increase by 20% after 22% of the resource base has been utilized, then 1.2 would be entered for the cost multiplier and 0.22 would be entered for the current resource utilization fraction for the second step of the Region 1 table in 'rendat'.

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<sup>15</sup>Northwest Power Planning Council, *Northwest Power in Transition: Opportunities and Risks*, Draft Fourth Northwest Conservation and Electric Power Plan (March 1996); California Energy Commission, *Technical Potential of Alternative Technologies*, Final Report, Contract 500-89-001 (Regional Economic Research, December 1999).

The resource cost multiplier is determined for each wind class based on the fraction of available windy land already utilized in that class. If desired, the capital cost for wind plant installation in each wind class for each year can be differentiated using a fixed ratio (using the "Multiplier or Cost by Wind Class" line in the WESAREA.TXT file). For *AEO2006*, the default ratio is 1.0 for all years and wind classes. Based on the 9-step supply curve for each region in each year, the levelized cost of each combination of the class-specific capacity factor, transmission cost adder, and class-specific resource multiplier is calculated using parameters passed from the Electricity Market Module for fixed charge factor and wind cost learning. The supply steps are then ordered by cost. The supply step with the lowest levelized cost is used to establish the wind class, transmission adder, and resource multiplier for the capacity available for that region. If the step with the lowest levelized cost does not have the minimum fraction of the previous year's regional capacity increment available (set as Percent Tolerance in the WESAREA.TXT file, set as 1.0 for default in *AEO2006*), the lowest cost step where the cumulative available capacity meets this tolerance level is used instead. If there is insufficient resource available in any step to meet the tolerance, the wind class, transmission adder, and resource multiplier are taken from the highest-cost step. The total capacity available for new builds in each region, each year is the lesser of the actual resource available or the maximum national wind capacity limit determined by the previous year's national capacity installations.

The short-term elasticity is determined in the EMM based on the past growth rate of wind capacity. This methodology is described in the EMM documentation.

### **Key Computations and Equations**

For the first model year, the subroutine WINDIN3 is called. This reads in the data from the WESAREA file. Where necessary, data entered in 5-year increments is linearly interpolated to produce annual values.

The subroutine WINDMISC3 is then called. This routine calculates cumulative builds and remaining windy land area in each region, wind class, and transmission buffer. The routine then determines the "best" wind class and buffer zone in each region based on currently available capacity factors for that wind class and region, and current technology costs and financial parameters passed from the EMM. The routine then calculates available capacity, capacity factors by time slice, and determines the T&D costs. Finally, the maximum capacity available and the amount of capacity currently used is calculated.

Subroutine WINDREPT3 writes the key parameters and calculation results to the output file AWINDDEBUG.TXT.

## Alternative Approaches

Recent models based on NEMS, particularly the version used in the *Scenarios for a Clean Energy Futures*<sup>16</sup> study and variations used in studies by the Union of Concerned Scientists,<sup>17</sup> have significantly modified the application of the regional resource constraint found in NEMS. These modifications have served to either severely reduce or eliminate any cost increases for wind resources in response to development of less-desirable sites as prime locations are utilized.

The CEF model essentially eliminates the resource constraints as such, and uses the model code to represent capital penalties in-lieu of an intermittency bound. This results in substantially reduced penalties, with the maximum being a 60% cost adder, compared to a 200% maximum adder for NEMS. Similarly, UCS eliminates the long-term constraint, but also reduces the amount of windy land available in each region to account for some of the land-use constraints modeled by the regional resource constraint factor in NEMS. As with CEF, UCS does not impose an absolute limit on penetration of intermittent technologies, but models additional costs incurred by increased use of back-up generation as grid-penetration increases.

EIA believes that the CEF approach of replacing the regional resource constraints with smaller grid-penetration penalties fails to adequately account for the theoretical and anecdotally observed “supply curve” of wind resource lands. By standard accounting, the U.S. wind market has utilized a very small fraction of theoretically available wind resources, yet has already encountered limits of the sort modeled in NEMS at much higher penetration levels. Examples include significant building in lower-quality resource areas in states where higher-quality resources exist; projects being delayed or denied through community or interest group pressure; and additional investments proposed to upgrade existing transmission facilities to accommodate new wind capacity. The UCS approach does attempt to account for these factors to an extent, but does so in an “all-or-nothing” approach that eliminates resources that, while expensive, could be developed under the right circumstances. The regional cost multiplier approach in NEMS accounts for the theoretical existence of a wind resource “supply curve”, even if the market is currently too poorly developed (relative to ultimate resource base) to empirically develop such a function.

The National Renewable Energy Laboratory (NREL) is currently developing a model with a detailed representation of the factors that are believed to have the largest impact on the widespread development of wind power in the U.S. A preliminary understanding of the WinDS model<sup>18</sup> indicates that some key factors, such as the cost of ensuring system reliability and of accounting for curtailed wind production are handled in a substantially similar manner as the current implementation of NEMS. In both WinDS and NEMS, a

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<sup>16</sup>[endues.lbl.gov/Projects/CEF.html](http://endues.lbl.gov/Projects/CEF.html)

<sup>17</sup>Clemer, S. et al “Clean Energy Blueprint”. Union of Concerned Scientists. October 2001. [www.uesusa.org/clem-energy/index.cfm](http://www.uesusa.org/clem-energy/index.cfm).

<sup>18</sup>See Short, W. et al. “WinDS - Wind Deployment Systems Model: A Update” *Proceedings of the 3<sup>rd</sup> Renewable Energy Modeling Summit*. June 13, 2003.

probabilistic formulation is used to account for the contribution of wind to regional capacity requirements and to account for surplus wind energy curtailed. NEMS calculates this for the 13 EMM regions, utilizing a statistical model to account for the geographical dispersion of the wind resource. WinDS is disaggregated to 358 regions to examine the impacts of geographical dispersion of the wind resource. Other factors, such as the cost of upgrading bulk transmission systems to accommodate increasingly remote-from-load wind sites, are accounted for in a significantly different approach. In NEMS, these costs are accounted for through an exogenously determined “supply curve”, based on regional studies of economic wind supply. In WinDS, location-specific transmission system capacity is directly modeled, and the use of specific wind resources is determined based on the lowest-cost resource with respect to transmission upgrades. Full evaluation of the WinDS model and its appropriateness for use in NEMS has not been performed and awaits more complete public documentation of WinDS algorithms, assumptions, and results.



# Wind Energy Submodule Structure

## Submodule Flow Diagram

A flow diagram showing the main computational steps and relationships of the Wind Energy Submodule is shown in Figure 2.

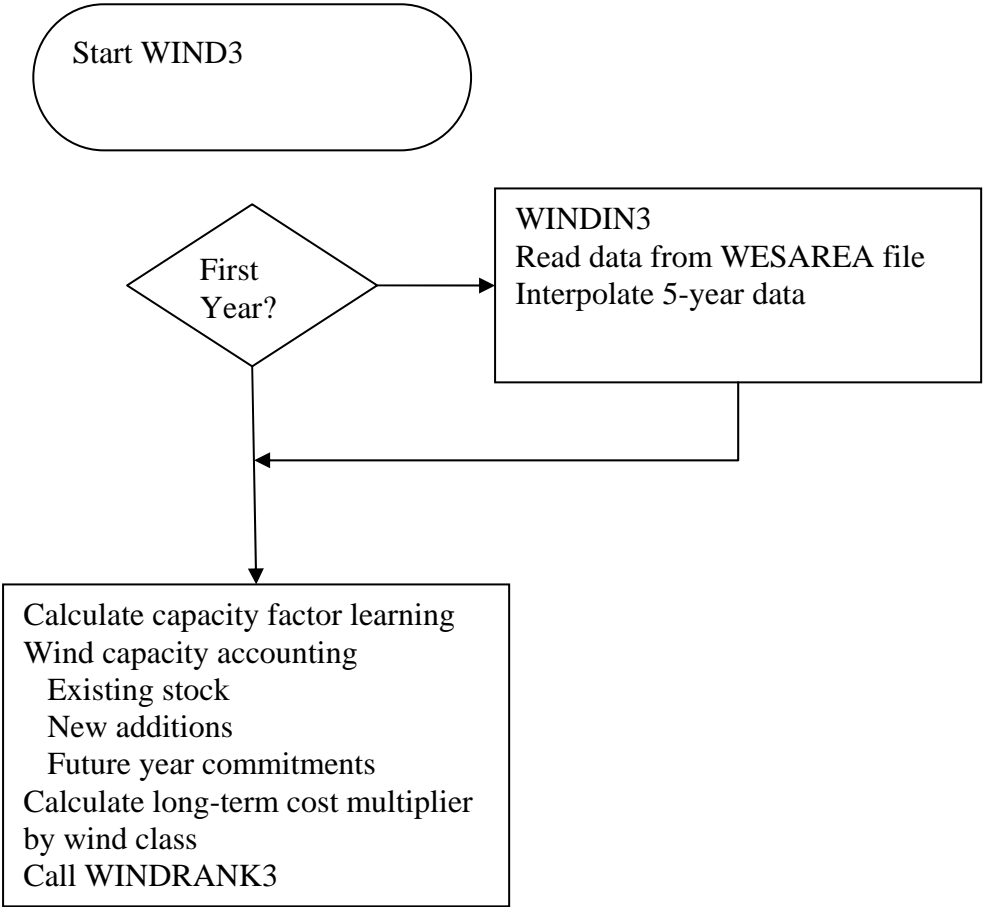
## Key Computations and Equations

Some of the input data are at 5-year intervals. For the first year, a linear interpolation on these data is performed to calculate yearly values.

For all years after the first year, subroutine WINDMISC3 is called to calculate the land area remaining for wind energy development, based on the previous wind capacity build decision by the EMM. The previous build decision is passed as a capacity unit (MW) which needs to be converted into a land area required for the development of wind site of that size. The conversion method considers the wind class of the available land area that is being offered for wind development. The entire U.S. wind energy supply is subdivided into 13 EMM regions, three wind classes, and three zones (along existing transmission lines).

Subroutine WINDMISC3 calculates subperiod (season, time of day) regional capacity factors. For each year, the subroutine calculates the remaining available wind generating capacity for each region. Finally, it assigns transmission and distribution cost adders for the remaining capacity in each distance zone.

Figure 2. Wind Energy Submodule Flowchart



## Appendix 3-A: Inventory of Variables, Data, and Parameters

This Appendix describes the variables, parameter estimates, and data inputs associated with the Wind Energy Submodule. Table 3A-1 provides a tabular listing of model variables and parameters. The table contains columns with information on item definitions, modeling dimensions, data sources, measurement units, and documentation page references.

The remainder of Appendix 3-A consists of detailed descriptions of data inputs and variables, including discussions on supporting data assumptions and transformations.

**Table 3A-1. NEMS Wind Energy Submodule Inputs and Outputs**

| Model Variable    | Definition and Dimensions   | Source                                | Units              |
|-------------------|---|---------------------------------------|--------------------|
| <b>INPUT DATA</b> |   |                                       |                    |
| CFANN             | User specified annual capacity factor by wind class and year  | No default value specified            | Unitless           |
| CFATX             | Improvement capacity factor at initial capacity.  | EIA, expert judgement.                | Unitless           |
| CFULT             | Ultimate capacity factor by class.  | EIA, expert judgement.                | Unitless           |
| CREDIT            | Wind capacity credit for EMM region <i>n</i> in year <i>y</i> .   | Determined within EMM.                | Unitless           |
| CTURNDOWN         | Minimum fraction of coal-fired capacity that must be kept running by region                                 | EIA, expert judgment                  | Unitless           |
| FIXEDX            | Initial installed capacity used to determine slope of capacity factor.                                      | EIA, expert judgement.                | GW                 |
| ICCMETH           | Method used to assign class-specific capital cost multipliers   | N/A                                   | Boolean            |
| ICCMULT           | Class-specific capital cost multipliers   | No default value specified            | Unitless           |
| INTREGCRL         | Regional correlation factor for intermittent resources  | EIA, expert judgment                  | Unitless           |
| INTSTDDV          | Normalized standard deviation of hourly output for intermittent resource facilities                         | EIA, expert judgment                  | Unitless           |
| NTURNDOWN         | Minimum fraction of nuclear capacity that must be kept running by region                                    | EIA, expert judgment                  | Unitless           |
| OVERRIDECF        | Switch to use user-specified capacity factors instead of capacity factor learning                           | N/A                                   | Boolean            |
| PCTTOL            | Minimum wind resource required to be available to be selected as the typical wind resource for a given year | EIA, expert judgment                  | Unitless           |
| PWRDEN            | Power density of a 10x5 diameter turbine array  | EIA, expert judgement.                | Mw/Km <sup>2</sup> |
| SLICE             | Hour fraction for subperiod <i>l</i> in EMM region <i>n</i> .   | WNSLICE preprocessing program (PERI). | Unitless           |

**Table 3A-1. NEMS Wind Energy Submodule Inputs and Outputs (Continued)**

| <b>Model Variable</b>       | <b>Definition and Dimensions</b>  | <b>Source</b>                                | <b>Units</b> |
|-----------------------------|---|--|--------------|
| <i>STAREA</i>               | Land area available for wind plant development in EMM region <i>n</i> and wind class <i>w</i> .           | Elliot, 1991.                                | Sq. km       |
| <i>SUBPER</i>               | Energy fraction for subperiod <i>l</i> in EMM region <i>n</i> .   | WNSLICE preprocessing program (PERI).        | Unitless     |
| <i>UADDWNT</i>              | Grid-connected wind electric capacity additions in EMM region <i>n</i> in on-line year <i>y</i> .         | EMM output variable in UECPOUT COMMON block. | MW           |
| <i>UPCLYR*</i>              | Construction lead time.   | EPRI TAGJ, 1993 .                            | Years        |
| <i>UPCPRO</i>               | Fraction of construction completed in each year of construction.  | EIA, expert judgment.                        | Unitless     |
| <i>UPFOM*</i>               | Fixed O&M cost.   | EIA expert judgement.                        | \$/kW        |
| <i>UPHTRT</i>               | Fossil fuel equivalent heat rate for wind.  | EIA, 1992.                                   | Btu/kWh      |
| <i>UPIRGSUB</i>             | Policy incentives for EMM region <i>n</i> in year <i>y</i> .  | Energy Policy Act of 1992.                   | Mills/kWh    |
| <i>UPOVR*</i>               | Installed capital cost of wind generation.  | EIA, expert judgment.                        | \$/kW        |
| <i>UPVOM*</i>               | Variable O&M cost.  | EIA expert judgement.                        | Mills/kWh    |
| <i>WNTDBFCS</i>             | Additional T&D cost for wind technology in EMM region <i>n</i> and buffer zone <i>b</i>                   | Kintner-Meyer, SAIC, 1995                    | \$/kW        |
| <b>CALCULATED VARIABLES</b> |   |  |              |
| <i>WCAWIEL</i>              | Available capacity in EMM region <i>n</i> in year <i>y</i> .  | RFM output variable in WRENEW COMMON block.  | MW           |
| <i>WSFWIEL</i>              | Capacity factor for EMM region <i>n</i> in year <i>y</i> , wind class <i>w</i> , and subperiod <i>l</i> . | RFM output variable in WRENEW COMMON block.  | Unitless     |
| <i>WNNTD</i>                | Additional T&D cost for wind technology in EMM region <i>n</i> and year <i>y</i>                          | RFM output variable in WRENEW COMMON block.  | \$/kW        |

\*Assigned in EMM input file ECPDAT.

\*\*Intermediate values, linearly interpolated from the source variable.

**MODEL INPUT:** CFANN

**DEFINITION:** Contains overwrite values for annual capacity factor (in 5-year increments), if preferred over having “learning” on capacity factor.

**SOURCE:** No default input defined

**MODEL INPUT:** CFATX

**DEFINITION:** Capacity factor for Class 6 wind sites used to initialize the capacity factor learning function (Unitless)

Historical analysis of wind capacity factors is complicated by the general inability to correlate individual sites with specific, independently determined wind class data. Even if able to locate a turbine on a low-resolution wind resource map, such as is used in NEMS, “micro-siting” issues within a wind farm can have significant effects on turbine performance. This variable is primarily intended to give reasonable starting point for the calculation of future improvements to wind turbine performance, and not necessarily to reflect absolute knowledge about the idealized state of wind turbine performance at a point in the historical record.

**SOURCE:**

EIA Form 860b, EIA expert judgement.

**MODEL INPUT:** CFULT

**DEFINITION:** Ultimate achievable annual wind capacity factor for wind class 6 in year *y* (Unitless).

Current wind turbine performance parameters are based on several factors. Discussions with experts from the DOE Wind Power Program and their consultants provided a general indication of recent trends and areas of expected performance increases. Analysis of wind power curves developed for the EPRI/DOE Wind Turbine Verification Program (TVP) provided a firm quantitative characterization of state-of-the-art turbine technology. Finally, analysis of historic trends provided a cross-check to these other sources. At some point, the trade-offs in the economics of increasing rotor size and tower height will balance-out. Improvements are assumed to occur as a result of experience in the design and construction of wind turbines.

**SOURCES:**

U.S. Department of Energy and Electric Power Research Institute, “TVP Project-at-a-Glance” for Big Spring, Texas Project; Iowa Distributed Generation Project; and Wisconsin Low-Speed Wind Turbine Project.

EIA Form 860b.

Personal communication with Stanley Calvert, U.S. DOE, Wind Program; Richard Price, Technology & Management Services, Inc.; and Joseph Cohen, Princeton Energy Resources Inc.

**MODEL INPUT:**     *CREDIT*

**DEFINITION:**     Wind capacity credit for EMM region *n* in year *y* at 5-year intervals (Unitless).

The Load Capacity Credit (LCC) or capacity value that can be attributed to intermittent generators is a debated issue. The percentage of rated power output for a wind generator that can be considered as firm capacity is dependent on the estimated change the generator effects in a specific utility system's loss-of-load probability (LOLP), generating mix, spinning reserve requirements, and other factors. Values of capacity credit are read into the WES from the WESTECH data file. This file currently assigns a value of zero to the capacity credit for all wind classes and all years. However, a value proportional to the capacity factor in the peak time period is calculated in the Electric Capacity Planning Submodule of the EMM.

**SOURCES:**           EIA Expert Judgement

**MODEL INPUT:**     CTURNDOWN

**DEFINITION:**     Maximum turndown limit for coal-fired capacity in region. Expressed as the minimum fraction of capacity that must be kept running.

**SOURCE:** EIA expert judgement following examination of PowerWorld transmission reliability data and conversations with system operators.

**MODEL INPUT:**     *FIXEDX*

**DEFINITION:**     Installed capacity base at which variable CFATX is assumed (GW).

Historical analysis of wind capacity factors is complicated by the general inability to correlate individual sites with specific, independently determined wind class data. Even if able to locate a turbine on a low-resolution wind resource map, such as is used in NEMS, "micro-siting" issues within a wind farm can have significant effects on turbine performance. This variable is primarily intended to give reasonable starting point for the calculation of future improvements to wind turbine performance, and not necessarily to reflect absolute knowledge about the idealized state of wind turbine performance at a point in historical record.

**SOURCES:**

EIA Form 860a and 860b, EIA expert judgement.

**MODEL INPUT:** ICCMETH

**DEFINITION:** Method for determining incremental capital cost for wind by wind class

Allows for overwrite of capital cost learning for wind calculated by the EMM. Capital cost declines can be differentiated by wind class to simulate separate technology/cost structures potentially used in each class.

**SOURCE:** Not used by default

**MODEL INPUT:** ICCMULT

**DEFINITION:** Capital cost factors for forcing capital cost for wind and/or differentiating capital cost by class.

Allows for overwrite of capital cost learning for wind calculated by the EMM. Capital cost declines can be differentiated by wind class to simulate separate technology/cost structures potentially used in each class.

**SOURCE:** No default input defined

**MODEL INPUT:** NTURNDOWN

**DEFINITION:** Maximum turndown limit for nuclear capacity in region. Expressed as the minimum fraction of capacity that must be kept running.

**SOURCE:** EIA expert judgement following examination of PowerWorld transmission reliability data and conversations with system operators.

**MODEL INPUT:** INTSTDDV

**DEFINITION:** Standard deviation of hourly wind plant output within a region.

Default setting of 38% of nameplate capacity is based on EIA simulation of a generic, 1 MW turbine, assuming a Rayleigh distribution of wind resource in a Class 5 area. The standard deviation is assumed to scale to a 50 MW size, which assumes perfect correlation among turbines on an hourly basis within a 50 MW wind farm.

**SOURCE:** Internal EIA calculation based on simulated performance of a state-of-the-art wind turbine. Analysis of wind power curves developed for the EPRI/DOE Wind Turbine Verification Program (TVP) provided a firm quantitative characterization of state-of-the-art turbine technology.

**MODEL INPUT:** INTREGCRL

**DEFINITION:** Correlation of hourly wind output at wind turbines within a region. Appendix 1-1A of this document contains further derivation of this approximation and of the correlation factors used as default values.

**SOURCE:** EIA expert judgement. See Appendix 1-1A.

**MODEL INPUT:** OVERRIDECF

**DEFINITION:** Switch to overwrite capacity factor learning with user specified capacity factors.

**SOURCE:** Not used by default

**MODEL INPUT:** PCTTOL

**DEFINITION:** Minimum wind resource required to be available within a region, wind class, and transmission buffer to be selected as the typical wind resource for a given year. Expressed as a fraction of prior-years regional wind capacity installations.

**SOURCE:** EIA expert judgement.

**MODEL INPUT:** PWRDEN

**DEFINITION:** Specific power density of an average wind plant(MW/km<sup>2</sup>)

Primarily used within the WES to convert available area of windy land to available MW of wind resource, and to decrement the available land area based on model builds. Although power efficiency varies somewhat from turbine model to turbine model, this factor is mostly a function of inter-turbine spacing within the turbine array. Recent U.S. installations are



generally placed on ridgelines, and tend to have a linear arrangement with relatively tight lateral turbine spacing. However, the factor used here must consider more extensive exploitation of wind resources where the turbines would be placed in more rectangular arrays. The current assumption of 6.5 MW/km<sup>2</sup> is consistent with spacing estimates from the PNL assessment of windy land used to provide the WES wind resource and the performance estimates from U.S. DOE and EPRI.

**SOURCES:** U.S. DOE and Electric Power Research Institute. *Renewable Energy Technology Characterizations*. <http://www.eere.energy.gov/power/techchar.html>

Elliott, D.L. et al. *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States*. August 1991. Pacific Northwest Laboratory. PNL-7789.

**MODEL INPUT:** SLICE

**DEFINITION:** Hour fraction for subperiod *l* in EMM region *n* (Unitless).

Data for 20 subperiods of the year are provided. The EMM maps the data for these 20 subperiods into nine subperiods used in the EMM and other NEMS modules. SLICE uses established NEMS subperiod definitions, daily and seasonal wind resource data, and a synthetic wind turbine power curve to estimate the fraction of the annual wind energy production that falls within the various subperiods

**SOURCE:**

Princeton Economic Research Incorporated (PERI), WNDSLICE preprocessor program, Bertrand L. Johnson.

**MODEL INPUT:** STAREA

**DEFINITION:** Land area available for wind plant development in EMM region *n* and wind class *w* (sq. km).

**SOURCES:**

Elliott, D.L., et al, "An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States," Pacific Northwest Laboratory; Report #PNL-7789, August 1991.

**MODEL INPUT:** SUBPER

**DEFINITION:** Wind energy fraction for superperiod *l* in EMM region *n* (unitless)

**SOURCES:** Princeton Economic Research Incorporated (PERI), WNDSLICE preprocessor program, Bertrand L. Johnson

**MODEL INPUT:**     *UADDWNT*

**DEFINITION:**     Total grid-connected wind electric capacity additions in EMM region *n* in on-line year *y* (MW).

**SOURCE:**           EMM output variable in UECPOUT COMMON block.

**MODEL INPUT:**     *UPCLYR*

**DEFINITION:**     Construction lead-time (Years).

The construction period for a wind generating station is currently set at 3.

