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Model Documentation

Renewable Fuels Module

of the National Energy Modeling System

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Contents

Tables

Figures

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 1998* (*AEO98*) 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.

For *AEO98*, the RFM was modified in three principal ways, introducing capital cost elasticities of supply for new renewable energy technologies, modifying biomass supply curves, and revising assumptions for use of landfill gas from municipal solid waste (MSW). In addition, the RFM was modified in general to accommodate projections beyond 2015 through 2020. Two supply elasticities were introduced, the first reflecting short-term (annual) cost increases from manufacturing, siting, and installation bottlenecks incurred under conditions of rapid growth, and the second reflecting longer term natural resource, transmission and distribution upgrade, and market limitations increasing costs as more and more of the overall resource is used. Biomass supply curves were also modified, basing forest products supplies on production rather than on inventory, and expanding energy crop estimates to include states west of the Mississippi River using information developed by the Oak Ridge National Laboratory. Finally, for MSW, several assumptions for the use of landfill gas were revised and extended.

Renewable Fuels Module Summary

The RFM consists of five analytical submodules that represent major renewable energy resources—biomass, municipal solid waste (MSW), solar (thermal and photovoltaic), wind, and geothermal energy.

The purpose of the RFM is to define the technological, cost and resource size characteristics of renewable energy technologies. They are provided to the Electricity Market Module (EMM) for grid-connected electricity capacity planning decisions. The characteristics include available energy

capacity, capital costs, fixed operating costs, variable operating costs, capacity factor, heat rate, construction lead time, and fuel product price.

Implemented for *Annual Energy Outlook 1997* (*AEO97*), 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 which are unique to specific renewable energy technologies, specific files and subroutines are used, such as for resource values for time slices for intermittent renewables.

Other renewables modeled elsewhere in NEMS include conventional hydroelectric (in the EMM), biomass in the industrial sector, ethanol in the Petroleum Market Module (PMM), wood in the residential sector, geothermal heat pumps 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 market; however, as these markets develop in importance they will be analyzed for their representation in NEMS.

The number and purpose of the associated technology and cost characteristics varies 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. As another example, the MSW Submodule's capital and operating cost characterization is used by the EMM solely to help determine electricity prices. Unlike the other RFM technology characterizations, the MSW-to-energy facility characterization is not used to compete MSW energy against other energy sources. This modeling treatment stems from the assumption that MSW energy, as a byproduct of the waste removal process, is fully utilized as it is produced.

Cost and performance values for RFM variables are often determined by EIA's Office of Integrated Analysis and Forecasting (OIAF). In addition, several sources for the cost and performance characterizations were examined for use in the RFM. The primary additional source is the Electric Power Research Institute's 1993 *Technical Assessment Guide* (EPRI TAG). The sources provide values for capital costs (excluding the construction financing and 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 five RFM submodules that are used for producing the *AEO98* forecasts: the Municipal Solid Waste Submodule (MSW), the Wind Energy Submodule (WES), the Solar Energy Submodule (SOLES), the Biomass Submodule, and the Geothermal Electricity Submodule (GES). The EMM's role in defining hydropower data is also described. The chapter concludes with information on the RFM archival package and EIA point of contact.

Municipal Solid Waste Submodule (MSW)

The Municipal Solid Waste Submodule provides annual projections of energy produced from the incineration of municipal solid waste (MSW) and estimates of landfill gas capacities. The Submodule uses the quantity of MSW produced (derived from an econometric equation that uses Gross Domestic Product and U.S. population as the principal forecast drivers), the heating value of a pound of MSW, and shares of MSW combusted for energy recovery. In addition, the landfill gas capacity is estimated based on reported waste and gas production data and judgement about future trends. The MSW Submodule supplies the utility sector (EMM) with capital and operating cost information. This cost information is only used by the EMM to calculate electricity prices; MSW-produced power is viewed as a byproduct of a community's waste disposal activities and only secondarily as a competitive alternative to other fuels for energy production.

Wind Energy Submodule (WES)

The Wind Energy Submodule (WES) projects the availability of wind resources as well as the cost and performance of wind turbine generators. This information 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 which are matched to electricity load curves within EMM.[1]

Solar Submodule (SOLAR)

Two solar technologies are represented in NEMS, a 5-megawatt fixed-flat plate central station photovoltaic (PV) unit, and a 200-megawatt central receiver (power tower) solar thermal (ST) unit. Both technologies are grid-connected, 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.

[1]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.

Biomass Submodule

The Biomass Submodule furnishes cost and performance characteristics for a biomass burning electricity generating technology to the EMM. The technology modeled for the *AEO98* is the 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 and energy crops.

Geothermal Electricity Submodule (GES)

The purpose of the GES is to model current and future regional supply, capital cost, and operation and maintenance costs of electric generating facilities using hydrothermal resources (hot water and steam). These resources are limited to the three western EMM regions: 11, 12, and 13. The data are assembled from 51 sites information which reflect the specific resource conditions of that location. The GES generates a regional resource supply curve for geothermal capacity consisting of the 51 geothermal sites. It truncates the supply curve based on the avoided cost for the construction and operation of new regional capacity and passes averaged cost and performance values of the truncated supply curve to the EMM.

Of the 51 geothermal sites represented in the GES, 49 are located in the regions 11, 12, and 13 and two are Hawaiian resource sites (region 14). The two Hawaiian sites, however, are not considered since EMM's capacity planning decisions are limited to regions 1 through 13.

Conventional Hydroelectric Plant Data

The assignment of conventional hydroelectric plant data resides in the EMM. The hydroelectric power data represent reported planned new conventional hydroelectric power capacity connected to the transmission grid. Reported plans are obtained from annual EIA power plant surveys (Forms EIA-860, EIA-759, EIA-867). Hydroelectric power does not compete with other power technologies for additional unplanned capacity.

Representation of Short-Term Elasticity for the Installation of New Technology

Rationale

Beginning with the *AEO98*, the NEMS Electricity Capacity Planning Module (ECP) includes a short-term elasticity of supply for the installation of new electricity generating technologies. The elasticity reflects the expectation that rapid expansions in the supply of installations using new generating technologies will incur shortages of critical input resources. Shortages reflect manufacturing bottlenecks. Shortages also represent limits on information - such as identification and resource assessment of specific sites' biomass, geothermal, solar, or wind conditions - bottlenecks in regulation, licensing, and public approval, and constraints incurred from shortages of construction and operation personnel and equipment.

Therefore, for *AEO98*, U.S. generating capacities of new generating technologies are permitted to increase substantially without incurring bottleneck costs, but above some rate of increase begin incurring increasing costs. For *AEO98*, in any future year, U.S. capacity can increase 25 percent over the previous year's total without any increase in capital costs. However, for every 1 percent increase in capacity greater than 25 percent, capital costs are assumed to increase ½ percent. By defining the threshold as a percentage of the existing installed capacity, the threshold criterion is dynamic, that is, the allowable amount of acceptable no-cost escalation capacity growth increases as the overall rate of capacity growth increases.

Methodology

The short-term elasticity represents additional capital cost that accounts for bottleneck phenomena in manufacturing, sales distribution, site selection, licensing, resource preparation, and installation of new energy technologies.

The Fortran program calculating the short-term elasticities resides in the RFM submodule; user-defined inputs reside in the RFM data file "rendat;" calculated prices and quantities resulting from the elasticity calculation are submitted to the ECP.

The representation of the short-term elasticities is based on percentage change of U.S. installed capacity of a technology. It is expressed by an exponential cost function that relates an increase in capacity exceeding a capacity threshold to a cost multiplier. This functional relation can be expressed as:

$$P_{elast} = P_{current} * (1-a_0)\left[\left(\left(\frac{C_{addition}}{C_{current}}\right) - a_{thres}\right)^{\frac{\ln(1+a_2)}{\ln(1+a_1)}} - 1\right] \qquad \text{(1-1)}$$

where:

P_{elast} = capital cost associated with capacity addition of $C_{addition}$ in [$/kW],
$P_{current}$ = current capital cost in [$/kW],
a_{thres} = threshold above which elasticity is active, defined as percent increase based on current installed capacity,
a_1 = increase in capital cost for every a_2 increase in capacity, faction,
a_2 = increase in capacity, fraction,
$C_{addition}$ = capacity additions in [MW],
$C_{current}$ = current capacity in [MW],
a_o = binary switch parameter [0,1] is defined as:

$$a_0 = \begin{cases} 0 \text{ if } \left(\frac{C_{addition}}{C_{current}}\right) \leq a_{thres} \\ 1 \text{ if } \left(\frac{C_{addition}}{C_{current}}\right) > a_{thres} \end{cases} \quad \text{(1-2)}$$

For *AEO98*, every 1 percent national increase in capacity over a capacity threshold, incurs a ½ percent increase in capital cost. The capacity threshold is currently set to 25 percent of current installed capacity. No changes in cost are incurred for annual capacity additions that are 25 percent or less than installed capacity. By defining the threshold as a percentage of the installed capacity, the threshold criterion is dynamic, i.e. the absolute capacity in [MW] is increasing with as the model builds a renewable technology.

Currently, the parameters are specified as:

a_{thres} = 0.25
a_1 = 0.01
a_2 = 0.005

expressing the following relation:

The cost elasticity relation of equation (1) is divided into three distinct points that represent the characteristics of the equation. The cost elasticities are used to establish a three step supply relation for the installation of renewable energy technology in the Electricity Capacity Planning (ECP) Module. A three step supply relation was chosen as a practical optimum that achieved a balance between the accurate approximation of the characteristics of the elasticity function and the need to limit the number of new decision variables in the ECP.

Passed to the ECP are three supply steps for each renewable energy technology. A supply step is defined by a cost multiplier (i.e. the cost elasticity) and the corresponding capacity for which the cost multiplier is valid. The ECP incorporates the supply steps in its LP framework.

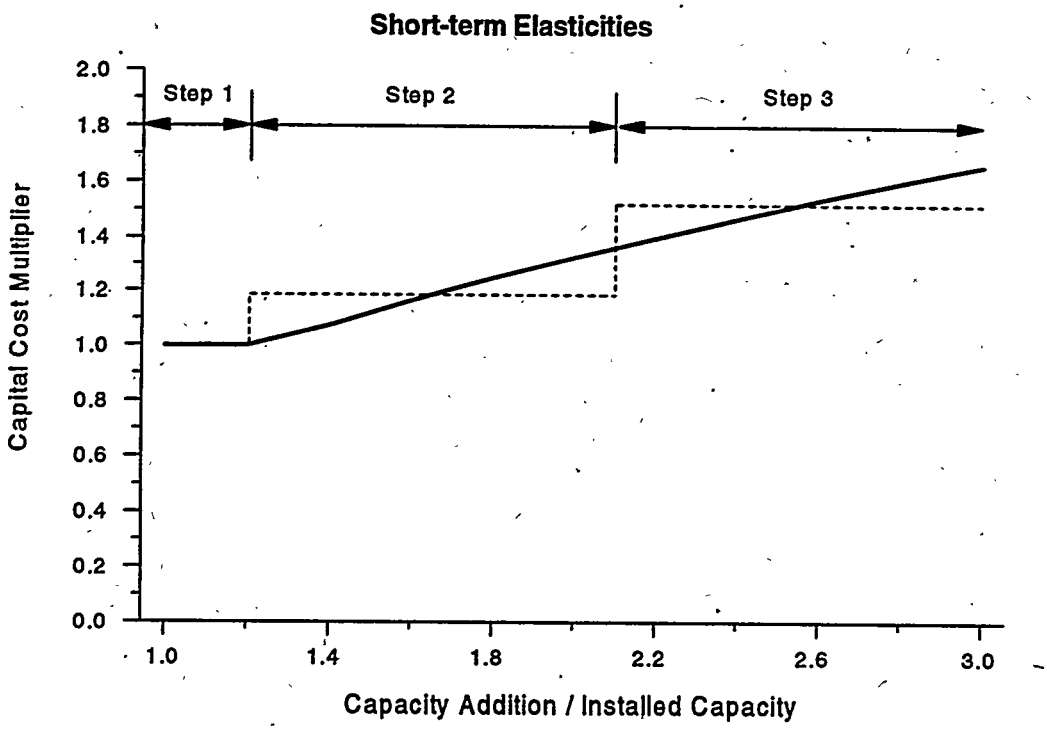
To represent the entire supply curve by three distinct steps, the following method was used:

(1) The supply curve must be truncated to present the ECP with the best degree of resolution for a relevant capacity addition range. The truncation of the supply curve is specified by the user. The truncation is formulated as a normalized capacity addition based on the installed total national capacity of a technology. Currently the supply curve is limited to a value of 3 times the current on-line capacity.

(2) The first point on the supply curve is defined by the threshold capacity addition (25 percent of the current capacity) with a cost multiplier of unity.

(3) The second and third points linearly approximate the log linear supply curve of equation (1-1) (Figure 1).

Figure 1. Representation of Capital Cost Supply Function



The definition of the three supply steps is user defined. The steps can be specified in the RFM input file 'rendat'.

Representation of Resource-Related Elasticity for the Installation of New Technology

Rationale

For *AEO98*, capital costs for generating technologies using biomass or wind resources are assumed to increase as a function of exhaustion of most favorable biomass or wind 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 competing for other uses of the resource, including increasing costs in meeting environmental concerns.

As a result, for *AEO98*, each EMM region's total biomass and wind resources are parceled among three broad ranges, including an initial resource share incurring no capital cost penalty, a second share for which capital costs are assumed to increase 25 to 50 percent, and a final share (all remaining resources) for which capital costs increase 100-250 percent over initial cost. Resource proportions vary by technology and region.

Methodology

The resource-related elasticity accounts for the additional capital costs that are not reflected in the RFM cost characterizations. EIA benchmarked the estimates of the elasticities using regional renewable energy market and resource assessments (reference: Northwest Power Planning Council study, and CEC).

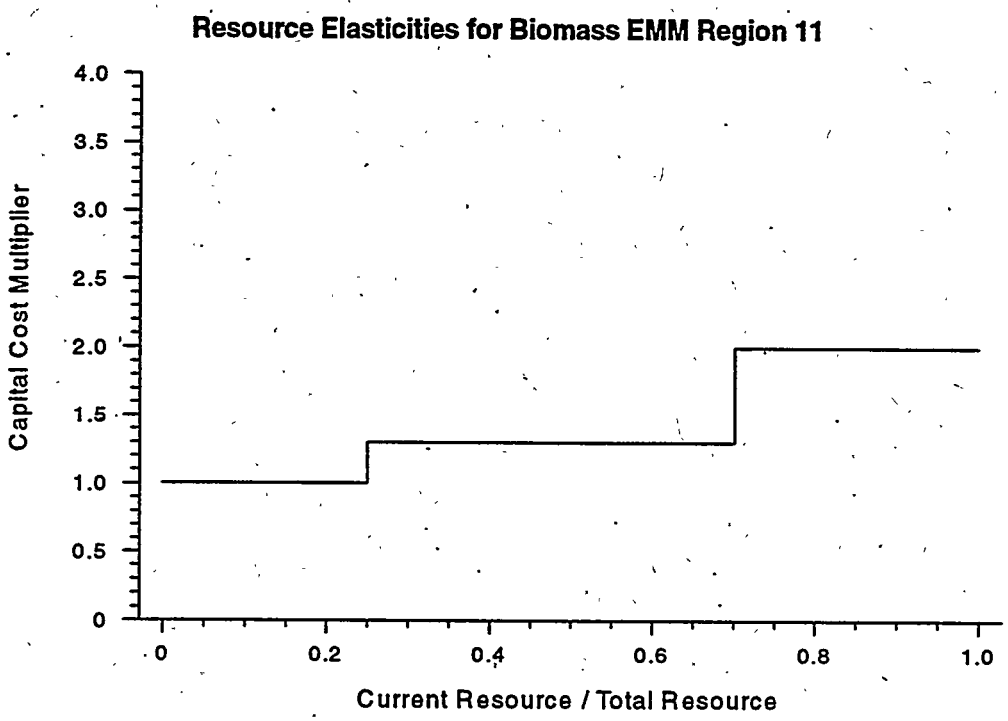
Because of the regional differences of the resource allocations and availability, the resource-related elasticity is defined by regions and formulated as a cost multiplier. Consistent with the short-term elasticity, a step function with three steps was formulated to be able to superimpose both elasticities to one combined representation of cost elasticities (Figure 2).

The step function is normalized by the total available resource in [MW] for a technology in the current year and region. The user specifies the step function in the input data file 'rendat'.

The Fortran program calculating the resource-related elasticities resides in the RFM submodule; user-defined inputs reside in the RFM data file "rendat;" calculated prices and quantities resulting from the elasticity calculation are submitted to the ECP.

Each year, the RFM determines the combined installed and planned capacity for each region and technology, calculates the total available resource remaining, and determines the cost multiplier associated with a particular step in the elasticity function.

Figure 2. Typical Resource-related Cost Elasticity for the Biomass Technology in Region 11 (Northwest)



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 summarization 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. Municipal Solid Waste (MSW) Submodule

Model Purpose

The main purpose of the Municipal Solid Waste (MSW) Submodule is to provide EMM with annual projections of electric power capacity of waste to energy plants (WTE) for municipal solid waste (MSW). It also furnishes the cost and performance characteristic of a generic incinerator technology to the EMM. The submodule uses the quantity of MSW produced, the heating value of MSW, and shares of MSW combusted for energy recovery to produce forecasts of the future electric power capacity. Added to this capacity projection are estimates for landfill gas capacity.

Relationship of the MSW Submodule to Other Models

The MSW submodule passes capacity estimates and cost and performance characteristics of the MSW incinerator technology to the EMM for capacity planning decisions. Beginning with *AEO97*, MSW cost and performance characteristics which are defined consistent with fossil and other characteristics reside in EMM's input file ECPDAT. Cost parameters such as tipping fees are evaluated in the MSW and converted into a variable O&M cost figure before it is passed to the EMM.

Unlike all other submodules of the Renewable Fuels Module, the MSW Submodule does not compete with alternative electricity generating technologies. Rather, forecasted MSW electricity production is accepted fully by the EMM and therefore used to reduce the amount of electricity demand that must be satisfied by all other supply sources. This treatment of MSW electricity production in NEMS stems from MSW energy being viewed primarily as a byproduct of a community's waste disposal activities rather than a competitive alternative to other fuels.

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

Modeling Rationale

Theoretical Approach

The modeling methodology employs a simple linear MSW supply function and multiplicative energy allocation shares for deriving disaggregated MSW electricity production forecasts. The methodology consists of four major steps. First, the total quantity of MSW in the United States is projected using a multivariate regression estimation to derive parameters for the MSW supply equation (an add factor representing the impact of MSW source reduction is also included in the

equation). Second, the current and future heat value of a typical pound of MSW is assessed for estimating the potential quantity of energy that can be produced from combusting MSW. Third, estimates of the total U.S. capacity to burn MSW with heat recovery are obtained using analyst judgement of factors affecting community approval and investments in WTE facilities. Fourth, regional projections of energy from MSW combustion are obtained by multiplying together MSW quantities, Btu heating values, percentages of MSW combusted, and sectoral energy allocation shares based on regional population distributions. Finally, regional landfill gas capacity estimates are added to the capacity projection for MSW combustion.

Because of the byproduct nature of MSW energy, the relatively small quantity of MSW in the U.S. energy mix, and the complexity of modeling the municipal WTE market, a simple modeling approach that excludes the consideration of energy demand, price, and technology investment signals from other NEMS modules was selected. One of the major limitations of this approach is that there are no economic or financial links for determining key parameters, especially the share of MSW combusted and the regional distribution of WTE energy capacity.

Fundamental Assumptions

MSW Quantity Projections

The definition of MSW for the initial regression in the MSW 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.

Projected Btu Value of MSW

The Btu value of a typical pound of MSW is changing rapidly in response to changes in the usage and disposal of specific materials. Curlee (1992) provides information on the historical and projected composition of MSW in terms of the waste stream's material composition. In this

estimate, the Btu value of one pound of MSW has increased from about 3,800 Btu in 1960 to about 5,100 Btu in 1990.

There are numerous factors that influence the Btu value of combusted MSW. For example, marketing efforts have been responsible for the gradual replacement of glass and some metal with plastic, especially for containers. Partially counteracting these marketing efforts are restrictions that have been successfully implemented in some States to limit the usage of plastics in selected packaging. Many communities require that yard waste (which has a low energy content) to be collected separately from other wastes and composted rather than burned or landfilled. Other communities simply restrict households from disposing of their yard waste along with other MSW. The number of curbside recycling programs is increasing, and most collect and recycle both plastics and paper (the highest Btu components of the waste stream), and glass and metals (from which no caloric value can be extracted).

Combining EPA projections of this changing MSW mix with the heat content of waste components, Curlee projects a total heat content for MSW of 5,569 Btu per pound of waste in the year 2000. It was assumed by EIA that, post-2000, the heat content would increase to 6,214 Btu by year 2015, based on the expectation that continued removal of low-Btu waste stream components (metal, glass, and yard waste) and continued increases of high-Btu components (paper and plastic) would occur. It is not believed that the relationship of GDP to tons generated will be affected by such changes.

Projected Percentage of MSW Combusted With Heat Recovery

Projections of WTE market penetration, and therefore the share of generated municipal waste combusted, are difficult to make. Projections for the near term—i.e., the next 5 years—can be based on existing data on WTE projects in the planning and construction phases. Consideration should be given to expected unit cancellations, which have occurred more frequently in recent years. The methodology adopted for the MSW Submodule beyond 1995 assumed that the fractions of MSW combusted for energy recovery remained constant throughout the model horizon.

Disaggregation Rules

National projections for energy from MSW are disaggregated into regional totals according to the geographical dispersion of current and planned WTE facilities. Information used for disaggregating MSW energy comes from the Form EIA-867 data for nonutility generators, modified as appropriate for NEMS. This database product includes information on locations, types of energy produced, ownership type, etc. for all existing U.S. WTE facilities, as well as those being planned.

Given that no data currently exist to indicate how these breakdowns may change beyond 1996, it is assumed that the percentage of total WTE capacity allocated to a region remains constant after 1996. Additional research into regional characteristics that could influence the shares, such as land

values or recycling markets, may result in an improved approach for disaggregation of projected national totals.

Generating capacity of the MSW units is calculated by dividing the output by heat rate, combustion capacity factor, and yearly hours. This quantity is expanded by adding an amount for capacity utilizing landfill gas as fuel before passage to the EMM.

Landfill Gas Use

As part of an analysis of potential greenhouse gas emissions, EIA has developed an approach to estimating methane emissions from U.S. landfills.[2] This approach was used as a basis and expanded to produce projections of generating capacity which uses a portion of these emissions. The procedure, off-line to NEMS, is contained in a spreadsheet which accumulates emissions from different vintages of landfilled waste.

The spreadsheet was expanded to include projected volumes of waste and an estimate of the share that will be landfilled (consistent with the estimated share combusted) to provide projected emissions. The methane generated is calculated by combining the amount of landfilled waste with yield values that vary by how easily the waste decomposes, as well as by a time profile. The portion of these emissions captured for energy conversion is assumed to increase by a factor of about three by year 2020, based on U.S. EPA estimates of new installations of landfills. The Btu value of the gas, heat rate and capacity factor are applied to these projections to provide capacity projections. The simplifying assumption is made that all the captured gas is converted to electricity.[3] This capacity total is added to the capacity for MSW combustion before being shared out to the EMM regions and passed to the EMM.