**SOURCE:**

Electric Power Research Institute, *TAGJ C Technical Assessment Guide*, 1993.

**MODEL INPUT:**     *UPCPRO*

**DEFINITION:**     Fraction of construction completed in each year of construction (Unitless).

The construction period for a wind generating station is currently set at 3 years. The construction fraction is set at 10, 45, and 45 percent, respectively.

**SOURCE:**

EIA, expert judgment following discussions with industry, government, and national laboratory sources.

**MODEL INPUT:**     *UPFOM*

**DEFINITION:**     Fixed O&M costs (\$/kW).

Fixed O&M costs are currently set in at \$21.12/kW (1987 dollars) for all years and all regions, based on the 1993 TAGJ and subsequent correspondence.

**SOURCE:**

Electric Power Research Institute, *TAGJC Technical Assessment Guide*, 1993 and subsequent correspondence.

**MODEL INPUT:**     *UPHTRT*

**DEFINITION:**     Fossil fuel equivalent heat rate for wind (Btu/kWh).

An equivalent fossil fuel displacement value of 10,280 Btu/kWh has been assigned, based on EIA data for 1995.

**SOURCE:**

Energy Information Administration, *Annual Energy Review 1994*, DOE/EIA-0384(93), July 1995, web accessible at <http://tonto.eia.doe.gov/FTPRoot/features/hlaer.pdf>.

**MODEL INPUT:** UPIRGSUB

**DEFINITION:** Policy incentives for wind generation (mills/kWh).

Any production incentives or other adjustments to the cost of wind energy are accounted for in the POLICY variable. Currently, a value of 15 mills per kilowatt hour for the years 1994 through 2001 and zero for all other years is assigned for all regions. This is based on the renewable energy policy incentive provision of the Energy Policy Act of 1992 as extended in 1999.

**SOURCE:**

Energy Policy Act of 1992 (Public Law 102-486), Section 1212, and extended as provided in section 507 of the Tax Relief Extension Act of 1999.

**MODEL INPUT:** UPOVR

**DEFINITION:** Installed capital cost of wind generation (\$/kW).

The number stored in ECPDAT is a  $n^{\text{th}}$ -of-a-kind value for the capital cost. This value is constant.

**SOURCE:**

EIA, expert judgment following discussions with industry, government, and national laboratory sources.

**MODEL INPUT:** UPVOM

**DEFINITION:** Variable O&M costs for EMM region  $n$  in year  $y$  at 5-year intervals (mills/kWh).

The variable O&M costs are currently set at zero for all years and all regions based on the 1993 TAGJ.

**SOURCE:**

Electric Power Research Institute, *TAGJC Technical Assessment Guide*, 1993.

**MODEL INPUT:**     *WNTDBFCS*

**DEFINITION:**       Additional T&D cost for wind development averaged for sites in buffer zone *b* and EMM region *n* (\$/kW).

The additional T&D cost for wind developments capture the expenditures unique for remote wind sites and, therefore, not included in the overall T&D cost estimating function applied to all technologies in EMM. The wind specific T&D costs represent the cost for construction of new transmission lines connecting a wind development with the closest point of the electric grid. The cost estimates include: (1) cost for land or easement, (2) material cost for conductors, (3) construction cost, and (4) cost for environmental analysis of project. Data for the above cost components are compiled from EIA publications using Bonneville Power Administration transmission cost estimating procedures.

The wind specific costs are determined for each EMM region and buffer zone. An important parameter for the cost estimates is the distance from a potential wind site to the grid. The average distance of each buffer zone was used as the representative length of the new transmission line. It is determined as the distance of the midpoint of each buffer zone to the grid.

**SOURCES:**

Science Applications International Corporation, "Geographic Information System Analysis," Report for EIA, Office of Integrated Analysis and Forecasting. May, 1995.

Energy Information Administration, Washington, D.C., September 1994. "Electric Trade in the United States 1992." Table 42: Transmission Lines Added by Investor-Owned Utilities, 1992. DOE/EIA 0531 (92).

Bonneville Power Administration. "Transmission Line Estimating Data." Internal Memorandum. BPA F 1325.01.e, December 3, 1993.

## Appendix 3-B: Mathematical Description

This Appendix provides the detailed mathematical specification of the Wind Energy Submodule as presented in the RFM FORTRAN code execution sequence. Subscript definitions are also as they appear in the FORTRAN code.

### Subroutine WNRESDEC

Equation 3B-1 calculates the land area (in sq. km) needed to supply the wind generating capacity called for by the EMM for each EMM region and current year:

$$LDUSED_{n,y} = \frac{UADDWNT_{n,y+Lead} * CF_{y,w} * 8760 * \alpha_{sp}}{AREA_{sub y,w} * \frac{\pi}{4}}$$

where:

$LDUSED_{n,y}$  = Land area used to supply EMM-called for wind generating capacity in EMM region  $n$  in decision year  $y$ , km<sup>2</sup>,

$UADDWNT_{n,y}$  = Grid-connected wind electric capacity additions in EMM region  $n$  decision year  $y+Lead$ , (MW), where

$LEAD$  = Construction lead time, in years (decision year + lead time = on-line year),

$Cf_{y,w}$  = Annual capacity factor for wind class  $w$  in year  $y$ ,

$AREA_{y,w}$  = Energy per unit swept rotor area for wind class  $w$  in decision year  $y$ , kwh/m<sup>2</sup>,

$\pi$  = 3.141593,

$\alpha_{sp}$  = Scalar derived from 5D x 10D grid spacing of wind generator ( $\alpha_{sp} = 50$ ).

Equations 3B-2 subtracts the land area needed to supply the wind generating capacity called for by the EMM from the available land area.

$$LDAREA_{n,y,w,bc} = LDAREA_{n,y-1,w,bc} - LDUSED_{n,y}$$

where:

$LDAREA_{n,y,w,bc}$  = land area available for wind development in EMM region  $n$ , in year  $y$ , in currently offered wind class  $w$  and buffer zone  $bc$ , ( $km^2$ ).

### Subroutine CALCAP

Equation 3B-3 calculates the time-dependent capacity factor for the currently offered wind class, EMM region, year and subperiod:

$$WSFWIEL_{n,y,w=1,l} = \left[ \frac{SUBPER_{n,l}}{SLICE_{n,l}} \right] * CF_{y,w}$$

where:

$WSFWIEL_{n,y,w=1,l}$  = Capacity factor for wind class  $w$  in EMM region  $n$  in year  $y$  in subperiod  $l$ . Although defined for three wind classes only  $w=1$  is used. EMM reads only  $WSFWIEL_{n,y,w=1,l}$

$SUBPER_{n,l}$  = Energy fraction for subperiod  $l$  in EMM region  $n$ ,

$SLICE_{n,l}$  = Hour fraction for subperiod  $l$  in EMM region  $n$ ,

$CF_{y,w}$  = Annual capacity factor for currently offered wind class  $w$  in year  $y$ .

### Subroutine CALMWA

Equation 3B-4 computes the total swept area by turbines for a particular wind class, EMM region and year:

$$SWAREA_{n,y,w} = \frac{\frac{\pi}{4} * LDAREA_{n,y,w,bc} * 10^6}{\alpha_{sp}}$$

where:

$SWAREA_{n,y,w}$  = Swept rotor area available for currently offered wind class  $w$  in EMM region  $n$  in year  $y$ , ( $m^2$ ),

$LDAREA_{n,y,w,bc}$  = land area available for wind development in EMM region  $n$ , in year  $y$ , in currently offered wind class  $w$  and buffer zone  $bc$ , ( $km^2$ ),

$\alpha_{sp}$  = Scalar derived from 5D x 10D grid spacing of wind generator ( $\alpha_{sp} = 50$ ).

Equation 3B-5 computes the available wind electric generation capacity in megawatts by wind class, EMM region and year:

$$WCAWIEL_{n,y} = \frac{AREA_{y,w} * SWAREA_{n,y,w}}{CF_{y,w} * 10^3 * 8760}$$

where:

$WCAWIEL_{n,y}$  = Available capacity in EMM region  $n$  in year  $y$ , MW.

### Subroutine WNDECR

Subroutine WNDECR decrements the wind resources that are subdivided by wind classes and buffer zones according to the following scheme:

| <u>Wind Class</u> | <u>Buffer Zone</u> |
|-------------------|--------------------|
| 1                 | 1 → 2 → 3 then     |
| 2                 | 1 → 2 → 3 then     |
| 3                 | 1 → 2 → 3.         |

Where wind class 1 is the highest quality resource and wind sites in buffer zone 1 are the closest to the grid incurring the least cost for new transmission construction.

The wind resource depletion scheme reflects an economic ranking based on an prioritized estimate of the energy cost of the wind technology. In general, the cost reductions due to the higher quality resource offset the increased cost for new transmission construction to farther distant sites. Therefore, the wind resource in the “best” wind class is depleted across all buffer zones before resources of the next lower quality are used.

### Subroutine WNTDEVAL

Equation 3B-6 assigns the wind specific T&D cost associated with wind resources of the buffer zone currently being offered

$$WWNTD_{n,y} = WNTDBFCS_{n,bc}$$

where:

$WWNTD_{n,y}$  = Wind specific T&D cost in EMM region  $n$  in year  $y$ , (\$/kW),

$WNTDBFCS_{n,bc}$  = Wind specific T&D cost in EMM region  $n$  in currently offered buffer zone  $bc$ , (\$/kW).

## Appendix 3-C: Bibliography

Bonneville Power Administration. "Transmission Line Estimating Data." Internal Memorandum. BPA F 1325.01.e, December 3, 1993.

Cohen, J.M., Schweizer, T.C., Hock, S.M., and Cadogan, J.B., "A Methodology for Computing Wind Turbine Cost of Electricity Using Utility Economic Assumptions," Proceedings of Windpower '89, American Wind Energy Association, September 1989.

Elliott, D.L., et al., "Wind Energy Resource Atlas of the United States," (1 volume), Report DOE/CH 10093-4, October 1986.

Electric Power Research Institute, *Technical Assessment Guide (TAGJ)*, 1993.

Energy Information Administration, Washington, D.C., September 1994. "Electric Trade in the United States 1992." Table 42: Transmission Lines Added by Investor-Owned Utilities, 1992. DOE/EIA 0531 (92).

Energy Information Administration, Washington, D.C., EIA 860, Annual Electric Generator Report, 2003.

Energy Information Administration, *Annual Energy Review 2002*, [www.eia.doe.gov/emeu/aer/contents.html](http://www.eia.doe.gov/emeu/aer/contents.html).

Energy Information Administration, "Component Design Report for Solar and Wind Submodules Renewable Fuels Module National Energy Modeling System," Draft, April 23, 1993.

Hock, S.M., Thresher, R.W., and Cohen, J.M.; "Performance and Cost Projections for Advanced Wind Turbines," *Proceedings of ASME Winter Annual Meeting*, Dallas, TX, November 1990.

Princeton Economic Research, Incorporated, *Data Development Report for Wind Electric Submodule Renewable Fuels Module National Energy Modeling System*, February 24, 1993.

Princeton Economic Research, Incorporated, *Software Overview Report for Wind Electric Submodule Renewable Fuels Module National Energy Modeling System*, March 29, 1993.

Schweizer, T. and Cohen, J., "A Technique for Estimating Project Risk: Beyond Traditional Sensitivity Analyses," Science Applications International Corporation, *Proceedings of the Windpower '88 Conference*, September 18-22, 1988.



## Appendix 3-D: Model Abstract

**Model Name:**

Wind Energy Submodule

**Model Acronym:**

WES

**Description:**

Resource quality data and the yearly capacity factor are used to calculate wind farm performance data on a sub-yearly level, as required by the EMM. Calculations are made for each time slice, wind class, and region.

**Purpose of the Model:**

The purpose of the Wind Energy Submodule (WES) is to project the cost, performance, and availability of wind-generated electricity, and provide this information to the Electricity Capacity Planning (ECP) component of the Electric Market Module (EMM) for building the new capacity in competition with other sources of electricity generation.

**Most Recent Model Update:**

September 2004.

**Part of Another Model?:**

The Wind Energy Submodule is a component of the Renewable Fuels Module (RFM) of the National Energy Modeling System (NEMS).

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**Documentation:** NEMS Documentation Report: *Renewable Fuels Module of the National Energy Modeling System*, April 2005.

## **Archive Media and Installation Manual(s):**

Archived as part of the NEMS production runs.

## **Energy System Described:**

A hybrid of various existing and proposed horizontal-axis wind turbines. Horizontal-axis wind turbines represent nearly 100 percent of U.S. wind-powered generating capacity.

## **Coverage:**

- Geographic: 13 EMM regions: East Central, Texas, Mid-Atlantic, Mid-America, Mid Continent, Northeast, New England, Florida, Southeastern, Southwest, Western, Rocky Mountain, California and South Nevada.
- Time/Unit Frequency: Annual, 1995 through 2030
- Products: Electricity
- Economic Sectors: Electric utility sector, nonutility generators (NUGS)
- Model Structure: Sequential calculation of available wind capacity by EMM region, wind class and year with a deduction of that year's installed capacity from the remaining available capacity
- Modeling Techniques: Accounting function of available windy land area and conversion of land area to swept rotor area and then to available generation capacity, taking system reliability effects into account.
- Special Features: Accounting for policy and/or production incentives.

## **Modeling Features:**

## **DOE Input Sources:**

Energy Information Administration, *Annual Energy Review*

EIA Form 906

EIA Form 412

Pacific Northwest Laboratory, Reports PNL-7789, DOE/CH 10093-4, and PNL-3195.

U.S. Department of Energy and Electric Power Research Institute, "TVP Project-at-a-Glance" for Big Spring, Texas Project; Iowa Distributed Generation Project; and Wisconsin Low-Speed Wind Turbine Project.

**Non-DOE Input Sources:**

Princeton Economic Research, Incorporated (PERI) C WNDLICENSE preprocessing program.

Electric Power Research Institute and U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, *Renewable Energy Technology Characterizations* (EPRI TR-109496, December 1997)

**Independent Expert Reviews Conducted:**

None.

**Status of Evaluation Efforts by Sponsor:**

None.

## Appendix 3-E: Data Quality and Estimation Processes

This Appendix discusses (1) the quality of the principal sources of input data used in the Wind Energy Submodule, along with a discussion of user-defined parameters and guidelines used to select them, and (2) estimation methods used to derive parameters.

Wind resources of the United States have been extensively charted and classified by the Pacific Northwest Laboratory (PNL) (See Elliott, 1986 in the Bibliography), with a current effort by the National Renewable Energy Laboratory (NREL) underway to refine these estimates based on modern computer modeling and geographic information systems (GIS) techniques. Three classes of wind resources, based on average annual wind speeds, are generally used. These classes correspond to PNL Class 4 winds and higher, (speeds greater than 5.6 m/s (12.4 mph)) which represent the assumed lowest economic limit of wind speeds for grid-connected systems in the United States.

Data on wind resource quantity are maintained in the *WESAREA* input file. It contains regional data on the land area (in square kilometers) estimated to be available for wind plant development, accounting for the exclusion of some land as a result of legal, environmental, and land-use considerations. Attachment 1 to this appendix contains the draft report from NREL to EIA on the derivation of the current data and data sources.

The *WESAREA* input file describes the variations in wind resource on a daily and seasonal basis, and estimates wind output during the different load condition subperiods to analyze the correlation with load profiles. The file is highly dependent on the raw wind speed file components chosen and incorporates data for many of the 975 stations in the Wind Energy Resource Information System (WERIS) from the National Climatic Data Center. Data from WERIS may not correspond to particular wind sites actually selected for development, but are believed to present a reasonable average for all sites within a region. The file also contains information on Load Duration Curve (LDC) subperiod definitions outside of the WES and the subperiod energy percentages. From this, WES estimates a capacity factor for a given subperiod. The specific subperiods correspond to season and time of day.

Data on the cost and performance of installed wind turbines extend back to the mid 1980's, and include several periods of rapid industry expansion, most recently starting in 2001. In 2001, EIA began collecting retrospective and current cost data from unregulated power plant owners (Form 412), including most of the U.S. wind industry. EIA has used this data to develop current capital cost and to help calibrate wind cost learning parameters. Cost data, based on published financial information of public and regulated utilities, project announcements in the trade press, and academic studies of the industry, provides a secondary check on data from Form 412. Wind turbine capacity factor and wind energy outputs are based on standard modeling of four recently installed turbines with actual operating data. These turbines, ranging from 600 to 1650 kW, were initially studied as part of the Department of Energy and EPRI Turbine Verification Program (TVP), and data conforms to international collection and quality standards. Actual power output varies among the wide variety of turbines currently installed, and will likely further

change as the technology advances. The algorithms for performance and cost learning within NEMS (and documented in this volume and the EMM documentation, respectively) are intended to capture the key characteristics of these changes without reference to the specific technologies employed.

Modeled wind speed parameters are based on a Rayleigh distribution about the median speed in each of the three key wind power classes of the WES (Classes 4, 5, and 6). Model results from three hub heights, 50, 65, and 100 meter, were analyzed to project reasonable technology improvements based on increasing tower sizes. A 0.14 “wind shear factor” is used to scale 10 meter nominal wind speeds to the respective hub heights. Field energy losses of 12% are also assumed, based on TVP results. Estimates are regularly compared with independent estimates, including national laboratory, industry, and other estimates and with monthly generation data collected through the EIA Form 906. Publicly available data on wind plant generation (such as the Form 906) do not typically specify the nominal wind regime that the turbine or plant is located in, therefore, there is no reliable statistical approach to determining turbine performance by wind class. Updates occur as field and other documented evidence – including test results – indicate changes in costs or performance.

## Appendix 3-E, Attachment 1.

### Subtask A: Incorporation of Existing Validated Wind Data into NEMS

#### Introduction

The Renewable Fuels Module (Wind) of the National Energy Modeling System (NEMS) currently uses data that is over a decade old. Updated wind resource data is available for many states, as well as updated information on environmentally sensitive lands and transmission line locations. NEMS plays a critical role in guiding the nations energy policy so it is important that the best data available is used to accurately portray wind resource availability. Recognizing this need, the Energy Information Administration (EIA) approached the National Renewable Energy Laboratory (NREL) to updated this data.

There have been significant changes over the last decade in wind resource assessment and analysis techniques, and in policies that affect wind development. With this in mind, NREL solicited expert opinions for revisions to the original wind electric potential methodology used in 1991. As a result, many of the assumptions used in the analysis have changed. A summary of the 1991 methodology for determining available windy lands is presented in Appendix A.

Updated, NREL-validated wind resource data was available for California, Connecticut, Delaware, Idaho, Illinois, Maine, Maryland, Massachusetts, Montana, New Hampshire, New Jersey, New Mexico, North Carolina, North Dakota, Oregon, Pennsylvania, Rhode Island, South Dakota, Vermont, Virginia, Washington, West Virginia and Wyoming. Other states in the southwestern United States are in progress, and are slated for completion over the next two months. The grid cell resolution of these data varies from 200 m to 1 km. Where updated and validated wind resource data was not available, the 1987 national wind resource assessment was used. The resolution of the 1987 national wind resource assessment is approximately 25 km.

#### Wind Electric Potential Methodology

The methodology used in this analysis was developed with the assistance of wind resource modelers, meteorological consultants, the Department of Energy, EIA, and NREL. Some of the steps are applied differently to the updated and the 1987 wind resource data, and are noted where applicable.

#### Criteria:

100% exclusions of areas with slope > 20% (updated data) or application of terrain exposure factor (1987 data).

#### Environmental exclusions

100% exclusion of all National Park Service and Fish and Wildlife Service lands

100% exclusion of federal lands with a specific designation that seem incompatible with wind development (parks, wilderness, wilderness study area, wildlife refuge, wildlife area, recreation area, battlefield, monument, conservation areas, and wild and scenic rivers)

100% exclusion of state parks and conservation areas

50% exclusion of remaining Forest Service, Department of Defense, and state forest lands

Land use exclusions

100% exclusion of water, wetlands, urban areas and airports/airfields

50% exclusion of non-ridge crest forest

100% exclusion of a 3 kilometer area surrounding 100% environmental and land use exclusions, except water exclusion

Minimum density criteria of 5 km<sup>2</sup> per 100 km<sup>2</sup> of class 3 or better wind resource, after the 100% exclusions have been applied

The following data layers were used to represent the land use and environmental exclusions:

**United States Geological Survey (USGS) North America Land Use Land Cover (LULC), version 2.0.** This data set has a 1-km nominal spatial resolution, and is based on 1-km Advanced Very High Resolution Radiometer (AVHRR) data spanning April 1992 through March 1993. A supplementary data set of urban areas is available from the USGS, generated from the Digital Chart of the World. To be conservative, the secondary urban area data set was used to specify areas in addition to those specified in the LULC data set.

**USGS federal lands and Indian reservations coverage (2003).** This data set contains polygons for federally owned or administered land and Indian reservations in the United States that are generally at least 640 acres in area. The government agencies that administer these lands include the Bureau of Indian Affairs, the Bureau of Reclamation, the Bureau of Land Management, the Department of Defense, the Forest Service, the Fish and Wildlife Service, the National Park Service, and the Tennessee Valley Authority. The polygons are attributed with information designating areas as wilderness, national monuments or other areas of particular concern.

**State and private environmentally sensitive lands.** A national data set was not found.

State and private land information that are available in a GIS format were gathered wherever possible, generally in the form of a USGS GAP land stewardship data set.

Eventually the USGS will provide a national data set of lands restricted for development through the Gap Analysis Program, and this will be the most consistent source of this type of information. The status of this effort is documented at:

<http://www.gap.uidaho.edu/Projects/States/default.htm>. However, the attributes of this data set are limited to a general designation without specific information on ownership or use. The designation has a range of values from 1 to 4, with 1 being the highest level and 4 the lowest level of protection from disturbance. For the purposes of this analysis, when GAP data is used areas that are designated as 1 will be 100% excluded and areas designated as 2 will be 50% excluded under the environmental criteria.

**Airports.** A dataset of airport runway locations was provided by Environmental Research Systems Institute (ESRI).

**Digital elevation model.** The USGS GTOPO30 global 30 arc second dataset was used for national level elevation processing. This dataset has a nominal spatial resolution of 1 km.

**PowerMap transmission lines.** NREL and EIA have licensed Platts' PowerMap database, which contains a spatially accurate transmission line data set. The transmission line data is generally complete down to a voltage of 100 kv and includes some lower voltage lines in many areas. The dataset was limited to existing lines with a voltage range between 69 and 345 kV in this analysis.

**NEMS regional boundary.** The boundaries of the 13 NEMS regions have been provided to NREL by EIA.

### **Analysis Methodology:**

All of the datasets used in the analysis were re-projected into a common equal-area projection raster dataset, using a nearest neighbor interpolation to populate the cells. A cell resolution of 200 m was used to preserve the information contained in the largest scale wind resource datasets.

### **Wind Resource Data:**

#### **High-resolution wind resource data**

The analysis uses high-resolution wind resource data where that information is available and has been validated by NREL. The high resolution data for 23 states were included in this analysis: California, Connecticut, Delaware, Idaho, Illinois, Maine, Maryland, Massachusetts, Montana, New Hampshire, New Jersey, New Mexico, North Carolina, North Dakota, Oregon, Pennsylvania, Rhode Island, South Dakota, Vermont, Virginia, Washington, West Virginia, and Wyoming.

The high-resolution wind data were generated over several years by different organizations and utilizing different methodologies. One significant difference is surface roughness; the data for North Dakota, South Dakota, and Illinois do not account for the effects of surface roughness in their resource estimates, while the other state assessments do. In areas of high roughness (i.e. forest), the resource may be 1-2 power classes lower than the estimate. However, the majority of the high resource areas in these states are located in grassy plains or agricultural lands with low roughness.