Capital and Operating Costs

The MSW submodule supplies the EMM with capital and operating costs as components in the determination of electricity prices. In lieu of actual cost data from WTE facilities, the MSW Submodule employs technology cost characterization information from the EPRI 1989 Technical Assessment Guide (TAG). Information for the mass burn technology is selected because this technology is the most common of three technology types.[4] For both capital and operating costs, the TAG assumes a WTE plant size of 40 megawatts with a single combustion unit.

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[2]Science Applications International Corporation, *Updated Estimates of Methane Emissions from U.S. Landfills*, (McLean, VA, June 1997).

[3]Units that are dedicated to electricity generation, or are co-generators, constitute over 97 percent of the total WTE combustion capacity.

[4]Mass burn WTE units combust MSW without preprocessing, other than the removal of large items from the feed system. Refuse Derived Fuel (RDF) facilities combust waste that has been preprocessed (i.e., sorted and shredded to increase the heating value). A third technology type—modular combustors—are small, prefabricated units. Mass burn units constitute 39 percent of operating WTE units and 79 percent of planned WTE units.

An important component of the WTE facility operating cost is the tipping fee. The tipping fee is a per-ton charge assessed to waste removal firms for depositing the MSW at the disposal site. Because the tipping fee is a revenue source, the MSW Submodule treats the tipping fee as a negative fuel cost.

At this time there are insufficient data on how tipping fees are determined, although it is likely that they are the balancing factor in plant economics. A complication with tipping fees is that some plants are privately owned, others are publicly owned, and subsidies may be involved in either case. As a result, tipping fee values are currently assumed to remain constant for all forecast years.

Alternative Approaches

Only two other sources of energy projections from MSW combustion have been identified -- the Solar Energy Research Institute (SERI, 1990) and Klass (1990). The projections from those reports are discussed in Curlee (1991). MSW energy projections given in Curlee (1991), which are based on the methodology adopted for the MSW Submodule, are significantly higher than those contained in the reports by SERI (SERI, 1990) and Klass (Klass, 1990). Note that MSW is one of several renewable energy sources evaluated in both the Klass and SERI studies, and the underlying assumptions and modeling methodologies are not explained sufficiently in either study to discuss and compare the differences between their approaches and the MSW Submodule approach. No other models of MSW energy consumption and production were identified in the research supporting the development of the MSW Submodule.

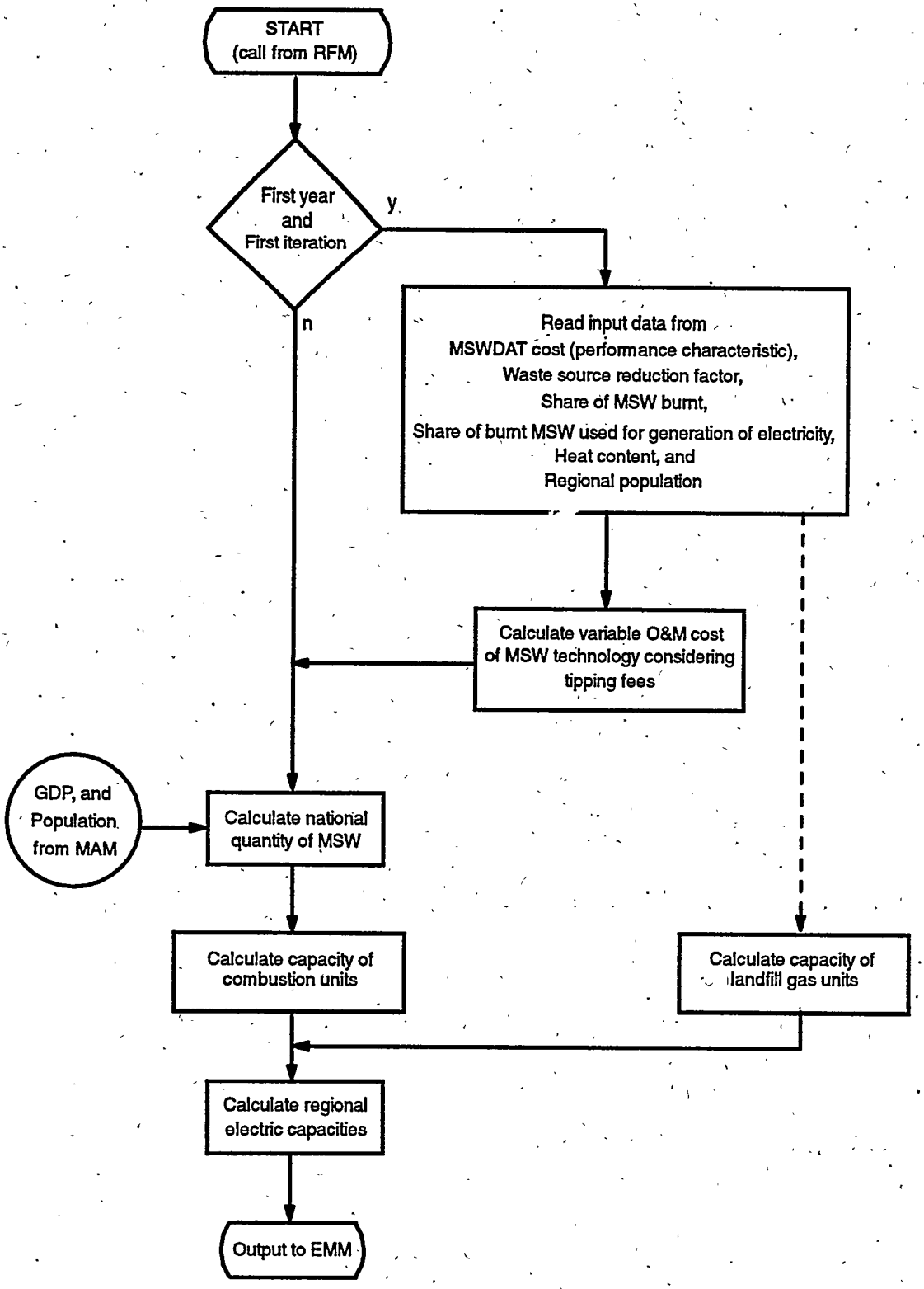
A key aspect of the selected modeling approach involves the application of expert judgement for specifying the projected regional fractions of MSW combusted for energy. (These fractions are multiplied by available MSW in order to determine the projected MSW quantities available for energy recovery.) Ideally, judgements concerning projected combustion fractions should be combined with an analysis of cost and capacity trends involving the reduction, recycling, composting, landfilling, processing, and combusting of MSW. However, relative cost information for the various alternatives to manage MSW is currently considered inadequate, and is therefore not used.

MSW Submodule Structure

Submodule Flow Diagram

This section presents a flow diagram (Figure 3) of the MSW Submodule that shows the Submodule's main computational steps and data relationships.

Figure 3. Municipal Solid Waste Submodule Flowchart



Key Computations and Equations

The MSW Submodule is largely independent of the rest of the RFM with the exception of obtaining the projected GDP and population values for the Macro Analysis Model. The projections are generated in two parts and then combined. These components are generating capacity of waste-to-energy (WTE) units and landfill gas-fueled units.

The WTE projection performs basic calculations of the waste stream, energy produced, and capacity for all years and regions by operating on RFM values contained on the file MSWDAT.

The landfill gas values are computed in a separate spreadsheet with a similar approach to the calculation for waste stream, energy, and capacity. These regional values are read in and added to the WTE values.

Variable operating costs are combined with the negative of the tipping fee and this value, the capital cost, and the capacity projections are passed to the EMM.

The formula for many 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 MSW 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 Municipal Solid Waste Submodule Inputs and Outputs

Model Variable	Definition and Dimensions	Source	Units
INPUT DATA			
F	Fraction of MSW combusted for use *U* and sector *S* in Census division *r*	Form EIA-867	Unitless
HC	MSW heat content values in Census division *r* in year *y*	Franklin Associates and Office of Technology Assessment	Btu/lb of MSW
*UPHTRT**	MSW heat rate for electricity production	Government Advisory Associates Oak Ridge	Btu/kWh
PCC	Percent combusted for Census division *r* in year *y*	Franklin Associates and EIA staff Oak Ridge	unitless
*UPMCF**	Capacity factor of a WTE plant	EPRI TAG	unitless
*UPOVR**	Capital cost for a WTE plant	EPRI TAG	$/KW
MSTIPPNR	Tipping fee for MSW in Census division *r*	Chupka, et al	$/ton
*UPFOM**	Fixed O&M cost for a WTE plant	EPRI TAG	mills/kWh
WVC	Variable O&M cost for a WTE plant	EPRI TAG	mills/kWh
SR	Annual source reduction factor	EIA staff	Percentage
TCLANDF	Total national electric capacity from landfill gas in year *y*	determined by EIA	MW
LFSHR	Share of total electric capacity fueled by landfill gas in EMM region *n*	determined by EIA	unitless
a_1	Regression coeff. representing GDP dependency	regressed by EIA	10^6ton/$10^9$$
a_2	Regression coeff. representing population dependency	regressed by EIA	10^6ton/10^6capita
α	waste stream adjustment factor	determined by EIA	unitless

Table 2A-1. NEMS Municipal Solid Waste Submodule Inputs and Outputs (Continued)

Model Variable	Definition and Dimensions	Source	Units
CALCULATED VARIABLES			
MC_GDP	Real gross domestic product for year *y*	determined in MAM	Billion $
MC_POPAFO	U.S. Population incl. Overseas armed forces	determined in MAM	10^6
Q	Quantity of energy from municipal solid waste for generation of electric power in EMM region *n*		MMBtu per year
QNAT	Quantity of municipal solid waste produced in the U.S.		million tons per year
WCAMSEL	MSW electric capacity for utilities in EMM region *n* in year *y*		Megawatts
WVCMSEL	Variable O&M cost of MSW electric generating capacity in EMM region *n* in year *y* adjusted for tipping fees		mills/kWh

*Assigned in EMM input file ECPDAT.

MODEL INPUT: *F*

DEFINITION: Fraction of total MSW generated that is combusted for generation of electricity in EMM region *n*

Once the total amount of MSW that is combusted for energy has been determined, it must be allocated among uses (electricity or other), regions, and sectors (commercial, industrial, and utility). The allocation factor matrix *F* accomplishes this task by using historical and 1995 projected plant level data from the Governmental Advisory Associates (GAA) 1991 Resource Recovery Database.

SOURCES: Oak Ridge National Laboratory, "Data and Sources: Biomass Supply Draft Report," prepared for EIA under Contract No. DE-AC05-84OR21400, Oak Ridge, TN, June 27, 1993, p. 13-14.

Government Advisory Associates, *Resource Recovery Yearbook* and 1991 Resource Recovery Database, 177 East 87th Street, New York, NY, 1991.

MODEL INPUT: *HC*

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 historic 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 Office of Technology Assessment. 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 increasing trend. Beyond 2000, it was assumed that HC remains level for the duration of the forecast horizon.

SOURCES: Oak Ridge National Laboratory, "Data and Sources: Biomass Supply Draft Report," prepared for EIA under Contract No. DE-AC05-84OR21400, Oak Ridge, TN, June 27, 1993, p. 7-10.

Franklin Associates, "Characterization of Municipal Solid Waste in the United States: 1994 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, November 1994.

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.

MODEL INPUT: *UPHTRT*

DEFINITION: Heat rate for WTE plants

The heat rate is assumed 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: *PCC*

DEFINITION: Percent MSW combusted EMM region *n*

Estimates of percent of MSW combusted for 1960 through 1990 were obtained from Franklin Associates. Data for the years after 1990 are projections based on analyses conducted by EIA staff.

SOURCES: Franklin Associates, "Characterization of Municipal Solid Waste in the United States: 1994 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, November 1994.

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.

MODEL INPUT: *UPMCF*

DEFINITION: Capacity factor for a MSW incinerator

SOURCES: Oak Ridge National Laboratory, "Data and Sources: Biomass Supply Draft Report," prepared for EIA under Contract No. DE-AC05-84OR21400, Oak Ridge, TN, June 27, 1993, p. 19.

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 a MSW incinerator

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

MODEL INPUT: *MSTIPPNR*

DEFINITION: Tipping fee charged for MSW in EMM region *n*

The tipping fee is structured as a negative adjustment to the variable O&M cost, WVCMSEL. Tipping fees were calculated based on data from Chupka, Howarth, and Zoi. The tipping fees, originally expressed in dollars per ton of MSW, are aggregated to EMM regions using MSW facility consumption weighting factors, converted to real 1987 dollars, and then transformed into mills-per-kilowatthour.

SOURCES: Chupka, Marc, D. Howarth, and C. Zoi. *Renewable Electric Generation: An Assessment of Air Pollution Prevention Potential*. EPA/400/R-92/005, U.S. Environmental Protection Agency, 1992.

National Solid Waste Management Association, "1990 Landfill Tipping Fee Survey," Washington, DC.

MODEL INPUT: *UPFOM*

DEFINITION: Fixed operation & maintenance (O&M) cost MSW incinerator

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: Oak Ridge National Laboratory, "Data and Sources: Biomass Supply Draft Report," prepared for EIA under Contract No. DE-AC05-84OR21400, Oak Ridge, TN, June 27, 1993, p. 19.

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 a MSW incinerator 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.

Oak Ridge National Laboratory, "Data and Sources: Biomass Supply Draft Report," prepared for EIA under Contract No. DE-AC05-84OR21400, Oak Ridge, TN, June 27, 1993, p. 19.

MODEL INPUT: *WVC*

DEFINITION: Variable O&M cost for MSW incinerator

Variable represents the unadjusted O&M cost for MSW incinerators.

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

Oak Ridge National Laboratory, "Data and Sources: Biomass Supply Draft Report," prepared for EIA under Contract No. DE-AC05-84OR21400, Oak Ridge, TN, June 27, 1993, p. 19.

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: 1994 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, November 1994.

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: 1994 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, November 1994.

MODEL INPUT: α

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," April issue, 1993.

Franklin Associates, "Characterization of Municipal Solid Waste in the United States: 1994 Update," prepared for the Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, November 1994.

Appendix 2-B: Mathematical Description

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

The MSW 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.

$$QNAT_y = (a_1 * MC\_GDP_y + a_2 * MC\_POPAFO_y) \quad \textbf{(2B-1)}$$

where:

$QNAT_y$	=	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_GDP_y	=	gross domestic product in year y, in [10^9 \$] (chain weighted)
MC_POPAFO_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:
where:

$$QNAT'_y = QNAT_y * (1-(y-1)\ SR) * \alpha \quad \textbf{(2B-2)}$$

$QNAT'_y$	=	Adjusted national annual waste stream in year y, in [10^6 ton]
y	=	NEMS year
SR	=	source reduction factor[5]
α	=	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 *Biocycle* magazine.[6]

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

[5]Allaway, David, "Does Source Reduction Work?", *Resource Recycling*, July 1992, pp. 52-61.
[6]"The State of Garbage in America" (repeated annually), *Biocycle*, April/May, 1989-1997.

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. Also, as of 1992 at least 38 States have passed laws mandating that disposal of their municipal waste streams be reduced by 25 percent or more by no later than the year 2000 (Glenn, 1992). Such 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 judgement to derive the *SR* parameter that is currently 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, α, is computed as a multiplier on the equation to represent the inclusion of these items. The value for α is the average of the incremental differences between the EPA value and one presented in an annual survey by *Biocycle* magazine. The value applies to all regions the same. While its empirical nature is a strength, the Biocycle value is deficient in that there is a lack of quality control, especially in that the definition of MSW may vary by State.

Fraction of MSW Combusted

The combustion fractions used in the MSW Submodule reflect a modest resumption of the use of WTE facilities over the long-term. Currently, the industry has slowed to a near-halt after a burst of construction activity in the mid-1980's. There are several factors driving the current status. First, there continues to be a general wariness of the environmental effects of the technology, however, the issue of the proper handling of ash has largely been resolved. Second, there has been a modest overbuilding of landfill capacity and while these new landfills must meet the revised RCRA Subtitle D regulations, their large size offers economies of scale that result in tipping fees comfortably below that required at a WTE unit. Third, the Supreme Court ruling restricting the use of local flow control ordinances has made the financial viability much more risky. Such ordinances required all waste from a jurisdiction to go to a designated facility, thereby guaranteeing a supply of waste and fees.

The current values for percent of waste combusted assume a constant share over the model horizon. A slight growth in capacity results as the waste stream continues to grow.

Using the waste stream $QNAT_y'$ in the equation (2B-2), the energy utilized for the generation of electricity can be determined as:

$$Q_{n,y} = QNAT_y' * PCC_n * F_n * HC_y * 2{,}000 * WNRPOP_n \quad \textbf{(2B-3)}$$

where:

$Q_{n,y}$ = energy used for generation of electricity in region n in year y, in [10^6 BTU],
$QNAT_y'$ = adjusted national waste stream in year y in [10^6 ton],
PCC_n = share of total MSW burnt in region n, dimensionless,
F_n = share of burnt MSW used for generation of electricity in region n, dimensionless,
HC_y = heat content of MSW in year y, in [BTU/lb],
$WNRPOP_n$ = share of national population in region n, dimensionless.

The electricity capacity is then computed as:

$$WCAMSEL_{n,y} = \frac{Q_{n,y}}{WHRMSWL_{n,y} * WCFMSEL_{n,y} * 8760} + TCLANDF_y * LFSHR_n \quad \textbf{(2B-4)}$$

where:

$WCAMSEL_{n,y}$ = MSW electric capacity in region n in year y, in [MW],
$WHRMSEL_{n,y}$ = heat rate in region n in year y, in [BTU/kWh],
$WCFMSEL_{n,y}$ = capacity factor for MSW incinerators in region n in year y, dimensionless,
$TCLANDF_y$ = total national electric capacity from landfill gas in year y, in [MW],
$LFSHR_n$ = share of total landfill capacity located in region n, dimensionless.

The exogenous variables of equations 2B-1, 2B-2, 2B-3, and 2B-4 are read in from the input file 'mswdat'.

Equation 2B-5 calculates WTE facility variable operating costs:

$$WVCMSEL_{n,y} = WVC - MSTIPPNR_n \quad \textbf{(2B-5)}$$

where:

$WVCMSEL_{n,y}$ = RFM variable operating cost common block variable for WTE facilities in EMM region n in year y,
WVC = Variable operation & maintenance cost in mills per kilowatthour,
$MSTIPPNR_n$ = Tipping fee in mills/kWh for a WTE plant for EMM region n.

Appendix 2-C: Bibliography

Biocycle, *"The State of Garbage in America,"* April and May issues, 1989-1997.

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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:
Municipal Solid Waste Submodule

Model Acronym:
MSW

Description:
The submodule uses the quantity of municipal solid waste produced (derived econometrically), the heating value of MSW, and forecasted shares of MSW combusted for energy recovery to produce forecasts of the production of electricity; projections of electricity from landfill gas are added.. Forecasts are disaggregated by region.

Purpose of the Model:
The MSW Submodule provides the NEMS Electricity Market Module with annual regional projections of energy produced from the incineration of municipal solid waste and 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:
October 1996.

Part of Another Model?:
The MSW submodule is a component of the Renewable Fuels Module (RFM) of the National Energy Modeling System (NEMS).

Official Model Representative:
Roger Diedrich
Coal, Uranium, and Renewable Fuels Analysis Branch
Energy Information Administration
Phone: (202) 586-0829

Documentation:
Model Documentation Report, Renewable Fuels Module of the National Energy Modeling System, January 1998.

Archive Media and Installation Manual(s):
Archived as part of the NEMS production runs.

Energy System Described:

Byproduct energy production and consumption from the combustion of municipal solid waste.

Coverage:

- Geographic: Thirteen modified EMM regions.
- Time Unit/Frequency; Annual, 1990 through 2020
- Products: generating capacity
- Economic Sectors: electric utility sector

Modeling Features:

- Model Structure: Sequential calculation of forecasted national municipal solid waste (MSW) 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

Computing Environment:

- Hardware Used: IBM RS 6000
- Operating System: unix
- Language/Software used: VS FORTRAN, Ver. 2.05

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 MSW Submodule, along with a discussion of user-defined parameters and guidelines used to select them.

A principal driver of the MSW 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.

Conversion of the waste stream to energy takes several steps, beginning with division into management methods, an extrapolation of current shares. The share to be burned in a WTE plant is reduced to reflect the portion used to produce direct heat. This is based on existing EIA survey data contained in the plant file. The heat content is derived from the literature but is a fairly stable value. Distribution to model regions is done according to population which was estimated from State-level census data.

Conversion of the energy values to capacity was performed by applying heat rates, which are known from current units and contained in the EIA data, and a capacity factor which is estimated nationally and used for all units.

The portion of capacity that was projected from the landfilled share of the waste is estimated in a separate spreadsheet. 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 region. 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 40 percent by 2020. 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, renewable energy production incentives under EPACT, construction profiles, and optimism and learning characteristics - are input directly from the ECPDAT file in the EMM.

The combination of wind supplies and technology costs yields regional wind technology cost supply information to the EMM.

Only grid-connected central station (50 megawatt scale) wind plants are considered. Projections are based on the performance of a defined, currently operational horizontal wind turbine, the Zond Z-48 750 kilowatt, horizontal axis wind turbine (HAWT).

After convergence, the EMM provides the WES information on installed wind capacity. WES then calculates the remaining wind resources available for future installations.

Relationship of the Wind Submodule to Other Models

As a submodule of the RFM, WES provides its output through, and receives data through, the RFM. WES is initiated by a call from the RFM. The RFM then provides input to and receives data from the EMM.

The WES model 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 energy per unit swept rotor area, and the annual capacity factor. The second array is calculated from the subperiod energy percentages and subperiod definitions. All other input data, such as economic life, construction profile, fixed operation and maintenance costs, the forced outage rate, and other values, are passed directly to the EMM. The model generates a 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 season), differ in distance from transmission lines, and may be precluded from use for environmental or other economic reasons. 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. Winds are defined in the WES by wind power class and by proximity to power transmission lines.

The submodule begins with estimates of land area exhibiting specified ranges of average annual wind speed. It uses the moderate exclusion scenario, which excludes lands assumed prohibited for other uses; it further differentiates the areas by average distances from transmission lines, and finally estimates the quantities of generating capacity remaining available in each forecast year in each wind quality-distance category. For use in calculating efficiencies and costs, WES also maintains data on 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 30-year life.

Substantial commercial wind installations have existed since the early 1980's. Counts of these pre-existing installations are used to adjust figures on 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 overnight capital cost, construction profile, fixed operations and maintenance costs, subsidies (e.g. renewable energy production incentive 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 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 height of 10 meters:

WES Wind Class	Average Annual Wind Speed (mph)
Class 1	Above 14.5 mph
Class 2	13.4 - 14.5 mph
Class 3	12.4 - 13.4 mph

The land area available for wind plant development has been extracted from data produced at Battelle Pacific Northwest Laboratory (PNL) in support of DOE's National Energy Strategy. In producing the Wind Energy Resource Atlas, PNL staff attempted to account for variations in such factors as anemometer height and placement through measures such as making determinations regarding the validity of data and extrapolating the wind speeds to a standard height.