The 50-m wind resource data were re-classified into the wind power classes as defined in the 1987 *Wind Energy Resource Atlas of the United States*. These power classes are, for the purposes of this project, assumed to be independent of height. The updated wind resource data validated by NREL, but not produced by NREL, will be processed to remove any areas with a slope > 20%. These areas are considered too steep for siting wind turbines.



### Low-resolution wind resource data

Data from the 1987 *Wind Energy Resource Assessment of the United States* was used for the remaining states that did not have an updated wind resource assessment at the time the analysis was completed. This assessment has a resolution of 1/4 degree of latitude by 1/3 degree of longitude. Associated with each power class 3 or greater grid cell is a terrain exposure factor indicating the percent of each grid cell that is well exposed to the stated wind power class. The terrain exposure factor varies from 5% (ridgecrests) to 90% (plains) exposed. This dataset was converted to the same projection, cell size and extent as the high-resolution data set.

### Exclusion Layers:

#### 100% land use exclusions

The USGS LULC and additional urban area data were merged together to impose the additional urban areas on the original LULC data. The data was reclassified according to the exclusion percentages detailed below, which conform with the other windy land analyses produced by NREL.

| Value | Exclusion % | Description                                  |
|-------|-------------|--|
| 1     | 100         | Urban and Built-Up Land                      |
| 2     | 0           | Dryland Cropland and Pasture                 |
| 3     | 0           | Irrigated Cropland and Pasture               |
| 4     | 0           | Mixed Dryland/Irrigated Cropland and Pasture |
| 5     | 0           | Cropland/Grassland Mosaic                    |
| 6     | 0           | Cropland/Woodland Mosaic                     |
| 7     | 0           | Grassland                                    |
| 8     | 0           | Shrubland                                    |
| 9     | 0           | Mixed Shrubland/Grassland                    |
| 10    | 0           | Savanna                                      |
| 11    | 0           | Deciduous Broadleaf Forest                   |
| 12    | 0           | Deciduous Needleleaf Forest                  |
| 13    | 0           | Evergreen Broadleaf Forest                   |
| 14    | 0           | Evergreen Needleleaf Forest                  |
| 15    | 0           | Mixed Forest                                 |
| 16    | 100         | Water Bodies                                 |
| 17    | 100         | Herbaceous Wetland                           |
| 18    | 100         | Wooded Wetland                               |
| 19    | 0           | Barren or Sparsely Vegetated                 |
| 20    | 0           | Herbaceous Tundra                            |
| 21    | 0           | Wooded Tundra                                |
| 22    | 0           | Mixed Tundra                                 |
| 23    | 0           | Bare Ground Tundra                           |
| 24    | 0           | Snow or Ice                                  |

Wetlands, urban areas, and water bodies were separated into separate datasets. The ESRI airport dataset was also converted to raster data set.

### 100% environmental exclusions

All National Park Service, Fish and Wildlife Service lands, and other federal lands with any type of special designation (wilderness, wilderness study area, national monument, national recreation area, etc.) were excluded from the analysis. It was felt that the purpose of these lands was generally incompatible with wind farm development.

Where available, data on potentially restricted state and private lands was gathered in a GIS format, generally from the USGS GAP analysis project. GAP land stewardship data with a value of 1 (the highest level of protection) were excluded entirely.

### 50% exclusions

Four categories were identified as 50% exclusions. These are Department of Defense lands, Forest Service lands, state/private forests and non-ridgecrest forest lands. The USGS federal lands data was used to identify the Department of Defense and Forest Service lands. The USGS GAP data was used to identify probable state and private 50% exclusions. GAP land stewardship data with a value of 2 (the second highest level of protection) were excluded at the 50% level.

Non-ridgecrest forest land was determined by using a terrain classifying program to produce a topographic position dataset, and the forest cover categories (11-15) of the land use dataset. The terrain classifying program compares the elevation of a given cell to the average elevation of surrounding cells and classifies it as ridge, slope, toe slope or valley. Ridge values were eliminated from the topographic position dataset, and filtered with forest cover data to yield cells that are non-ridgecrest and forested.

The data for the Department of Defense lands, Forest Service lands, state/private forests, and non-ridgecrest forest were merged into one dataset representing the lands to be excluded at the 50% level.

### Three kilometer buffer exclusion

All 100% excluded areas, with the exception of water features, were further extended by three kilometers to limit potential development problems in lands adjacent to areas deemed sensitive in this analysis.

The buffered exclusion areas are combined with the water features to create one dataset representing the areas to be 100% excluded.

### **Density Analysis:**

The purpose of the density analysis is to eliminate small, isolated wind resource areas with a low likelihood of development. A criteria of 5 km<sup>2</sup> within the surrounding 100 km<sup>2</sup> area of class 3 or greater resource was chosen after extensive testing of different variations. This criteria is applied after the 100% exclusions have been applied to the high-resolution wind resource dataset. It is not applied to the low resolution wind resource data.

This criteria is applied by assigning each eligible wind cell a value of 1, and for each cell

summing up the values in the surrounding circular 100 km<sup>2</sup>. Those cells with a value of 5% of the total number of cells in that area are reclassified as having met the criteria. The dataset is then expanded by the 100 km<sup>2</sup> area to capture the wind resource cells that contributed to the cell's density value. This dataset is used to filter the 100% non-excluded resource areas.

**Available Windy Land:**

The high-resolution wind resource dataset remaining after the density analysis is concluded is merged with the non-excluded low-resolution wind resource dataset. This dataset is combined with the 50% exclusion grid so that a unique value exists for each combination of power class and exclusion percentage. This is the final resource data set.

**Distance to Transmission Lines:**

The PowerMap data set was defined to include only existing transmission lines with a voltage <= 345 kV. This subset was buffered at 5, 10 and 20 miles and converted to a raster dataset. This dataset was combined with the available windy land data with unique values for each combination of power class, exclusion percentage, and distance to transmission lines.

This dataset is then summarized against the NEMS regions to yield the area in km<sup>2</sup> by power class (3, 4, 5, and 6) and transmission line buffer distance (0-5, 5-10, and 10-20 kilometers).

## 4. Solar Submodule

### Model Purpose

The solar submodule SOLAR estimates supply characteristics for grid-connected central station photovoltaic (PV) and solar thermal (ST) electricity generating power plants. SOLAR does not characterize distributed or off-grid solar technologies. PV and ST cost and performance characteristics which are defined consistent with fossil and other generating technology characteristics reside in ECPDAT. ECPDAT is a data file resident in the Electricity Capacity Planning Submodule of the EMM. Performance characteristics unique to these technologies (such as season and region-dependent capacity factors), however, are passed to the EMM via the solar submodule SOLAR.

Both common and uniquely defined characteristics are described below. The three characteristics unique to renewables and therefore to SOLAR are:

1. PV and ST capacity factors: Because solar radiation varies, capacity factors for solar technologies are assumed to vary by time of day, by season, and by region. Factors are provided for all regions for PV. Capacity factors for solar thermal are only provided for the six regions west of the Mississippi River. These regions are the only ones with sufficient direct normal insolation for cost effective solar thermal installations.
2. Selected Supplemental Capacity Additions (“floors” or “solar lower bounds”): Recognizing that some new solar generating capacity is installed for reasons other than represented in the EMM, such as for market testing or unique economic requirements, EIA includes estimates of minimal new grid-connected generating capacity using solar resources.

### Relationship of the Solar Submodule to Other Models

SOLAR assigns performance data to global variables to be used by the EMM. SOLAR does not interact with other submodules of the RFM or NEMS.

# Modeling Rationale

## Theoretical Approach

Solar energy supplies are fundamentally different from those for most other renewable sources. It is appropriate to model other renewables such as wind, geothermal, and biomass, which consist of limited quantities of high-quality resources, with supply functions which are upward sloping with increasing quantities demanded. In contrast, the solar resource within each EMM region for both kinds of solar technologies (ST and PV) is relatively constant for supply quantities and well in excess of conceivable demand. As a result, the supply for solar is assumed to be perfectly elastic at any moment. NEMS does not increase the cost of the resources with increasing quantities supplied, because high quality resource sites are not exhausted.

Since the two solar electric technologies generate electricity in fundamentally different ways, the nature of the solar resource for each technology is significantly different. The most important difference is the nature of the solar radiation (insolation) that each technology uses. ST technology can utilize only direct normal insolation while PV can utilize both direct and diffuse insolation. Direct normal insolation is defined as sunlight arriving at a location in a path directly from the sun onto a surface without being scattered or reflected. Diffuse insolation is sunlight that has been scattered by clouds, fog, haze, dust, or other substances in the atmosphere and arrives at a location indirectly. The sum of direct normal and diffuse insolation is also referred to as global insolation.

A single type of each of the ST and PV technologies is used for all regions. Accordingly, capital and O&M costs and the efficiency in converting sunlight into electric energy are held constant across regions. Differences in regional resources are captured through the capacity factor variable that represents the solar energy input to the technology.

The default solar thermal electric technology is a 100 MW solar-only central receiver (power tower) with 6-hour molten salt thermal storage. The resource data incorporate climatological data on the frequency and duration of cloud cover. The resource availability or energy output data for central receiver solar thermal consist of both daytime and evening values for the four seasons for a total of nine values. Since a sequence of overcast days can exceed the storage capacity of the system, a derating factor is included to reflect this intermittent availability.

The default PV technology is a 5 megawatt fixed flat-plate crystalline silicon single-axis tracking array tilted at an angle equal to the site's latitude (based on the now defunct Carissa Plains Plant).

## Fundamental Assumptions

The regional classification plan is the same for both ST and PV. As an input to EMM, SOLAR operates on the same 13 regions. These correspond to the nine EMM regions with New York separated from New England; Florida separated from the rest of the Southeast; and the West separated into three regions consisting of California and Southern Nevada (CNV), the Northwest Power Pool Area (NWP), and the combination of the Rocky Mountain and Arizona-New Mexico Power Areas (RA). Each region has its own resource data for both ST and PV, where applicable.

## **Short-Term Cost Adjustment Factors**

Both PV and ST technologies are subject to short-term capital cost adjustment factors, wherein large annual increases in capacity are assumed to be raise costs because of supply bottlenecks (see EMM documentation).

# Solar Submodule Structure

## Submodule Flow Diagram

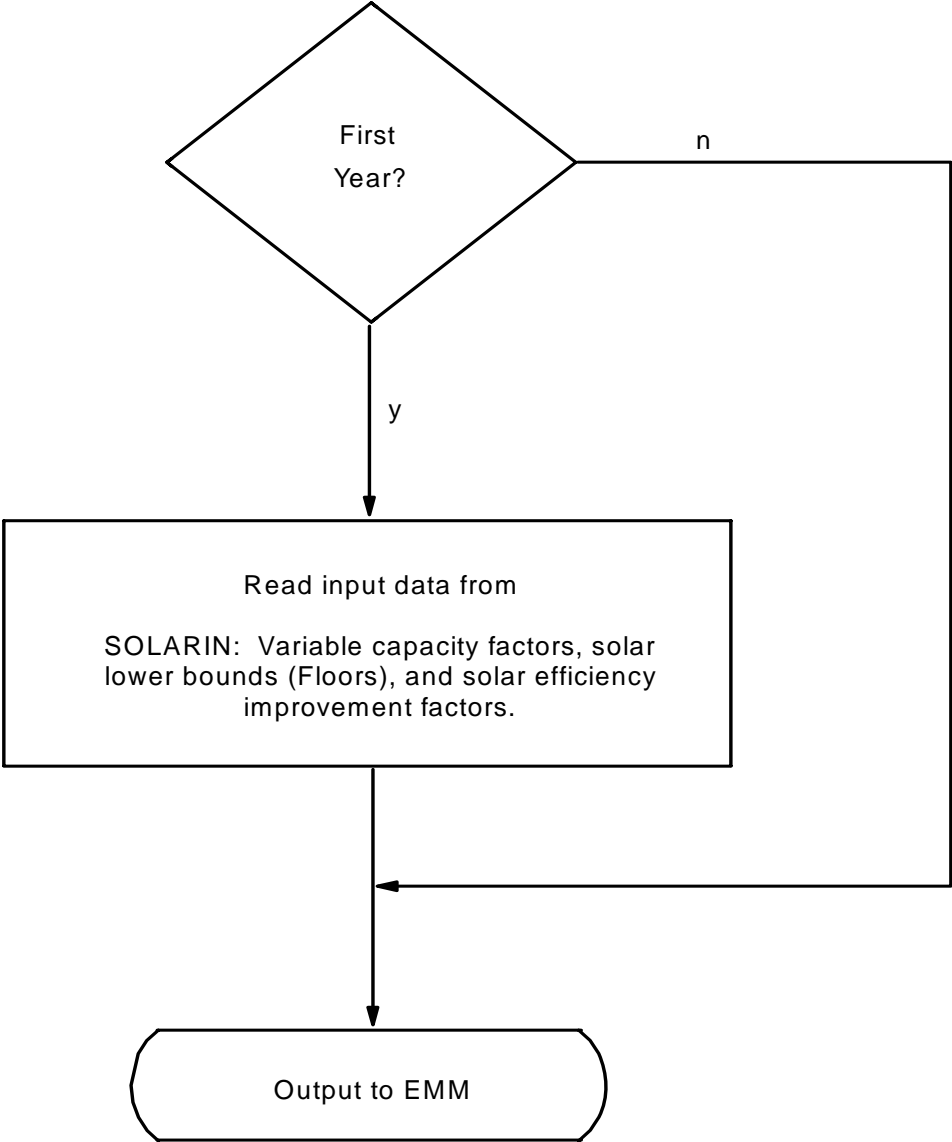
A flow diagram showing the main computational steps and relationships of the Solar Submodule is shown in Figure 3.

## Key Computations and Equations

SOLAR passes data directly, without any computations, through assignments to the appropriate COMMON variables. These are the utility generating capacities and subperiod capacity factors for each technology.



Figure 3. Solar Energy Submodule Flowchart



## Appendix 4-A: Inventory of Variables, Data, and Parameters

This Appendix describes the variables, data inputs, and parameter estimates associated with the cost/performance characteristics of the two solar technologies. PV and ST cost and performance characteristics which are defined consistent with fossil and other generating technology characteristics reside in ECPDAT. Performance characteristics unique to these technologies (such as season and region-dependent capacity factors), however, are passed to the EMM via the solar submodule SOLAR.

Table 4A-1 provides a tabular listing of model variables and parameters. The table contains columns with information on item definitions, modeling dimensions, data sources, measurement units, and documentation page references.

The remainder of Appendix 4-A consists of detailed descriptions of data inputs and variables, including discussions on supporting data assumptions and transformations.

**Table 4A-1. NEMS Solar Model Inputs and Outputs**

| Model Variable     | Definition and Dimensions                                  | Source                      | Units     |
|--------------------|--|-----------------------------|-----------|
| <b>INPUT DATA</b>  |  |                             |           |
| <i>EFFMULPV</i>    | Efficiency multiplier for photovoltaic technology          | EIA, expert judgment        | —         |
| <i>EFFMULST</i>    | Efficiency multiplier for solar thermal technology         | EIA, expert judgment        | —         |
| <i>UPCLYR*</i>     | Construction period.                                       | CEC, 1993.                  | Years     |
| <i>UPCPRO*</i>     | Completion fraction.                                       | CEC, 1993.                  | Percent   |
| <i>UPFOM (19)*</i> | Fixed O&M cost for solar thermal technology.               | Sandia National Laboratory. | mills/kW  |
| <i>UPFOM (21)*</i> | Fixed O&M cost for photovoltaic technology.                | EPRI TAG, 1993.             | mills/kW  |
| <i>UPICCF*</i>     | Investment policy incentive as a fraction of capital cost. | Energy Policy Act, 1992.    | Percent   |
| <i>UPIRGSUB*</i>   | Production policy incentive.                               | Energy Policy Act, 1992.    | mills/kWh |
| <i>UPOVR (19)*</i> | Capital cost of solar thermal technology.                  | Sandia National Laboratory. | \$/kW     |
| <i>UPOVR (21)*</i> | Capital cost of photovoltaic technology.                   | EIA.                        | \$/kW     |
| <i>UPVOM (19)*</i> | Variable O&M cost for solar thermal technology.            | CEC, 1993.                  | mills/kWh |

**Table 4A-1. NEMS Solar Model Inputs and Outputs (Continued)**

| Model Variable     | Definition and Dimensions   | Source          | Units     |
|--------------------|---|-----------------|-----------|
| <i>UPVOM (21)*</i> | Variable O&M cost for photovoltaic technology.  | EPRI TAG, 1993. | mills/kWh |
| <i>WCAPVEL</i>     | Capacity constraints for photovoltaic technology in EMM region <i>n</i> in year <i>y</i> .                        | EIA Estimates.  | MW        |
| <i>WCASTEL</i>     | Capacity constraints for solar thermal technology in EMM region <i>n</i> in year <i>y</i> .                       | EIA Estimates.  | MW        |
| <i>WSSPVEL</i>     | Prototype photovoltaic system capacity factor for EMM region <i>n</i> in time period <i>p</i> in year <i>y</i> .  | NREL, 1995.     | Percent   |
| <i>WSSSTEL</i>     | Prototype solar thermal system capacity factor for EMM region <i>n</i> in time period <i>p</i> in year <i>y</i> . | CEC, 1993.      | Unitless  |

\*Assigned in EMM input file ECPDAT.

**MODEL INPUT:**     *EFFMULPV*

**DEFINITION:**     Efficiency multiplier applied to the time segment capacity factors for PV.

The efficiency multiplier for values > 1.0 allows modeling system improvements that increase the capacity factor.

**SOURCE:**

EIA, expert judgment following discussions with industry, government, and national laboratory sources.

**MODEL INPUT:**     *EFFMULST*

**DEFINITION:**     Efficiency multiplier applied to the time segment capacity factors for solar thermal technology.

The efficiency multiplier for values > 1.0 allows modeling system improvements that increase the capacity factor by utilizing lower energy solar insolation (set to zero for solar thermal).

**SOURCE:**

EIA, expert judgment following discussions with industry, government, and national laboratory sources.

**MODEL INPUT:**     *UPCLYR*

**DEFINITION:**     Construction period of technology *t*, years, (Solar Thermal: *t*=7; PV: *t*=8).

**SOURCES:**

For ST: The California Energy Commission, Memorandum, "Technology Characterization for ER94," August 6, 1993.

For PV: Electric Power Research Institute, "Technical Assessment Guide 1993 (TAG)," 1993.

**MODEL INPUT:**     *UPCPRO*

**DEFINITION:**     Fraction of construction of technology *t* completed in year *y* (Percent).  
(Solar Thermal:  $t=7$ ; PV:  $t=8$ ).

**SOURCES:**

For ST: The California Energy Commission, Memorandum, "Technology Characterization for ER94," August 6, 1993.

For PV: Electric Power Research Institute, "Technical Assessment Guide 1993 (TAG)," 1993.

**MODEL INPUT:**     *UPFOM (21)*

**DEFINITION:**     Fixed O&M cost for photovoltaic technology in EMM region *n* and year *y* (\$/kW).

**SOURCE:**

Derived by EIA, Office of Integrated Analysis and Forecasting, from Electric Power Research Institute, "Technical Assessment Guide 1993 (TAG)," 1993.

**MODEL INPUT:**     *UPFOM (19)*

**DEFINITION:**     Fixed O&M cost for solar thermal technology in EMM region *n* and year *y* (\$/kW).

**SOURCE:**

Derived from Sandia National Laboratory, "Technology Characterization," Draft, July 2, 1997.

**MODEL INPUT:**     *UPICCF*

**DEFINITION:**     Investment policy incentive for technology *t* and year *y* (\$/kW).

This is currently set at 10 percent of the capital cost, based on a 10 percent investment tax credit.

**SOURCE:**

Energy Policy Act of 1992 (P.L.102-486), Title 19, Section 1916.

**MODEL INPUT:** *UPIRGSUB*

**DEFINITION:** Production policy incentive for technology  $t$  and year  $y$  (\$/kWh).

This subsidy is not applied to taxpaying solar technologies. Applications of section 1212, offering the subsidy to publicly owned facilities are not represented, both because most facilities are expected to be from taxpaying entities and because the section 1212 subsidy is dependent upon uncertain annual Federal appropriations.

**SOURCE:** Energy Policy Act of 1992, Public Law 102-486, Section 1914.

**MODEL INPUT:** *UPOVR (21)*

**DEFINITION:** Capital cost (nth-of-a-kind) for PV technology in EMM region  $n$  and year  $y$  (\$/kW).

**SOURCE:**

Electric Power Research Institute, "Technical Assessment Guide 1993 (TAG)," 1993.

**MODEL INPUT:** *UPOVR (19)*

**DEFINITION:** Capital cost (nth-of-a-kind) for solar thermal technology in EMM region  $n$  and year  $y$  (\$/kW).

**SOURCE:**

Derived from Sandia National Laboratory, "Technology Characterization," Draft, July 2, 1997.

**MODEL INPUT:** *UPVOM (21)*

**DEFINITION:** Variable O&M costs in EMM region  $n$  and year  $y$

The variable O&M costs for the PV technology are set to zero for all EMM regions and all years.

**SOURCE:**

Derived by EIA, Office of Integrated Analysis and Forecasting, from Electric Power Research Institute, "Technical Assessment Guide 1993 (TAG)", 1993.

**MODEL INPUT:** *UPVOM (19)*

**DEFINITION:** Variable O&M costs in EMM region  $n$  and year  $y$

The variable O&M costs for the ST technology are set to zero for all EMM regions and all years.

**SOURCE:**

The California Energy Commission, Memorandum, "Technology Characterization for ER94," August 6, 1993.

**MODEL INPUT:** *WCAPVEL*

**DEFINITION:** Constraint for PV capacity resource in EMM region  $n$ ; and year  $y$  (MW).

The variable is currently used to represent estimated minimum (Floor) capacity plans in the EMM. EIA uses off-line estimates to assign regional capacities that represent installations for experimental reasons or for commercial testing.

**SOURCE:**

EIA, expert judgment following discussions with industry, government, and national laboratory sources.

**MODEL INPUT:** *WCASTEL*

**DEFINITION:** Constraint for solar thermal capacity resource in EMM region  $n$ ; and year  $y$  (MW).

The variable is currently used to represent estimated minimum (Floor) capacity plans in the EMM. EIA uses off-line estimates to assign regional capacities that represent future installations of other ST technologies (such as dish Stirling and trough), and installations for experimental reasons or for commercial testing.

**SOURCE:**

EIA, expert judgment following discussions with industry, government, and national laboratory sources.

**MODEL INPUT:** *WSSPVEL*

**DEFINITION:** Time segment system capacity factor for PV in EMM region  $n$  in time period  $p$  in year  $y$  (Percent).

**SOURCE:**

National Renewable Energy Laboratory. Memorandum facsimile transmission, August 23, 1995, Christy Herig to Thomas Petersik.

**MODEL INPUT:**     *WSSSTEL*

**DEFINITION:**     Time segment capacity factor for solar thermal system in EMM region *n* in time period *p* in year *y* (Unitless).

Solar thermal capacity factors, by region and time segment, are derived by EIA from factors provided by NREL; all NREL capacity factors are adjusted by a constant (0.8427) which yields an average annual capacity factor for California (EMM region 13) matching the California Energy Commission (CEC) average for that region.

**SOURCES:**

National Renewable Energy Laboratory, based on total solar radiation data from the National Solar Radiation Database.

The California Energy Commission, Memorandum, "Technology Characterization for ER94," August 6, 1993.

## **Appendix 4-B: Mathematical Description**

The SOLAR submodule does not incorporate any modeling equations. It assigns values that are read from input files, to the appropriate RFM common blocks.



## **Appendix 4-C: Bibliography**

California Energy Commission, "1992 Energy Technology Status Report," December 1992.

California Energy Commission, Memorandum, "Technology Characterization for ER94," August 6, 1993.