PNL developed their area assessments of available resources by breaking down their wind resource maps into one-third degree longitude by one-quarter degree latitude grids. These grid cells formed the basic unit for which wind power and land availability were estimated. Because of resolution limitations, details of wind resource were lost, particularly in mountainous and coastal areas. Since wind speed estimates in mountainous regions apply only to those areas free of obstructions, only a fraction of the areas shown in the Atlas are actually available for development. These fractions were estimated by PNL when producing areal estimates.

PNL developed scenarios covering a range of land exclusion amounts. The WES input data are based on the "moderate" exclusion scenario, which excludes all environmentally protected lands (such as parks and wilderness areas), all urban lands, all wetlands, 50 percent of forest lands, 30 percent of agricultural lands, and 10 percent of range and barren lands.

Second, windy land areas are further disaggregated - or eliminated - by distance from existing transmission 115kV or 230kV transmission lines:

Zone	Land Distance from Transmission Line (miles)
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 2-½, 5, and 10 miles.

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 and the energy capture of each turbine. For *AEO98*, EIA assumes an array of contemporary horizontal axis wind turbines, the Zond Z-48, spaced 5 rotor diameters between turbines and 10 rotor diameters between turbine rows. Using estimated capacity factors, CALMWA and the WES then calculate the electric generating capability that can be placed within the area.

Finally, wind supply increments, expressed in megawatts, are provided the EMM, first by wind class (Class 1 first) and then by distance (within wind class). As a result, all Class 1 wind resources are exhausted before any Class 2 or Class 3 resources.

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.

Elasticities

Capital costs for wind technologies increase as a function of either short-term or resource-constraint elasticities. The short-term elasticity (see page 5 and following pages) 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. For wind, every 1 percent addition of new U.S. generating capacity in one year more than 25 percent greater than total capacity in the prior year results in a ½ percent increase in capital costs.

Resource-constraint elasticities represent the increased costs of using less efficient or more costly land and wind resources for reasons of (1) resource quality - for example, steep or rough terrain or wind sheer, (2) costs of upgrading existing transmission and distribution networks, or (3) cost increases in competition with other uses, including for environmental reasons. For wind, each EMM region's wind resources fall among three classes, the first enjoying no capital cost increase, the second a 50 percent increase, and the third a 250 percent increase in capital cost. Proportions vary among the EMM regions as a function of external information about the region's wind resources. For most regions (though not necessarily for the most critical regions), 10 percent of regions' resources fall in each of the first and second classes, with the remainder assumed to be highest cost.

Alternative Approaches

In most national-level energy models, wind technologies have not been considered on an equivalent basis with other sources of electricity generation. The few models that have are the Electric Power Research Institute's (EPRI) Electric Generation Expansion Analysis System (EGEAS) and the Environmental Defense Fund's (EDF) "Elfin". Also, DOE's Wind/Hydro/Ocean Division has developed spreadsheet models that project utility market penetration of wind technologies based on comparisons of wind plant costs of energy (COE's) and marginal COE's for conventional generators.

EGEAS was developed jointly by EPRI and Stone and Webster. It consists of a set of computer programs for utility system planners which determines an optimal expansion plan or simulates a pre-specified plan. Expansion plans define the type, size, and installation date for each new generating facility. The objective is to find an expansion plan which minimizes the sum of operating expenses and capital fixed charges. EGEAS provides three main optimization techniques which offer a balance between modeling flexibility and computational efficiency. EGEAS can handle a wide range of dispatchable and nondispatchable technologies, including wind.

The limitation of EGEAS with regard to renewables is that the variability or intermittency of wind resources is not explicitly incorporated into the model but rather is treated as a deterministic negative load, (e.g., as an hourly time series of power outputs over a year) and simply subtracted from utility demand. Therefore, wind is not explicitly competed or dispatched against other energy forms on an equal basis.

The ELFIN model from EDF, which stands for Electric Utility Financial and Production Cost Model, is a probabilistic model which simulates electric-system dispatch in order to calculate expected cost of operation. It has been used most extensively in utility rate hearings before state energy commissions. Elfin can also be used to choose the optimal expansion plan for a utility based on annual present-value of system costs and benefits. No attempt is made to compare life-cycle costs and benefits. Elfin's outputs include the generating level of each plant, per week, and year, fixed and variable costs, fuel usage, and emissions. Reliability is measured by loss-of-load probability (LOLP) and is displayed in days per year.

ELFIN is a utility-scale model; therefore, unlike WES, ELFIN is not well suited to regional and national level forecasts. Furthermore, because ELFIN does not calculate life-cycle costs, it is best suited for short-run forecasts rather than the medium and long-run requirements met by WES in NEMS.

The DOE Wind/Hydro/Ocean Division's Model projects the growth of the U.S. electric utility market for wind turbines on a regional basis. Market share to the year 2030 is allocated on the basis of financial attractiveness, market acceptance of the technology, plant types and capacities, coincidence of utility load and wind power curves, wind resource limitations, and limitations on wind penetration into regional power pools. The model is limited compared with the RFM both in comparing renewables technologies to fossil and nuclear competitors, and in incorporating broader market efforts, such as natural gas market price feedbacks.

The model is built around concepts of new product diffusion into the marketplace. It is a spreadsheet-based tool that estimates market capture in competition with conventional fossil fuel-fired generating plants on a regional basis. It expands on previous techniques by incorporating a market acceptance factor based on ratios of levelized costs of energy for conventional plants and wind turbines (benefit cost ratios). Although sensitivities to fuel costs and mixes can be evaluated with this model, unlike WES, nonfinancial policy incentives and political factors cannot be incorporated, so it is of limited usefulness for other purposes such as policy analyses.

Wind Energy Submodule Structure

Submodule Flow Diagram

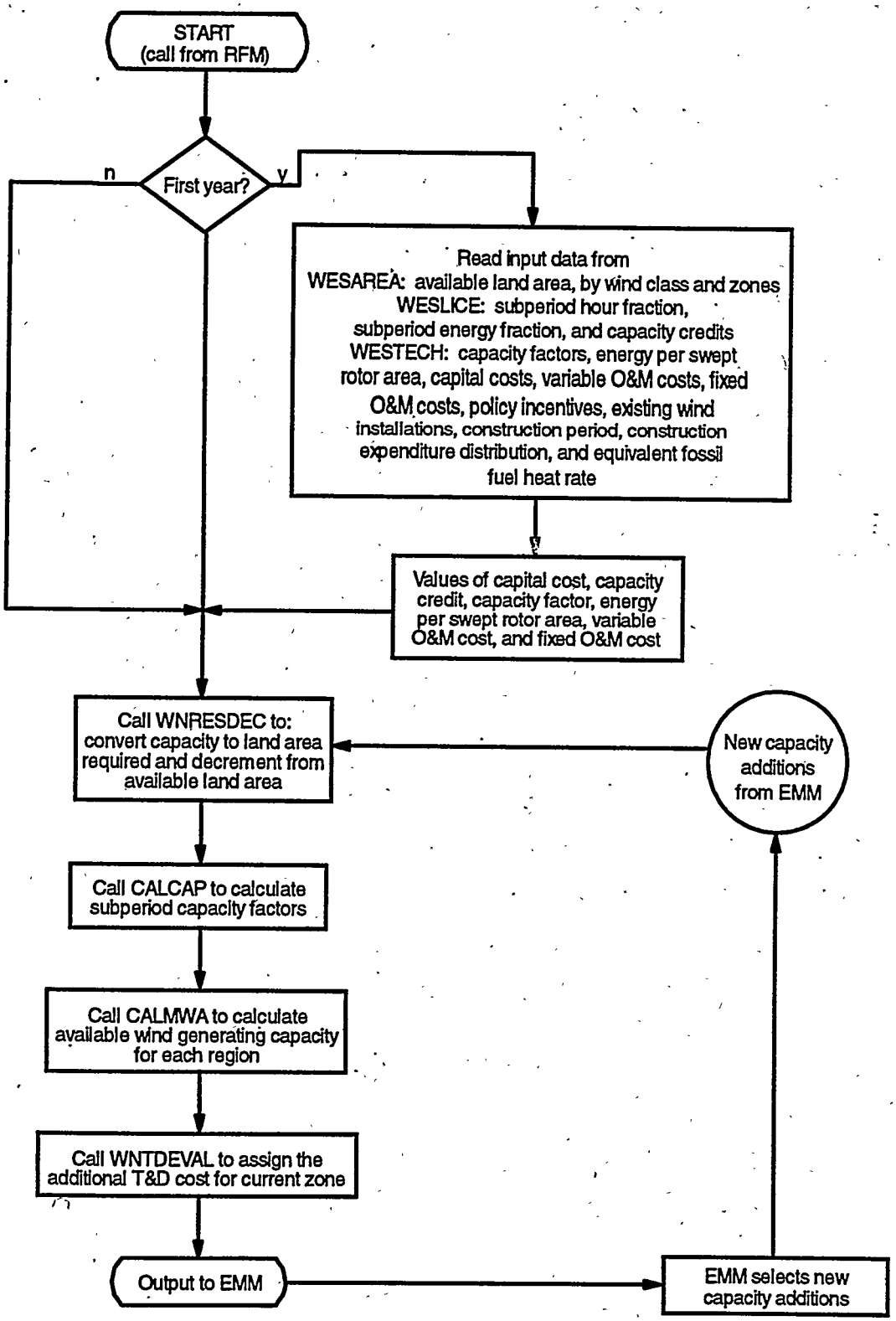
A flow diagram showing the main computational steps and relationships of the Wind Energy Submodule is shown in Figure 4.

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 WNRESDEC 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. A given wind generation capacity requires less land area associated with a high wind class than with a low wind class. The entire U.S. wind energy supply is subdivided into 13 EMM regions, three wind classes, and three zones (along existing transmission lines).

Figure 4. Wind Energy Submodule Flowchart



Subroutine CALMWA is then called to convert the land area available for wind generation development to the swept rotor area needed to fully develop the available land area. The calculation assumes a turbine spacing of 5D x 10D, where D is the diameter of the turbine rotor. This swept rotor area is then converted to the amount of wind energy generation capacity available in each region for each year and each wind class.

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
INPUT DATA			
*UPOVR**	Installed capital cost of wind generation.	EIA, expert judgment.	$/kW
*UPFOM**	Fixed O&M cost.	EPRI TAG™, 1993 and subsequent correspondence.	$/kW
*UPVOM**	Variable O&M cost.	EPRI TAG™, 1993.	mills/kWh
CFANN	Annual wind capacity factor for wind class *w* in year *y*.	SAIC, 1990.	Unitless
CREDIT	Wind capacity credit for EMM region *n* in year *y*.	Determined within EMM.	Unitless
ENAREA	Energy per swept rotor area for wind class *w* in year *y*.	SAIC, 1990.	kWh/m^2
EXWIND	Pre-existing total wind electric capacity installed in EMM region *n* through year *y*.	EIA, Form 860/867.	MW
UPHTRT	Fossil fuel equivalent heat rate for wind.	EIA, 1992.	Btu/kWh
*UPCLYR**	Construction lead time.	EPRI TAG™, 1993 .	Years
UPCPRO	Fraction of construction completed in each year of construction.	EIA, expert judgment.	Unitless
UPIGSUB	Policy incentives for EMM region *n* in year *y*.	Energy Policy Act of 1992.	mills/kWh
SLICE	Hour fraction for subperiod *l* in EMM region *n*.	WNDSLICE preprocessing program (PERI).	Unitless
STAREA	Land area available for wind plant development in EMM region *n* and wind class *w*.	Elliot, 1991.	sq. km
SUBPER	Energy fraction for subperiod *l* in EMM region *n*.	WNDSLICE preprocessing program (PERI).	Unitless

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

Model Variable	Definition and Dimensions	Source	Units
AREA	Energy per unit swept rotor area for wind class *w* in year *y*.	*ENAREA*, and interpolation for intermediate years.	kWh/m²
CF	Annual capacity factor for wind class *w* in year *y*.	*CFANN*, and interpolation for intermediate years.	Unitless
UADDWNT	Grid-connected wind electric capacity additions in EMM region *n* in on-line year *y*.	EMM output variable in UECPOUT COMMON block.	MW
WNTDBFCS	Additional T&D cost for wind technology in EMM region *n* and buffer zone *b*	Kintner-Meyer, SAIC, 1995	$/kW
LDAREA	Land area remaining for wind plant development in EMM region *n*, in year *y*, for wind class *w*, in buffer zone *b*	Model determined.	sq. km
CALCULATED VARIABLES			
LDUSED	Land area needed to supply wind generating capacity in EMM region *n* in year *y*, by wind Class *1*.	Model determined.	sq. km
SWAREA	Swept rotor area available for wind class w in EMM region n in year y, m².	PERI, 1993.	sq. m
WCAWIEL	Available capacity in EMM region *n* in year *y*.	RFM output variable in WRENEW COMMON block.	MW
WSFWIEL	Capacity factor for EMM region *n* in year *y*, wind class *w*, and subperiod *l*.	RFM output variable in WRENEW COMMON block.	Unitless
WNNTD	Additional T&D cost for wind technology in EMM region *n* and year *y*	RFM output variable in WRENEW COMMON block.	$/kW

*Assigned in EMM input file ECPDAT.
**Intermediate values, linearly interpolated from the source variable.

MODEL INPUT: *UPOVR*

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

The number stored in ECPDAT is a n^{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: *CFANN*

DEFINITION: Annual wind capacity factor for wind class *w* in year *y* (Unitless).

Current performance estimates are based on a composite analysis of commercial turbines. Performance data are based on expert judgment projected for 5-year intervals. Specifically, 1995 data are based on the improvements expected from a turbine similar in technological development to the U.S. Windpower 33M-VS. The improvement factors are for years 2000 and beyond are kept constant at the 2000 value.

Performance projections are based on the accelerated federal wind technology R&D funding scenario used in the 1990 National Energy Strategy technology characterizations and modified by EIA.

SOURCES: Science Applications International Corporation, "Renewable Energy Technology Characterizations." Report in support of the National Energy Strategy for the U.S. Department of Energy, Office of Conservation and Renewable Energy, October 1990.

Science Applications International Corporation, "Renewable Energy Technology Evolution Rationales." Report in support of the National Energy Strategy for the U.S. Department of Energy, Office of Conservation and Renewable Energy, October 1990.

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 equal to three quarters of the capacity factor in the peak time period is assigned to the capacity factor in the Electric Capacity Planning Submodule of the EMM.

SOURCE: Value determined by EMM.

MODEL INPUT: *ENAREA*

DEFINITION: Energy per swept rotor area for wind class *w* in year *y* (kWh/m^2).

Current performance estimates are based on a composite analysis of commercial turbines. Performance data are based on expert judgment projected for 5-year intervals. Specifically, 1995 data are based on the improvements expected from a turbine similar in technological development to the U.S. Windpower 33M-VS. The improvement factors are for years 2000 and beyond are kept constant at the 2000 value.

Performance projections are based on the accelerated federal wind technology R&D funding scenario used in the 1990 National Energy Strategy technology characterizations and modified by EIA.

SOURCES: Science Applications International Corporation, "Renewable Energy Technology Characterizations." Report in support of the National Energy Strategy for the U.S. Department of Energy, Office of Conservation and Renewable Energy, October 1990.

Science Applications International Corporation, "Renewable Energy Technology Evolution Rationales." Report in support of the National Energy Strategy for the U.S. Department of Energy, Office of Conservation and Renewable Energy, October 1990.

MODEL INPUT: *EXWIND*

DEFINITION: Pre-existing total wind electric capacity installed in EMM region *n* through year *y* (MW).

EIA data on existing commercial wind installations are used from the current EMM Plant file compiling electric generator data from sources such as EIA 860 and 867 surveys.

SOURCES: EIA 860, Annual Electric Generator Report, 1995. Energy Information Administration, Washington, D.C.

EIA 867, Annual Nonutility Power Producer Report, 1995. Energy Information Administration, Washington, D.C.

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.

MODEL INPUT: *UPCLYR*

DEFINITION: Construction lead time (Years).

The construction period for a wind generating station is currently set at 3, which is the minimum lead time allowed in the EMM.

SOURCE: Electric Power Research Institute, *TAG™— Technical Assessment Guide*, 1993.

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 TAG™ and subsequent correspondence.

SOURCE: Electric Power Research Institute, *TAG™—Technical Assessment Guide*, 1993 and subsequent correspondence.

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 TAG™.

SOURCE: Electric Power Research Institute, *TAG™—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: *UPIGSUB*

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 2003 and zero for all other years is assigned for all regions. This is based on the policy incentive provision of the Energy Policy Act of 1992.

SOURCE: Energy Policy Act of 1992 (Public Law 102-486), Section 1212.

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.

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.

Elliott, D.L., et al, "Wind Energy Resource Atlas" (12 volumes), Pacific Northwest Laboratory, Report PNL-3195; 1980.

Economic Research Incorporated. WNDSLICE 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, WNDSLICE preprocessor program.

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: *LDAREA*

DEFINITION: Available windy land area in EMM region *n*, in year *y*, of wind class *w*, in zone *b* (km^2).

The U.S. windy land area supply has been disaggregated into three buffer zones representing varying proximities to existing transmission lines. The three buffer zones are defined as: Buffer zone 1: 0-5 miles, Buffer zone 2: 5-10 miles, Buffer zone 3: 10-20 miles to an existing power line. The land area disaggregation is based on a geographic information system analysis using geographic locations of transmission lines and the PNL gridded wind resource data. The transmission lines considered included voltage ratings between 115 kV and 230 kV which are generally used for plants with a capacity less than 500 MW.

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

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:

$$LDUSED_{n,y} = \frac{UADDWNT_{n,y+Lead} * CF_{y,1} * 8760 * \alpha_{sp}}{AREA_{y,w} * \frac{\pi}{4}} \quad \text{(3B-1)}$$

where:

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

$UADDWNT_{n,y}$ = 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^2,

π = 3.141593,

α_{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.

$$LDAREA_{n,y,wc,bc} = LDAREA_{n,y-1,wc,bc} - LDUSED_{n,y} \quad \textbf{(3B-2)}$$

where:

$LDAREA_{n,y,wc,bc}$ = land area available for wind development in EMM region n, in year y, in currently offered wind class wc 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:

$$WSFWIEL_{n,y,w=1,l} = \left[\frac{SUBPER_{n,l}}{SLICE_{n,l}}\right] * CF_{y,wc} \quad \textbf{(3B-3)}$$

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,

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

Subroutine CALMWA

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

$$SWAREA_{n,y,wc} = \frac{\frac{\pi}{4} * LDAREA_{n,y,wc,bc} * 10^6}{\alpha_{sp}} \quad \textbf{(3B-4)}$$

where:

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

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

α_{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:

$$WCAWIEL_{n,y} = \frac{AREA_{y,wc} * SWAREA_{n,y,wc}}{CF_{y,wc} * 10^3 * 8760} \quad \textbf{(3B-5)}$$

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:

Wind Class	Buffer Zone
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 levelized cost of the wind technology. In general, the cost benefits due to the higher quality resource offsets 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

$$WWNTD_{n,y} = WNTDBFCS_{n,bc} \quad \textbf{(3B-6)}$$

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.

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

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

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:
August, 1996.

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

Official Model Representative:
Tom Petersik
Coal, Uranium, and Renewable Fuels Analysis Branch
Energy Information Administration
(202) 586-6582

Documentation:
NEMS Documentation Report: *Renewable Fuels Module of the National Energy Modeling System*, January 1998.

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 over 95 percent of U.S. generating capacity.

Coverage:

- Geographic: 15 EMM regions: East Central, Texas, Mid-Atlantic, Mid-America, Mid-Continent, Northeast, New England, Florida, Southeastern, Southwest, Western, Rocky Mountain, California and South Nevada, Alaska, and Hawaii
- Time/Unit Frequency: Annual, 1990 through 2020
- 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
- Special Features: Accounting for policy and/or production incentives.

Modeling Features:

DOE Input Sources:

Energy Information Administration, *Annual Energy Review 1991*, DOE/EIA-0384(91), June 1992.

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

Non-DOE Input Sources:

Princeton Economic Research, Incorporated (PERI) — WNDSLICE preprocessing program.

Science Applications International Corporation (SAIC) — Cost and performance data as prepared for the National Energy Strategy project.

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

Computing Environment:

- Hardware Used: IBM RS6000
- Operating System: Unix
- Language/Software Used: VS FORTRAN, Ver. 2.05

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). 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 (12.5 mph)) which represent the generally-accepted, lowest economic limit of wind speeds for grid-connected systems in the United States.

Data on wind resource quantity are maintained in the *Wind Resource Quantity File* as derived from published assessments or compilations of U.S. wind resources. 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 environmental and land-use considerations. WES uses the PNL "moderate" exclusion scenario. The percent of total windy land unavailable under this scenario consists of all environmentally protected lands (such as parks and wilderness areas), all urban lands, all wetlands, 50 percent of forest lands, 30 percent of agricultural lands, and 10 percent of range and barren lands. Within each region, the available land area is provided for each of the three levels of wind resource, according to the estimated average annual wind speed in that region and other factors. Lastly, since wind power increases significantly with height, a minimum height is usually specified for measurement and installation purposes, to achieve an associated wind power density.

The *Wind Resource Quality 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. 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.

The *Cost and Performance of Installed Wind Turbines* have been monitored for over a decade. During that period, a wind turbine database and turbine simulation program have been developed and refined. Also, analyses of manufacturer-supplied wind turbine power curves and installed costs were performed for a number of the best current, commercially available wind turbines. Wind turbine energy output estimates were made, assuming a Weibull wind speed distribution at several wind speeds, as well as corrections to wind speed for turbine hub height. Energy losses were based on field estimates from California wind plants. Average performance was estimated from the range of energy output data. Average costs were similarly calculated, and included major repairs such as rotor replacements and O&M costs.

The *Wind Turbine Cost and Performance Projections* to be used initially for the WES data files are based on the accelerated Federal wind technology R&D funding scenario used in the 1990 NES technology characterizations. The funding levels termed "accelerated" correspond most closely to present levels and emphasis, namely R&D in the basic sciences and the "Advanced Wind Turbine" development program. There are also comprehensive cooperative programs with industry and utilities to assist in both near-term problem solving and long-term development.

Estimates for the mid-term technology characterizations were based on (1) projections for the U.S. Windpower 33M-VS turbine, and (2) analysis conducted by NREL of potential advanced design improvements based on technical insights from the current R&D program. The general approach used in the NREL analysis to determine the effects of design improvements on existing wind turbine technology can be described by three basic steps. First, a reference system was selected to represent current technology and its performance and costs were tabulated. Second, two configurations representing possible improvements to the reference design were identified, and the effect of each improvement on performance and cost was estimated. Lastly, estimated changes to wind plant cost of energy (COE) were calculated from the reference and improved design parameters.

Estimates are regularly compared with independent estimates, including national laboratory, industry, and other estimates. Updates occur as field and other documented evidence -- including test results -- indicate changes in costs or performance.

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.

3. Solar efficiency improvement factors: Assumed capacity factor improvements for PV over time are submitted through SOLAR.

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 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 eight values. Since the number 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 (Carissa Plains).

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 plus Alaska and Hawaii. 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.

Elasticities

Both PV and ST technologies are subject to short-term capital cost elasticities, wherein large annual increases in capacity are assumed to be raise costs because of supply bottlenecks (see page 5 and following pages). For both PV and ST technologies, total U.S. grid-connected generating capacity can increase 25 percent each year without any capital cost increase; additional capacity incurs a ½ percent increase in capital cost for every 1 percent additional capacity beyond 25 percent.

Alternative Approaches

Solar technologies have not often been incorporated in national-level energy models. Three exceptions are the Integrated Planning Model (IPM) from ICF Resources, FOSSIL2 from Applied Energy Services (AES) which was utilized by DOE in the 1991 National Energy Strategy (NES), and the MARKAL Model from Brookhaven National Laboratory.

The IPM is the electricity model within the Electric and Gas Utility Modeling System (EGUMS) which was developed under a joint effort of ICF Resources and RCG/Hagler, Bailly, Inc. It can also be run in a stand-alone mode. EGUMS was also used by EPA for the analysis of greenhouse gas emission policies. Like the NEMS-EMM capacity planning submodule, IPM is a linear program that derates the capacity of a technology by multiplying its rated capacity by its availability factor. IPM uses a regionalization scheme, similar to EMM, based on 11 EMM regions and subregions. IPM credits the intermittent resources on an hourly basis before creating a load duration curve and solving for an inter-temporal optimum. However, IPM does not try to incorporate the effect of experience or learning on the cost of the technology. As an emerging technology, solar is expected to experience sharp reductions in cost with additional penetrations so varied representations of "learning-by-doing" are certainly important in solar modeling.

FOSSIL2's fundamentally different structure uses system dynamics with logit functions adapted from consumer choice methodologies. As a system dynamics model, FOSSIL2 uses difference equations to simulate the evolution of a system by taking steps (four per year) through time rather than an optimization approach. The model compares the marginal costs of new technologies and chooses the least cost option according to a logit function that prevents knife-edge solutions. This adjustment is particularly important because FOSSIL2 treats the entire nation as a single region.

In modeling renewables, FOSSIL2 does distinguish between off-grid and centralized electricity generation and between utility and nonutility generators (NUGS). However, in treating intermittent resources, FOSSIL2 has difficulty because it implicitly assumes that intermittent and dispatchable technologies are supplying identical services. Intermittents are treated the same as conventional baseload technologies which gives intermittents a capacity credit equal to their rated capacity and overstates their contribution. On the other hand, FOSSIL2 does not capture the correlation of solar with load which increases its energy value. A later version of FOSSIL2, named IDEAS, does capture this correlation by giving it more output during peak periods. This is accomplished by forcing an appropriate percentage of the intermittent resource's output into the peak portion of the load duration curve.

As discussed earlier, an important capability when modeling renewables is how new technology penetration is treated. FOSSIL2 applies a premium to the discount rate when calculating marginal cost. While the premium diminishes with cumulative production to reflect increased penetration, FOSSIL2 does not embody the notion of "learning-by-doing" and industry acceptance of new technologies.

The third modeling system for solar-based electricity generation is the MARKAL model, developed, in part, at Brookhaven National Laboratory with the support of 17 nations and two international agencies. MARKAL is a multi-period, linear-programming model that performs energy systems optimization and addresses all aspects of the energy system. Its primary objective is to assess the attractiveness of existing and new energy technologies and resources in satisfying future demand. Within the energy network, the model user has total control over the level of technology detail. However, MARKAL cannot easily or transparently incorporate non-price-based consumer choices or new technology penetration.

Solar Submodule Structure

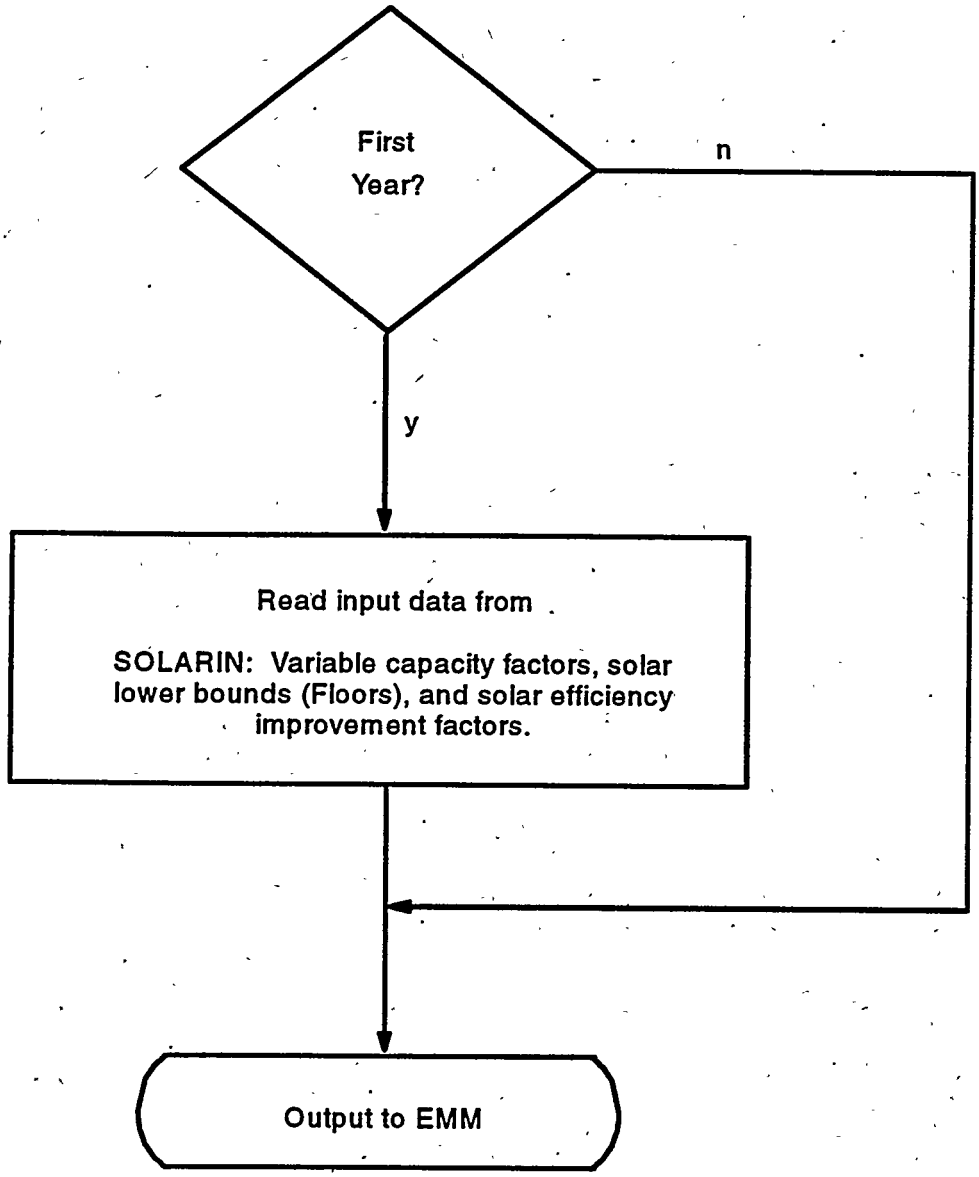
Submodule Flow Diagram

A flow diagram showing the main computational steps and relationships of the Solar Submodule is shown in Figure 5.

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 5. 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
INPUT DATA			
WCAPVEL	Capacity constraints for photovoltaic technology in EMM region *n* in year *y*.	EIA Estimates.	MW
WCASTEL	Capacity constraints for solar thermal technology in EMM region *n* in year *y*	EIA Estimates.	MW
*UPOVR (21)**	Capital cost of photovoltaic technology.	EIA.	$/kW
*UPOVR (19)**	Capital cost of solar thermal technology.	Sandia National Laboratory.	$/kW
*UPICCF**	Investment policy incentive as a fraction of capital cost.	Energy Policy Act, 1992.	Percent
*UPIGSUB**	Production policy incentive.	Energy Policy Act, 1992.	mills/kWh
*UPVOM (21)**	Variable O&M cost for photovoltaic technology.	EPRI TAG, 1993.	mills/kWh
*UPVOM (19)**	Variable O&M cost for solar thermal technology.	CEC, 1993.	mills/kWh
*UPFOM (21)**	Fixed O&M cost for photovoltaic technology.	EPRI TAG, 1993.	mills/kW
*UPFOM (19)**	Fixed O&M cost for solar thermal technology.	Sandia National Laboratory.	mills/kW
WSSPVEL	Prototype photovoltaic system capacity factor for EMM region *n* in time period *p* in year *y*.	NREL, 1995.	Percent

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

Model Variable	Definition and Dimensions	Source	Units
WSSSTEL	Prototype solar thermal system capacity factor for EMM region *n* in time period *p* in year *y*.	CEC, 1993.	Unitless
*UPCLYR**	Construction period.	CEC, 1993.	Years
*UPCPRO**	Completion fraction.	CEC, 1993.	Percent
EFFMULPV	Efficiency multiplier for photovoltaic technology	EIA, expert judgment	—
EFFMULST	Efficiency multiplier for solar thermal technology.	EIA, expert judgment	—

*Assigned in EMM input file ECPDAT.

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: *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: *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: *UPIGSUB*

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

A value of 15 mills per kilowatt hour for the years 1999 through 2009 and zero for all other years is assigned for all regions, based on Section 1212 of the Energy Policy Act of 1992. The act states that the incentive is payable for ten years for a facility that first generates electricity during the ten fiscal year period occurring after enactment. Since solar thermal technology is not scheduled to occur until 2000, it would seem appropriate to shift this incentive for that technology to the years 2000 through 2009. The incentive is levelized over the life of the plant.

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

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: *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: *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.

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: *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 by utilizing lower energy solar insolation.

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.

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:
October, 1995.

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:
Thomas Petersik
Coal, Uranium, and Renewable Fuels Analysis Branch
Energy Information Administration
(202) 586-6582

Documentation:
NEMS Documentation Report: *Renewable Fuels Module of the National Energy Modeling System*, January 1998.

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: 15 EMM regions: East Central, Texas, Mid-Atlantic, Mid-America, Mid-Continent, Northeast, New England, Florida, Southeastern, Southwest, Western, Rocky mountain & Arizona, California & So. Nevada, Alaska, and Hawaii.
- 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: Cost and performance characteristics, PV technology.

Energy Policy Act of 1992

- Production policy incentive.

IRS Tax Code

- 10 percent investment tax credit.

National Solar Radiation Database

- Regional Insolation

DOE Input Sources:

- Office of Energy Efficiency and Renewable Energy, "Technology Characterizations," draft, May 1994.

Computing Environment:

- Hardware Used: IBM RS6000
- Operating System: Unix
- Language/Software Used: VS FORTRAN, Ver. 2.05

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 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"; photovoltaic cost and performance estimates are obtained primarily from the Electric Power Research Institute, "Technical Assessment Guide 1993 (TAG)," 1993. Capacity factors for both technologies are determined by EIA based on estimates in the "Typical Meteorological Year" data base 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 Utility Technologies; finally, the estimates are made available for outside uses and comment, both in response to specific requests and in EIA-sponsored forums.

Individual cost and performance elements for solar technologies and estimates for capacity factors have been revised (including in 1995 and 1996) in response to such comments.

Photovoltaic Performance

Photovoltaic performance is based on a fixed array PV system. The technology characterization assumes that peak rated output is reached at an insolation level of 1000 Watts per square meter. The fraction of rated capacity of the PV system is assumed to vary linearly with (direct plus diffuse) insolation, so that at any instant the capacity is equal to the insolation in W/m^2 divided by 1000.

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.

Beginning with *AEO97*, cost and performance characteristics which are defined consistent with fossil and other technology characteristics reside 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 this 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 data from the commercial, 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

The biomass use in NEMS is decomposed and 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). The biomass waste combustion in captive markets serves the dual role of energy supplier and waste disposal method. The captive biomass market is modeled by 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 commercial and electric utility sectors, as well as the resources marketed in the industrial sector. It is necessary to include commercial and industrial consumption in order to properly estimate supply and demand conditions, as these represent alternative economic uses of the biomass supply. There is an additional noncaptive market serving residential uses of biomass. This market is modeled in the residential demand module.

Because of the scarcity of reliable data and the relatively small size of the noncaptive market, EIA decided to develop a fairly simple model structure consisting of one supply schedule per region. This schedule defines the quantity and cost relationships of biomass resources accessible by all noncaptive, non-residential consumers. It is based on an aggregation of supply/price information from U.S. Forest Service and forest product experts. The wood portion of the cost-supply schedule is static throughout the model period.

Energy crop cost-supply schedules are also developed and superimposed onto the wood total. This component was developed with the use of the Forest and Agricultural Sector Optimization Model (FASOM) operated by the U.S. Environmental Protection Agency.[7] Separate schedules were developed for each year, 2010 through 2020.

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.

Another important 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. Based on a hauling distance of 50 miles and $0.10/ton-mile, costs were calculated as $0.30/MMBtu for trees and $0.34/MMBtu for switch grass. Because no interregional biomass trade exists, it is assumed that no biomass is transported among EMM regions.

Alternative Approaches

There are limited examples of alternative working models that include market penetration of biomass technology. 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.

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[7]Winnett, S. et al, "Forest and Agricultural Sector Optimization Model: Model Description," Environmental Protection Agency, Climate Change Division, March 23, 1994.

The Biomass Submodule of NEMS has several simplifying features of its supply functions which may offer opportunities for improvement. One assumption is to limit it to 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 it will vary considerably by terrain and distance to the conversion facility. A preferred method, data and resources permitting, would have these variable costs built into the supply curves. 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. In the initial preparation of the biomass supply curves using EPA's FASOM model, many aspects of these markets were built in.[8] However, because of other limitations of FASOM, primarily geographic, significant parts of those supply curves were replaced for *AEO98* by schedules developed from the Oak Ridge database, which is static.[9] Additional analysis is underway which may permit better treatment of these factors in subsequent years.

Biomass Submodule Structure

Submodule Flow Diagram

A flow diagram showing the main computational steps and relationships of the Biomass Submodule is shown in Figure 6.

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, commercial, 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.

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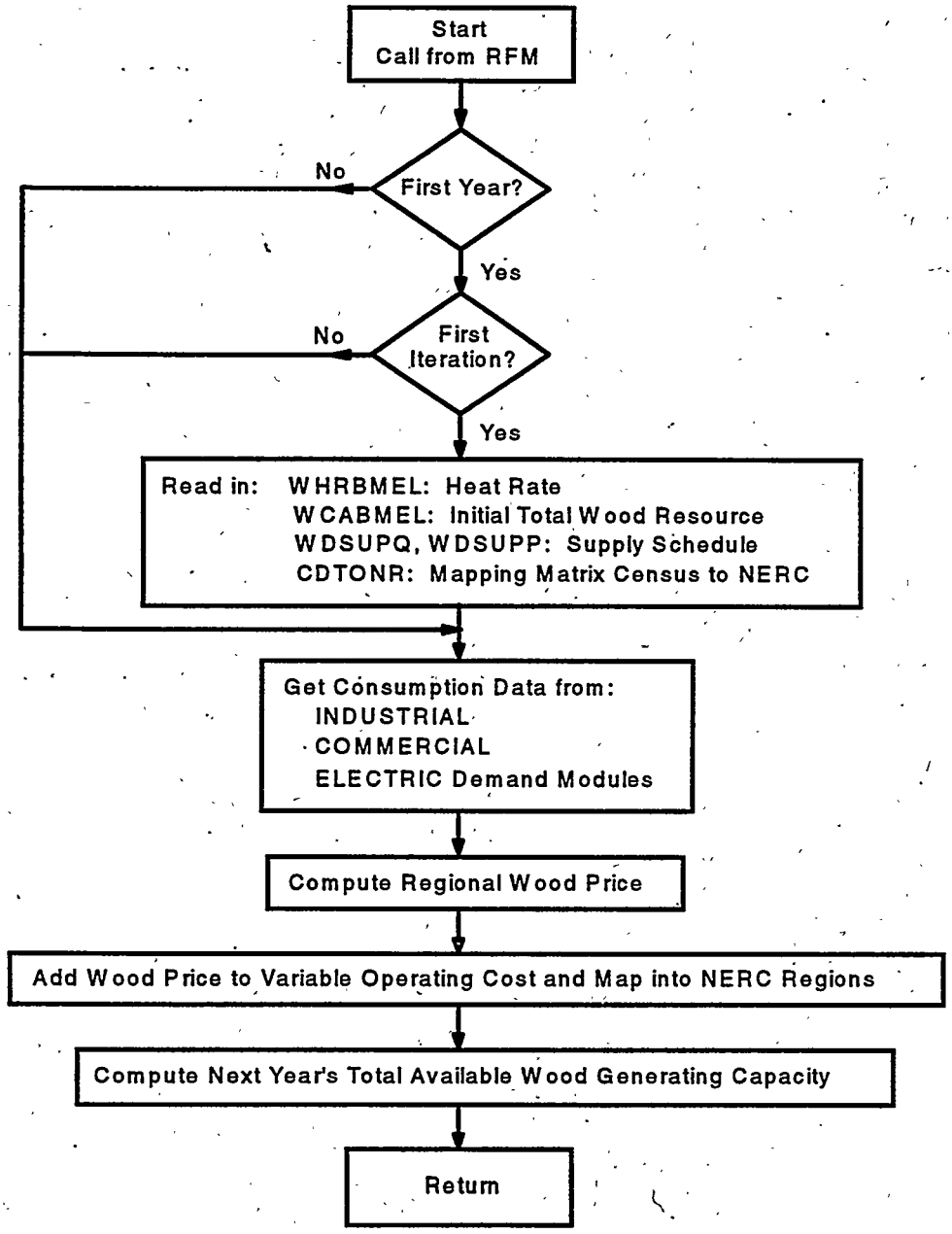
[8]U.S. Department of Agriculture, Forest Service, "Forest Services of the United States, 1992," General Technical Report RM-234, September 1993 (revised June 1994).

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

Figure 6. 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 form the previous limit. The initial total generating capacity for each region is determined by dividing the maximal quantity of biomass reserves in the supply curve by the heat rate, the 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 unit cost is modular and 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
INPUT DATA			
CDTONR	Conversion factors for converting Census division *r* to EMM region *n*	DAC	Unitless
WDSUPQ	Biomass quantity step function in EMM region *n*, year *y*, step *I*	DAC	trillion Btu
WDSUPR	Biomass price step function in EMM region *n*, year *y*, step *I*	DAC	$/MMbtu
*UPOVR**	Capital cost for biomass technology	NREL	$/kW
*UPMCF**	Capacity factor for biomass technology electricity sector	NREL	Unitless
$WVC_{n,y}$	Constant variable O&M cost component for biomass technology electricity sector in EMM region *n* in year *y*	NREL	$/MMbtu
$UPFOM_{n,y}$*	Fixed O&M costs for biomass technology electricity sector in EMM region *n* in year *y*	NREL	$/kW
$WHRBMEL_{n,y}$	Heat rate for biomass technology in EMM region *n* in year *y*	EPRI	Btu/kWh
VARIABLES			
QBMCM	Quantity of biomass consumed in the commercial sector in Census division *r* in year *y*	NEMS	trillion Btu
QBMEL	Quantity of biomass consumed by utilities in Census division *r* in year *y*	NEMS	trillion Btu
QBMIN	Quantity of biomass consumed in the industrial sector in Census division *r* in year *y*	NEMS	trillion Btu
CURWDCON	Quantity of biomass consumed in all sectors in EMM region *n* and year *y*	NEMS	trillion Btu
CURWDPR	Price of biomass from the all-sector supply curve in EMM region *n* and year *y*.	NEMS	$/MMBtu

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

Model Variable	Definition and Dimensions	Source	Units
OUTPUTS			
$WCABMEL_{n,y}$	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: *CDTONR*

DEFINITION: Conversion factors for converting Census division r to EMM 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 EMM region n, year y, and step I.

WDSUPQ is part of the biomass supply schedule. The variable represents quantity of a biomass composite consisting of the following biomass types: (1) whole tree chips, (2) logging residues, (3) mill residues, (4) other biomass, and (5) energy crops.

SOURCE: Decision Analysis Corporation of Virginia, "Data Documentation for the Biomass Cost-Supply Schedule, prepared for the Energy Information Administration, Washington, DC, July 28, 1995.

MODEL INPUT: *WDSUPP*

DEFINITION: Price of biomass supply in EMM region n, year y, and step I.

WDSUPP is part of the biomass supply schedule. The variable represents the price of a biomass composite consisting of the following biomass types: (1) whole tree chips, (2) logging residues, (3) mill residues, (4) other biomass, and (5) energy crops.

SOURCE: Decision Analysis Corporation of Virginia, "Data Documentation for the Biomass Cost-Supply Schedule," prepared for the Energy Information Administration, Washington, DC, July 28, 1995.

MODEL INPUT: *UPOVR*

DEFINITION: Capital costs for electricity sector.

UPOVR represents the n^{th}-of-a-kind capital cost for an advanced Biomass Integrated Gasification Combined Cycle (BIGCC) technology which is estimated to be commercially available in the year 2000. The cost estimates incorporate the removal of interest during construction and contingency costs, which are added later in EMM.

SOURCE: Electric Power Research Institute, Biomass and Waste-Fired Power Plant Performance and Cost Model (BIOPOWER), Version 1.0. Values are modified using additional information from EPRI and engineering estimates by EIA.

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, Biomass and Waste-Fired Power Plant Performance and Cost Model (BIOPOWER), Version 1.0. Values are modified using additional information from EPRI and engineering estimates by EIA.

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. It is assumed that the heat rate will decrease linearly over time to reflect the probable efficiency improvements of this technology. The decrease was based on the efficiency improvements of the similar coal 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: *QBMEL*

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, "Technical Assessment Guide," Vol. 1, Revision 7, EPRI TR-102276S, Palo Alto, CA, June, 1993. Values are modified using additional information from EPRI and engineering estimates by EIA.

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 a composite 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 to the ECP, the cost for biomass 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. The sectoral biomass consumptions are provided by Census divisions. They are mapped to EMM regions using the following mapping:

commercial sector:

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

industrial sector:

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

electric power sector:

$$WDQNREL_{n,y} = \sum_{r=1}^{R=9} \sum_{n=1}^{N=13} CDTONR_{n,r} * QBMEL_{n,y}$$

where:

$CDTONR_{n,r}$ = mapping matrix to map Census divisions into EMM regions,

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

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

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

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

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

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

It is assumed that 3 percent of the industrial consumption is in the noncaptive market. The total consumption of biomass by EMM region is:

$$CURWDCON_{n,y} = WDQNRCM_{n,y} + WDQNRIN_{n,y} + 0.03\ WDQNREL_{n,y} \quad \textbf{(5B-1)}$$

where:

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

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

$$CURWDPR_{n,y} = WDSUPP_{n,y,i} + \left[\frac{CURWDCON_{n,y} - WDSUPQ_{n,y,i}}{WDSUPQ_{n,y,i+1} - WDSUPQ_{n,y,i}}\right](WDSUPP_{n,y,i+1} - WDSUPP_{n,y,i}) \quad \textbf{(5B-2)}$$

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 I,

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

Since the biomass submodule does not have a vehicle to pass fuel cost 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:

$$WVCBMEL_{n,y} = WVC_{n,y} + CURWDPR_{n,y} * WHRBMEL_{n,y} * C_1 \quad \textbf{(5B-3)}$$

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, $C_1=10^{-3}$.