Electric Power Research Institute, "Technical Assessment Guide 1993 (TAG)," 1993.

Energy Policy Act of 1992, Public Law 102-486, Section 1212.

National Renewable Energy Laboratory, "National Solar Radiation Data Base (1961 - 1990) Version 1.0 NSRDB-Volume 1, September, 1992," Prepared by NREL, distributed by National Climatic Data Center, Asheville, NC 28801.

National Renewable Energy Laboratory. Memorandum facsimile transmission, August 23, 1995, Christy Herig to Thomas Petersik.

## Appendix 4-D: Model Abstract

### **Model Name:**

Solar Submodule

### **Model Acronym:**

SOLAR

### **Description:**

SOLAR defines of costs and performance characteristics for photovoltaic and solar thermal electricity generating systems by EMM region and year. EMM regions are based on the North American Electric Reliability Council (NERC) regions as modified by the Energy Information Administration (EIA) for NEMS. For PV technologies, all EMM regions are represented in SOLAR. For ST technologies, however, only six selected regions are represented, since insufficient direct normal insolation (sunlight) bars this technology will from other regions of the country.

### **Purpose of the Model:**

The purpose of the NEMS Solar Submodule (SOLAR) is to define the costs and performance characteristics of Solar Thermal (ST) and Photovoltaic (PV) electricity generating technologies and to pass them to the EMM for capacity planning decisions.

### **Most Recent Model Update:**

August 1999.

### **Part of Another Model?:**

The Solar Submodule is a component of the Renewable Fuels Module (RFM) of the National Energy Modeling System (NEMS).

### **Official Model Representative:**

Chris Namovicz  
Coal and Electric Power Division  
Energy Information Administration  
(202) 586-7120  
e-mail: cnamovicz@eia.doe.gov

## **Documentation:**

NEMS Documentation Report: Renewable Fuels Module of the National Energy Modeling System. February 2001.

NEMS Documentation Report: *Renewable Fuels Module of the National Energy Modeling System*, January 2000.

## **Archive Media and Installation Manual(s):**

Archived as part of the NEMS production runs.

## **Energy System Described:**

Solar thermal performance is based on a central receiver system with molten salt storage. The storage allows the electricity output to be dispatched over a somewhat longer period than hours of highest solar insolation. At low levels of insolation the output of the central receiver system is zero. Once the insolation exceeds a threshold level sufficient to overcome thermal losses, the daily total output is assumed to be linear with total daily insolation. The output is allocated first to day periods, then to evening periods, and then to nighttime periods. Photovoltaic performance is based on a fixed axis PV system. The technology characterization assumes that rated output is reached at an insolation level of 1000 Watts per square meter.

## **Coverage:**

- Geographic: 13 EMM regions: East Central, Texas, Mid-Atlantic, Mid-America, Mid-Continent, Northeast, New England, Florida, Southeastern, Southwest, Western, Rocky mountain & Arizona, California & So. Nevada.
- Time Unit/Frequency: Annual, 1990 through 2020.
- Products: Electricity.

## **Modeling Features:**

### **Non-DOE Input Sources:**

California Energy Commission: Cost and performance characteristics, solar thermal technology.

Electric Power Research Institute and U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, *Renewable Energy Technology Characterizations* (EPRI TR-109496, December 1997).

Electric Power Research Institute: Cost and performance characteristics, PV technology.

IRS Tax Code

- 10 percent investment tax credit.

National Solar Radiation Database

- Regional Insolation

**DOE Input Sources:**

- Electric Power Research Institute and U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, *Renewable Energy Technology Characterizations* (EPRI TR-109496, December 1997).

**Independent Expert Reviews Conducted:**

None.

**Status of Evaluation Efforts by Sponsor:**

None.

## **Appendix 4-E: Data Quality and Estimation Processes**

This Appendix discusses (1) the quality of the principal sources of input data used in the Solar Submodule, along with a discussion of user-defined parameters and guidelines used to select them, and (2) estimation methods used to derive parameters.

### **Solar Thermal Performance**

Solar thermal performance (capacity factor) is based on a central receiver system with six hours molten salt storage. The storage allows the electricity output to be dispatched at any time of day, i.e., it is "decoupled" from the periods of high insolation. Because it uses concentrators, the central receiver system can utilize only direct insolation.

Solar thermal cost and performance estimates are obtained primarily from the California Energy Commission, "Technology Characterization for ER94." Capacity factors are determined by EIA based on estimates in the "Typical Meteorological Year" database of the National Renewable Energy Laboratory, and adjusted to match overall estimates accompanying the technology cost and performance characterizations. In all cases, characteristics selected for EIA use are compared with any other available measures or estimates, as obtained from State or federal government offices, industry, trade, and private research and analysis firms.

All cost and performance estimates are made available for review within EIA; they are also circulated for comment among appropriate DOE offices in the Office of Energy Efficiency and Renewable Energy's Office of Power Technologies; finally, the estimates are made available for outside uses and comment, both in response to specific requests and in EIA-sponsored forums.

### **Photovoltaic Performance**

Photovoltaic performance is based on a single axis tracking PV system. The technology characterization assumes that peak rated capacity and output are reached at an insolation level of 1000 Watts insolation per square meter. The fraction of peak rated capacity of an actual PV system is assumed to vary linearly with (direct plus diffuse) insolation, so that at any instant actual capacity is equal to peak rated capacity multiplied by actual insolation in  $W/m^2$  divided by 1000. Photovoltaic system cost and performance estimates are obtained primarily from the Electric Power Research Institute, "Technical Assessment Guide 1993," 1993, and, for capital costs, derived from data obtained from the Sacramento Municipal Utility District (SMUD). As with solar thermal estimates, capacity factors are determined by EIA based on estimates in the "Typical Meteorological Year" database of the National Renewable Energy Laboratory, and adjusted to match overall estimates accompanying the technology cost and performance characterizations.

## 5. Biomass Submodule

### Model Purpose

The purpose of the Biomass Submodule is to furnish cost and performance characteristics of the biomass gasification integrated combined cycle (BIGCC) technology to the Electricity Market Module (EMM) of the National Energy Modeling System (NEMS). The submodule utilizes a regional biomass supply schedule from which the biomass price is determined. The biomass supply schedule is based on the accessibility of biomass resources by the consuming sectors from existing wood resources and future biomass energy crops. Cost and performance characteristics of a representative BIGCC system is defined to be consistent with fossil and other technology characteristics, and resides in the EMM input file ECPDAT.

Performance characteristics unique to the biomass gasification integrated combined cycle technology (such as heat rates and variable O&M costs) are computed in the renewables submodule and then passed to the EMM. The fuel component of the cost characteristic is determined from the regional biomass supply schedules and then converted to a variable O&M cost.

### Relationship of the Biomass Submodule to Other Models

The Biomass Submodule interacts with EMM and the sectoral demand modules. It does not interact with other submodules in the RFM. Regional biomass consumption requirements from the industrial and electricity modules are used in the biomass module to determine the regional biomass supply price. A total capacity potential is calculated from regional supply curve data and each year, the accumulated capacity from the EMM is measured against this limit and is constrained if it exceeds the limit.

### Modeling Rationale

#### Theoretical Approach

Biomass use in NEMS is modeled as two distinct markets, the *captive* and *noncaptive* biomass markets. The captive market pertains to users with dedicated biomass supplies that obtain energy by burning biomass byproducts resulting from the manufacturing process (i.e., the pulp and paper and forest products industries). Biomass waste combustion in captive markets serves the dual role of energy supplier and waste disposal method. The captive biomass market is modeled in the industrial module of NEMS.

The noncaptive biomass market is represented in the Biomass Submodule of the RFM. The noncaptive market is defined to include the electric utility sectors and the resources marketed in the industrial sector. It is necessary to include industrial consumption in order to properly estimate supply and demand conditions, as these represent alternative economic

uses of the biomass supply. There are additional noncaptive markets serving residential and commercial uses of biomass. These markets are modeled in the residential and commercial demand modules.

Because of the scarcity of reliable data and the relatively small size of the noncaptive market, EIA developed a simple model structure consisting of one supply schedule per region. The fuel supply schedule in each region defines the quantity and cost relationships of biomass resources accessible by all noncaptive consumers. It is based on an aggregation of supply/price information for forestry residues, urban wood waste and mill residues, agricultural residues, and energy crops. The latter is made available starting in 2010. Additional detail on the biomass supply curves is provided in Appendix 5-E.

## Fundamental Assumptions

A basic assumption of the Biomass Submodule is that the supply price for noncaptive biomass energy is the same across all sectors. This assumption allows the construction of a single supply schedule for all sectors to yield a supply price for the electric utility sector. It is also assumed that there are no discounts for large orders of biomass.

Another fundamental assumption relates to the treatment of biomass transportation costs. The difficult aspect of building supply curves for biomass is modeling the economic accessibility to the resource, rather than estimating the physical amount of biomass that can be used. This submodule assumes a fixed "typical" transportation distance in calculating costs. For agricultural residues, forestry residues, and energy crops, it has been assumed that the maximum distance that this type of material can be transported economically is 50 miles. Within a circular area with a radius of 50 miles, it has been assumed that the transportation cost will be \$10 to 12/dry ton. This fixed amount has been added to the supply curves for agricultural residues, forestry residues, and energy crops to reflect the transportation cost from the farm-gate to the power plant.

For urban wood waste and mill residues, the assumptions and methodology for calculating transportation costs is slightly different than for the other types of biomass. For urban wood waste and mill residues it is assumed that all residues are within 100-mile radius of a potential biopower site. Transportation costs are estimated for 25, 50, 75, and 100-mile hauling distances. Based on data for the national outlay on local transportation and local trucking ton-miles logged, a national average freight charge of \$0.24/ton-mile (\$96) is assumed. The national average freight charge is then converted to state averages, by state transportation price indices. Because no interregional biomass trade exists, it is assumed that no biomass is transported among EMM regions.

## Alternative Approaches

Generally, biomass conversion can be modeled similar to other solid fuel technologies, i.e. coal, with appropriate attention to cost assumptions. The unique characteristics of this resource reside in the treatment of the fuel supply function.

The Biomass Submodule of NEMS has several simplifying features of its supply functions which may offer opportunities for improvement. The submodule treats only the marketed portion of the fuel, when there could be interaction with entities with captive fuel, i.e. the forest products industry, as well as with the residential fuel market. Another simplification is the assignment of a constant factor for transportation costs. The fuel transport costs could be a significant share of the delivered costs and will vary considerably by terrain and distance to the conversion facility. A final limiting assumption pertains to the treatment of competing uses of the resource, either as land or as other product uses. For example, the land could be used for other fiber or food crops or the wood could be used for construction, at alternate prices.



## **Biomass Submodule Structure**

### **Submodule Flow Diagram**

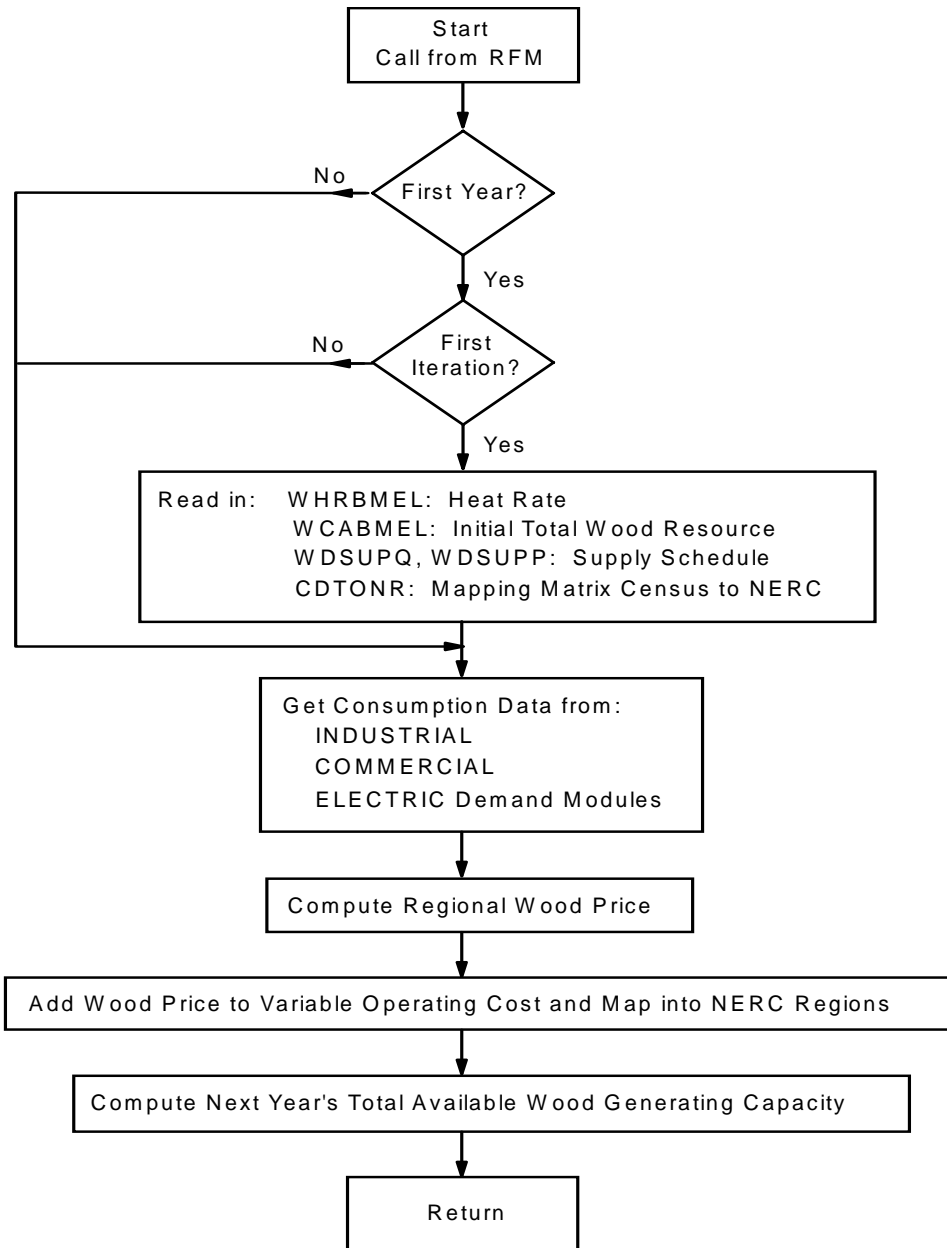
A flow diagram showing the main computational steps and relationships of the Biomass Submodule is shown in Figure 4.

### **Key Computations and Equations**

The biomass submodule consists of one FORTRAN subroutine. It computes the regional biomass supply price given the current regional biomass consumption passed from the industrial, and electric generating modules. The biomass price is added to the variable operating cost and passed to the Electricity Planning Submodule (ECP) along with the heat rate.

The biomass quantity-price relations are implemented in a matrix representing the supply curve as step functions. A linear interpolation scheme is used to determine the biomass price given a biomass quantity.

**Figure 4. Biomass Submodule Flowchart**



Since the biomass consumption data are defined in NEMS by Census divisions, and the cost and performance characteristics of the biomass technology are defined for EMM regions, a geographic mapping was necessary to generate biomass prices by EMM regions.

In addition to the assignment of cost/performance characteristics, the biomass submodule passes the maximum available electricity generating capacity using biomass to the ECP. This capacity limit is computed by decrementing the initial total potential by already installed

capacity and for each subsequent year, decrementing the last year's unplanned new capacity from the previous limit. The initial total generating capacity for each region is determined by dividing the maximum quantity of biomass reserves in the supply curve by the product of the heat rate, capacity factor, and 8760 as the number of hours per year.

The technology represented by the cost and performance values for new capacity is the Biomass Integrated Gasification Combined Cycle (BIGCC) system for biomass. The cost is for a modular unit, capable of being shop fabricated. The cost values include storage and biomass handling, magnetic separators, and ash handling equipment. The gasifier is equipped with solid and gas recycling systems. A modular hot gas filtration unit is included in the cost assumptions.

## Appendix 5-A: Inventory of Variables, Data and Parameters

Appendix 5-A provides information on variables used in the Biomass Submodule. Table 5A-1 gives a complete listing of all variables including definitions and dimensions, sources, measurement units, and page references. Variables are classified as Submodule data inputs, calculated variables, and Submodule outputs. Following Table 5A-1 are detailed descriptions of each input data item.

**Table 5A-1. NEMS Biomass Submodule Inputs and Variables**

| Model Variable               | Definition and Dimensions  | Source | Units        |
|------------------------------|--|--------|--------------|
| <b>INPUT DATA</b>            |  |        |              |
| <i>CDTOCLWDTI</i>            | Conversion factors for converting Census division <i>r</i> to coal demand region <i>n</i>                              | DAC    | Unitless     |
| <i>WDSUPQ</i>                | Biomass quantity step function in coal demand region <i>n</i> , year <i>y</i> , step <i>l</i>                          | DAC    | trillion Btu |
| <i>WDSUPR</i>                | Biomass price step function in coal demand region <i>n</i> , year <i>y</i> , step <i>l</i>                             | DAC    | \$/MMbtu     |
| <i>UPOVR*</i>                | Capital cost for biomass technology  | NREL   | \$/kW        |
| <i>UPMCF*</i>                | Capacity factor for biomass technology electricity sector  | NREL   | Unitless     |
| <i>WVC<sub>n,y</sub></i>     | Constant variable O&M cost component for biomass technology electricity sector in EMM region <i>n</i> in year <i>y</i> | NREL   | \$/MMbtu     |
| <i>UPFOM<sub>n,y</sub>*</i>  | Fixed O&M costs for biomass technology electricity sector in EMM region <i>n</i> in year <i>y</i>                      | NREL   | \$/kW        |
| <i>WHRBMEL<sub>n,y</sub></i> | Heat rate for biomass technology in EMM region <i>n</i> in year <i>y</i>   | EPRI   | Btu/kWh      |
| <b>VARIABLES</b>             |  |        |              |
| <i>QBMCM</i>                 | Quantity of biomass consumed in the commercial sector in Census division <i>r</i> in year <i>y</i>                     | NEMS   | trillion Btu |
| <i>QBMEI</i>                 | Quantity of biomass consumed by utilities in Census division <i>r</i> in year <i>y</i>                                 | NEMS   | trillion Btu |
| <i>QBMIN</i>                 | Quantity of biomass consumed in the industrial sector in Census division <i>r</i> in year <i>y</i>                     | NEMS   | trillion Btu |
| <i>CURWDCON</i>              | Quantity of biomass consumed in all sectors in EMM region <i>n</i> and year <i>y</i>                                   | NEMS   | trillion Btu |
| <i>CURWDPR</i>               | Price of biomass from the all-sector supply curve in EMM region <i>n</i> and year <i>y</i> .                           | NEMS   | \$/MMBtu     |

**Table 5A-1. NEMS Biomass Submodule Inputs and Variables (continued)**

| Model Variable  | Definition and Dimensions  | Source | Units     |
|-----------------|--|--------|-----------|
| <b>OUTPUTS</b>  |  |        |           |
| $WCABMEL_{n,y}$ | Capacity for utilities in EMM region $n$ in year $y$   | EMM    | MW        |
| $WVCBMEL_{n,y}$ | Variable O&M costs for biomass technology electricity sector in EMM region $n$ in year $y$ . Incorporated the converted fuel cost for biomass. | RFM    | mills/KWh |

\*Assigned in EMM input file ECPDAT.

**MODEL INPUT:**  $CDTOCLWDTI$

**DEFINITION:** Conversion factors for converting Census division  $r$  to coal demand region  $n$ .

**SOURCE:**

Oak Ridge National Laboratory, "Data and Sources Biomass Supply." Draft prepared for EIA under Contract No. DE-AC05-84OR21400, Oak Ridge, TN, June 27, 1993.

**MODEL INPUT:**  $WDSUPQ$

**DEFINITION:** Quantity of biomass supply in coal demand region  $n$ , year  $y$ , and step  $l$ .

$WDSUPQ$  is part of the biomass supply schedule. The variable represents quantity of a biomass composite consisting of the following biomass types: (1) forestry materials, (2) mill residues, (3) agricultural residues, and (4) energy crops.

**SOURCES:**

U.S. Department of Agriculture, Forest Service, "Forest Resources of the United States, 1992" General Technical Report RM-234 (Revised), (Fort Collins, CO, June 1994).

Graham, R.L., et.al., Oak Ridge National Laboratory, "The Oak Ridge Energy Crop County Level Database", September 20, 1996 version, Oak Ridge, TN.

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Antares Group Inc., "Biomass Residue Supply Curves for the U.S.", (Landover, MD, September 1998).

**MODEL INPUT:**     *WDSUPP*

**DEFINITION:**     Price of biomass supply in coal demand region *n*, year *y*, and step *l*.

WDSUPP is part of the biomass supply schedule. The variable represents the price of a biomass composite consisting of the following biomass types: (1) forestry materials, (2) mill residues, (3) agricultural residues, and (4) energy crops.

**SOURCES:**

U.S. Department of Agriculture, Forest Service, "Forest Resources of the United States, 1992" General Technical Report RM-234 (Revised), (Fort Collins, CO, June 1994).

Graham, R.L., et.al., Oak Ridge National Laboratory, "The Oak Ridge Energy Crop County Level Database", September 20, 1996 version, Oak Ridge, TN.

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Antares Group Inc., "Biomass Residue Supply Curves for the U.S.", (Landover, MD, September 1998).

**MODEL INPUT:**     *UPOVR*

**DEFINITION:**     Capital costs for electricity sector.

UPOVR represents the *n*<sup>th</sup>-of-a-kind capital cost for an advanced Biomass Integrated Gasification Combined Cycle (BIGCC) technology of unit size 80 MW. The cost estimates incorporate the removal of interest during construction and contingency costs, which are added later in EMM.

**SOURCE:**

Electric Power Research Institute, and U.S. Department of Energy, Office of Utility Technologies, "Renewable Energy Technology Characterizations", EPRI TR-109496, (Palo Alto, CA, December 1997). Values were further adjusted by EIA for consistency with coal gasification costs.

**MODEL INPUT:**     *UPFOM*

**DEFINITION:**     Fixed O&M costs for biomass technology.

The fixed O&M cost is assumed to be constant across all regions and for all years.

**SOURCE:**

Electric Power Research Institute, and U.S. Department of Energy, Office of Utility Technologies, "Renewable Energy Technology Characterizations", EPRI TR-109496, (Palo Alto, CA, December 1997).

**MODEL INPUT:**     *UPMCF*

**DEFINITION:**     Capacity factor for the utility sector.

Capacity factor is assumed to be constant for all years and all regions.

**SOURCE:**

Craig, K.R.; Mann, M.K.. 1993. Cost and Performance Analysis of Integrated Gasification Combined Cycle (IGCC) Power Systems Incorporating a Directly Heated Biomass Gasifier. Milestone Completion Report. NREL. December 1993.

**MODEL INPUT:**     *WHRBMEL*

**DEFINITION:**     Heat rate for biomass technology in EMM region *n* in year *y*

The heat rate represents the biomass gasification combined cycle technology.

**SOURCES:**

Gas Turbine Handbook, 1995 Handbook, Gas Turbine World.  
Electric Power Research Institute, "Technical Assessment Guide," Vol. 1, Revision 7, EPRI TR-102276S, Palo Alto, CA, June, 1993.

**MODEL INPUT:**     *QBMCM*

**DEFINITION:**     Biomass/wood consumption in commercial sector in Census division *r* and year *y*.

NEMS variable, calculated in the commercial demand model.

**SOURCE:**

NEMS.

**MODEL INPUT:**     *QBMEEL*

**DEFINITION:** Biomass/wood consumption in electric power sector in Census division  $r$  and year  $y$ .

NEMS variable, calculated in the EMM model.

**SOURCE:**

NEMS.

**MODEL INPUT:**  $QBMIN$

**DEFINITION:** Biomass/wood consumption in industrial sector in Census division  $r$  and year  $y$ .

NEMS variable, calculated in the industrial demand model.