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:
October 1996.

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:
Roger Diedrich
Coal, Uranium, and Renewable Fuels Analysis Branch
Energy Information Administration
Phone: (202) 586-0829

Documentation:
NEMS Documentation Report: *Renewable Fuels Module of the National Energy Modeling System*, January 1998.

Decision Analysis Corporation of Virginia, "Data Documentation for the Biomass Cost-Supply Schedule, prepared for the Energy Information Administration, Washington, DC, July 28, 1995.

Archive Media and Installation Manual(s):

Energy System Described:
Non-captive biomass supply and associated price.

Coverage:
USA.

Modeling Features:
Data from nine Census divisions are restructured into 13 EMM supply regions.

Non-DOE Input Sources:
None.

Computing Environment:

- Hardware Used: IBM RS 6000
- Operating System: Unix
- Language/Software Used: VS FORTRAN, Ver. 2.05

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

Data for the biomass supply curves were of two types: the forest products data developed from U.S. Forest Service data, 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 the same price steps.

The assumption was made that availability of wood resources could be represented by values for a portion of U.S. annual forestry production. The primary source of information was "Forest Resources of the United States, 1992."[10] The specific data were of roundwood products, logging residues and other removals from U. S. forests. Several steps were taken to process these data. In each of eight Forest Service regions, there are values for roundwood products, logging residues and other removals in Table 38. It was necessary to remove an amount from each of these values for fuelwood, since that amount is part of the captive market addressed in the Industrial model. A fuelwood component of roundwood products is given in Table 36. This amount, as well as 15 percent of logging residues and other removals, was first subtracted from roundwood. The total volume for each region was then disaggregated into state-level values by the shares of timber volume given in Table 11. Using mapping factors in the DAC documentation of the previous supply curves, the values were reaggregated to EMM regions and then converted to BTU values.[11] The assumption was made that 30 percent of annual production would be available for electricity production. While this is a significant share, it is an upper limit that would only be available at high cost. The range of prices used were retained from earlier work by DAC, which relied primarily on earlier Forest Service analysis such as by McQuillan, et al and other industry contacts. The final step in generating supply functions was to normalize the quantities into a set of price steps for each region.

A representation of energy crop costs was also developed and superimposed onto the forest product supply curves. The original set of supply curves were developed from a run of EPA's Forest and Agricultural Sector Optimization Model (FASOM). The FASOM is a dynamic, nonlinear programming model for the domestic forest and agricultural sectors. It was developed as an aid in studying carbon sequestration policies and other land uses. The model considers representative energy crops of willow, switchgrass and poplar in eleven regions east of the Mississippi River. Supply schedules for each year from 2010 - 2020 were produced, showing increasing availability of energy crops over time.

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[10]U.S. Department of Agriculture, Forest Service, "Forest Services of the United States, 1992," General Technical Report RM-234, September 1993 (revised June 1994).

[11]Decision Analysis Corporation of Virginia, "Data Documentation for the Biomass Cost-Supply Schedule," prepared for the Energy Information Administration, Washington, DC, July 28, 1995.

In order to extend beyond the eastern U.S., these data are supplemented by information from the Oak Ridge National Laboratory database.[12] This database contained information on yields and production costs for three land types and two crop types. Crop yields, which were in the range of 3-7 tons/acre were converted to energy potential for each county and aggregated up to EMM regions. An assumption was made that the availability of the resource would be 30 percent of cropland and pasture and 100 percent of the Conservation Reserve Program lands. While 30 percent is a significant share, like the value for forests, it is an upper bound and costly. The Union of Concerned Scientists in their study of Midwestern biomass resources, used a slightly higher value (35 percent) for their land use assumptions.[13] Using these data, quantities of energy crops were expanded in four regions: Texas (2), Mid-continent (5), Southwest (10) and Western (11).

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

[13]Brower, et al, Union of Concerned Scientists," Powering the Midwest," 1993.

6. Geothermal Electricity Submodule

Model Purpose

The purpose of the Geothermal Electricity Submodule is to model the current and future regional supply, capital cost, and operation and maintenance costs of electric generating facilities exploiting U.S. hydrothermal resources, based on available resource data and on current technology with reasonable assumptions as to learning-curve and technological improvements.

More specifically, in the context of NEMS, the purpose of GES is:

- to provide the Electricity Market Module's (EMM's) capacity planning submodule with the amount of new capacity that can be built, with related cost and performance data;
- to provide EMM's electricity dispatch submodule with cost and performance data for all installed capacity, including capacity reported on EIA surveys as existing or planned and capacity added as a result of a model calculation — known as "unplanned" capacity, or more accurately "modeled" capacity.

Relationship of the Geothermal Electricity Submodule to Other Models

The major relationships between GES and other NEMS components are:

- GES provides new capacity availability, performance and cost information for the Electricity Capacity Planning (ECP) submodule's use in making its planning decisions;
- GES provides cost and performance data on installed capacity for use by the Electric Fuel Dispatch (EFD) submodule;
- GES uses ECP new capacity build decisions obtained from the EMM output common block, EMMOUT;
- As an option, GES uses drilling and other field cost improvement parameters used in the Oil and Gas Supply module (OGSM);
- GES uses the following EMM data:
  - financial parameters and tax data for calculations related to the competing geothermal resource sites
  - ECP's "cut-off" or "shadow" price to truncate the geothermal supply curves.

Modeling Rationale

The GES projects regional supply curves relating new geothermal electric capacity and the capital cost to provide the new capacity. Annual operations and maintenance (O&M) costs are also projected for the new capacity. These are used to determine the costs for the amount of new geothermal capacity requested by the market, represented in NEMS by the Electricity Market Module (EMM). Costs for previously installed capacity and those for new capacity are consolidated to project the costs for all geothermal electricity dispatched by the market.

The supply curves are aggregated based on EMM regions defined by the North American Electric Reliability Council (NERC). Supply curves are modeled for EMM regions 11, 12, 13, and 15, the only regions of the U.S. with economic geothermal resources.

The cost of generating electricity from geothermal resources is largely a function of the resource temperature, depth, and chemistry. Because these parameters, and consequently the cost of electricity, vary considerably at different resource sites, the methodology employs pre-processing site-specific geothermal resource data to model site-specific costs and operational characteristics. The data pre-processing is performed by the PC-based GES Data Preprocessor (GESDPP), which was adapted from an existing PC-based model, IM-GEO.[14] Developed by Sandia National Laboratory in the mid 1980s, "IM-GEO" stands for Impacts of Research and Development on the Cost and Performance of Geothermal Electric Systems.

The resource data set includes data on 51 known geothermal resource sites in the U.S. The site data include measured parameters as well as parameters which were estimated based on other measured data for the site in question or on more complete knowledge of a geologically and hydrologically similar site. These data were compiled during a study completed in 1991 for EIA and the Geothermal Division of DOE[15], using U.S. Geological Survey data and other sources. The data include potential site capacity; reservoir parameters such as temperature, depth, salinity, noncondensible gas content; well costs; well mechanical life; time between well workovers; flow rate per well; etc.

The GESDPP, for each site, calculates the costs and performance of a single 50 MW (net) plant based on the site data and writes the output to a file which serves as input for GES. The costs are modeled on historical cost data for independent geothermal power projects developed during the mid to late 1980s.

Using the output from the GESDPP, the GES models the incremental development of each resource site within the framework of a behavioral model based upon observed past experience with geothermal development. The key decision variable is the percentage of total site capacity previously installed.

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[14]Entigh, D., Livesay, B. and Petty, S., *Geothermal Cost of Power Model IM-GEO Version 3.05: User's Manual*, February 1989.

[15]Petty, Susan, et al, *Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power in 20 and 40 years*, Susan Petty Consulting, Solana Beach, CA, June 1991.

At previously undeveloped sites extreme conservatism dictates limiting initial development to a single plant of no more than 20 MW. After the initial plant has been installed, a larger plant may be installed, but still no more than one 50 MW plant at a time, until at least 15 percent of the estimated potential capacity has been successfully installed. Additional new capacity will not be considered during the lead time. Reflecting the greater confidence in the viability for further development after the first 15 percent of potential capacity has been installed, up to four 50 MW plants may be built at the same time. Also, further capacity additions will be considered after the lead time of three years. As successive installations account for more and more of the estimated total potential capacity, conservatism returns in order to avoid overdevelopment of the site. The developer will not risk building more than 75 percent of the remaining undeveloped estimated site capacity.

Fundamental Assumptions

Type of Resource

Development of hydrothermal resources is the only commercially viable geothermal electric generation option with current technology, and therefore hydrothermal resources are the only geothermal resource considered in the GES. For the purpose of this study, a hydrothermal resource is defined as a large volume of hot water trapped in hot, permeable rock at depths up to 11,000 feet and with temperatures ranging from 105°C to 680°C. The model is based upon the historical costs of exploring, confirming and developing hydrothermal resources and installing power plants to bring incremental capacities on-line at known geothermal sites.

Conversion Technologies

Two types of geothermal technologies are modeled in the GES, dual-flash and binary cycle. These systems represent the complete cycle, from extraction of the hydrothermal fluids (equivalent to the fuel in conventional fossil-fueled systems) to electricity generation to reinjection of the spent geothermal fluid (often referred to as brine). Both technology types are used to convert liquid-dominated hydrothermal fluids into electricity. Technologies for dry steam reservoirs, such as the Geysers geothermal field in northern California, are not modeled since this type of resource is extremely rare and unrepresentative of the bulk of hydrothermal resources in the U.S. However, the existing capacity at the Geysers is included in total installed hydrothermal capacity in the GES for capacity dispatch.

Dual-flash plant technology is employed to convert the heat from high temperature (greater than 200° C) liquid-dominated resources to electricity. With this technology, a portion of the geothermal liquid extracted from the reservoir is "flashed" to steam at two different pressures. The steam is separated and used to drive a conventional turbine-generator. The remaining liquid portion of the geothermal fluid is injected back into the ground.

Electricity is generated from lower temperature (less than 200° C)[16] liquid-dominated resources using binary cycle technologies. The geothermal liquid is circulated through a closed-loop system where its heat is used to vaporize a secondary working fluid (hence the name binary) with a low boiling point, such as isopentane. The vapor of the secondary fluid is used to drive a turbine-generator, and the cooled geothermal liquid is injected back into the ground.

Based on the performance of existing geothermal power plants, a plant capacity factor of 80 percent is used.[17]

Drilling and Extraction Technologies

All geothermal electricity systems require drilling and extraction technologies derived from the petroleum industry. These "borrowed" technologies are modified to accommodate the high temperature and sometimes harsh chemical environments related to working with geothermal fluids. The GES models geothermal field development costs based on current geothermal drilling technology.

Alternative Approaches

U.S. geothermal resources were evaluated in the mid 1970s by the U.S. Geological Survey[18] (USGS) and in 1991 by Petty et. al. (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 U.S. At the time of the USGS study, geothermal development in the U.S. was limited to The Geysers steam field in northern California, and exploration and delineation of the nation's liquid-dominated hydrothermal resources was only beginning. The 1991 study used the USGS study as a basis, but took advantage of considerable hydrothermal resource data and developmental experience gained in the interim.

The IM-GEO model developed by Sandia originally included only four generic geologic sites, typical of those found in the U.S. In 1992, it was modified to process data for all the sites identified in the 1991 Petty et. al. resource study. Thus, it made sense to incorporate it into the GES. However, since it was coded in Quick Basic, it was decided to incorporate it as a PC-based data pre-processor, rather than rewrite it in Fortran as an endogenous component of GES. The data pre-processor is referred to as the GES Data Pre-Processor or GESDPP, for short. See Appendix 6-E for further details on the GESDPP.

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[16]Petty, et al, (*Ibid.*) established 110° C as the minimum temperature for resource consideration (P. 6) and 200° C as the maximum temperature for the binary cycle technology (P. 11).

[17]EIA, *Annual Energy Review*, DOE/EIA 0384(93), Washington, DC, July 1994.

[18]Muffler, L.P.J., editor, *Assessment of Geothermal Resources of the United States - 1978*. United States Geological Survey Circular 790, 1978.

Although various projections of future geothermal electric capacity have been made by numerous individuals and organizations over the last 30 years, these have been, for the most part, educated guesses. NEMS is the first national-level, energy supply and demand model incorporating a geothermal supply model which integrates geothermal resource assessments with a cost and performance model of geothermal electric generation systems.

Geothermal Electricity Submodule Structure

Submodule Flow Diagrams

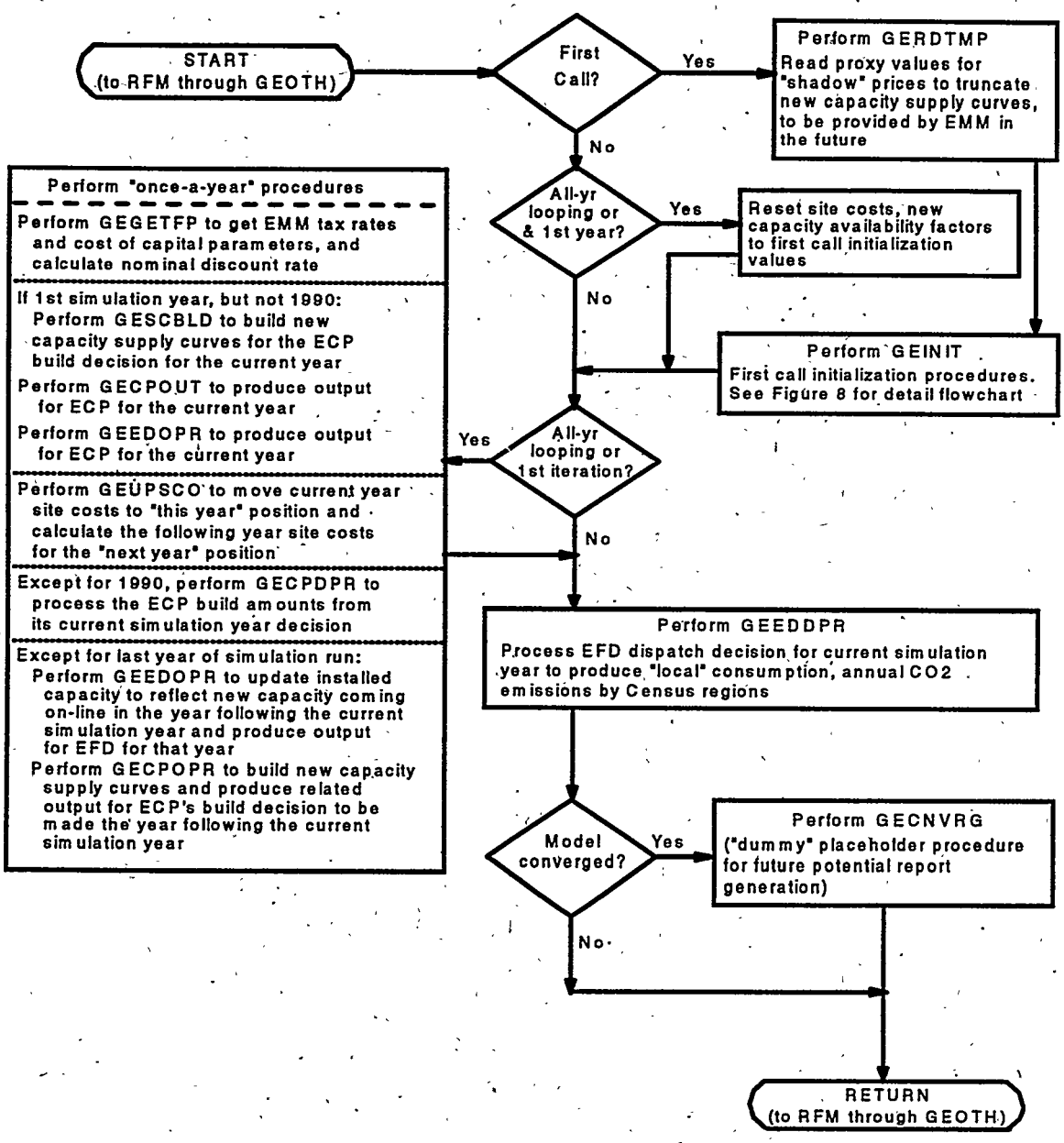
This section contains two flow diagrams showing the logical structure of the Geothermal Electricity Submodule, its principal procedures, and the relationships among them.

Figure 7 provides a high level overview of the controlling procedure, Subroutine ***RFMGES***. There are four sets of procedures at this level:

(1) **Initialization Procedures** — When ***RFMGES*** is first called (first iteration for the first simulation year), ***GEINIT*** reads data from files and calculates and sets other initial values. A flow diagram for ***GEINIT*** procedures is shown in Figure 8. Currently, a separate procedure ***GERDTMP*** reads from a file "shadow" prices used to truncate new capacity supply curves. It is separate because an interface is to be established in the future whereby EMM will provide the values. Site costs and unplanned new capacity factors that are set initially through ***GEINIT*** are changed as the submodule is run for successive years. When "all year" looping is being used for the NEMS run, their initial values must be restored on subsequent calls to RFMGES for the first simulation year.

(2) **Standard "Once-A-Year" Procedures** — These procedures are characterized as "standard" because they comprise the principal algorithms of the model. Reflecting the dynamics of the interfaces with EMM, they generally are performed only once each year, on calls for the first iteration. However, they are performed on all calls for any NEMS runs with "all years" looping. As a second reflection of EMM interface dynamics, the procedures produce output not for the current simulation year, but for the year following the current simulation year. As a special case, output is first produced for the current simulation year when it is the first simulation year, but later than 1990. Two procedures produce internal data used by the primary model procedures. ***GEGETFP*** obtains EMM tax rates and cost of capital parameters and calculates nominal discount rates. ***GEUPSCO*** updates site costs, moving costs for the current simulation year from the "next year" to the "this year" position in the cost arrays and calculating the costs for the following year for the "next year" position. There are three principal model procedures. ***GECPDPR*** processes the new capacity build decisions made by the ECP, allocating the regional build amounts to individual sites in the region through the new capacity supply curve data for the region. ***GEEDOPR*** updates installed capacity and related data for both sites and regional

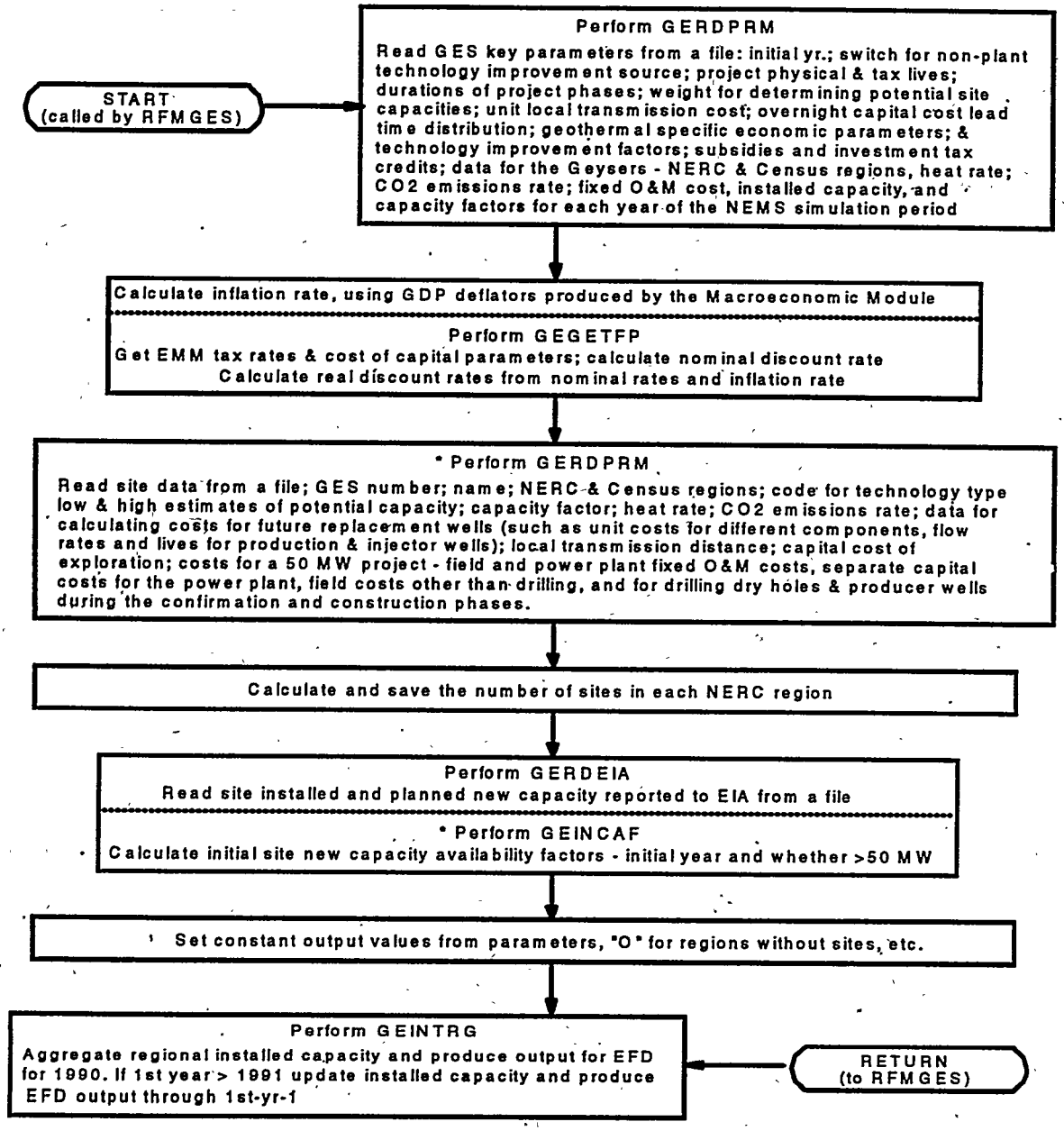
Figure 7. Geothermal Electricity Submodule Overview Flowchart



aggregations, and produces output for use by the EFD submodule of the EMM. ***GECPOPR*** uses a set of procedures to build new capacity supply curves and produce related output for use by the ECP submodule of the EMM. These procedures, ***GESCBLD*** and ***GECPOUT***, respectively, are performed separately for the "first simulation year, but after 1990" special case.

(3) **Dispatch Processing Procedure** — ***GEEDDPR*** is the only model procedure which is performed on all calls to RFMGES. Originally designed to produce for NEMS annual energy "consumption" and CO_2 emissions by Census division from the dispatch amount

Figure 8. GEINIT First Call Initialization Overview Flowchart



by NERC region, the "output" is now local to RFMGES. It is available for reports for comparison with the NEMS output now being produced by the EMM.

(4) **"Converged" Procedure** — ***GECNVRG*** is run only if a "post-convergence" reporting run is signaled by the NEMS integrating module. Currently, this is a placeholder procedure with no functionality.

Figure 8 provides an overview of Subroutine GEINIT, the controlling procedure for first call initialization. GEINIT uses many of the same lower level procedures used for "standard" processing. The procedures that are used to reset site costs and new capacity availability factors to their initial values on subsequent first simulation calls for "all year" looping runs are marked with an asterisk in Figure 8.

Key Computations and Equations

This section describes the most important equations of the GES model. All algorithms for each GES subroutine are mathematically described in full in Appendix 6-B. The section is divided into computations for individual sites and those for geographic regions. GES operations will generally fall into one of these levels or the other. However, the most important GES function of building new capacity supply curves entails first site computations, then regional computations.

Computations for Geothermal Sites

Data for geothermal sites are read from a file by Subroutine ***GERDSITE*** into local variables with no site dimension. These variables have names beginning with "***GSF.***" Variables with computed site data or site data retained for use in computations have a site dimension and are included within the ***WGENUM*** Common block. Their names all begin with "***WGES.***" In all site data computations outside of ***GERDSITE***, "***PS***" is the index or subscript used for the site dimension. Unless specified otherwise, all site computations are performed for each site, and this should be understood in the descriptions which follow.

New Capacity Availability Factors. $WGESNCAv_{PS,PY}$ is the new capacity availability factor for site "PS" for *year of availability* "PY." Because the year definition relates to year of availability, the year dimension size is (MNUMYR+10), or 39. However, because only the first 26 positions of MNUMYR are in use and an ECP planning horizon of 6 years, rather than 10, is in use, only the first 31 (26 + 6 - 1) positions of the year dimension are used for ***WGESNCAv*** and all other GES variables with a (MNUMYR+10) year of availability dimension.

Values may be 0 (no new capacity available for the year), 1 (new capacity is available for the year, but can only range between 5 MW and 50 MW), or 2 (new capacity in excess of a 50 MW project may be available). For each site, the values at any time during the NEMS run will be consecutive "0's" from subscript 1 (1990) through the index for the year prior to initial new capacity availability, followed by either consecutive "1's" or "2's" from the initial year of new capacity availability through subscript 31.

Values are first set during "first call" initialization in Subroutine ***GEINCAF***, using the site's installed capacity ($WGESICap_{PS,PY}$) and planned capacity additions ($WGESPCap_{PS,PY}$) data reported to EIA and the site's potential capacity, $WGESPtl_{PS}$. Local, undimensioned variables are used for intermediate computations.

$$WGESNCAv_{PS,PY} = 0 \qquad \text{for PY} < IAY$$

$$WGESNCAv_{PS,PY} = AvVAL \qquad \text{for PY} = IAY \text{ and} > IAY$$

where:

IAY	=	the initial year of new capacity availability at the site
AvVAL	=	1 if no more than 50 MW can be built; 2 if more than 50 MW can be built

The computations for *AvVAL* and *IAY* utilize the following "decision variable":

$$DV = (TIC + TP) / WGESPtlPS \qquad (6\text{-}1)$$

where:

TIC	=	reported installed capacity
TP	=	sum of all reported planned capacity additions

DV represents total installed and planned capacity as a fraction of total potential capacity. *AvVAL* is computed directly from *DV*. The other factor computed from *DV* is *BDCon*, a development constraint factor representing the minimum number of years between successive projects at a site.

CASE 1 - *DV* between 0.15 and 0.85

AvVal	=	1	More than a 50 MW project may be available
BDCon	=	3	Minimum of 3 years between projects

CASE 2 - *DV* either < 0.15 or > 0.85

AvVal	=	2	Project limited to no more than 50 MW
BDCon	=	5	Minimum of 5 years between projects

IAY is computed as follows:

CASE 1 - *DV* = 0 (*TIC* = 0 and *TP* = 0)

$$IAY = \max(9, Y + WGEPLEAD) \qquad (6\text{-}2)$$

where:

Y	=	the index for the first year of the run
WGEPLEAD	=	the lead time for new capacity

CASE 2 - $DV > 0$

$$IAY = \max(LPY + BDCon, Y + WGEPLEAD) \quad (6\text{-}3)$$

where LPY is a year index computed as follows:

CASE 1 - $TP > 0$

$LPY = P2$, the year of the last planned capacity addition

CASE 2 - $TP = 0$, $WGESICap_{PS,1} > 0$, all other non-zero $WGESICap_{PS,PY} = WGESICap_{PS,1}$

$LPY = 1$

CASE 3 - $TP = 0$ and not CASE 2

$LPY = IL$

where:

IL = the last year of a change in reported installed capacity

Site Cost Computations. Site cost computations use the base year (1990) costs, read from the site data file, that are produced off-line by a PC-based program, ***PC-GES***. These, and updated site costs that are computed, are placed in variables with a dimension corresponding to "this year" (index = 1) and "next year" (index = 2). When read by Subroutine ***GERDSITE***, the base year costs are placed into the "next year" position for initial updating. The site cost arrays include:

$WGESFIOC_{2,PS}$	Field fixed O&M cost
$WGESPIOC_{2,PS}$	Power plant fixed O&M cost
$WGESCCst_{2,CC,PS}$	Capital cost for component "CC," where:
	CC = 1 Exploration phase
	CC = 2 Confirmation phase dry holes
	CC = 3 Confirmation phase producer wells
	CC = 4 Construction phase dry holes
	CC = 5 Construction phase producer wells
	CC = 6 Construction phase field costs other than drilling
	CC = 7 Power plant
	CC = 8 Local transmission equipment
	CC = 9 Reservoir failure insurance

Values are read from the file for all but the capital costs for local transmission equipment and reservoir failure insurance, which are computed. The values are in units of millions of 1990

dollars. Exploration phase capital costs represent a one-time cost at the site preceding any development. All other costs are for a nominal 50 MW plant.

Initial computations are made in Subroutine ***GERDSITE*** after the input data for a site is read. The principal computation is for costs related to supplemental wells that will be needed as enthalpy declines and replacements for failed wells. Site data such as unit well costs, lifetimes for producer and injector wells, beginning year and extent of enthalpy decline, and minimum flow requirements are used in this computation, which is detailed in the Appendix 6-B explanation of the ***GERDSITE*** algorithm. Using EMM economic parameter values, all capital costs and additional O&M costs associated with supplemental and replacement wells are computed as an equivalent annual O&M cost over the life of the project, ***TSPV***, which is added as an increment to the value read for $WGESFIOC_{2,PS}$.

The capital cost for local transmission equipment is computed as the product of a local transmission distance read from the site data file and a cost per mile key parameter. So that all transmission costs are accounted for in EMM, the site costs are set to 0 by setting the cost per mile parameter to zero.

All site costs are adjusted in Subroutine ***GERDSITE*** to convert their units from millions of 1990 dollars to thousands of 1987 dollars (multiplication by $1000/MC\_PGDP_1$, the GDP deflator for 1990). All site costs are also adjusted to reflect derating due to enthalpy decline. The factor for this adjustment is the ratio of the net present "value" (but with an annual value of "1" per unit of output) of a constant annual output from a 50 MWe plant over an assumed 30-year life to the same net present value computation for an output stream that declines over the last years of the plant, according to the specific initial year of decline and rate of decline values read for the site.

The site costs are updated to reflect technological/learning curve improvements over time in Subroutine ***GEUPSCO***.

For *AEO98*, the power plant capital cost improvements conform with the EMM learning curve approach. According this approach, the cost decline is a function of market penetration and not a function of time. Modifications were made to adopt the EMM learning curve approach for only the plant capital cost. For more information see "Modifications to the Geothermal Electricity Supply Submodule" (EIA, 1995) and the comprehensive GES documentation "Model Documentation Geothermal Electric Submodule of the Renewable Fuels Module on the National Energy Modeling System" (EIA, 1994).

For each of the site cost variables, the "next year" values with index 2 are first moved to the "this year" position with index 1, and the new "next year" values computed as follows (where ***NY*** is the index for the "next year" and ***PT*** is the site's index value for type of plant -- binary or flash).

$$WGESFIOC_{2,PS} = WGESFIOC_{1,PS} * WGEPGFOT_{NY} \quad (6\text{-}4)$$

$$WGESPIOC_{2,PS} = WGESPIOC_{1,PS} * WGEPGPOT_{PT,NY} \quad (6\text{-}5)$$

$$WGESCCst_{2,CC,PS} = WGESCCst_{1,CC,PS} * WGEPGDCT_{NY} \quad \text{for CC} < 6 \qquad (6\text{-}6)$$

$$WGESCCst_{2,CC,PS} = WGESCCst_{1,CC,PS} * WGEPGFCT_{NY} \quad \text{for CC} = 6 \qquad (6\text{-}7)$$

$$WGESCCst_{2,CC,PS} = WGESCCst_{1,CC,PS} * WGEPGPCT_{PT,NY} \quad \text{for CC} = 7 \qquad (6\text{-}8)$$

$$WGESCCst_{2,CC,PS} = WGESCCst_{1,CC,PS} \quad \text{for CC} > 7$$

The factors used for updating power plant capital and O&M costs are currently those input as GES key parameters. However, there is an option controlled by the parameter ***WGETSW***, which, when it is reset to 1, would direct parameters input for drilling and field cost update factors to be replaced by Oil & Gas Supply Submodule factors. Using an OGSM algorithm, these would be computed as a dimensioned ***OGF*** variable, corresponding to an improvement index. Since this is 1. + a percentage improvement, and the GES parameters represent the ratio of the new cost to the previous cost, the GES parameters would be replaced as follows:

$WGEPGDCT_{NY} = 2. - OGF_1$ for updating drilling capital cost

$WGEPGFCT_{NY} = 2. - OGF_2$ for updating other field capital cost

$WGEPGFOT_{NY} = 2. - OGF_3$ for updating field O&M cost

The site costs in these variables are not used directly when costs for a site are needed for a computation. When site costs are needed for an algorithm, Subroutine ***GEADCST*** adjusts the drilling and other field capital costs for economic factors specific to geothermal projects, scales power plant costs, if necessary, for projects other than the nominal 50 MW, calculates reservoir failure insurance costs, converts the costs other than exploration capital costs to a $/kW unit cost for a particular capacity, and consolidates computed costs into the following variables with no dimensions:

WGEAdXCC	Adjusted exploration capital costs (units retained as thousand $)
WGEAdFCC	Adjusted confirmation capital costs ($/kW)
WGEAdSCC	Adjusted construction phase capital costs ($/kW)
WGEAdICC	Adjusted reservoir insurance capital costs
WGEAdOC	Adjusted total fixed O&M costs

GEADCST has a single argument (***CI*** in the subroutine), with a value of 1 if "this year" costs are to be used for the computations, or 2 if "next year" costs are to be used. ***PS***, a variable in a Common block, provides the site index to be used. ***PQCAP***, also a Common block variable, provides the amount of capacity for the project.

The tax rate used in making the economic factors adjustments is that obtained from EMM for the site's region:

$$CTXR = TAXRT_{PN} \quad \text{where } PN = WGESNR_{PS}$$

The year index to be used for parameters dimensioned by year is set from the current NEMS simulation year Y and the "processing year" PY as follows:

$$DY = Y + 1 \quad \text{if } PY > Y + WGEPLEAD \text{ and } Y < 26$$
$$DY = Y \quad \text{if } PY \text{ not} > Y + WGEPLEAD \text{ or } Y = 26$$

A combined factor is used to adjust for severance taxes, royalty payments, and depletion allowances:

$$SRDFct = \frac{1.}{(1. - WGEPROY_{DY} - WGEPSEV_{DY} + CTXR * WGEPDpA_{DY})} \tag{6-9}$$

Computation results for initial adjustments are placed in local variables. For capital costs:

$$LACC_1 = WGESXSS_{PS} * IntFct_1 * SRDFct \tag{6-10}$$

$$LACC_{CC} = WGESCCst_{CI,CC,PS} * IntFct_{CC} * SRDFct \quad \text{for } 1 < CC < 7 \tag{6-11}$$

$$LACC_{CC} = WGESCCst_{CI,CC,PS} * IntFct_{CC} \quad \text{for } CC \text{ not} < 7 \tag{6-12}$$

The $IntFct$ factor for all capital costs adjusts for the expensing of intangible capital expenditures, and is calculated from the tax rate, the percentage that is intangible for the particular capital cost category, and the percentage of intangible cost that is expensed (currently 100 percent for all years), as follows:

$$IntFct_{CC} = 1. - (WGEPINXP_{DY} * WGEPPctX_{CC} * CTXR) \tag{6-13}$$

For O&M costs,

$$LAFOC = WGESFlOC_{CI,PS} * SRDFct \tag{6-14}$$

$$LAPOC = WGESPlOC_{CI,PS} \tag{6-15}$$

Reservoir failure insurance cost is 5 percent of construction phase capital cost, which encompasses the components with index values 4 through 8. Two scaling factors are needed for its computation:

$$PSF = PQCAP / 50 \quad \text{if } PQCAP < 50 \tag{6-16}$$

$$PSF = 1 \quad \text{if } PQCAP \text{ not} < 50 \tag{6-17}$$

$$PCSF = PSF^{0.7} \quad \text{if } PQCAP < 50 \text{ and } WGESPTyp_{PS} = 2 \text{ (flash technology site)} \tag{6-18}$$

$$PCSF = 1 \quad \text{if } PQCAP \text{ not} < 50 \text{ or } WGESPTyp_{PS} = 1 \tag{6-19}$$

PCSF is a scaling factor for both plant capital cost (index value 7) and plant O&M cost and is needed because flash plant unit costs are dependent on plant size.

The cost of reservoir failure insurance, *TRIC*, is computed as 5 percent of the sum of the following terms:

$$LACC_{CC} * PSF \quad \text{for } CC = 4, 5, 6, 8 \tag{6-20}$$

$$LACC_7 * PSF \quad \text{if } PCSF = 1 \tag{6-21}$$

$$LACC_7 * PCSF \quad \text{if } PCSF < 1 \tag{6-22}$$

Exploration phase costs (retained in units of thousand $) and confirmation phase costs ("unitized" to $/kW) are independent of the scaling factors and may be computed directly:

$$WGEAdXCC = LACC_1 \tag{6-23}$$

$$WGEAdFCC = (LACC_2 + LACC_3) / 50 \tag{6-24}$$

Cost components that are also independent of the scaling factors are initially consolidated into the construction phase capital costs and total O&M costs:

$$WGEAdSCC = LACC_4 + LACC_5 + LACC_6 + LACC_8 \tag{6-25}$$

$$WGEAdOC = LAFOC \tag{6-26}$$

Because any impact of the flash plant scaling factor is reflected in the calculation of *TRIC*, computation of unit reservoir insurance cost depends only on the *PSF* scaling factor:

$$WGEAdICC = TRIC / 50 \quad \text{if } PSF = 1 \text{ (}QCAP\text{ is 50 or more)} \tag{6-27}$$

$$WGEAdICC = TRIC / PQCAP \quad \text{if } PSF < 1 \tag{6-28}$$

Computations of unit capital costs for the construction phase and plant O&M costs depend on both scaling factors:

$$WGEAdSCC = (WGEAdSCC + LACC_7) / 50 \quad \text{if } PSF = 1 \tag{6-29}$$

$$WGEAdOC = (WGEAdOC + LAPOC) / 50 \tag{6-30}$$

$$WGEAdSCC = (WGEAdSCC + LACC_7 * PSF) / PQCAP \quad \text{if } PSF < 1 \text{ and } PCSF = 1 \tag{6-31}$$

$$WGEAdOC = (WGEAdOC + LAPOC * PSF) / PQCAP \tag{6-32}$$

$$WGEAdSCC = (WGEAdSCC + LACC_7 * PCSF) / PQCAP \quad \text{if } PSF < 1 \text{ and } PCSF < 1 \tag{6-33}$$

$$WGEAdOC = (WGEAdOC + LAPOC * PCSF) / PQCAP \tag{6-34}$$

Two site cost computations relate only to new capacity planning. Exploration phase capital costs, incurred once at each site prior to initiation of capacity installation, must be allocated to individual projects at the site. This computation is primarily made in Subroutine *GESCBLD* to build new capacity supply curves. However, it is also used in Subroutine *GECPDPR*, which processes ECP build decisions, to "re-compute" costs for any sites for which a smaller project that is offered in the supply curve is to be built.

For sites with potential capacity greater than 300 MW, the costs are allocated uniformly over the first 250 MW of installed capacity. All of the costs are allocated to the first installed capacity at sites with less potential capacity. Unless this is the case, exploration phase capital costs allocated to a project are computed as follows:

$$WGEAdXCC = 0 \quad \text{if } WGESPtl_{PS} \text{ not} > 300 \text{ and } TIC > 0 \tag{6-35}$$

$$WGEAdXCC = (PQCAP / 250) * WGEAdXCC \quad \text{if } WGESPtl_{PS} > 300 \text{ and } TIC \text{ not} > 250 \text{ and } TIC+PQCAP \text{ not} > 250 \tag{6-36}$$

$$WGEAdXCC = ((250-TIC) / 250) * WGEAdXCC \quad \text{if } WGESPtl_{PS} > 300 \text{ and } TIC \text{ not} > 250 \text{ and } TIC+PQCAP > 250 \tag{6-37}$$

where:

TIC = total previously installed capacity plus any planned capacity additions

$PQCAP$ = the amount of capacity being costed

After allocated exploration cost is computed for a project, the unit cost (units of $/kW) is computed as:

$$WGEAdXCC / PQCAP$$

Generation of new capacity supply curves also entails computation of a levelized cost, in units of cents per kWh for offered new capacity of *PQCAP* MW at site *PS*. This computation is made in

Subroutine ***GELEVEL*** when called by ***GESCBLD***. Details of the computation are in Appendix 7-B.

A levelized capital charge rate, ***LAFCR***, is computed from sinking fund depreciation, a retirement dispersion allowance, straight line depreciation income taxes, a double declining balance tax preference allowance, a flow through accounting tax preference allowance, and property tax and insurance. The capital charge rate is adjusted with an inflation factor, ***GLVL***, in the computations.

Using financial functions, the future value of all capital costs as of plant start-up is aggregated as ***TFVCC***. The future value computations use a 3-year confirmation phase and 2-year construction phase, rather the shortened total lead time of four years used to facilitate ECP's planning horizon.

Using the results of these preliminary calculations, levelized cost is calculated as:

$$LCOST = ADJ * (TFVCC * (LAFCR/GLVL) + WGEAdOC) \quad (6\text{-}38)$$

where:

ADJ = factor for conversion from annual $/kW to cents per kWh.

Computations of New Capacity Amounts Offered at Sites. In generating new capacity supply curves, costs are computed for specific project sizes at specific sites. This section describes the computation of the project sizes, ***PQCAP***. The computation uses the site's new capacity availability factor and uses the same decision variable, ***DV***, used to determine the factor's value -- total previously installed capacity and known capacity additions (planned or unplanned), ***TIC***, as a fraction of the site's total potential capacity -- to determine ***PQCAP***. This computation is performed in Subroutine ***GESCBLD***.

For a given new capacity availability year, ***PY***, the computation applies only to sites with a non-zero new capacity availability factor ($WGESNCAv_{PS,PY}$). For these sites, a preliminary project size is computed as a percentage of total potential capacity as follows:

$$NCQ = WGESPtl_{PS} * .01 \quad \text{if } DV = 0 \quad (6\text{-}39)$$

$$NCQ = WGESPtl_{PS} * (.01 + (.14/.15)*DV) \quad \text{if } DV > 0 \text{ and } DV \text{ not} > .15 \quad (6\text{-}40)$$

$$NCQ = WGESPtl_{PS} * .15 \quad \text{if } DV > .15 \text{ and } DV \text{ not} > .8 \quad (6\text{-}41)$$

$$NCQ = 0.75 * (WGESPtl_{PS} - TIC) \quad \text{if } DV > .8 \quad (6\text{-}42)$$

After rounding upward to the nearest 5 MW, the preliminary value is modified as indicated if one of the following constraints is violated (***NCQ**** in the conditions refers to the preliminary value):

$NCQ = 20$ if $WGESNCAv_{PS,PY} = 1$ and $DV = 0$ and $NCQ^* > 20$

$NCQ = 50$ if $WGESNCAv_{PS,PY} = 1$ and $DV > 0$ and $NCQ^* > 50$

$NCQ = 10$ if $WGESNCAv_{PS,PY} = 1$ and $DV > 0$ and $NCQ^* < 10$

$NCQ = 200$ if $WGESNCAv_{PS,PY} = 2$ and $NCQ^* > 200$
$NCQ = 10$ if $WGESNCAv_{PS,PY} = 2$ and $NCQ^* < 10$

$NCQ = 50$ if $WGESNCAv_{PS,PY} = 2$ and $NCQ^* > 50$ and $NCQ^* < 70$
$NCQ = 100$ if $WGESNCAv_{PS,PY} = 2$ and $NCQ^* > 100$ and $NCQ^* < 120$
$NCQ = 150$ if $WGESNCAv_{PS,PY} = 2$ and $NCQ^* > 150$ and $NCQ^* < 170$

If NCQ is less than 50 MW or is a multiple of 50 MW (50, 100, 150, or 200), there is a single new capacity project offered at the site, with $PQCAP = NCQ$. Otherwise, there will be two projects, each with its own calculated costs, which may differ due to the flash plant scaling factor or completion of the allocation of exploration phase capital cost. For these, the project sizes will be:

$PQCAP = NCQ - \text{MOD}(NCQ,50)$ for the multiple of 50 MW project (6-43)

$PQCAP = \text{MOD}(NCQ,50)$ for the "residual" project (6-44)

Computations for EMM Regions

Most GES regional computations are for EMM regions. These typically map data for sites in a region into analogous data for the region as a whole. Such computations are made successively for each EMM region in which any sites are located, with the initial computations made successively for each site in the region. The standard method for these computations uses the number of sites in a region to determine the site index for the last site in the region. The index for the first site in all regions after the first is simply the next index value after that for the last site in the previous region. The standard method, then, may be summarized as follows:

Set last site index (*LS*) to 0.
Repeat for each EMM region with geothermal sites:
  Set EMM region (*PN*) for computations
  Set any initial values for region (generally accumulators set to 0)
  Set initial site index *FS* to *LS* + 1
  Increment last site index (*LS*) by $WGEINumS_{PN}$
  Repeat initial computations for each site from index *FS* to *LS*
  Perform final computations for region *PN*

There are also GES computations for Census divisions, which are performed within the repetitive EMM region computational structure. Specifically,:

Prior to start of EMM region repetitions: Set initial values for all Census regions

During initial site computation repetitions: Set Census division index (*CI*) to $WGESCR_{PS}$
Update Census division *CI* data with site *PS* data

After end of EMM region repetitions: Perform final computations for all Census divisions

New Capacity Supply Curve Computations. For given year of availability, *PY*, new capacity supply curves are generated for each EMM region with geothermal sites. A supply curve's index, *SC*, is related to the corresponding EMM region's index, *PN*, by the value of $WGEUNRgn_{SC}$. A new capacity supply curve for each qualifying region is generated by four sets of computations in Subroutine *GESCBLD*.