**SOURCE:**

NEMS.

**MODEL OUTPUT:**  $WVC_{n,y}$

**DEFINITION:** Constant variable O&M cost component in EMM region  $n$  and year  $y$ .

This constant cost component, representing operation costs, is added to fuel costs to produce a total variable cost.

**SOURCE:**

Electric Power Research Institute, and U.S. Department of Energy, Office of Utility Technologies, "Renewable Energy Technology Characterizations", EPRI TR-109496, (Palo Alto, CA, December 1997).

**MODEL OUTPUT:**  $CURWDCON$

**DEFINITION:** Quantity of biomass energy consumed in all sectors.

Sum of biomass energy consumed in the commercial, industrial, and utility sectors.

**SOURCE:**

NEMS

**MODEL OUTPUT:**  $CURWDPR$



**DEFINITION:** Price of biomass energy from the all-sector supply schedule

**SOURCE:** NEMS

**MODEL OUTPUT:** *WCABMEL*

**DEFINITION:** Available generating capacity [MW] in EMM region *n* and year *y*.

The maximal generating capacity is determined by the maximal value in each regional supply curve and converted into MW using the performance characteristics of the biomass technology, represented in the RFM.

**SOURCE:** NEMS.

**MODEL OUTPUT:** *WVCBMEL*

**DEFINITION:** Variable costs for biomass electricity generation for the utility sector in EMM region *n* in year *y*.

Variable cost is model determined. It is the sum of two factors: (1) a constant factor accounting for operational maintenance expenses, and (2) fuel cost. Since there is no vehicle to pass fuel cost separately to the ECP, the cost for biomass fuel is converted into mills per kWh and added as an additional variable O&M cost component.

**SOURCE:** NEMS.

## Appendix 5-B: Mathematical Description

### Subroutine WDREALJOB

The subroutine evaluates the consumption of biomass in the commercial, industrial, and electric power sectors by regions and determines the regional biomass price. Census divisions provide the sectoral biomass consumption levels. They are mapped to EMM regions using the following mapping:

commercial sector:

$$WDQNRCM_{n,y} = \sum_{r=1}^{R=9} \sum_{n=1}^{N=13} CDTONR_{n,r} * QBMCM_{r,y} \quad (1)$$

industrial sector:

$$WDQNRIN_{n,y} = \sum_{r=1}^{R=9} \sum_{n=1}^{N=13} CDTONR_{n,r} * QBMIN_{r,y} \quad (2)$$

electric power sector:

$$WDQNREL_{n,y} = \sum_{r=1}^{R=9} \sum_{n=1}^{N=13} CDTONR_{n,r} * QBME_{r,y} \quad (3)$$

where:

$CDTOCLWDTI_{n,r}$  = mapping matrix to map Census division  $r$  into coal demand region  $n$

$QBMCM_{r,y}$  = biomass/wood consumption in commercial sector in Census division  $r$  and year  $y$ , in trillion Btu.

$QBMIN_{r,y}$  = biomass/wood consumption in industrial sector in Census division  $r$  and year  $y$ , in trillion Btu.

$QBME_{r,y}$  = biomass/wood consumption in electric power sector in Census division  $r$  and year  $y$ , in trillion Btu.

$WDQNRCM_{n,y}$  = biomass/wood consumption in commercial sector in EMM region  $n$  and year  $y$ , in trillion Btu.

$WDQNRIN_{n,y}$  = biomass/wood consumption in industrial sector in EMM region  $n$  and year  $y$ , in trillion Btu.

$WDQNREL_{n,y}$  = biomass/wood consumption in electric power sector in EMM region  $n$  and year  $y$ , in trillion Btu.

$$CURWDCON_{n,y} = WDQNRCM_{n,y} + WDQNRIN_{n,y} \quad (4)$$

Where:

$$CURWDPR_{n,y} = WDSUPP_{n,y,i} + \left[ \frac{CURWDCON_{n,y} - WDSUPQ_{n,y,i}}{WDSUPQ_{n,y,i+1} - WDSUPQ_{n,y,i}} \right] (WDSUPP_{n,y,i+1} - WDSUPP_{n,y,i}) \quad (5)$$

$CURWDCON_{n,y}$  = quantity of biomass energy consumed in all sectors (trillion Btu).

The submodule does a linear interpolation between two steps  $l$  and  $l+1$  on the supply curve to determine the price of biomass given a quantity. The interpolation is expressed as:

where:

$CURWDPR_{n,y}$  = price of biomass energy from the all-sector supply schedule, EMM region  $n$ , year  $y$ , \$/MMBtu,

$WDSUPP_{n,y,i}$  = price of biomass supply in EMM region  $n$ , year  $y$ , and step  $l$ ,

$WDSUPQ_{n,y,i}$  = quantity of biomass supply in EMM region  $n$ , year  $y$ , and step  $l$ .

Since the biomass submodule does not have a vehicle to pass fuel cost separately to the ECP module, the price  $CURWDPR$  of biomass is converted into a variable O&M cost component and added to the constant variable cost factor. The conversion is expressed as:

$$WVCBMEL_{n,y} = WVC_{n,y} + CURWDPR_{n,y} * WHRBMEL_{n,y} * C_1 \quad (6)$$

where:

$WVC_{n,y}$  = constant variable O&M cost component in EMM region  $n$  and year  $y$ .

$WHRBMEL_{n,y}$  = heat rate for biomass technology in EMM region  $n$  and year  $y$ .

$C_1$  = conversion factor to transform from \$/MMBTU \* BTU/kWh to mills/kWh,  $C_1=10^{-3}$ .

$WVCBME_{L,n,y}$  = Variable cost for biomass electricity generation for the utility sector in EMM region n in year y.

$CURWDPR_{n,y}$  = Price of biomass from the supply schedule for EMM region n in year y.

## Appendix 5-C: Bibliography

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## Appendix 5-D: Model Abstract

**Model Name:**

Biomass Submodule.

**Model Acronym:**

None.

**Description:**

The submodule passes to the EMM cost and performance characteristics by EMM regions and years. The fuel component of the cost characteristic is determined from the regional biomass supply schedules and then converted to a variable O&M cost.

**Most Recent Model Update:**

August 1999.

**Part of Another Model?:**

The Biomass Submodule is a component of the Renewable Fuels Module (RFM) of the National Energy Modeling System (NEMS).

**Official Model Representative:**

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Energy Information Administration  
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**Documentation:**

NEMS Documentation Report: *Renewable Fuels Module of the National Energy Modeling System*, June 2005.

**Archive Media and Installation Manual(s):**

Archived as part of the NEMS production runs.

**Energy System Described:**

Non-captive biomass supply and associated price.

**Coverage:**

USA.

**Modeling Features:**

Data from nine Census divisions are restructured into 14 coal demand regions.



**Non-DOE Input Sources:**

None.

**Independent Expert Reviews Conducted:**

None.

**Status of Evaluation Efforts by Sponsor:**

None.

## Appendix 5-E: Data Quality and Estimation Processes

### Derivation of the All Sector Biomass Supply Curve

The biomass supply curves represent four categories of materials: the forest products data developed from U.S. Forest Service data, wood residue data obtained from regional and state agencies and crop residue and energy crop data developed from information obtained from the Oak Ridge National Laboratory. The information was merged and formatted into the shell of the previously assembled supply curves, using common price steps.

Under the category of forestry residues, to estimate regional supply schedules for softwood and hardwood chips McQuillan et. al. (1984) use forestry inventory data along with information on a variety of factors such as: logging and chipping costs, hauling distances and costs, stocking densities, wood types, slope, and equipment operability constraints. The base year of the McQuillan study was 1983. Original data used by McQuillan et. al. comes from a 1976 national inventory on “waste wood”. Waste wood is defined to include logging residues, rough, rotten, and salvable dead wood (live cull and sound dead wood) and excess sapling and small poll trees.

The forestry residue supply schedule currently being used in NEMS is based on the original analysis by McQuillan et. al., and Turhollow and Cohn (1994) which was later revised for use in NEMS by DAC (1995). ORNL has updated the amount of waste wood available using the most recent USDA/Forest Service inventory data. This update was necessary because the data that McQuillan et. al. used was 25 years old. ORNL also made other adjustments to reflect availability of waste wood. These adjustments include: the exclusion of sapling trees, the exclusion of small pole trees, changes to the recoverability factors, the addition of a nominal stumpage fee, and the conversion of 1980\$ to 1998\$ based on an index of agricultural prices paid.

Urban wood waste and mill residue data were assembled from state and regional agency reports by Antares Group, Inc.<sup>19</sup> who then combined quantities and provided estimates of prices. The types of wood included were silviculture, mill residues, urban waste and construction and demolition debris. Price estimates were based on sales contract information or tipping fees in various regions combined with transportation costs, pre-processing costs and profits where appropriate.

Crop residue data include wheat straw and corn stover estimates developed by Oak Ridge National Laboratory.<sup>20</sup> Additional crops that have been included are: barley, cotton field trash, cotton gin trash, oats, orchard prunings, rice straw, rye, sorghum and sugar cane bagasse. Although a large amount of soybeans are produced in the U.S., the residues are

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<sup>19</sup> Antares Group, Inc., “Biomass Residue Supply Curves for the U.S.”, prepared for the National Renewable Energy Laboratory by Antares Group, Inc., Landover, MD, November, 1998.

<sup>20</sup> Walsh, M.E., et.al., Oak Ridge National Laboratory, “Evolution of the Fuel Ethanol Industry: Feedstock Availability and Price”, Oak Ridge, TN, April 1998.

modest and readily decompose in the field. This makes collection of soybean residues unattractive. Hay is harvested and almost entirely fed to livestock. Therefore, it is assumed that there would be no useful amount of hay residue available. Prices represent the costs of gathering and transporting the material, a premium paid to farmers, and transportation costs.

Energy crops data were compiled from the Oak Ridge National Laboratory database.<sup>21</sup> This database contained information on yields and production costs for three land types and two crop types. Crop yields, which are in the range of 3-7 tons/acre were converted to energy potential for each county and aggregated up to coal demand regions. The crops included are hybrid poplar, willow and switchgrass. Separate crop supply curves are developed for each model year, 2010-2020 and added to the other three categories.

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<sup>21</sup> Graham, R.L., et al, Oak Ridge National Laboratory, "The Oak Ridge Energy Crop County Level Database," September 20, 1996 version .Oak Ridge, TN.

## 6. Geothermal Electricity Submodule

### Model Purpose

The Geothermal Electricity Submodule (GES) represents U.S. geothermal resources supply and technology cost and performance characteristics used to project use of geothermal energy for central station electricity supply through the mid-term future. More specifically, the GES –

- In the National Energy Modeling System (NEMS), provides the Electricity Market Module (EMM) Electricity Capacity Planning (ECP) submodule the supply (megawatts) of new geothermal generating capacity and its related average cost and performance characteristics based upon information for resources at 51 known U.S. geothermal sites;
- Reduces supply available for future capacity as geothermal resources are used, including already chosen capacity identified from historical data reported to EIA, from reported plans of future geothermal capacity, or from resources already chosen in earlier forecasting iterations by the ECP; and
- Changes geothermal capital costs, reducing them to reflect experience (learning-by-doing) and increasing them as warranted by rapid increases in demand (short-term cost elasticities of supply).

For the *Annual Energy Outlook 2002 (AEO2002)* and retained for *AEO2006*, the simplified GES structure introduced in *AEO2001* was modified in three ways, to -

- Reduce the number of megawatts available geothermal supply at each of the 51 geothermal sites in order to better represent mid-term supplies rather than the 40-year supplies modeled in *AEO2001*, usually reducing to a few hundred megawatts geothermal resources often times estimated earlier at more than one thousand megawatts.
- Limit the number of megawatts able to be built at any site in a specific year (annual build bounds) in order to better represent industry practice of gradual expansion at geothermal sites; bounds may be modified by individual site by year. For the reference case *AEO2006*, each site was permitted a maximum development of 25 megawatts per year through 2015 and 50 megawatts per year thereafter; for the high renewables case, the 50 megawatt annual limit applies to all years.
- Permit changes in the capital costs of specific sites by individual year (Capital cost multipliers), enabling the GES to represent geothermal capital cost assumptions different from the reference case. The capital cost multipliers are numeric weights, less than, equal to, or greater than 1.00 separately affecting the total base capital cost of each of the 51 geothermal sites; the design allows different weights for different sites and different weights for different years for each site.

Changes to annual build bounds and capital cost multipliers are made in the WGESITE input data file.

## **Relationship of the Geothermal Electricity Submodule to Other Models**

The GES interacts primarily with the ECP. Relationships between GES and other NEMS components include –

- GES provides new capacity availability, performance, and cost information for the ECP in making planning decisions;
- GES uses new capacity build decisions from the ECP to decrement available new geothermal resources and capacity.
- GES uses financial parameters and tax data for calculations related to the competing geothermal resource sites and ECP-based avoided costs to determine the highest cost at which new geothermal supply can compete, setting the upper-cost bound of geothermal supply.

## Modeling Rationale

The GES develops regional geothermal capacity supplies (megawatts available in increasing order of cost per kilowatthour) used in competing geothermal technologies with fossil, nuclear, and other renewable energy generating alternatives for each forecast year and region needing new generating capacity. Water-based (hydrothermal) resources in the 3 Western EMM regions (11,12, and13) are assumed to be the only cost-effective, accessible geothermal resources available during the forecast period. Hot-dry rock technologies are excluded because they are not expected to become cost competitive beyond 2030.

Each geothermal site is characterized by (1) a capital cost estimate, (2) low and high estimates of the number of megawatts of capacity available, (3) increasing capital costs for increasing portions of the high estimate, and (4) capacity factor, fixed operation and maintenance cost, heat rate, and carbon dioxide (CO<sub>2</sub>) emissions rate. Within each region for each model iteration in each forecast year the GES subtracts resources already used, arrays all geothermal supply segments in increasing cost order, determines from the EMM the maximum price (avoided cost) likely to be competitive, and then provides the EMM a geothermal supply in the form of three leveled cost-quantity pairs of available capacity that compete with other technologies.

Input data for the supplies were provided by DynCorp Corporation ("DynCorp data base), based upon 1992 work by Sandia National Laboratory for EIA and the Geothermal Division of DOE<sup>22</sup> and reflecting earlier work by the U.S. Geological Survey and others.<sup>23</sup> The input data are available from the Office of Integrated Analysis and Forecasting, Coal and Electric Power Division. For *AEO2002*, and continued for *AEO2006*, EIA reduced these estimates from sometimes more than a thousand megawatts to usually a few hundred, in order to better represent mid-term, rather than long-term supplies. Observation of development at actual U.S. geothermal sites indicates that, whatever a geothermal resource' ultimate potential, actual development almost always occurs in small increments, 50 megawatts or so, followed by multiple years operation without additional development. Therefore, in EIA's judgment, the likelihood of geothermal development over the mid-term exceeding a few hundred megawatts at any one site, even under assumptions of somewhat greater than reference case demand, is highly unlikely.

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<sup>22</sup> Sandia National Laboratory, Petty, Susan; Livesay, B.J; Long, William.P.; Geyer, John: *Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power in 20 and 40 Years*, Contractor Report SAND92-7302, Albuquerque, New Mexico, November 1992.

<sup>23</sup>Muffler, L.P.J., editor, *Assessment of Geothermal Resources of the United States – 1978*, U.S. Geological Survey Circular 790, 1978.

# Fundamental Assumptions

## Type of Resource

The GES represents hydrothermal geothermal resources, defined as large volumes of water trapped in permeable rock at depths to 11,000 feet and with temperatures ranging from 110° C to 680° C. Costs of utilizing hot dry rock resources are unknown but believed to be multiples of commercially competitive values; hot dry rock technologies are therefore not expected to be commercially competitive until after 2030 and are not represented in NEMS. Cost estimates are based on historical costs of exploring, confirming, and developing hydrothermal resources and installing power plants to bring additional capacity on-line at known geothermal sites.

## Estimates of Resources

In addition to identifying the number of megawatts of geothermal generating capacity already developed, the DynCorp data base provides two estimates of the potential capacity able to be developed at each of the 51 geothermal resource sites described in the data base. The “low” estimate identifies the number of megawatts that could be developed within 20 years at the costs specified in the data base from already identified resources, including existing capacity already built. The “high” estimate reflects the number of megawatts that could be developed at those same costs, but in 40 years and from both identified and as yet unidentified resources at each site.

Beginning with the *AEO2001* and continued for *AEO2006*, EIA significantly modified the DynCorp estimates: Using the DynCorp data base and the more detailed estimates in the Sandia report, EIA converted the high estimates (40 year, including unidentified resources) for each of the 51 sites into four incremental capital cost subgroups, under the basic assumption that the greater supplies currently unidentified but becoming available at the same cost in 40 years, could only be currently identified and accessed at greater cost.

The various estimates prepared by Susan Petty and others and used in the deliverable and other reports basically display (a) 20 and 40 year estimates of “identified resources” and (b) 20 and 40 year estimates of “unidentified” resources, allowing EIA to distinguish and assign costs to both the 20 and 40 year time difference and the process of identification. EIA assigned a +33% drilling and other field cost premium for employing currently any capacity shown as becoming available in 40 years rather than 20; second, EIA doubled the exploration cost for any 20 or 40 year resources classified as “unidentified.”

- The first, least cost, estimate includes all identified resources in the DynCorp “low” estimate, the 20-year identified resources.
- The second, higher cost, category applies to identified capacity only becoming available in 40 years, and equals the capacity difference between the 40-year identified resources and the 20-year identified resources in step 1. Under the assumption that there is an additional

field cost distinguishing 40-year availability from 20-year, EIA increased by 33% the estimated drilling and other field cost estimates for this incremental quantity. EIA did not change the assumed power plant costs for this group.

- Third, EIA separately identified from the Sandia report the 20-year estimates for identified *plus unidentified* resources, and assigned to the difference between that and identified resources in step 1 double the estimated exploration cost for this quantity of capacity. In effect, EIA doubles exploration cost”
- Fourth, EIA assumed that all remaining capacity in the difference between the 40-year identified plus unidentified (high) estimates and the 20-year identified (low) represents capacity affected by both the additional exploration and the additional drilling and field costs.

The effect of the EIA segmenting is to parcel each of the 51 sites’ potential into four increasing capital cost categories.

Beginning in *AEO2002*, and continued through *AEO2006*, EIA significantly reduced the estimates of geothermal resources supply. Cost-increasing steps introduced for *AEO2001* proved too small to prevent NEMS building hundreds or thousands of megawatts of geothermal at individual sites, far in excess of likely actual construction at any one site. Therefore, for *AEO2002*, EIA introduced two steps designed to reduce both the absolute supply available at an individual site and to slow the rate of capacity expansion at sites.

- First, quantities of capacity available in individual cost steps at individual sites were greatly reduced in many cases, generally reduced to a maximum of 100 megawatts per cost step per site, quantities which for *AEO2001* were many hundreds or even more than one thousand megawatts. Overall, the effect of the reduction is to reduce the total supply from any one site – especially for those likely to be competitive – from over a thousand megawatts to a few hundred megawatts.
- Second, GES is modified to permit site and year specific limits (annual build bounds) on the number of megawatts able to be selected from a site. For the reference case *AEO2006*, a maximum of 25 megawatts new geothermal can be built at any one site for all years 2000 – 2015, and 50 megawatts per site per year thereafter; for the “high renewables case,” a limit of 50 megawatts is set for all sites for all years.

## Existing Capacity and Retirements

Existing capacity is enumerated, by facility name, on-line date, plant size, state, region, heat rate, and capacity factor, as described in the generating unit plant file showing all U.S. utility and nonutility generating units as reported on forms EIA-860A (Annual Electric Generator Report – Utility) and EIA-860B (Annual Electric Generator Report – Nonutility). Beginning with *AEO2001* and continued through *AEO2006* EIA no longer independently assumes that geothermal units will retire at the end of their 40th year. EIA does not assume retirement



dates for geothermal power plants; however, retirements are imposed when the EIA-860 respondent or other independent information externally establishes the actual or anticipated retirement.

## Exploration Costs

The DynCorp database provides per-kilowatt exploration costs for each of the 51 geothermal resource sites. However, because DynCorp calculated costs based on an estimated 250 megawatts at each site, EIA recalculated the per-kilowatt exploration cost based on the actual estimated low estimate at each resource site, thereby in most instances increasing the average per-kilowatt exploration cost.<sup>24</sup> The reestimation can be found in the Excel file "GeoT.xls."

## Capital Costs

Capital costs in the DynCorp data base were derived from detailed resource characteristic data provided by the Sandia report and others, using the geothermal electricity supply data preprocessor (GESDPP) of the IM-GEO PC-based geothermal model.<sup>25</sup> Developed by Sandia National Laboratory in the mid 1980's, the IM-GEO (Impacts of Research and Development on the Cost of Geothermal Power) preprocessor converts resource information about the 51 sites - including information on resource temperature, depth, and well chemistry (salinity, noncondensable gas content), flow rate per well – into site-specific capital cost components based on a 50 megawatt plant. Data inputs date from 1991 or earlier.

Capital costs are a composite of four separate costs, (1) exploration, (2) drilling, (3) pipeline and other field, and (4) power plant. Land is assumed to be leased rather than purchased, and land costs are included in fixed operations and maintenance charges. Separate from the DynCorp database, within the GES all four components receive the 10 percent EPACT investment tax credit (ITC). In the GES, total capital costs are also decreased by learning-by-doing.

Drilling costs are a fixed value, affected only by the ITC and learning-by-doing. Consideration was given to decreasing geothermal drilling costs in response to the rate of decrease in drilling costs determined in NEMS for the oil and gas industry. The decrease was not incorporated because it was not certain that advances occurring in discovery and drilling (such as horizontal drilling) for the oil and gas industries also uniformly apply to geothermal.

The GES permits total capital costs for any site (and any step at any site) to be changed via use of a site and individual year specific capital cost weight. As a result, capital costs for any site may be exogenously changed from year to year. For the reference case all weights are 1.00.

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<sup>24</sup> Because exploration costs must be paid and because they are usually very small, they are included in the geothermal capital costs; however, because exploration costs are usually paid before the decision for a specific power plant, the decision to build the plant is not dependent upon exploration costs. EIA's reestimation of exploration costs can be found in the Excel file "GeoT.xls."

<sup>25</sup> Entingh, D., Livesay, B., and Petty, S., *Geothermal Cost of Power Model IM-GEO Version 3.05: User's Manual*, February, 1989. EIA files "IMGEO.ZIP" and "QB45.ZIP" contain the IM-GEO preprocessor and data.

## **Operations and Maintenance Costs**

As for capital costs, the DynCorp database contains each site's fixed operations and maintenance costs, separately distinguishing (a) pumps and field, from (b) power plant costs, determined based on individual site characteristics using data from Susan Petty et al, using the IM-GEO preprocessor. Pumps and field costs include an estimate for land lease costs.

## **Heat Rates**

The energy in geothermal resources differs significantly from site to site. Furthermore, differing measurement techniques can yield dramatically different heat rates. For example, heat rates can reflect the gross heat energy of the geothermal fluid at the surface or account for only the energy used at some later stage in its application. The GES submodule heat rate is defined as the difference in the heat content of the incoming energy as it reaches the earth's surface and the heat content of the energy as it is reinjected into the ground after use in production. Heat rates for binary plants, which adapt low-temperature resources (less than 200<sup>o</sup> Centigrade) require much more input energy – averaging about 70,000 Btu/kWh – than heat rates for dual flash plants using higher temperature resources (greater than 200<sup>o</sup> Centigrade) – averaging about 30,000 Btu/kWh. The geothermal heat rate estimates used in the GES have been adopted from the earlier version of the GES, derived earlier using the preprocessor IM-GEO.

## **Conversion Technologies**

Two geothermal generating technologies are represented in GES, dual-flash and binary. The lower-cost dual-flash technology is employed to convert high temperature (greater than 200<sup>o</sup> C) fluids to turbine steam by “flashing” the liquid to steam at two different stages, with the steam then used to drive a conventional turbine generator. The remaining liquid portion of the geothermal fluid is reinjected into the ground. Generally higher-cost binary technologies convert lower temperature (less than 200<sup>o</sup> C) liquids to turbine steam by circulating the liquid through a closed loop system in which the fluid heats and vaporizes a second fluid with a low boiling point, such as isopentane. The vapor of the second fluid drives the turbine generator and the low-temperature geothermal fluid is reinjected into the ground. Because there are no other major “dry” steam resources, such as are found at the Geysers in California, the dry steam geothermal technology is not represented in the GES.

## Capacity Factors

Based upon actual performance of other plants, when estimating costs for building new plants, GES assumes an 95 percent capacity factor for dual-flash plants and 80 percent for binary units; after new plants are built, actual annual generation is estimated at the average of the two technologies, using an 87 percent capacity factor. Dry steam units from the Geysers are dispatched at their historical actual rates of performance.

## Alternative Approaches

U.S. Geothermal resources were evaluated in the mid 1970s by the U.S. Geological Survey<sup>26</sup> (USGS) and in 1991 by Sandia National Laboratory (see footnote 1). These assessments included estimates of potential electric generation capacities in terms of number of megawatts for 30 years at known geothermal hydrothermal resource sites in the United States. At the time of the USGS study, domestic geothermal development was limited to the Geysers steam field in northern California, and exploration and delineation of the nation's liquid-dominated hydrothermal resources was in its early stages. The 1991 Sandia effort took advantage of considerable hydrothermal resource data and developmental experience gained in the interim.

The IM-GEO model developed by Sandia National Laboratories originally included only four generic geologic sites, typical of those found in the United States. In 1992 IM-GEO was modified to process data for all the sites identified in the Sandia report. IM-GEO is coded in Quick Basic and was executed separate from the GES; it may be referred to as the GES Data Pre-Processor or GESDPP. The GESDPP was used by DynCorp to develop the capital cost estimates for each of the 51 sites.

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<sup>26</sup> Muffler, L.P.J., editor, *Assessment of Geothermal Resources of the United States-1978*. U. S. Geological Survey Circular 790, 1978.

## Geothermal Electricity Submodule Structure

The GES “SUBROUTINE GEO2000” has five basic components:

- 1. Incorporates data:** On its initial iteration, subroutine “GET-SITE-DATA” reads the data from the “WGESITE” input data file characterizing the 51 U.S. geothermal sites, including capacity, cost components, operations and maintenance (O&M) costs, capacity factor, heat rate, emissions rate, *and annual capital cost multipliers and build bounds*; subroutine “GET\_PARM\_DATA” reads geothermal parameters from the “WGE Parm” file. Together the two build the “GEOSITE” geothermal data structure. Capital costs are the sum of DynCorp estimates for drilling, other field, and power plant costs, plus exploration costs; annual fixed O&M costs are pump and field plus power plant costs; there are no fuel charges for geothermal. *The annual capital cost multipliers are applied to the capital costs before leaving the “GET-SITE-DATA” subroutine. The cost multipliers will usually have a value of 1.00 for base cases and various values <1.00 for alternate scenarios including the high renewable case. Two sites in Hawaii are not used in the modeling, leaving 49 sites in the three Western regions (11, 12, and 13) contributing to geothermal supply.*
- 2. Develops overall regional geothermal supplies:** In each iteration, subroutine “BUILD-GEO-CURVES” first creates regional geothermal supplies for each of the three Western EMM regions with geothermal resources, using the 49 sites’ data (a) distributing each site’s total available capacity (megawatts) among 4 increasing capital cost subgroups, and ( b) arraying all sites’ quantity-cost subgroups in each EMM region from least- to highest-cost, resulting in an aggregate regional geothermal supply array “GEOCRV.” *The total available capacity for each site is limited to the annual build bound for the site.*
- 3. Provides sub-supplies for specific regional demands:** For each iteration of the EMM, the GES determines a maximum levelized cost (avoided cost) at which geothermal supply in each of the regions will be able to compete. The maximum value is (1) the levelized cost of the highest-cost technology actually selected in the immediately prior iteration of the ECP plus (b) an additional percentage representing the market sharing algorithm.<sup>27</sup> The average value of the market sharing algorithm is about 17 percent. As a result, all remaining geothermal capacity able to generate at or below 1.17 times the previous iteration’s highest cost selection is offered as new geothermal supply in the current iteration. “BUILD-GEO-CURVES” selects from each aggregate regional supply “GEOCRV” only that unused supply available at or below the adjusted avoided cost, and then distributes it among three increasing-cost geothermal

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<sup>27</sup> The market sharing algorithm exists in recognition that in real markets technologies that are “close” in cost to the least cost technology will occasionally be selected for economic and other reasons not represented in the modeling. Under the sharing algorithm, the closer in cost a specific other technology is to the least cost technology, the greater (yet small) share of the available market will be taken by that technology.

cost-quantity pairs using capacity-weighted average per kilowatthour costs, such that the EMM receives for each region three quantities of available geothermal capacity at three (increasing) levelized costs, plus an overall (over all 3 steps) capacity-weighted heat rate, O&M costs, and carbon dioxide and hydrogen sulfide emissions rates. The least-cost group includes all unused capacity in the least-cost price quartile (capacity whose levelized cost is equal to or less than +25% of the gross cost difference between the least cost available unit and the ECP-avoided cost; the resulting quantity is not the least-cost 25 percent of unused capacity, but all unused capacity in the first 25 percent of the cost range). The second group includes all capacity between the 25<sup>th</sup> and the 75<sup>th</sup> price quartile; and the third group includes all remaining, highest cost, capacity. All available capacity in each cost group is then conveyed to the EMM as available supply, with one levelized cost associated with each group; the one levelized cost transmitted for each group equals the capacity-weighted levelized average cost for the individual sites' costs within the group.

4. **Decrements available capacity:** Within subroutine "CRV-INFO," for each iteration GES reduces available geothermal capacity in each region in response to (a) external reports of new geothermal builds or (b) previous selection by the EMM in earlier iterations;
5. **Provides diagnostics:** For each iteration, Subroutine "WRITE-DB" provides diagnostic information on geothermal capacity and sites chosen and technology costs and performance.

"Diagnostics provided through Excel output file "geo\_out.xls" include

**Geo\_Input\_Data** displaying quantities of capacity available at each of 51 U.S. geothermal sites, including capacity in each of four cost categories;

**Geo\_Curve\_Data** displaying in least-to-highest cost order each geothermal subsite's available geothermal capacity and estimated per kilowatthour cost;

**Geo\_Curve\_Info** displaying aggregate geothermal supplies and average per kilowatthour cost as available to each of four NEMS regions for each forecast year, values transmitted to the Electricity Market Module (EMM) as aggregate geothermal supply; and

**Geo\_Builds** displaying quantities of geothermal capacity built in each of four NEMS regions in each forecast year.

## Key Computations and Equations

This section describes the most important equations in the GES.

### Reading the Data

In the first iteration, data for geothermal sites are read from a file **WGESITE** by the GES Subroutine **GET\_SITE\_DATA** into the **GEOSITE** data structure. Subroutine **GET\_PARM\_DATA** reads the geothermal parameters from the parameter file **WGEPARM**.

GEOSITE Data Structure:

|                            |  |
|----------------------------|--|
| <b>SITE_ID</b>             |  |
| <b>EIA_ID</b>              |  |
| <b>NAME</b>                | = Site Name  |
| <b>STATE</b>               |  |
| <b>AVAIL_SUPPLY</b>        | = Potential capacity -1990 capacity  |
| <b>CAP_COST_ADJ</b>        | = Drilling + Field + Plant Costs adjusted by capital cost multiplier (\$1987/KW) |
| <b>CAP_COST</b>            | = Drilling + Field + Plant costs   |
| <b>CAPACITY_1990</b>       | = Installed capacity 1990  |
| <b>CAPACITY_FACTOR</b>     | = 0.00 to 1.00 (0.80 – Binary, 0.87 – Dual Flash)                                |
| <b>CAPCOST_MULT</b>        | = Annual Capital Cost Multiplier for Site (Fraction)                             |
| <b>CENSUS</b>              | = Census region of site  |
| <b>CO2_RATE</b>            | = LBS. per megawatthour  |
| <b>COE</b>                 | = 4 levelized costs, (\$1987) mills per kilowatthour                             |
| <b>DRILL_CAP_COST</b>      | = Per kilowatt capital cost component (\$1987)                                   |
| <b>DRILL_CAP_COST_ADJ</b>  | = Capital cost component adjusted by capital cost multiplier (\$1987/KW)         |
| <b>EXPLOR_CAP_COST</b>     | = Per kilowatt capital cost component (\$1987)                                   |
| <b>EXPLOR_CAP_COST_ADJ</b> | = Capital cost component adjusted by capital cost multiplier (\$1987/KW)         |
| <b>FIELD_CAP_COST</b>      | = Per kilowatt capital cost component (\$1987)                                   |
| <b>FIELD_CAP_COST_ADJ</b>  | = Capital cost component adjusted by capital cost multiplier (\$1987/KW)         |
| <b>FIELD_OM-COST</b>       | = Per kilowatt annual field O&M cost component (\$1987)                          |
| <b>H2S_RATE</b>            | = LBS. per megawatthour  |
| <b>HEAT_RATE</b>           | = BTU per kilowatthour   |
| <b>NERC</b>                | = NERC region of site  |
| <b>PFILE_EXCAP</b>         | = Existing capacity (from EMM plant file)  |
| <b>PLANT_CAP_COST_ADJ</b>  | = Capital cost component adjusted by capital cost multiplier (\$1987/KW)         |
| <b>PLANT_CAP_COST</b>      | = Per kilowatt capital cost component (\$1987)                                   |

|                       |   |
|-----------------------|---|
| <b>PLANT_OM-COST</b>  | = Per kilowatt annual plant O&M cost component (\$1987) |
| <b>POTENTIAL_CAP</b>  | = 4 increasing-cost quantities of capacity at each site |
| <b>SITE_BOUND</b>     | = Annual Build Bound for Site (MW)                      |
| <b>SUBSITEOM_COST</b> | = Field O&M + Plant O&M costs                           |
| <b>TECHTYPE</b>       | = Technology, 1- Binary; 2 – Dual Flash                 |
| <b>TEMP</b>           | = Temporary data structure for sorting geosites         |

In each iteration, the capital, fixed O&M, and levelized cost of energy for each of 4 increasing-cost subsites at each site are calculated, with capital costs adjusted for learning and technological optimism. Existing capacity is subtracted from each site's available supply. Technological optimism and learning effects are estimated in subroutine ELEC\_OPT in the electricity capacity planning (ECP) submodule of the EMM.

### Building Regional Geothermal Supplies

In each iteration, available geothermal supplies at each site are merged with costs from other sites in the region and arrayed for competition in the ECP in each region. GES first constructs a complete array of increasing levelized cost/quantity pairs as the cumulative geothermal supply available for the region. GES then segments the competitive part of that array into three generalized increasing cost segments, passing to the ECP the total capacity available in each increasing cost segment along with the capacity-weighted average cost of energy (mills per kilowatthour) for the capacity in the segment.

In each iteration, the subroutine **BUILD\_GEO\_CURVES** creates up to four records (above) for each site resulting in the quantity of capacity and levelized cost of energy (**COE**) for each subsite. Quantities are read directly from **POTENTIAL\_CAP**. *The potential capacity is limited by the site build bound for the current year.* Capital cost for record 1 includes drilling + field + plant + exploration cost; for record 2, drilling and field costs are increased 33 percent; for record 3, exploration costs are doubled; and for record 4, both drilling and field costs are increased 33 percent and exploration costs are doubled.

In each region and in each iteration, GES receives a maximum cost from the EMM, a value equal to the COE of the highest cost capacity previously selected in each region, called the Regional Avoided Cost, plus the market-sharing tolerance (about 17 percent).

Avoided Cost = (Regional Maximum Prior COE) \* (1.0 + Market Sharing Tolerance)

The subroutine "**BUILD\_GEO\_CURVES** iterates within each region until the capacity available in the first (lowest cost) step is greater than zero or 10 iterations have occurred, incrementing the threshold cost 10 percent for each iteration.

The subroutine **ECPLVCST** develops levelized cost groups for submission to the ECP.

|                     |   |
|---------------------|---|
| <b>AVAIL_SUPPLY</b> | = Megawatts available for each record               |
| <b>CUM_SUPPLY</b>   | = Cumulative sum available megawatts in each region |

**SYS\_CAP\_COST** = Cumulative capacity-weighted capital cost, 3 segments  
**SYS\_CAP\_FAC** = Cumulative capacity-weighted capacity factor, 3 segments  
**SYS\_CO2\_RATE** = Cumulative capacity-weighted CO2 emissions rate, 3 segments  
**SYS\_COST** = Cumulative capacity-weighted COE, 3 segments  
**SYS\_HEAT\_RATE** = Cumulative capacity-weighted heat rate, 3 segments  
**SYS\_OM\_COST** = Cumulative capacity-weighted O&M cost, 3 segments

From these cumulative values **BUILD\_GEO\_CURVES** then determines the specific value for each variable for each of the 3 segments of available geothermal supply in each region

**CAP\_COST** = Capital cost  
**CAP\_FAC** = Capacity factor  
**CO2\_RATE** = CO2 emissions rate  
**HEAT\_RATE** = Heat rate  
**OM\_COST** = O&M cost

In fact, the GES passes the ECP actual values only for the first of the three segments; values for steps 2 and 3 are expressed as weights applicable to the values in the first segment.

**EMM\_CAP\_COST**  
**EMM\_CAP\_FAC**  
**EMM\_CAPACITY**  
**EMM\_CO2\_RATE**  
**EMM\_HEAT\_RATE**  
**EMM\_OM\_COST**

$$\text{Average\_Capital\_Cost} = \left( \sum_{i=1}^n (\text{Cap\_Cost}_{(i)} * \text{Capacity}_{(i)}) \right) / \text{Cumulative\_Capacity}$$

$$\text{Average\_O\&M\_Cost} = \left( \sum_{i=1}^n (\text{O \& M\_Cost}_{(i)} * \text{Capacity}_{(i)}) \right) / \text{Cumulative\_Capacity}$$

Where n = number of site records.



## Other Features of the Geothermal Submodule

**Regional Labor Cost Weights:** Because the capital costs for geothermal sites in the DynCorp deliverable are already specific to individual sites, regional labor cost weights in the EMM are set to 1.00 for all geothermal sites.

**Investment Tax Credit:** The 10% Energy Policy Act (EPACT) investment tax credit is not included in the DynCorp capital cost estimates, and is separately subtracted from the capital cost estimates in the GES.

**Land Costs:** Lands used for geothermal well fields can be either purchased and accounted for in the capital costs of the project or be leased and therefore included in the project's fixed operation and maintenance costs. In the DynCorp deliverable, land is assumed to be leased and its costs are included in fixed O&M.<sup>28</sup>

**Construction Lead Time, Construction Cost Profile, and First On-Line Year:** In the GES, new geothermal plants are constructed over a 4 year time period, but with most capital costs allocated to the last two years, in the annual proportions 2%, 1%, 50%, and 47%, with costs in the first two years limited to licensing and permitting. For *AEO2006*, the first year in which a model built new geothermal plant can enter service is 2009.

**Learning, Short-Term Elasticities, and Technological Optimism:** Capital Costs for geothermal generating technologies are affected by learning-by-doing as are all generating technologies, as well as by technological optimism. For a description of these characteristics and assumptions and values assigned geothermal for *AEO2006*, see *Assumptions for the Annual Energy Outlook 2006*, Table 39, "Learning Parameters for New Generating Technology Components".

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<sup>28</sup> Petty, Susan, personal communication, November 20, 2000 (file name Petty, LandCosts.rtf)

## **Appendix 6-A: Inventory of Variables, Data and Parameters**

Values for this inventory are included in the body of this chapter, along with the Excel files supporting the geothermal submodule. Questions about the submodule can be directed to:

Robert K. Smith  
Coal and Electric Power Division  
Energy Information Administration  
(202) 586-9413  
[robert.smith@eia.doe.gov](mailto:robert.smith@eia.doe.gov)

## Appendix 6-B: Mathematical Description

Questions about GES algorithms can be directed to –

Robert K. Smith  
Coal and Electric Power Division  
Energy Information Administration  
(202) 586-9413  
robert.smith@eia.doe.gov

The Geothermal submodule computes the levelized cost of energy for 4 increasing cost subsites at each geothermal site, with capital costs adjusted for learning and technological optimism. The rationale and cost differentials for these 4 subsites are explained in the “Estimates of Resources” section in the “Fundamental Assumptions” portion of this documentation.

$$\text{COE}(i,1) = ( ( (\text{DCST}(i,y) + \text{FCST}(i,y) + \text{ECST}(i,y) + \text{PLNTCST}(i,y)) * \text{FCF}(r) * \text{LFACT} * \text{OPFACT} ) + (\text{FOM}(i) + \text{POM}(i)) ) / (\text{CF}(i) * 8760.0) * 1000.0$$

$$\text{COE}(i,2) = ( ( ( 1.33 * (\text{DCST}(i,y) + \text{FCST}(i,y)) + \text{ECST}(i,y) + \text{PLNTCST}(i,y)) * \text{FCF}(r) * \text{LFACT} * \text{OPFACT} ) + (\text{FOM}(i) + \text{POM}(i)) ) / (\text{CF}(i) * 8760.0) * 1000.0$$

$$\text{COE}(i,3) = ( ( ( \text{DCST}(i,y) + \text{FCST}(i,y) + 2.0 * \text{ECST}(i,y) + \text{PLNTCST}(i,y)) * \text{FCF}(r) * \text{LFACT} * \text{OPFACT} ) + (\text{FOM}(i) + \text{POM}(i)) ) / (\text{CF}(i) * 8760.0) * 1000.0$$

$$\text{COE}(i,4) = ( ( ( 1.33 * (\text{DCST}(i,y) + \text{FCST}(i,y)) + 2.0 * \text{ECST}(i,y) + \text{PLNTCST}(i,y)) * \text{FCF}(r) * \text{LFACT} * \text{OPFACT} ) + (\text{FOM}(i) + \text{POM}(i)) ) / (\text{CF}(i) * 8760.0) * 1000.0$$

Where:

i = Geothermal Site i

y = Current Year

r = NEMS Region

COE(i,1) = Levelized Cost of energy for subsite 1 for geothermal site i.

COE(i,2) = Levelized Cost of energy for subsite 2 for geothermal site i.

COE(i,3) = Levelized Cost of energy for subsite 3 for geothermal site i.

COE(i,4) = Levelized Cost of energy for subsite 4 for geothermal site i.

DCST(i,y) = Drilling component of capital costs for geothermal site i in year y, \$/KW.

ECST(i,y) = Exploration component of capital costs for geothermal site i in year y, \$/KW.

FCST(i,y) = Field component of capital costs for geothermal site i in year y, \$/KW.

PCST(i,y) = Plant component of capital costs for geothermal site i in year y, \$/KW.

PLNTCST(i,y) = Fixed Charge Factor in EMM region r for geothermal technology, fraction.

LFACT(y) = Learning Factor for geothermal technology in year y, fraction.

OPFACT(y) = Technological Optimism Factor for geothermal technology in year y,

FOM(i) = Field component of fixed O&M costs for geothermal site i, \$/KW.

POM(i) = Plant component of fixed O&M costs for geothermal site i, \$/KW.  
CF(i) = Capacity Factor for geothermal site i, fraction.

The levelized costs by geothermal site and subsite are then sorted from least to highest cost, resulting in an aggregate regional geothermal supply array. These regional supply arrays are then used to generate the three step EMM supply curves.

## Appendix 6-C: Bibliography

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Petty, Susan, Susan Petty Consulting; Livesay, Bill, Livesay Consultants, Inc., prepared for National Renewable Energy Laboratory, "Database of Hydrothermal Sites in the U.S. With Potential for Electric Power Generation," March, 1993

Cassel, Thomas A.V.; Edelstein, Robert H.; Blair, Peter D.; Amundsen, Chris B., Technecon Analytic Research, Inc., final report DOE/RA/4713-1 for the U.S. Department of Energy, Assistant Secretary for Resource Application, under contract ET-78-S-02-4713A001 "Geothermal Investment and Policy Analysis With Evaluation of California and Utah Resource Areas," Philadelphia, PA, October, 1979.

Muffler, L.P.J., editor, "Assessment of Geothermal Resources of the United States – 1978 ," U.S. Geological Survey Circular 790, 1978.

## Appendix 6-D: Model Abstract

### **Model Name:**

Geothermal Electric Submodule

### **Model Acronym:**

GES

### **Description:**

The GES develops regional geothermal capacity supplies and cost and performance characteristics used in competing geothermal technologies with fossil, nuclear, and other renewable energy generating alternatives for each forecast year and region needing new generating capacity in the EMM. Regional geothermal supplies are based on each region's share of geothermal resources estimated for 51 identified U.S. geothermal sites, with (1) capital cost estimates for each geothermal site, (2) four-step low-to-high cost estimates of the number of megawatts of capacity available at each site, (3) assumptions for increasing capital costs for increasing portions of the high estimates for each site, and (4) capacity factors, fixed operation and maintenance costs, heat rates, and CO<sub>2</sub> emissions rates for each site. Within each region for each model iteration in each forecast year the GES decrements already chosen resources, arrays all unused geothermal supply in increasing cost order, determines from the EMM the maximum price (avoided cost) likely to be competitive in the EMM, and then provides the EMM three increasing levelized cost-quantity pairs of available capacity in each region for use in competition with other technologies.

### **Purpose of the Model:**

The purpose of the GES is to provide the Electricity Capacity Planning module (ECP) the amounts of available geothermal generating capacity and its cost and performance characteristics for competition in the ECP for new regional electricity supply in the Western United States.

### **Most Recent Model Update:**

The new GES was introduced for the *Annual Energy Outlook 2001* in June, 2000.

### **Part of Another Model?:**

The GES submodule is a component of the Renewable Fuels Module (RFM) of the National Energy Modeling System (NEMS).

## **Official Model Representative:**

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## **Documentation:**

This chapter constitutes the documentation of the GES.

## **Archive Media and Installation Manual(s):**

The GES is archived as part of the NEMS production runs.

## **Energy System Described:**

Hydrothermal geothermal energy resources of the Western United States and the costs and performance characteristics of the technologies converting them to electricity supply.

## **Coverage:**

- Geographic: EMM regions 11, 12, and 13.
- Time Unit/Frequency: Annual, 1990 through 2030.
- Products: Electricity
- Economic Sectors: Electricity Generators

## **Modeling Features:**

- Modeling Structure: The model operates at the level of individual geothermal sites aggregated to segmented EMM regional averages.
- Model Technique: Levelized electricity costs from each supply segment of each site in each region are arrayed in increasing cost order, then aggregated into three increasing average-cost segments in each iteration in each year, along with attendant quantities (megawatts) and average heat rates and capacity factors.
- Incorporates short-term cost elasticities of supply, technological optimism, and learning.

## **Input Sources:**

DynCorp I&ET, "Geothermal Supply and Cost Performance Characteristics," contract deliverable for Purchase Order #36727 for the Energy Information Administration, Coal and Electric Power Division, Office of Integrated Analysis and Forecasting, June 30, 2000.

Input and other data files are maintained in the Coal and Electric Power Division, including input data files "PettyData.xls", "PettyData-Annotated.xls", and "SimplPetty.xls." File "gensite.xls" summarizes the DynCorp data plus heat rates for each site. Plant file data for existing geothermal capacity and its performance can be found on the file "Geo97.xls," and data on expected retirements can be found in the file "GeotRetirementsAEO2001.xls." More detailed capacity data, also from Susan Petty and rooted in the same research, used by EIA to allocate each site's supply over four categories, can be found on the file "DE-PTY1C.xls. The reallocation to four increasing-cost levels is located on the file "GeoT.xls."