In the initial computations, repeated over each site in the region, the computations for new capacity offered at the site, described above, identify either one or two potential projects for each site, PS, with a non-zero new capacity availability factor for the year. Each project has a corresponding size, *PQCAP*, for which a levelized cost, *LCOST*, is computed. If *LCOST* does not exceed a supply curve "truncation" value for the EMM region and availability year, $WELSCST_{PN,PY}$, data characterizing the project are saved with the next "step" index, *NS*.

$$NDX_{NS} = NS$$
$$WID_{NS} = PS$$
$$WLC_{NS} = LCOST$$
$$WSQ_{NS} = PQCAP$$

For *AEO96*, the methodology for the supply curve truncation was changed. The new methodology evaluates a cumulative average levelized cost of geothermal sites for the supply curve truncation criterion. The cumulative average levelized cost of each supply step must be less than the "truncation" value to be included in the supply curve. For more information see the "Modifications to the Geothermal Electricity Supply Submodule" (EIA, 1995) and the comprehensive GES documentation "Model Documentation Geothermal Electric Submodule of the Renewable Fuels Module on the National Energy Modeling System" (EIA, 1994).

After the computations have been completed for each site in the region, the value of *NS* is retained in $WGEUNoSt_{SC}$. If 0, no site had a non-zero new capacity availability factor, so no new capacity is available in the region. Values for all supply curve variables for the region also remain 0 and no further computations are performed for the region. Otherwise, Subroutine *GESORT* is performed. Its computations sort the levelized costs in *WLC* into ascending order, also adjusting the "tag" array, *NDX*, so that its step index values are placed in the same position as the project's levelized cost in the *WLC* array. The *WID* and *WSQ* arrays are not changed.

A third set of computations adjusts the sequencing in *WLC* and *NDX*, if necessary, to ensure that a smaller project (< 50 MW) does not precede a larger project (multiple of 50 MW) at the same site, even if its levelized cost is less.

The final computations generate the supply curve data for the region. Variables used in the computations are defined here in relation to "$Project_{ST}$," which is the project with original step index *NX*, where:

$$NX = NDX_{ST}$$

Computations are performed sequentially for $Project_1$, $Project_2$, etc., through $Project_{NS}$. Data for step 1 of the supply curve is for $Project_1$ only; step 2 data is for $Project_1$ and $Project_2$ combined; and so on, through the last step with data for all NS projects combined. The site index and size for $Project_{ST}$ are:

$$PS = WID_{NX}$$
$$PQCAP = WSQ_{NX}$$

These are used to compute costs for the project, using the previously described site data computations of Subroutine *GEADCST*. This is also done in the first set of computations, to calculate the levelized cost of the project, but it is simpler to repeat the computations than retain the values of all cost components for all projects. Although values for undimensioned variables are produced by the subroutine and used in the computations, a subscript will be used for their mathematical description.

OC_{ST} (for *WGEAdOC*) is the fixed O&M cost for $Project_{ST}$

CC_{ST} (for *WGEAdXCC* + *WGEAdFCC* + *WGEAdSCC* + *WGEAdICC*) is the total overnight capital cost for $Project_{ST}$

Other variables for the project are similarly subscripted here.

$PQCAP_{ST}$ is the size of $Project_{ST}$

$CF_{ST} = WGESCFct_{PS}$ is the capacity factor for $Project_{ST}$

$HR_{ST} = WGESHtRt_{PS}$ is the heat rate for $Project_{ST}$

$CO2R_{ST} = WGESCO2R_{PS}$ is the CO_2 emissions rate for $Project_{ST}$

The site index for step *ST** of supply curve *SC* (for EMM region $WGEUNRgn_{SC}$) is set as:

$WGEVSI_{SC,ST*} = PS$ (where $PS = WID_{NX}$, where $NX = NDX_{ST*}$)

In all of the following computations, summations are over all projects from $Project_1$ through $Project_{ST*}$, and the computations are made for all values of *ST** from 1 through *NS*.

$$WGEVNCCQ_{SC,ST*} = \sum PQCAP_{ST} \quad \text{(6-45)}$$

$$WGEVCFct_{SC,ST*} = \sum (PQCAP_{ST} * CF_{ST}) / \sum PQCAP_{ST} \quad (6\text{-}46)$$

$$WGEVOVCC_{SC,ST*} = \sum (PQCAP_{ST} * OC_{ST}) / \sum PQCAP_{ST} \quad (6\text{-}47)$$

$$WGEVFOC_{SC,ST*} = \sum (PQCAP_{ST} * CF_{ST}) / \sum PQCAP_{ST} \quad (6\text{-}48)$$

$$WGEVHtRt_{SC,ST*} = \sum (PQCAP_{ST} * CF_{ST} * HR_{ST}) / \sum (PQCAP_{ST} * CF_{ST}) \quad (6\text{-}49)$$

$$WGEVCO2R_{SC,ST*} = \sum (PQCAP_{ST} * CF_{ST} * CO2R_{ST}) / \sum (PQCAP_{ST} * CF_{ST}) \quad (6\text{-}50)$$

New Capacity Planning Output Computations. New capacity planning output for ECP, produced with Subroutine *GECPOUT*, is taken directly from the supply curve data, but is limited to data for a single point on the "curve." Accordingly, the output variables are dimensioned only by EMM region and year. A set of "local" variables for the output values are defined so that the year index corresponds to the initial year of availability if the new capacity is built. These variables are used in all GES computations and are consistent with the year index interpretation for the corresponding ECP new capacity build decision. However, a different year index interpretation is used for the global variables from which EMM obtains the values. For the interface variables that have been established for all renewable technologies, the year index corresponds to the year prior to that for which ECP uses the data for its new capacity planning. From the 4-year lead time for new geothermal capacity, the GES availability year index, *PY*, translates into a year index of *PY*-5 for the global interface variables.

Computations are made successively for each of the $WGENum_{SC}$ supply curves. For the supply curve with index *ST*, the region and number of steps are set as follows:

$$PN = WGEUNRgn_{SC}$$
$$RS = WGEUNRgn_{SC}$$

The upper bound on the amount of new capacity that can be built is the total capacity of all projects, computed for the last step.

$$WCAGPEL_{PN,PY-5} = WGEPMAXC_{PN,PY} = WGEVNCCQ_{SC,RS} \quad (6\text{-}51)$$

Other output values may also correspond to those for the last step, but there are circumstances under which a different step is used for these values. The reason is that the ECP linear programming model treats the unit costs provided by the GES as constant for all build amounts. Unit costs in GES are not fixed and, by construction, increase from one step to the next. Costs for the last step are the maximum unit costs. If only these maximum costs are provided to the ECP, build decisions will never reflect the lower costs if less than the maximum available new capacity is built. Therefore, after the first ECP build decision, when there are more that four steps in a supply curve and the ECP build decision for the previous year was less than the maximum amount available, the value of *RS*, the step that is used for the output, is changed to:

$$RS = WGEUNRgn_{SC} / 2 \quad \text{(rounded down if there is an odd number of steps)}$$

The additional new capacity planning output is set as follows:

$$WCFGPEL_{PN,PY-5} = WGEPCF_{PN,PY} = WGEVCFct_{SC,RS} \quad (6\text{-}52)$$

$$WCCGPEL_{PN,PY-5} = WGEPCC_{PN,PY} = WGEVOVCC_{SC,RS} \quad (6\text{-}53)$$

$$WOCGPEL_{PN,PY-5} = WGEPFXOC_{PN,PY} = WGEVFOC_{SC,RS} \quad (6\text{-}54)$$

$$WHRGPEL_{PN,PY-5} = WGEPHtRt_{PN,PY} = WGEVHtRt_{SC,RS} \quad (6\text{-}55)$$

$$WEMGPEL_{3,PN,PY-5} = WGEPCO2R_{PN,PY} = WGEVCO2R_{SC,RS} \quad (6\text{-}56)$$

Other New Capacity Output Related Computations. New capacity supply curves are built and output for ECP produced by setting the year of availability, *PN*, then running Subroutines *GESCBLD* and *GECPOUT*. As a special case, this is done in Subroutine *RFMGES* for *PY* = *FIRSYR* + 4 (unless *FIRSYR* is 1 — for 1990 — which would result in a 0 year index (1 + 4 - 5) for the global output variables). This special case produces the data needed to process any ECP build decision made that year, before RFM is first run.

Apart from this special case, Subroutine *GECPOPR* controls the capacity planning output processing. Specifically, for each year, supply curves are built and output for ECP produced for each year of the ECP planning horizon for the decisions to be made the following year. When GES runs for simulation year *Y*, the planning horizon for the following year covers years *Y*+1 through *Y*+6. The initial year of availability for geothermal new capacity is (*Y*+1 + 4) or *Y*+5. Supply curves are generated and ECP output produced, first for *PY* = *Y*+5, and then for *PY* = *Y*+6.

For the *PY* = *Y*+6 computations, it is assumed that all new capacity offered for *Y*+5 in all EMM regions is built. Before this is done, it is first necessary to save all of the supply curve data for the initial year, as well as all site new capacity availability factors and unplanned capacity amounts. Then, new site availability factors are computed for use in the *Y*+6 computations, using the maximum available being built assumption. Lastly, after ECP output is produced for the last year of the planning horizon, the saved site new capacity availability factors and unplanned capacity values, and *PY* = *Y*+5 supply curve data are restored.

Computations for Processing ECP New Capacity Build Decisions. The computations for processing ECP new capacity build decisions are in Subroutine *GECPDPR*. No computations are made for regions where no new capacity is to be built. Where any new capacity is to be built, *CP* and *CPQ* are computed initially, where:

CP is the maximum step index *ST* such that $WGEVNCCQ_{SC,ST}$ does not exceed the amount to be built.

$$CPQ = WGEVNCCQ_{SC,CP} \quad (6\text{-}57)$$

If ***CPQ*** is less than the amount to be built, ***CP*** is incremented by 1. Only part of the additional capacity in this step will be built.

The principal computations are done sequentially by step, from 1 through ***CP***. For step ***ST***, the site index and amount of new capacity offered from the site are:

$$PS = WGEVSI_{SC,ST} \qquad (6\text{-}58)$$

$$PQCAP = WGEVNCCQ_{SC,ST} \quad \text{for } ST = 1$$
$$PQCAP = WGEVNCCQ_{SC,ST} - WGEVNCCQ_{SC,ST-1} \quad \text{for } ST > 1$$

With the possible exception of the last step, ***PQCAP*** is also the amount to be built at the site. If less than the capacity offered in step ***CP*** is to be built, the amount to be built at the site is the difference between the amount to be built in the region and ***CPQ***, so ***PQCAP*** is recomputed as this value.

Site unplanned capacity additions are computed with an incremental formula, since two different projects may be built at a site (one a multiple of 50 MW and the other < 50 MW):

$$WGESUCap_{PS,PY} = WGESUCap_{PS,PY} + PQCAP$$

Site new capacity availability factors are updated to reflect the information for the next available new capacity at the site. The algorithm is the same as is used to set the initial values during initialization.

The output used by ECP in making the decision, other than the build limit, is modified if necessary so that it corresponds to the amount being built. If less then the maximum available new capacity is being built, the site costs for the additional capacity to be built from step ***CP*** may be different from the costs for the additional amount offered, requiring adjustment before the revised ECP output can be computed.

To make the adjustment, it is necessary to break the capital cost down into its different components. Initially, the original added total capital cost is saved and costs are computed for the offered quantity. Where $PS = WGEVSI_{SC,CP}$:

$$PQCAP = WGEVNCCQ_{SC,CP} \quad \text{if } CP = 1$$
$$UCCADJ = WGEVOVCC_{SC,SP}$$

$$PQCAP = WGEVNCCQ_{SC,CP} - WGEVNCCQ_{SC,CP-1} \quad \text{if } CP > 1$$

$$UCCADJ = \frac{(WGEVNCCQ_{SC,CP} * WGEVOVCC_{SC,CP}) - (WGEVNCCQ_{SC,CP-1} * WGEVOVCC_{SC,CP-1})}{PQCAP} \qquad (6\text{-}59)$$

The original construction phase capital costs (*WGEAdSCC*) and reservoir failure insurance capital cost (*WGEAdICC*) are subtracted from *UCCADJ*, leaving the sum of confirmation phase and any exploration phase capital costs. These unit costs ($/kW) do not vary with size. *PQCAP* is changed to the amount to be built and the unit costs for this quantity are computed with Subroutine *GEADCST*. Adding the new values of *WGEAdSCC* and *WGEAdIOC* to *UCCADJ* gives total unit capital costs for the new quantity

If the computations are for the first step (*CP* = 1), there are no other projects to be built. Heat and emissions rates are fixed for the project site, so only the two cost values need to be computed.

$$WGEVOVCC_{SC,CP} = UCCADJ + WGEAdSCC + WGEAdIOC \quad (6\text{-}60)$$

$$WGEVFOC_{SC,CP} = WGEAdOC$$

When *CP* > 1, other projects are to be built. All output data must be adjusted to reflect the "last step's" smaller percentage of the total amount to be built in the region than in the original supply curve computations. Letting *WELRQCA* represent the ECP build decision for the region:

$$WGEVOVCC_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{OVCC}{}_{SC,CP-1}) + PQCAP*(UCCADJ + WGEAdSCC + WGEAdIOC)}{WELRQCA} \quad (6\text{-}61)$$

$$WGEVFOC_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGE^{VFOC}{}_{SC,CP-1}) + (PQCAP*WGEAdOC)}{WELRQCA} \quad (6\text{-}62)$$

$$WGEVCFct_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{CFct}{}_{SC,CP-1}) + (PQCAP*WGESCFct_{PS})}{WELRQCA} \quad (6\text{-}63)$$

$$WGEVHtRt_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{CFct}{}_{SC,CP-1} * WGEV^{HtRt}{}_{SC,CP-1}) + (PQCAP*WGESCFct_{PS} * WGESHtRt_{PS})}{(WELRQCA * WGEVCFct_{SC,CP})} \quad (6\text{-}64)$$

$$WGEVCO2R_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{CFct}{}_{SC,CP-1} * WGEV^{CO2R}{}_{SC,CP-1}) + (PQCAP*WGESCFct_{PS} * WGESCO2R_{PS})}{(WELRQCA * WGEVCFct_{SC,CP})} \quad (6\text{-}65)$$

All local and global new capacity output variables except those for the build constraint are set to the corresponding value computed for step ***CP***. The fixed O&M cost for the new capacity to be built in EMM region ***PN*** with initial availability in year ***PY*** is saved for later use in computing output for all installed capacity for year ***PY***.

$$WGENUOC_{PN,PY} = WGEPFXOC_{PN,PY}$$

Dispatch Related Output Computations for All Installed Capacity. Regional (EMM and Census) output for all installed capacity in 1990 is computed as part of the initialization process with Subroutine ***GEINTRG***. Output for later years may also be computed during initialization, or may be computed as part of the standard processing for every year with subroutine ***GEEDOPR***. The determining factor is the first simulation year index, ***FIRSYR***. If ***FIRSYR*** is 1 or 2, output for all years after 1990 is computed with ***GEEDOPR***. Otherwise, output for all years after 1990, but prior to ***FIRSYR***, is computed with ***GEINTRG*** during initialization; output for all years starting with ***FIRSYR*** is computed with ***GEEDOPR***. Output for all installed capacity for ***FIRSYR*** (if > 1) is computed as part of the special processing for that year in Subroutine ***RFMGES***. The standard procedure for all years (with index < 26) produces output for the following year (***FIRSYR***+1 output when run for ***FIRSYR***, etc.)

There are only minor differences between the computations performed in ***GEINTRG*** and in ***GEEDOPR***. In both cases, one of the computations for years after 1990 updates the installed capacity at each site. The primary difference is that the ***GEEDOPR*** computations update for both planned and unplanned capacity additions, while the ***GEINTRG*** update is limited to planned capacity additions.

$$WGESICap_{PS,PY} = WGESICap_{PS,PY-1} + WGESPCap_{PS,PY} \quad (GEINTRG)$$

$$WGESICap_{PS,PY} = WGESICap_{PS,PY-1} + WGESPCap_{PS,PY} + WGESUCap_{PS,PY} \quad (GEEDOPR)$$

As usual, the computations are made sequentially for each EMM region, with the initial computations performed sequentially for the sites in the region. Totals are aggregated for both EMM regions and Census divisions.

Except for fixed O&M cost, by EMM region, the output computations aggregate fixed site parameters that do not change over time. These computations are generally the same for all years and in both subroutines. The only variability is due to the requirement to reflect data for The Geysers in the output for its EMM region and Census division. Initial computations when processing each site in successive EMM regions are identical.

For the one EMM region computation, summation is over all sites in the region being processed.

$$NRCRFCT = \sum (WGESICap_{PS,PY} * WGESCFct_{PS}) \quad (6\text{-}66)$$

For the Census division computations, summation for region ***CI*** is over all sites in all EMM regions such that $WGESCR_{PS} = CI$.

$$CRCRFCT_{CI} = \sum (WGESICap_{PS,PY} * WGESCFct_{PS}) \quad (6\text{-}67)$$

$$CRHtRt_{CI} = \sum (WGESICap_{PS,PY} * WGESCFct_{PS} * WGESHtRt_{PS}) \quad (6\text{-}68)$$

$$CRECO2_{CI} = \sum (WGESICap_{PS,PY} * WGESCFct_{PS} * WGESCO2R_{PS}) \quad (6\text{-}69)$$

EMM region output is produced after all sites in the region have been processed. Total installed capacity in the region is:

$$NRICAP = \sum WGESICap_{PS,PY}$$

CASE 1 - $NRICAP = 0$ and PN not $= WGEGNR$

No computations, output value remains 0.

CASE 2 - $NRICAP = 0$ and $PN = WGEGNR$

$WCFGIEL_{PN,PY} = WGEGCFct_{PY}$ (capacity factor for The Geysers for year PY)

CASE 3 - $NRICAP > 0$ and PN not $= WGEGNR$

$$WCFGIEL_{PN,PY} = NRCFCT / NRICAP$$

CASE 4 - $NRICAP > 0$ and $PN = WGEGNR$

$$WCFGIEL_{PN,PY} = \frac{(NRCFCT + WGEGICAP_{PY} * WGEG^{CFct}{}_{PY})}{(NRICAP + WGEGICAP_{PY})}$$

Census division output is produced after all sites in all regions have been processed. Total installed capacity in Census division CI is:

$$CRICAP_{CI} = \sum WGESICap_{PS,PY}$$

CASE 1 - $CRICAP_{CI} = 0$ and CI not $= WGEGCR$

No computations, output value remains 0.

CASE 2 - $CRICAP_{CI} = 0$ and $CI = WGEGCR$

$WHRGIEL_{CI,PY} = WGEGHtRt$
$WEMGIEL_{3,CI,PY} = WGEGCO2R$

CASE 3 - $CRICAP_{CI} > 0$ and CI not $= WGEGCR$

$$WHRGIEL_{CI,PY} = CRHTRT_{CI} / CRCFCT_{CI} \quad (6\text{-}70)$$

$$WEMGIEL_{3,CI,PY} = CRECO2_{CI} / CRCFCT_{CI} \quad (6\text{-}71)$$

CASE 4 - $CRICAP_{CI} > 0$ and $CI = WGEGCR$

$$WHRGIEL_{CI,PY} = \frac{(CRHTRT_{CI} + WGE^{GICAP}{}_{PY} * WGEG^{CFct}{}_{PY} * WGEGH^{tRt})}{(CRCFCT_{CI} + WGE_{GICAP_{PY}} * WGEG_{CFct_{PY}})} \quad (6\text{-}72)$$

$$WEMGIEL_{3,CI,PY} = \frac{(CRECO2_{CI} + WGE^{GICAP}{}_{PY} * WGEG^{CFct}{}_{PY} * WGEGC^{O2R})}{(CRCFCT_{CI} + WGE_{GICAP_{PY}} * WGEG_{CFct_{PY}})} \quad (6\text{-}73)$$

Fixed O&M cost computations are not the same under all circumstances. For 1990, the computations are analogous to that for output related to fixed site data. The computations aggregate the costs for installed capacities. For the initial computations, ***PQCAP*** is set to $WGESICap_{PS,1}$ and the computations of Subroutine ***GEADCST*** produce the costs for the capacity. ***NRFXOC*** is computed as the sum of the product of ***PQCAP*** and ***WGEAdOC***. After all sites in the region have been processed:

CASE 1 - $NRICAP = 0$ and PN not $= WGEGNR$

No computations, output value remains 0.

CASE 2 - $NRICAP = 0$ and $PN = WGEGNR$

$$WOCGIEL_{PN,PY} = WGEGOC$$

CASE 3 - $NRICAP > 0$ and PN not $= WGEGNR$

$$WOCGIEL_{PN,PY} = NRFXOC / NRICAP$$

CASE 4 - $NRICAP > 0$ and $PN = WGEGNR$

$$WCFGIEL_{PN,PY} = \frac{(NRFXOC + WGEGICAP_{PY} * WGEG^{OC})}{(NRICAP + WGEGICAP_{PY})} \quad (6\text{-}74)$$

The general approach for years after 1990 is to compute fixed O&M cost as a weighted average of the cost of previously installed capacity and any new capacity additions. In Subroutine ***GEINTRG***, only planned capacity additions need be considered. The initial computations are the same as for 1990, except that ***PQCAP*** is set to $WGEGPCap_{PS,PY}$, so that the computation for ***NRFXOC*** produces total O&M costs of all planned capacity additions for the region.

It there is no capacity installed in the region (either previously installed or as new capacity additions), the cost, as for 1990, is 0 (no change from initialization value) except for The Geyser's region; or, for that region, *WGEGOC*. For "CASE 3" and "CASE 4":

CASE 3 - *WGENICAP* > 0 and *PN* not = *WGEGNR*

$$WOCGIEL_{PN,PY} = \frac{(NRFXOC + WOCGIEL_{PN,PY-1} * WGENICap_{PN,PY-1})}{WGENICAP_{PN,PY}} \quad (6\text{-}75)$$

CASE 4 - *WGENICAP* > 0 and *PN* = *WGEGNR*

$$WOCGIEL_{PN,PY} =$$

$$\frac{(NRFXOC + WOCGIEL_{PN,PY-1} * (WGENICap_{PN,PY-1} + WGEGICAP_{PY=1}) + A}{(WGENICAP_{PN,PY} + WGEGICAP_{PY})} \quad (6\text{-}76)$$

where:

$$A = WGEGOC * (WGEGICAP_{PY} - WGEGICAP_{PY-1}) \quad (6\text{-}77)$$

This term is always zero in the current version of GES, but it is included so the computation will be made correctly if installed capacity at The Geysers changes over time in a future version.

The same initial computations for planned capacity additions are made in Subroutine *GEEDOPR*, but there additional computations are required for unplanned new capacity additions. Only the total unplanned capacity addition, *NRUCAP*, need be computed. The fixed O&M cost for these capacity additions are saved when the ECP capacity planning decision was made. For total fixed O&M costs for unplanned capacity additions:

$$NRUFOC = NRUCAP * WGENUOC_{PN,PY} \quad (6\text{-}78)$$

The computations are so similar there is no need to state the final computations of fixed O&M cost output. It is only necessary to replace total costs for planned additions (*NRFXOC*) with the total cost of planned and unplanned additions, which is (*NRPFOC* + *NRUFOC*).

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

Due to its size, Appendix 6-A has not been included here. The reader is referred to the report, "Model Documentation: Geothermal Electric Submodule of the Renewable Fuels Module of the National Energy Modeling System," December 1994, prepared by DynCorp-Meridian Inc. for the Energy Information Administration. The Inventory of Variables, Data, and Parameters is in Appendix A, pp. 27-176. A copy of the report is maintained in the files of:

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Also see: "Modifications to the Geothermal Electricity Supply Submodule," September, 1995.