For GES modeling, Excel file "Geo-out1.xls" displays the basic building block data used in building regional geothermal supply curves; Excel file "Geotherm.xls" contains a simulation of the 3-step supply curve derivation methodology useful for testing changes in various parameters testing the GES methodology.

## **Independent Expert Reviews Conducted:**

None. However, during development of the submodule ongoing review and comment were obtained from the DOE Office of Energy Efficiency and Renewable Energy, Office of Power Technologies, the National Renewable Energy Laboratory, and from DynCorp Corporation, among others. See Appendix 6C "Bibliography," above.

## **Status of Evaluation Efforts by Sponsor:**

None.



## Appendix 6-E: Data Quality and Estimation Process

Input data for the supplies were provided by DynCorp Corporation (“DynCorp data base), based upon 1992 work by Sandia National Laboratory for EIA and the Geothermal Division of DOE<sup>29</sup> and reflecting earlier work by the U.S. Geological Survey and others.<sup>30</sup> The input data are available from the Office of Integrated Analysis and Forecasting, Coal and Electric Power Division. For *AEO2002*, and continued for *AEO2006*, EIA reduced these estimates from sometimes more than a thousand megawatts to usually a few hundred, in order to better represent mid-term, rather than long-term supplies.

### Fundamental Assumptions

#### Type of Resource

The GES represents hydrothermal geothermal resources, defined as large volumes of water trapped in permeable rock at depths to 11,000 feet and with temperatures ranging from 110° C to 680° C. Cost of utilizing hot dry rock resources are unknown but believed to be multiples of commercially competition values; but dry rank technologies are therefore not expected to be commercially competitive until after 2030 and are not represented in NEMS. Cost estimates are based on historical costs of exploring, confirming, and developing hydrothermal resources and installing power plants to bring additional capacity on-line at known geothermal sites.

#### Estimates of Resources

In addition to identifying the number of megawatts of geothermal generating capacity already developed, the DynCorp data base provides two estimates of the potential capacity able to be developed at each of the 51 geothermal resource sites described in the data base. The “low” estimate identifies the number of megawatts that could be developed within 20 years at the costs specified in the data base from already identified resources, including existing capacity already built. The “high” estimate reflects the number of megawatts that could be developed at those same costs, but in 40 years and from both identified and as yet unidentified resources at each site.

For *AEO2001*, EIA significantly modified the DynCorp estimates: Using the DynCorp data base and the more detailed estimates in the Sandia report, EIA converted the high estimates (40 year, including unidentified resources) for each of the 51 sites into four incremental capital cost subgroups, under the basic assumption that the greater supplies currently unidentified but becoming available at the same cost in 40 years, could only be currently identified and accessed at greater cost.

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<sup>29</sup> Sandia National Laboratory, Petty, Susan; Livesay, B.J; Long, William.P.; Geyer, John: *Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power in 20 and 40 Years*, Contractor Report SAND92-7302, Albuquerque, New Mexico, November 1992.

<sup>30</sup>Muffler, L.P.J., editor, *Assessment of Geothermal Resources of the United States – 1978*, U.S. Geological Survey Circular 790, 1978.

The various estimates prepared by Susan Petty and others and used in the deliverable and other reports basically display (a) 20 and 40 year estimates of “identified resources” and (b) 20 and 40 year estimates of “unidentified” resources, allowing EIA to distinguish and assign costs to both the 20 and 40 year time difference and the process of identification. EIA assigned a +33% drilling and other field cost premium for employing currently any capacity shown as becoming available in 40 years rather than 20; second, EIA doubled the exploration cost for any 20 or 40 year resources classified as “unidentified.”

- The first, least cost, estimate includes all identified resources in the DynCorp “low” estimate, the 20-year identified resources.
- The second, higher cost, category applies to identified capacity only becoming available in 40 years, and equals the capacity difference between the 40-year identified resources and the 20-year identified resources in step 1. Under the assumption that there is an additional field cost distinguishing 40-year availability from 20-year, EIA increased by 33% the estimated drilling and other field cost estimates for this incremental quantity. EIA did not change the assumed power plant costs for this group.
- Third, EIA separately identified from the Sandia report the 20-year estimates for identified *plus unidentified* resources, and assigned to the difference between that and identified resources in step 1 double the estimated exploration cost for this quantity of capacity. In effect, EIA doubles exploration cost”
- Fourth, EIA assumed that all remaining capacity in the difference between the 40-year identified plus unidentified (high) estimates and the 20-year identified (low) represents capacity affected by both the additional exploration and the additional drilling and field costs.

The effect of the EIA segmenting is to parcel each of the 51 sites’ potential into four increasing capital cost categories.

For *AEO2002*, and continued for *AEO2006*, EIA significantly reduced the estimates of geothermal resources supply. Cost-increasing steps introduced for *AEO2001* proved too small to prevent NEMS building hundreds or thousands of megawatts of geothermal at individual sites, far in excess of likely actual construction at any one site by 2030. Therefore, EIA introduced two steps designed to reduce both the absolute supply available at an individual site and to slow the rate of capacity expansion at sites.

- First, quantities of capacity available in individual cost steps at individual sites were greatly reduced in many cases, generally reduced to a maximum of 100 megawatts per cost step per site (and for the *AEO2005* reference case, to 25 megawatts through 2015), quantities which for *AEO2001* were many hundreds or even more than one thousand megawatts. Overall, the effect of the reduction is to reduce the total supply from any one site – especially for those likely to be competitive – from over a thousand megawatts to a few

hundred megawatts.

- Second, GES is modified to permit site and year specific limits (annual build bounds) on the number of megawatts able to be selected from a site. For the reference case *AEO2006*, a maximum of 25 megawatts new geothermal can be built at any one site for all years 2000 – 2015, and 50 megawatts per site per year thereafter; for the “high renewables case,” a limit of 50 megawatts is set for all sites for all years.

## Existing Capacity and Retirements

Existing capacity is enumerated, by facility name, on-line date, plant size, state, region, heat rate, and capacity factor, as described in the generating unit plant file showing all U.S. utility and nonutility generating units as reported on forms EIA-860A (Annual Electric Generator Report – Utility) and EIA-860B (Annual Electric Generator Report – Nonutility). Beginning with *AEO2001* EIA no longer independently assumes that geothermal units will retire at the end of their 40th year. EIA does not assume retirement dates for geothermal power plants; however, retirements are imposed when the EIA-860 respondent or other independent information externally establishes the actual or anticipated retirement.

## Exploration Costs

The DynCorp database provides per-kilowatt exploration costs for each of the 51 geothermal resource sites. However, because DynCorp calculated costs based on an estimated 250 megawatts at each site, EIA recalculated the per-kilowatt exploration cost based on the actual estimated low estimate at each resource site, thereby in most instances increasing the average per-kilowatt exploration cost.<sup>31</sup>

## Capital Costs

Capital costs in the DynCorp data base were derived from detailed resource characteristic data provided by the Sandia report and others, using the geothermal electricity supply data preprocessor (GESDPP) of the IM-GEO PC-based geothermal model.<sup>32</sup> Developed by Sandia National Laboratory in the mid 1980’s, the IM-GEO (Impacts of Research and Development on the Cost of Geothermal Power) preprocessor converts resource information about the 51 sites - including information on resource temperature, depth, and well chemistry (salinity, noncondensable gas content), flow rate per well – into site-specific capital cost components based on a 50 megawatt plant. Data inputs date from 1991 or earlier.

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<sup>31</sup> Because exploration costs must be paid and because they are usually very small, they are included in the geothermal capital costs; however, because exploration costs are usually paid before the decision for a specific power plant, the decision to build the plant is not dependent upon exploration costs. EIA’s reestimation of exploration costs can be found in the Excel file “GeoT.xls.”

<sup>32</sup> Entingh, D., Livesay, B., and Petty, S., *Geothermal Cost of Power Model IM-GEO Version 3.05: User’s Manual*, February, 1989. EIA files “IMGEO.ZIP” and “QB45.ZIP” contain the IM-GEO preprocessor and data.

## **Operations and Maintenance Costs**

As for capital costs, the DynCorp database contains each site's fixed operations and maintenance costs, separately distinguishing (a) pumps and field, from (b) power plant costs, determined based on individual site characteristics using data from Susan Petty et al, using the IM-GEO preprocessor. Pumps and field costs include an estimate for land lease costs.

## 7. Conventional Hydroelectricity Submodule

### Model Purpose

The Conventional Hydroelectricity Submodule (CHS) represents U.S. conventional hydroelectricity resources supply along with each site's technology cost and performance characteristics used to project new conventional hydroelectric capacity for central station electricity supply through the mid-term future. More specifically, the CHS –

- In the National Energy Modeling System (NEMS), provides the Electricity Market Module (EMM) Electricity Capacity Planning (ECP) submodule the available supply (megawatts) of new conventional hydroelectric generating capacity 1 megawatt or greater (and not more than 10 cents per kilowatt-hour) and its related average cost and performance characteristics based on information about known conventional hydroelectric sites.
- Reduces supply available for additional future capacity as conventional hydroelectric (“hydro”) capacity resources are used, including capacity identified from historical data, from reported plans, and from resources already chosen in earlier forecasting iterations by the ECP.
- Increases estimated levelized costs of hydroelectricity from each site based on its public acceptance, the probability of meeting environmental requirements (environmental suitability factor).
- Changes average calculated hydro capital costs, reducing them to reflect experience (learning-by-doing); short-term elasticities are not applied for conventional hydroelectric.
- For use in alternative cases, through use of capital cost weights permits changes in the assumed hydro capital costs by (a) individual site or (b) for all sites in a specific year or years.

Identification of sites and costs for use in the CHS was originally estimated by the Idaho National Engineering and Environmental Laboratory from lists assembled from Federal Energy Regulatory Commission license applications and other survey information.<sup>33</sup> However, for AEO2006 EIA staff eliminated some large sites found by inquiry to no longer exist and, for retained sites 100 megawatts or greater, replaced generalized site capacity factors with individual site capacity factors estimated by the Federal Energy Regulatory Commission.

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<sup>33</sup> Douglas G. Hall, Richard T. Hunt, Kelly S. Reeves, and Greg R. Carroll, Idaho National Engineering and Environmental Laboratory, *Estimation of Economic Parameters of U.S. Hydropower Resources* INEEL/EXT-03-00662 (Idaho Falls, Idaho, June 2003).

## Relationship of the Conventional Hydroelectricity Submodule to Other Models

The CHS interacts primarily with the ECP. Relationships between the CHS and other NEMS components include –

- CHS provides new capacity availability, performance, and cost information to the ECP for making planning decisions.
- CHS uses new capacity build decisions from the ECP to decrement available new conventional resources and capacity.
- CHS uses financial parameters and tax data for calculating ECP-based avoided costs to determine the highest cost at which new hydro supply can compete, setting the upper-cost bound of hydro supply.

## Modeling Rationale

For each NEMS region, the Conventional Hydroelectricity Submodule (CHS) develops three-part regional conventional hydroelectric supplies – total megawatts available in order of three increasing-cost per kilowatthour cost and megawatts available pairs – used in competing conventional hydroelectric technologies with fossil, nuclear, and other central station renewable energy generating alternatives, for each forecast year and region needing new generating capacity.

## Fundamental Assumptions

In the underlying hydro resource database, each named hydroelectric site is characterized by its name, location, ownership, resource, cost, and performance characteristics, notably including its (a) components of capital cost, (b) average monthly and annual capacity factors, (c) fixed and variable operating costs, and (d) estimated probability of meeting legal, cultural, and other environmental barriers, plus additional identifying information. Within each region for each model iteration within each forecast year the CHS arrays all available hydro sites from least to highest cost at or below the avoided cost (plus about 5 percent to account for market-sharing, that is, to accept some capacity that is “close” to competitive) determined in the previous model iteration (an estimate of the upper bound of likely acceptable cost in the current iteration). The CHS then segments the array into three parts, a least cost, middle, and upper cost segment, and determines the capacity-weighted average (a) capital cost, (b) operations and maintenance costs, and (c) capacity factors for each group, and then provides the EMM a conventional hydro supply in the form of three increasing levelized cost-quantity pairs of available hydroelectric capacity.

Determining the proportions of the overall cost range attributed to each segment is a significant submodule operational tool available to the analyst, enabling adjusting the submodule to influence forecast new hydro capacity. Analysts may modify the cost

proportions of the array being averaged in each segment. Decisions decreasing the proportion of the array (share of the overall range of cost) characterized in the lowest-cost segment, for example, thereby lower both the average cost of the first segment – thereby increasing the probability of being selected – but relatively decrease the quantity of capacity likely to be selected. Increasing the proportion of the overall cost range in a segment increases the amount of capacity available in that range, but increases the average capital cost of the capacity as a consequence. Moreover, because each of the three segments characterize averages, decisions regarding proportions also influence the magnitude of the increase in cost between steps, with large proportions yielding large cost increases and small steps yielding small average increases.

Input for the supplies were initially provided by the Idaho National Engineering and Environmental Laboratory (INEEL) under a project jointly funded by the US Department of Energy's Office of Energy Efficiency and Renewable Energy and the Energy Information Administration's Office of Integrated Analysis and Forecasting.<sup>34</sup> The effort is described in the publication *Estimation of Economic Parameters of U.S. Hydropower Resources*; the original database, named IHRED, "Idaho Hydropower Resource Economics Database," is available through INEEL or through EIA's Office of Integrated Analysis and Forecasting as an appendix to the report. The INEEL database, moreover, represents an initial effort in assigning cost attributes to an already developed site database, the "Hydropower Evaluation Software" (HES) database, based on (1) The Federal Energy Regulatory Commission's Hydropower Resource Assessment database developed from hydropower licensing actions, (2) the Nationwide Rivers Inventory Database developed and maintained by the National Park Service, and (3) supporting information from state resource and energy agencies.<sup>35</sup> The more recent INEEL IHRED effort supplemented the HES by providing generalized estimates of capital and other costs, as well as generalized (regional) estimates of capacity factors. Costs and other monetary values in IHRED are expressed in \$2002 (NEMS expresses these same values in \$1987).

For AEO2006, EIA modified the IHRED in the following ways: First, HES-estimated capacity factors specific to each hydro site replaced the regional generalized estimates from IHRED; in general, the specifically estimated capacity factors are lower than the IHRED factors but are considered superior, based on specific assessments of the sites. Second, in order to reduce workload, EIA eliminated from consideration all sites for which an offline estimate of the levelized cost of generation exceeded 10 cents per kilowatthour (\$2002), given the near impossibility of any such site being selected in any conceivable scenario. Third, the IHRED database was separated into two groups, "small" sites, 100 megawatts or less, and "large" sites, greater than 100 megawatts; all "small sites" were accepted. Finally, large sites were arrayed from least to highest cost and then individually reviewed to the extent permitted by time and resources, contacting site owners or state agencies to verify the existence and viability of such sites; as a result, many large sites were found unavailable (already developed, otherwise developed, now precluded by Wild and Scenic Rivers, or other circumstance making development naturally or legally

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<sup>34</sup> Contract DE-AC007-99ID13727, completed June, 2003.

<sup>35</sup> Alison M. Conner, James E. Francfort, and Ben N. Rinehart, Idaho National Engineering and Environmental Laboratory, U.S. Hydropower Resource Assessment, Final Report, Contract DE-AC07-94ID13223 (Idaho Falls, Idaho, December 1998).

impossible). Not all large sites were examined. Documentation of calculations and modifications can be found in the EIA-maintained Excel files “HydroLessThan10cents033004.xls,” and “HydroCritiqueTop100041904.xls.”

## **Resources**

The CHS characterizes economic supply of both run-of-river and storage dams for conventional hydroelectric power at new or existing sites 1 megawatt or greater. The supply includes undeveloped sites with no dam, opportunities for adding hydroelectric capacity at existing dams without hydropower, and opportunities to increase capacity at existing hydroelectric facilities.

The CHS does not represent all hydroelectric potential. First, the CHS does not represent opportunities less than 1 megawatt. Second, the CHS does not enumerate pumped storage hydroelectricity potential, an energy storage technology using off-peak coal or nuclear-powered electricity to lift water to an upper pool for later peaking hydro generation. Third, the supply also omits sites excluded from development by Federal statutes and policies, including hydro resources excluded by the Wild and Scenic Rivers Act (or sited at the upstream or downstream ends of wild and scenic streams or on a tributary, in National parks, or otherwise excluded by Federal or state law or in a Federally designated exclusion zone. Furthermore, the CHS does not represent offshore (ocean) hydro, in-stream (non-impoundment) potential, additional potential from refurbishing existing hydro capacity, or increased output opportunities from efficiency or operational improvements, any or all of which could also add to U.S. hydroelectric supply. In addition, the CHS does not represent any sites for which off-line EIA estimates made in 2004 indicated levelized per-kilowatthour costs (\$2002) greater than 10 cents per kilowatthour; moreover, EIA staff eliminated from the supply a number of sites 100 megawatts or greater that, based on contacts with owning firms, were concluded to not be available today – with the identified resources already developed, excluded from development by law, or otherwise unable to offer additional potential today. Finally, the CHS likely does not account for an unknown amount of additional conventional hydroelectric potential that might become available at known sites included in these estimates, but at higher than costs than competitive when FERC licenses were sought or surveys conducted – and therefore not estimated.

## **Capital Costs**

Overnight capital costs – and all other costs - are expressed in \$2002. Components of overnight capital costs include licensing, construction, and a range of individual environmental mitigation costs (See below) as applicable to individual sites. Construction costs include land and rights, structures and improvements, reservoirs, dams, waterways, equipment, and access roads, rail, and bridges. Construction costs were derived by INEEL primarily from 1990-2000 FERC Form I, *Annual Report of Major Electric Utilities, Licensees, and Others*.



## Learning by Doing

“Learning by Doing” refers to reductions in a technology’s capital costs as experience with the technology is gained, expressed in NEMS as a function of the total amount of capacity in place. Therefore, the capital costs of conventional hydroelectric plants decrease in NEMS as additional capacity is built.

For a description of learning by doing in NEMS, see either *Assumptions for the Annual Energy Outlook* or *Electricity Market Module of the National Energy Modeling System, Model Documentation Report* for the relevant *Outlook* year.<sup>36</sup> The Electricity Market Module (EMM) is the electricity supply component of the National Energy Modeling System (NEMS). The EMM represents the generation, transmission, and pricing of electricity. It consists of four submodules: the Electricity Capacity Planning (ECP) Submodule, the Electricity Fuel Dispatch (EFD) Submodule, the Electricity Finance and Pricing (EFP) Submodule, and the Load and Demand-Side Management (LDSM) Submodule. Conventional hydroelectricity is considered a mature technology, meaning that hydro is already well developed and that capital costs will likely decrease at the slowest rate.

NEMS also includes a minimum decrease in capital costs independent of actual builds.

## Short-Term Elasticities

In NEMS, capital costs for most technologies are assumed to increase if capacity increases rapidly within a given year, thereby temporarily squeezing supply resources (such as skilled labor, engineering, and construction expertise, and materials bottlenecks). More information for these elasticities can also be found in the *Assumptions and Documentation* reports.<sup>37</sup> These short-term elasticities are not applied to conventional hydroelectricity because U.S. and global infrastructure are currently considered fully capable of meeting all demand for the mature technology.

## Mitigation Costs – Construction Component

For sites not prohibited from development but nevertheless facing environmental mitigation requirements, the construction costs of such mitigation are individually estimated and included among capital costs derived from a variety of sources documented in the INEEL report. Individual categories of potential mitigation cost include for archeological requirements, fish and wildlife protection, scenic or recreation requirements, water quality monitoring, and fish passage requirements. All are expressed in \$2002 dollars per kilowatt and are included among capital costs.

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<sup>36</sup> For the *Annual Energy Outlook 2005* the relevant publications are *Assumptions for the Annual Energy Outlook 2005*, Washington, D.C., (DOE/EIA-0554(2005), February, 2005), “Electricity Market Module,” and *Electricity Market Module of the National Energy Modeling System, Model Documentation Report 2005*, Washington, D.C., (DOE/EIA-M068(2005), March, 2005), “Electricity Capacity Planning Submodule.”

<sup>37</sup> For the *Annual Energy Outlook 2005* the relevant publications are *Assumptions for the Annual Energy Outlook 2005*, Washington, D.C., (DOE/EIA-0554(2005), February, 2005), “Electricity Market Module,” and *Electricity Market Module of the National Energy Modeling System, Model Documentation Report 2005*, Washington, D.C., (DOE/EIA-M068(2005), March, 2005), “Electricity Capacity Planning Submodule.”

## Mitigation Costs – Public Acceptance Component

IHRED-estimated mitigation costs account for the “bricks and mortar” construction costs of mitigation requirements. To account for the litigation, licensing, and public acceptance costs of mitigation, EIA adapted for costing a particular feature developed for the HES database, namely the HES environmental “suitability factor” representing an estimate of the probability of a hydro project’s successful development in light of all individual environmental characteristics of the site. Suitability factors range from 0.90, the greatest probability of meeting environmental requirements and being developed, through 0.75, 0.50, 0.25, and finally, 0.10. The HES included no estimates of the costs of overcoming likely objections. However, EIA incorporated into its submodule an arbitrary estimate of levelized additional costs per kilowatthour, in order to represent the added costs of meeting environmental requirements – such as for legal challenges, studies, public outreach, etc. - in addition to the engineering costs already accounted:

If Site Probability = 0.90, then add 0.00 mills to levelized cost (\$2002 converted to \$1987)

If Site Probability = 0.75, then add 3.00 mills to levelized cost (\$2002 converted to \$1987)

If Site Probability = 0.50, then add 5.00 mills to levelized cost (\$2002 converted to \$1987)

If Site Probability = 0.25, then add 8.00 mills to levelized cost (\$2002 converted to \$1987)

If Site Probability = 0.10, then add 10.00 mills to levelized cost (\$2002 converted to \$1987)

Adders of the size assigned to 0.25 and 0.10 probability sites in most cases almost certainly eliminates the sites from practical consideration and greatly reduces the competitive potential of 0.50 sites as well. Changing the costs associated with site probabilities offers another opportunity for analyst influence on hydro supply costs.

## Fixed Operation and Maintenance Costs

Fixed Operation and Maintenance (O&M) costs include operation and maintenance supervision and engineering, and maintenance of structures, reservoirs, dams, waterways, and electric plant; where applicable, fixed O&M includes the FERC annual charge noted below. Fixed O&M costs were derived from FERC Form I data 1990-2001 and are expressed in \$2002 per kilowatt per year.

## FERC Annual Charge

For plants with a capacity greater than 1.5 megawatts, FERC charges plant owners an annual fee based on plant capacity and annual generation. Using an estimate of constant annual generation derived by INEEL from 1999 charges, the FERC annual charge is considered part of fixed O&M.

## Variable Operation and Maintenance Costs

Variable O&M maintenance costs, also derived from FERC Form I data, include estimates for charges for water for power, hydraulic and electric expenses, miscellaneous hydraulic power expenses, and rents. Variable O&M is expressed in \$2002 mills per kilowatthour.

## Capacity Factors

The IHRED database contains both estimated monthly and annual capacity factors for each site. However, EIA replaced these regional average annual capacity factors with the individually determined annual capacity factors established by FERC or in other specific studies underlying the HES database; monthly IHRED capacity factors were then modified in proportion to the annual factor adjustment. In general, the individual capacity factors are lower than the generalized estimates. Moreover, EIA also applied exceptions, using the IHRED estimate or 65 percent (whichever was lower) for undeveloped sites for which no FERC capacity factor was available, and 35 percent for incremental capacity for which no FERC capacity factor was available. Where the FERC capacity factor exceeded 65 percent for new sites or 35 percent for incremental capacity, EIA assigned either 65 percent or 35 percent, given that the EIA bound, while arbitrary, is higher than the averages for known sites, and the FERC values appear to often be in error (at times exceeding 100 percent).

## Heat Rates

Conventional hydroelectric facilities tend to be highly efficient; the Federal Energy Regulatory Commission cites modern hydroelectric turbines to be about 90 percent efficient (90 percent of input energy converted to output electricity), suggesting an average input heat rate equivalent under 3800 Btu per kilowatthour.<sup>38</sup> Nevertheless, in NEMS and for *AEO2006* EIA employs the common convention of assigning to conventional hydroelectricity the heat rate of the fossil fuels presumed to be displaced by hydropower rather than its own equivalent heat rate, about 10,280 Btu per kilowatthour.

## Alternative Approaches

Prior to developing the conventional hydroelectric submodule, EIA staff extensively polled hydroelectricity analysts and organizations, including contacts and ongoing exchange with the American Hydropower Association, Oak Ridge National Laboratory, the Bonneville Power Administration, the Tennessee Valley Authority, and others. Although many annual

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<sup>38</sup> Federal Energy Regulatory Commission, *Hydroelectric Power Resources of the United States, Developed and Undeveloped* (Washington, D.C. January 1, 1992), page xx. Applying the 90 percent efficiency cited by FERC to the 3412 Btu per kilowatthour energy content of electricity yields an input heat rate of 3,791 input Btu per kilowatthour.

and short-term regional forecasting models of expected output from existing hydroelectric capacity can be found, no models of mid or longer term hydroelectric supply were found, either of resources expressed in terms of economic supply or in terms of their competition with other central station electricity supplies.

## Conventional Hydroelectricity Submodule Structure

The CHS “SUBROUTINE HYDRO” has five basic components:

1. **Incorporates data:** On its initial iteration, subroutine “GET\_HYSITE\_DATA” reads the hydro site data from the “HYDSITE.TXT” input data file containing records of each individual hydroelectric site, including state and NEMS region, nameplate capacity, capital and O&M cost components, and capacity factors. Subroutine “GET\_HYDATA” reads in the annual capital cost multipliers, build bounds, public acceptance mitigation costs and the supply curve cost segment ranges from the input data file, “WHYDRO.TXT”. Together the two build the HYDSITE conventional hydroelectric supply structure. Capital costs are the sum of licensing, construction, and environmental mitigation costs; both fixed and variable O&M costs are incorporated; there are no fuel charges for hydro, although the FERC annual charge is included, where applicable, with fixed O&M. The annual capital cost multipliers are applied to the capital costs before leaving the “GET\_HYSITE\_DATA” subroutine. The cost multipliers will usually have the value 1.00 for reference cases and various values <1.00 for alternate scenarios such as the high renewables case.
2. **Develops overall regional conventional hydroelectric supplies:** In each iteration, subroutine “BLD\_HYD\_CURVES” first creates NEMS regional conventional supplies for each NEMS region (Alaska and Hawaii are processed in the hydro submodule but not used by EMM). Within each NEMS region, sites are arrayed from least to greatest in order of estimated levelized cost, resulting in an aggregate conventional hydroelectric supply for each region in each iteration, in the array “HYDCURVE”.
3. **Provides sub-supplies for specific regional demands:** For each iteration of the EMM, the CHS determines the maximum levelized cost (avoided cost) at which hydroelectric supply in each region can compete. The maximum competitive value is (1) the levelized cost of the highest-cost technology actually selected in the immediately prior iteration of the ECP plus (2) an additional percentage representing the market-sharing algorithm.<sup>39</sup> The average value of the market-sharing algorithm is about 17 percent. As a result, all remaining hydroelectric capacity able to generate at or below 1.17 times the previous iteration’s highest cost

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<sup>39</sup> The market-sharing algorithm exists in recognition that in real markets technologies that are “close” in cost to the least cost technology will occasionally be selected for economic and other reasons not represented in the modeling. Under the sharing algorithm, the closer in cost a specific other technology is to the least cost technology, the greater (yet small) share of the available market will be taken by that technology.

selection is offered as new hydroelectric supply in the current iteration. Next the subroutine “BUILD\_HYD\_CURVES” segments each region’s aggregate hydro supply among three increasing-cost quantity pairs using capacity-weighted average per kilowatthour costs, such that the EMM receives for each region three quantities of available conventional hydroelectric capacity at three increasing levelized costs, plus for each the capacity-weighted capital cost, O&M costs and seasonal and annual capacity factors. The least-cost group includes all unused capacity in the least cost price quartile (capacity whose levelized cost is equal to or less than +25% of the gross cost difference between the least-cost unused hydro capacity and the ECP-adjusted avoided cost (Note: the quantity is not the least-cost 25 percent of capacity, but whatever proportion of capacity occurs in the lowest 25 percent of the cost range). The second group includes all capacity between the 25<sup>th</sup> percentile and the 75<sup>th</sup> percentile; and the third group includes all remaining capacity above the 75<sup>th</sup> cost percentile. All available capacity in each cost group is then conveyed to the EMM as available supply, with one levelized cost associated with each group; the one levelized cost transmitted for each group equals the capacity-weighted levelized average cost for the individual sites’ costs within the group. Changing percentage thresholds constitutes a model variable enabling the analyst to choose lower or higher initial thresholds; the consequence of lower thresholds is lower average costs – and greater ability to compete – but reduced quantities available to compete, whereas higher thresholds yield greater supplies but higher (and less competitive) average costs. Recognizing that the three segments yield significant increases in average costs (discontinuities) from one step to the next, the choice of thresholds can result in significant differences in NEMS selections of conventional hydroelectric capacity, particularly if choices have the effect of limiting supply to one (or none of) the segments.

4. **Decrements available capacity:** Within subroutine “BUILD\_HYD\_CURVES”, for each iteration CHS reduces available conventional hydroelectric capacity in each region in response to (a) external reports of new hydro builds in the region or (b) selection by the EMM in earlier iterations.
5. **Provides diagnostics:** For each iteration, Subroutine “WRITE-HYDB” provides diagnostic information on hydroelectric capacity and sites chosen and technology costs and performance. Diagnostics provided through Excel output file “hydro\_out.xls” include:

**Hyd\_Input\_Data** displaying quantities of capacity available at each hydroelectric site;

**Hyd\_Curve\_Data** displaying in least-to-highest cost order each hydro site’s capacity and estimated per kilowatthour cost;

**Hyd\_Curve\_Info** displaying aggregate conventional hydro supplies and average per kilowatthour cost as available in each NEMS region for each forecast year, values transmitted to the Electricity Market Module (EMM) as aggregate

hydroelectric supply; and

**Hyd\_Builds** displaying quantities of conventional capacity built in each NEMS region in each forecast year.

# Key Computations and Equations

This section describes the most important equations in the CHS.

## *Reading the Data*

In the first iteration, data for the hydro sites is read in from the **HYDSITE** input file by the CHS subroutine, **GET\_HYSITE\_DATA**. The site data is stored in the **HYDSITE** data structure, which is defined below. Subroutine **GET\_HYDATA** reads the hydro parameters from the input file **WHYDRO**.

### **HYDSITE Data Structure:**

|            |   |
|------------|---|
| PROJNAME   | Project Name  |
| PROJNUM    | Project Number  |
| STATE      | State Location  |
| SITE_ID    | Site ID   |
| NERC       | EMM Region  |
| LATITUDE   | Latitude  |
| LONGITUDE  | Longitude   |
| CLASS      | Site Class Code, C=Coop, F=Federal, I=Industrial, M=Municipal., P=Private Utility, R=Private Non-Utility, N/A=Not Available   |
| UNITTYPE   | C=Conventional, R=Reversible, Z=Missing   |
| PLNTTYPE   | Plant Type  |
| PROJSTATUS | Project Status  |
| DAMSTATUS  | Dam Status  |
| WSPROT     | Wild/Scenic Protection Y=Yes, N=No  |
| WSTRIB     | Wild/Scenic Tributary, Location Y=Yes, N=No   |
| ENVVALUES  | Environmental Values, Y=Yes, N=No<br>1=Cultural Value, 2=Fish, 3=Geological, 4=Historical, 5=Other, ie. rare wetland, wilderness designation, 6=Recreation<br>7=Scenic, 8=Wildlife, 9=Threatened/Endangered Wildlife<br>10=Threatened/Endangered Fish   |
| LANDCODES  | Federal Land Codes, Y=Yes, N=No<br>1=FLC103, National Park, Monument, Rec area, etc.,<br>2=FLC104, National Forest or Grassland,<br>3=FLC105, National Wildlife Refuge, Game Preserve, or Fish Hatchery<br>4=FLC106, National Scenic Waterway or Wilderness Area<br>5=FLC107, Indian Reservation<br>6=FLC108, Military Reservation<br>7=FLC198, Not on Federal Land |
| SITEPROB   | Project Environmental Suitability Factor<br>.10 = Development prohibited or highly unlikely   |

.25 = Major reduction in likelihood of development  
 .50 = Likelihood of development reduced by half  
 .75 = Minor reduction in likelihood of development  
 .90 = Little effect on likelihood of development

|                         |  |
|-------------------------|--|
| LISCCOST                | Licensing Cost 1987 \$K  |
| CONSCOST                | Construction Cost 1987 \$K   |
| DEVCOST                 | Overnight Development Cost 1987 \$K                                  |
| MIT_ARCH                | 30 Year Archaeological and Historical mitigation cost 1987 \$K       |
| MIT_FISH                | 30 Year Fish and Wildlife mitigation cost 1987 \$K                   |
| MIT_SCEN                | 30 Year Scenic and Recreation mitigation cost 1987 \$K               |
| MIT_WATER               | 30 Year Water Quality Monitoring Cost 1987 \$K                       |
| MIT_PASS                | 30 Year Fish Passage cost 1987 \$K                                   |
| MIT_TOTAL               | Total mitigation cost 1987 \$K                                       |
| TOTDEV_COST             | Total Development Costs (Mit_Total + Devcost) 1987 \$K               |
| UNITDEV_COST            | Total Unit Development Costs 1987 \$/KW                              |
| COE                     | Levelized Cost 1987 mills/kwh  |
| CAP_COST                | Capital Cost 1987 \$/KW  |
| TOTFOM_COST             | Avg Annual Fixed O&M Cost 1987 \$K                                   |
| TOTVOM_COST             | Avg Annual Variable O&M Cost 1987 \$K                                |
| FOM_COST                | Avg Annual Fixed O&M Unit Cost 1987 \$/KW                            |
| VOM_COST                | Avg Annual Variable O&M Unit Cost 1987 mills/kwh                     |
| FERC_COST               | FERC Annual Charge (Applicable if >= 1.5 MW) 1987 \$K                |
| UNITFERC_COST           | FERC Annual Charge Unit Cost (Applicable if >= 1.5 MW)<br>1987 \$/KW |
| POTENTIAL_CAP           | Potential Capacity (MW)  |
| CAPCOST_MULT            | Yearly Capital Cost Multipliers by Hydro Sites                       |
| CAP_COST_ADJ            | Capital Cost Adjustment Factors                                      |
| MON_CAPACITY_FACTOR(12) | 0.00 TO 1.00 - monthly capacity factors                              |
| AVG_CAPACITY_FACTOR     | 0.00 TO 1.00 - average annual capacity factors                       |

In each iteration, the capital, O&M, and levelized cost of energy for each site is calculated, with capital costs adjusted for learning and technological optimism. Technological optimism and learning effects are estimated in subroutine ELEC\_OPT in the electricity capacity planning (ECP) submodule of the EMM.

### **Building Regional Hydrothermal Supplies**

In each iteration, supplies at each site are merged with costs from other sites in the region and arrayed for competition in the ECP in each region. The CHS first constructs a complete array of increasing levelized cost/quantity pairs as the cumulative hydrothermal supply available for the region. CHS then segments the competitive part of that array into three generalized increasing cost segments, passing to the ECP the total capacity available in each increasing cost segment along with the capacity-weighted cost and performance parameters for the segment.



In each region and in each iteration, the CHS receives a maximum cost from the EMM, a value equal to the COE of the highest cost capacity previously selected in each region, called the Regional Avoided Cost, plus the market-sharing tolerance (about 17 percent). This avoided costs is used to determine the competitive part of the arrayed costs.

$$\text{Avoided Cost} = (\text{Regional Maximum Prior COE}) * (1.0 + \text{Market Sharing Tolerance})$$

The subroutine “**BUILD\_HYD\_CURVES**” iterates within each region until the capacity available in the first (lowest cost) step is greater than zero or 10 iterations have occurred, incrementing the threshold cost 10 percent for each iteration. The cumulative values calculated in this subroutine include:

|                        |   |
|------------------------|---|
| <b>AVAIL_SUPPLY</b>    | = Megawatts available for each record                               |
| <b>CUM_SUPPLY</b>      | = Cumulative sum available megawatts in each region                 |
| <b>SYS_CAP_COST</b>    | = Cumulative capacity-weighted capital cost, 3 segments             |
| <b>SYS_CAP_FAC</b>     | = Cumulative capacity-weighted capacity factor, 3 segments          |
| <b>SYS_MON_CAP_FAC</b> | = Cumulative capacity-weighted monthly capacity factors, 3 segments |
| <b>SYS_COST</b>        | = Cumulative capacity-weighted COE, 3 segments                      |
| <b>SYS_VOM_COST</b>    | = Cumulative capacity-weighted Variable O&M cost, 3 segments        |
| <b>SYS_FOM_COST</b>    | = Cumulative capacity-weighted Fixed O&M cost, 3 segments           |

From these cumulative values **BUILD\_HYD\_CURVES** then determines the specific value for the cost and performance variables for each of the 3 segments of available hydrothermal supply in each region. The cost and performance variables calculated include:

|                    |                            |
|--------------------|----------------------------|
| <b>CAP_COST</b>    | = Capital cost             |
| <b>CAP_FAC</b>     | = Capacity factor          |
| <b>MON_CAP_FAC</b> | = Monthly Capacity factors |
| <b>FOM_COST</b>    | = Fixed O&M Cost           |
| <b>VOM_COST</b>    | = Variable O&M cost        |

The above values are calculated as weighted averages as shown in the equations below:

$$\text{Average\_Capital\_Cost} = \frac{(\sum_i (\text{CAP\_COST}_{(i)} * \text{Capacity}_{(i)}))}{\text{Cumulative\_Capacity}}$$

$$\text{Average\_FOM\_Cost} = \frac{(\sum_i (\text{FOM\_COST}_{(i)} * \text{Capacity}_{(i)}))}{\text{Cumulative\_Capacity}}$$

$$\text{Average\_VOM\_Cost} = \frac{(\sum_i (\text{VOM\_COST}_{(i)} * \text{Capacity}_{(i)}))}{\text{Cumulative\_Capacity}}$$

$$\text{Average\_Cap Fac} = \frac{(\sum_i (\text{CAP\_FAC}_{(i)} * \text{Capacity}_{(i)}))}{\text{Cumulative\_Capacity}}$$

$$\text{Average\_Mon\_Cap Fac} = \frac{(\sum_i (\text{Sum} (\text{MON\_CAP\_FAC}_{(i)} * \text{Capacity}_{(i)}))}{\text{Cumulative\_Capacity}}$$

The CHS passes the ECP actual values only for the first of the three segments; values for steps 2 and 3 are expressed as weights applicable to the values in the first segment. The variables passed to the EMM include:

**EMM\_CAP\_COST**  
**EMM\_CAP\_FAC**  
**EMM\_MON\_CAP\_FAC**  
**EMM\_CAPACITY**  
**EMM\_VOM\_COST**  
**EMM\_FOM\_COST**

### **Other Features of the Hydrothermal Submodule**

Construction Lead Time, Construction Cost Profile, and First On-Line Year: In the CHS, new hydrothermal plants are constructed over a 4 year time period, with capital costs allocated in the annual proportions 15%, 22%, 30%, and 33%. For AEO2006 the first year in which a new hydrothermal plant can enter service is 2009.

Learning, Short-Term Elasticities, and Technological Optimism: Capital Costs for hydrothermal generating technologies are affected by learning-by-doing as are all generating technologies, as well as by technological optimism. For a description of these characteristics and assumptions and values assigned hydrothermal for AEO2006, see “ Electricity Market Module “ Assumptions to the Annual Energy Outlook 2006.<sup>40</sup>

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<sup>40</sup> Energy Information Administration, *Assumptions to the Annual Energy Outlook 2005 (AEO2005)*, DOE/EIA-0554(2005), (Washington, D.C.) April 2005.

## Appendix 7-A: Inventory of Variables, Data and Parameters

Values for this inventory are included in the body of this chapter, along with reference to the Excel files supporting the conventional hydroelectricity submodule. Questions about the submodule can be directed to:

Chris Namovicz  
Energy Information Administration  
(202) 586-7120  
[cnamovicz@eia.doe.gov](mailto:cnamovicz@eia.doe.gov)

Data files for the CHS are maintained in the Coal and Electric Power Division (CEPD). The INEEL deliverable is also available through CEPD.

For the *AEO2006* reference case, Excel file “Hydro\_Out1.xls” maintained by CEPD, contains the conventional hydroelectric supply input values.

## Appendix 7-B: Mathematical Description

Questions about the CHS algorithm can be directed to –

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The conventional hydroelectricity submodule computes the levelized cost of energy for three increasing cost segments of conventional hydroelectric supply in each NEMS region in each NEMS iteration for each forecast year. Rationales are explained in the “Model Purpose” and “Fundamental Assumptions” portion of this documentation. The levelized cost for each site is calculated as follows:

$$\text{COE}(i) = ( ( \text{CCST}(i,y) + \text{LCST}(i,y) + \text{MCST}(i,y) ) * \text{FCF}(r) * \text{LFACT}(y) * \text{OPFACT}(y) ) + \text{FOM}(i) + \text{FERC}(i) ) / ( \text{CF}(i) * 8760.0 * 1000.0 ) + \text{VOM}(i) + \text{PUBCOST}(i)$$

Where:

$i$  = Hydrothermal Site  $i$

$y$  = Current Year

$r$  = NEMS Region

$\text{COE}(i)$  = Levelized cost of energy for hydrothermal site  $i$ .

$\text{CCST}(i,y)$  = Construction costs for hydrothermal site  $i$  in year  $y$ , \$/KW.

$\text{LCST}(i,y)$  = Licensing costs for hydrothermal site  $i$  in year  $y$ , \$/KW.

$\text{MCST}(i,y)$  = Total mitigation costs for hydrothermal site  $i$  in year  $y$ , \$/KW.

$\text{FCF}(r)$  = Fixed Charge Factor in EMM region  $r$  for hydrothermal technology, fraction.

$\text{LFACT}(y)$  = Learning Factor for hydrothermal technology in year  $y$ , fraction.

$\text{OPFACT}(y)$  = Technological Optimism Factor for hydrothermal technology in year  $y$ , fraction.

$\text{FOM}(i)$  = Fixed O&M costs for hydrothermal site  $i$ , \$/KW.

$\text{FERC}(i)$  = FERC Annual Charge for hydrothermal site  $i$ , 1987 \$/KW

$\text{CF}(i)$  = Capacity Factor for hydrothermal site  $i$ , fraction.

$\text{VOM}(i)$  = Variable O&M costs for hydrothermal site  $i$ , mills/kwh.

$\text{PUBCOST}(i)$  = Public Acceptance Cost for hydrothermal site  $i$ , mills/kwh

The levelized costs by hydrothermal site are then sorted from least to highest cost, resulting in an aggregate regional hydrothermal supply array. These regional supply arrays are then used to generate the three step EMM supply curves.

## Appendix 7-C: Bibliography

Conner, Alison M. , Francfort, James E., and Rinehart, Ben N., Idaho National Engineering and Environmental Laboratory, *U.S. Hydropower Resource Assessment, Final Report*, Contract DE-AC07-94ID13223 (Idaho Falls, Idaho, December 1998).

Federal Energy Regulatory Commission, *Hydroelectric Power Resources of the United States, Developed and Undeveloped* (Washington, D.C. January 1, 1992).

Hall, Douglas G., Hunt, Richard T., Reeves, Kelly S., and Carroll, Greg R., Idaho National Engineering and Environmental Laboratory, *Estimation of Economic Parameters of U.S. Hydropower Resources* INEEL/EXT-03-00662 (Idaho Falls, Idaho, June 2003).

## Appendix 7-D: Model Abstract

### Model Name:

Conventional Hydroelectricity Submodule

### Model Acronym:

CHS

### Description:

The CHS converts lists of identified available US conventional hydroelectric potential and costs into 3-part increasing-cost regional supplies (quantity-cost pairs) for each NEMS region for each forecast year. Input data for each site includes its state and NEMS region, components of capital cost, fixed and variable operations and maintenance costs, and capacity factors. All sites able to produce electricity at or below an avoided cost determined by NEMS in the previous forecast cycle (adjusted upward for market sharing) become eligible to compete as new hydroelectric supply averaged among one of the 3 increasing cost groups. After selecting some capacity, the CHS decrements the available supply for the next iteration by the amount taken in the current cycle.

### Purpose of the Model:

The purpose of the CHS is to provide the Electricity Capacity Planning module (ECP) the amounts of available conventional hydroelectric generating capacity, their costs, and performance characteristics for competition in the ECP for new regional electricity supply.

### Most Recent Model Update:

The CHS is introduced for the *Annual Energy Outlook 2004*.

### Part of Another Model?:

The CHS submodule is a component of the Renewable Fuels Module (RFM) of the National Energy Modeling System (NEMS).

## **Official Model Representative:**

Chris Namovicz  
Energy Information Administration  
(202) 586-7120  
cnamovicz@eia.doe.gov

## **Documentation:**

This chapter constitutes the documentation of the CHS

## **Archive Media and Installation Manual(s):**

The CHS is archived as part of NEMS production runs.

## **Energy System Described:**

Conventional hydroelectric supply potential 1 megawatt or greater for impoundment sites (a) undeveloped, (b) with dams but no hydroelectric, or (c) with potential for additional hydro; the supply does not include pumped storage opportunities, in-stream (non-impoundment) potential, ocean-current potential, or refurbishments of existing capacity or operational changes increasing output.

## **Coverage:**

- Geographic: EMM regions 1 – 13 (Note: Alaska and Hawaii are included in the database and processed in the submodule, but excluded from the EMM).
- Time Unit/Frequency: Annual 1990 through 2030.
- Products: Electricity
- Economic Sectors: Central Station Electricity Generators

## **Modeling Features:**

- Modeling Structure: The model operates at the level of individual conventional hydroelectric sites aggregated to segmented EMM regional averages.
- Model Technique: Levelized electricity costs from each supply segment of each site in each region are arrayed in increasing cost order, then aggregated into three increasing average-cost segments in each iteration in each year, along with attendant quantities (megawatts) and average heat rates and capacity factors.
- Incorporates short-term cost elasticities of supply, technological optimism, and learning.

**Input Sources:**

The primary input for the conventional hydroelectricity supply is the contract work prepared specifically to support the modeling, carried out by the Idaho National Engineering and Environmental Laboratory, Hall, Douglas G., Hunt, Richard T., Reeves, Kelly S., and Carroll, Greg R., Idaho National Engineering and Environmental Laboratory, *Estimation of Economic Parameters of U.S. Hydropower Resources* INEEL/EXT-03-00662 (Idaho Falls, Idaho, June 2003). The INEEL contract work integrated information from other documents cited in the section 6-C “Bibliography” section of this documentation.

**Independent Expert Reviews Conducted:**

None. However, the CHS methodology was presented at a May 10, 2005 Renewable Energy Modeling Forum with the specific purpose of exposing the submodule to independent expert review. Representatives from Oak Ridge National Laboratory, the National Energy Renewable Laboratory, The Tennessee Valley Authority, Resources for the Future, and other organizations are beginning to review the CHS and the list of potential hydroelectric sites.

**Status of Evaluation Efforts by Sponsor:**

None.