Appendix 6-B: Mathematical Description

Due to its size, Appendix 6-B has not been included here. For Appendix 6-B, the reader is referred to the report, "Model Documentation: Geothermal Electric Submodule of the Renewable Fuels Module of the National Energy Modeling System," December 1994, prepared by DynCorp-Meridian Inc. for the Energy Information Administration. The Mathematical Description is given in Appendix B, pp. 177-225. A copy of the report is maintained in the files of:

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Also see: "Modifications to the Geothermal Electricity Supply Submodule," September, 1995.

Appendix 6-C: Bibliography

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B. Other References

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Appendix 6-D: Model Abstract

Model Name:
Geothermal Electric Submodule

Model Acronym:
GES

Description:
The GES models economic supply curves, aggregated by EMM region, for electric generation capacity utilizing known U.S. geothermal hydrothermal resources. The costing algorithms model the impacts of specific resource site parameters at known geothermal sites on the capital cost, operation and maintenance cost, and energy prices at those sites. For each year, GES processes new capacity build decisions made by the Electricity Capacity Planning (ECP) submodule, allocating the regional build amounts to individual sites in the region through the new capacity supply curve data for the region; updates installed capacity and related data for both sites and regional aggregations, and produces output for use by the Electric Fuel Dispatch submodule; and produces new capacity supply curves and related output for use by the ECP submodule.

Purpose of the Model:
The purpose of GES is to supply the Electric Market Model (EMM) of NEMS with geothermal supply curves and annual capacity information for dispatch.

Most Recent Model Update:
July 1996

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:
Roger Diedrich
Coal, Uranium, and Renewable Fuels Analysis Branch
Energy Information Administration
Phone: (202) 586-0829

Documentation:
NEMS Documentation Report: *Renewable Fuels Module of the National Energy Modeling System*, January 1998.

Archive Media and Installation Manual(s):
Archived as part of the NEMS production runs.

Energy System Described:
Complete systems for extracting geothermal heat from the earth and converting it to electricity, including wells, fluid gathering systems, both binary and flash rankine cycle energy conversion systems, and fluid reinjection systems.

Coverage:

- Geographic: EMM regions 11, 12, and 13
- Time Unit/Frequency: Annual, 1990 through 2020
- Products: Electricity
- Economic Sectors: Electric utility

Modeling Features:

- Model Structure: The model operates at the level of individual geothermal sites. Regional inputs from the Electricity Market Module are disaggregated to the individual sites and are operated upon at that level. Results are then rolled up to the regional level at which NEMS is structured for output.
- Model Technique: Risk avoidance model of developer behavior is used to determine timing and extent of further development at each site. New capacity supply curves are generated in terms of minimizing levelized cost for any new capacity amounts. Regional aggregate data is computed as weighted average of analogous individual site data, using either capacity or generation as weights, as appropriate.
- Special Feature:
    - Accommodates runs for either type of looping. Incorporates dynamic interface in which the output needed by the EMM for processing the next year is produced, rather than the output for the current year.
    - Employs a PC-based data pre-processor to calculate site-specific costs and performance of geothermal systems based on resource data for 51 known U.S. geothermal resource sites.

Non-DOE Input Sources:
None.

DOE Input Sources:

Petty, Susan, et al, *Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power in 20 and 40 Years*, Susan Petty Consulting, Solana Beach, CA, June 1991 for the Energy Information Administration and Geothermal Division of DOE.

- Geothermal Resource Site Data

  Entingh, D., McLarty L., Nichols, K., Livesay, W., and Petty. S., "Geothermal Cost of Power Model IM-GEO Version 3.05" developed for Sandia National Laboratory and the Geothermal Division of the DOE.

- Geothermal systems operational and cost parameters and algorithms.

Computing Environment:

- Hardware Used: IBM RS/6000
- Operating System: Unix
- Language/Software used: VS Fortran, Version 2.05

Independent Expert Reviews Conducted:

None.

Status of Evaluation Efforts by Sponsor:

None.

Appendix 6-E: Data Quality and Estimation Processes

This appendix provides an overview of the Geothermal Electric Supply Data Pre-Processor model, or GESDPP. A PC-based model, GESDPP serves as the main source of input data used in the GES. It is adapted from an earlier PC-based model, IM-GEO[19], developed by a team of geothermal industry experts for Sandia National Laboratory in the mid 1980s. "IM-GEO" stands for Impacts of Research and Development on the Cost and Performance of Geothermal Electric Systems.

The GESDPP, calculates typical capital and operation and maintenance costs (as well as heat rates, flow rates, and other technical parameters) for a single 50 MW (net) plant at each of 51 known geothermal resource sites in the western U.S., including Hawaii. Based on historical cost data for independent geothermal power projects developed during the 1980s, GESDPP models existing, commercially available technologies associated with power generation from hydrothermal resources. To date, hydrothermal resources are the only geothermal resources for which commercial development has been feasible.

The main input to GESDPP is a geothermal resource data set which includes data on 51 known geothermal resource sites in the U.S. The site data include measured parameters as well as parameters which were estimated based on other measured data for the site in question or on more complete knowledge of a geologically and hydrologically similar site. These data were compiled during a study completed in 1991 for EIA and the Geothermal Division of DOE[20], using U.S. Geological Survey data and other sources.

The cost and performance data and algorithms within GESDPP are considered accurate since costs as modeled by IM-GEO have been found to be reasonably similar to costs for actual geothermal projects. The resource site data are considered less reliable. For the 17 resource sites with existing geothermal capacity, and especially for those that have been operating for several years, the data are probably quite reliable. However, for most of the other sites, geological, geophysical and hydrological investigations have been limited, and much of the data have been estimated based on knowledge of geothermal resource sites with similar general geological conditions.

Immediately following are general flow diagrams for GESDPP, presented in Figures 6E-1, 6E-2, and 6E-3, and a listing of mathematical descriptions of the key costing and performance algorithms. A list of the input resource data and output data from GESDPP are presented in Part 3 of Appendix 6-A. A description of the output file, WGESITE, which serves as the main input file for GES can also be found in Appendix 6-A.

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[19]Entingh, D.J. and Mclarty, L. *Geothermal Cost of Power Model - IM-GEO Version 3.05: User's Manual*, for Sandia National Laboratory, November 1991.

[20]Petty, Susan, et al, *Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power in 20 and 40 Years*, Susan Petty Consulting, Solana Beach, CA, June 1991.

Figure 6E-1. Main Flow Chart of GESDPP

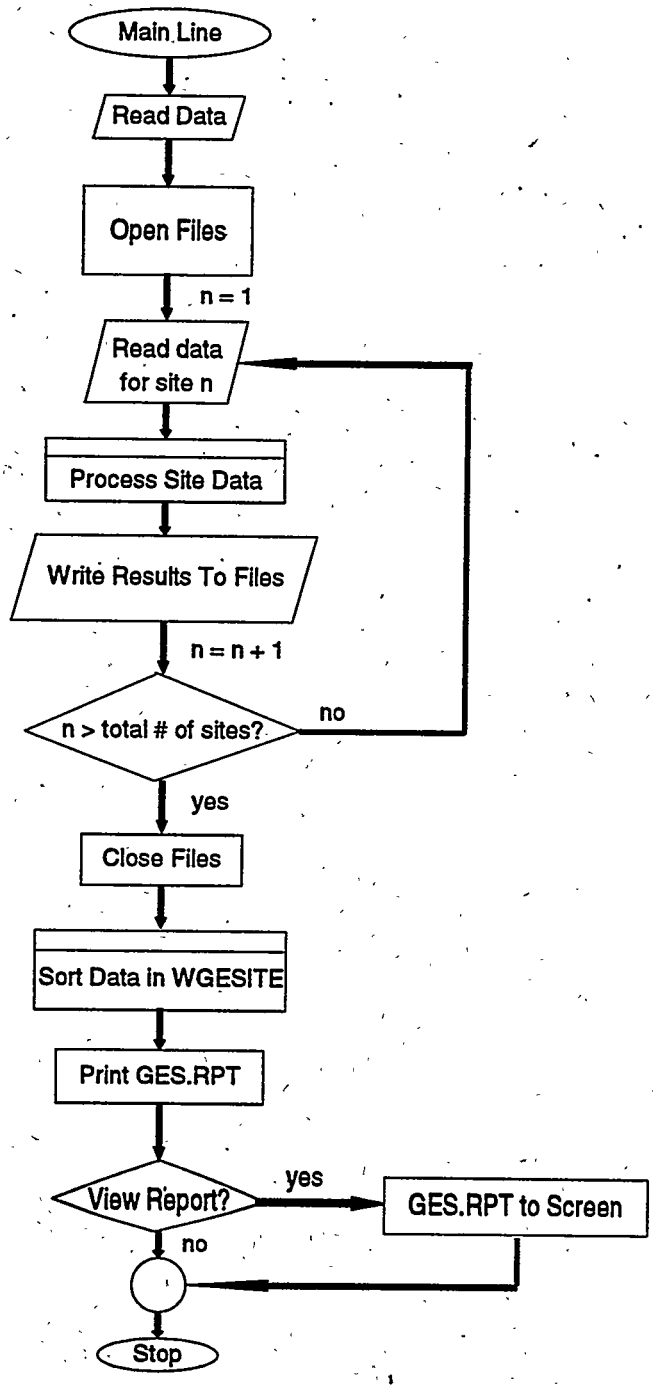


Figure 6E-2. Flow Diagram for Process Site Data Routine

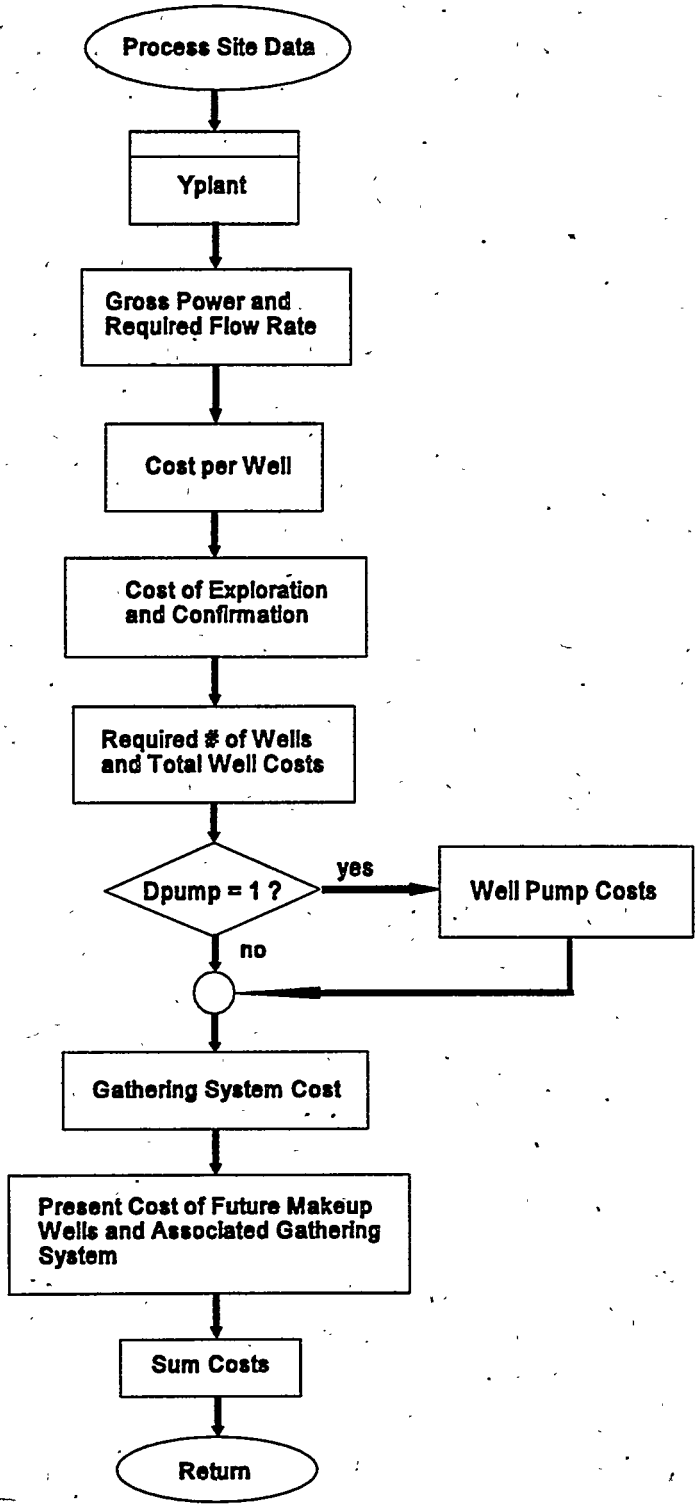
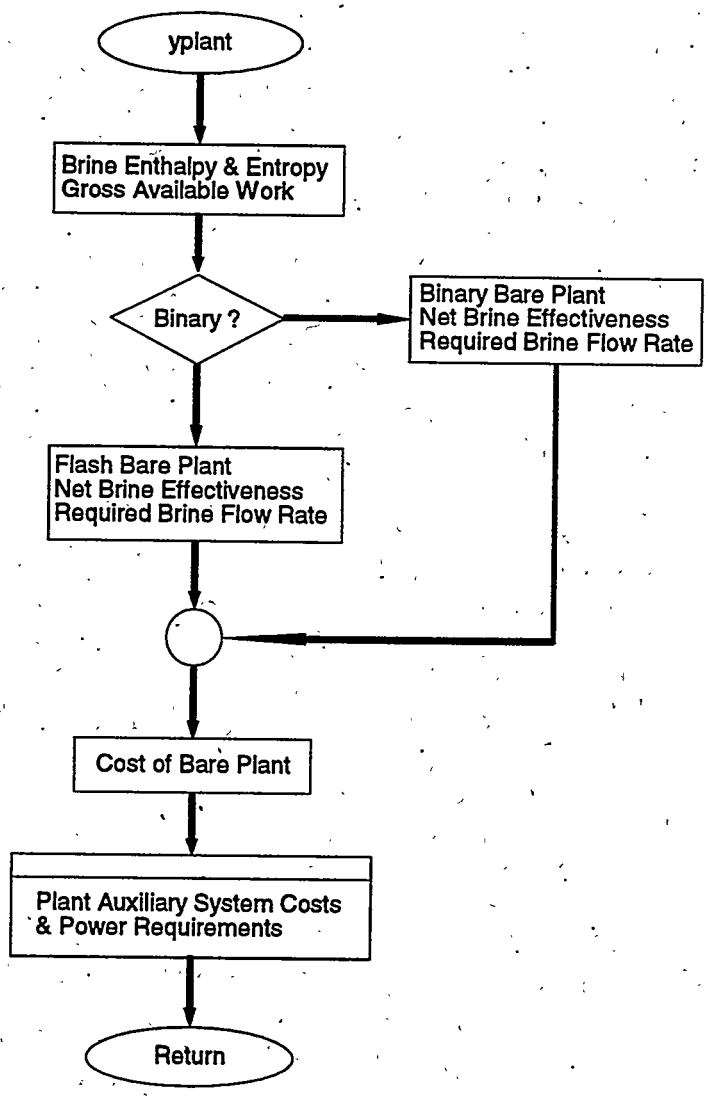


Figure 6E-3. Flow Chart for Yplant Routine



Mathematical Descriptions of Key Algorithms

Heat Rate (GESDPP)

$$HEAT.RATE \text{ (BTU/kWh)} = 1000 * (H.IN - H.COND) / NETBE \quad \text{(6E-1)}$$

where:

H.IN	=	enthalpy of fluid entering plant (BTU/lb)
H.COND	=	enthalpy of fluid in the condenser (BTU/lb)
NETBE	=	net brine effectiveness (watt-hr/lb)

Plant Costs (GESDPP)

Flash and binary plants do not require all the same auxiliary systems, and differing site characteristics sometimes dictate different auxiliary systems (such as dry cooling systems in an arid region). For this reason, GESDPP calculates the cost of a bare plant (excluding auxiliary systems) and then calculates the additional costs for the necessary auxiliary systems. Unless otherwise noted, capital costs are expressed in 1990 dollars per kilowatt capacity and O&M costs are in either millions of 1990 dollars per year or millions of 1990 dollars per kW capacity per year.

Cost of Bare Plant (GESDPP)

Based on data fits during development of IM-GEO in 1987 and modifications in 1989 to reflect more recent cost data, the capital cost ($/kW) of a bare (excluding auxiliary systems) flash plant was

$$COST.FLASH = 0.75 * (1.3336 - 5.4308 * TX + 0.013179 * TX^2 + 1.0752 * (EFFIC - 30)) \quad \text{(6E-2)}$$

where:

TX	=	*RESERVOIR.TEMPERATURE* (degrees F) - 300
EFFIC	=	efficiency according to the 2nd law of thermodynamics as calculated based on physical properties of the geothermal brine.

The capital cost ($/kW) equation for a bare (excluding auxiliary systems) binary plant was developed in 1987 based on the cost of the 50 MW Heber binary plant in California and modified in 1989 to reflect more recent cost data:

$$COST.BINARY = 1.06 * (1595 - 4.9836 * TX + 0.0087648 * TX^2 + 3.4082 * (EFFIC - 40)) \quad \text{(6E-3)}$$

where:

TX = $RESERVOIR.TEMPERATURE - 260$

$EFFIC$ = same as above

Cost of Auxiliary Systems (GESDPP)

Binary plants require a heat exchanger (HXC) which is included in the bare plant cost. However, the capital cost of the HXC is isolated to determine the operation and maintenance costs associated with the HXC. The capital cost of the HXC is:

$$COST.HXC = HXF * COST.BINARY \quad \text{(6E-4)}$$

where:

HXF = the fraction of the bare plant cost attributable to the HXC
= $0.2 - 0.1 * (RESERVOIR.TEMPERATURE - 250) / 150$

or, if $RESERVOIR.TEMPERATURE >= 400$ then $HXF = 0.1$

or, if $RESERVOIR.TEMPERATURE <= 250$ then $HXF = 0.2$

The annual cost ($ million/kW/yr) of the operation and maintenance of the HXC is:

$$HXC.O\&M = 0.030 * COST.HXC \quad \text{(6E-5)}$$

The capital costs of the brine injection pumps are a function of the power required to run them:

$$FLASH.INJ.POWER = 100.3774 - 0.7504002 * T.IN + 2.116543^{-3} * T.IN^2 - 2.638822^{-6} * T.IN^3 + 1.220977^{-9} * T.IN^4 \quad \text{(6E-6)}$$

$$FLASH.INJ.PUMP.COST (\$/kW) = 230 * FLASH.INJ.POWER \quad \text{(6E-7)}$$

$$BINARY.INJ.POWER = 16.89875 - 5.613919^{-2} * T.IN - 1.016828^{-4} * T.IN^2 + 5.666449^{-7} * T.IN^3 - 5.496635^{-10} * T.IN^4 \quad \text{(6E-8)}$$

$$BINARY.INJ.PUMP.COST (\$/kW) = 230 * BINARY.INJ.POWER \quad \text{(6E-9)}$$

where:

$T.IN$ = plant inlet temperature (degrees F)

The annual operating cost for the bare plant and injection pumps is 2 percent of the capital cost of the bare plant and injection pumps.

The cost of the bare plant includes the cooling system. However, where dry cooling is necessary as indicated by the site data, an extra $111/kW is added to the cost of the bare plant. Often brine condensate is used for cooling tower water. Water losses in the cooling system are calculated by:

$$WATER.LOSS \text{ (acre-ft/kW/yr)} = 2300 / (RESERVOIR.TEMPERATURE * 1234) \quad \textbf{(6E-10)}$$

where:

RESERVOIR.TEMPERATURE = reservoir temperature (degrees F)

The annual cost of the water is calculated by

$$TOTAL.WATER.COST \text{ (\$/kW)} = WATER.LOSS * WATER.COST \quad \textbf{(6E-11)}$$

where:

WATER.COST = cost of water ($/acre-ft) (from site data)

For sites where the brine chemistry includes high concentrations of total dissolved solids, precipitation (scaling) of the solids can be problematic. As a result of being designed to operate at temperatures and pressures to avoid precipitation of dissolve solids, binary plants incur additional capital and O&M costs. Flash plants incur additional capital and O&M costs by including a clarifier, an auxiliary system to precipitate and remove the dissolved solids upstream from the turbine. The costs for the flash system are:

$$CLARIFIER.COST \text{ (\$/kW)} = 140 * B \quad \textbf{(6E-12)}$$

$$CLARIFIER.O\&M \text{ (\$/kW/yr)} = 3 * B \quad \textbf{(6E-13)}$$

where:

B	=	0	if total dissolved solids < 0.5 percent
	=	1	if total dissolved solids >= 0.5 percent
	=	2	if total dissolved solids >= 10 percent

$$CLARIFIER.WASTE.DISPOSAL \text{ (\$/kW/yr)} = SLUDGE * (137.50) / PLANT.SIZE / 1000 \quad \textbf{(6E-14)}$$

where:

$$SLUDGE\text{(tons/yr)} = 57.2769 * TFLIN * TDS * (CAP.FAC + 1) \quad \textbf{(6E-15)}$$

where:

TFLIN	=	brine flow into plant (million lbs/hr)
TDS	=	percentage total dissolved solids
CAP.FAC	=	capacity factor (fraction).

General flash plant O&M costs (apart from clarifier O&M costs) due to scale precipitation vary with the amount of total dissolved solids (TDS) in the brine. At TDS < = 2 percent, the O&M cost is zero. At TDS = 15 percent, the O&M costs are 0.2 percent of the bare plant cost:

$$FLASH.SCALE.O\&M = 0.002 * (TDS/15) * (COST.FLASH + INJ.PUMP.COST) \quad \text{(6E-16)}$$

The additional scale-related costs for a binary plant are 50 percent of the cost of the heat exchanger at a TDS of 15 percent:

$$BINARY.SCALE.COST = 0.50 * (TDS/15) * COST.HXC \quad \text{(6E-17)}$$

$$BINARY.SCALE.O\&M = 0.015 * (TDS/15) * COST.HXC \quad \text{(6E-18)}$$

Total dissolved solids also effect capital costs by increasing corrosion. These effects are also scaled based on TDS = 15 percent:

$$FLASH.CORROSION.COST = 0.03 * (TDS/15) * (COST.FLASH + INJ.PUMP.COST) \quad \text{(6E-19)}$$

$$BINARY.CORROSION.COST = 0.015 * (TDS/15) * (COST.BINARY + INJ.PUMP.COST) \quad \text{(6E-20)}$$

The existence of noncondensible gases (NCG) in the brine have no effect on binary systems, but at concentrations greater than 0.5 percent, NCG content effects the cost of flash systems:

$$FLASH.NCG.COST\ (\$/kW) = 13.5 * NCG \quad \text{(6E-21)}$$

$$FLASH.NCG.O\&M\ (\$/kW/yr) = 0.02 * 13.5 * NCG \quad \text{(6E-22)}$$

where:

NCG	=	per cent noncondensible gas content of brine

The existence of hydrogen sulphide (H_2S) in the brine has no effects on the cost of a binary system since the brine is contained in a closed system. However, with flash systems, to avoid emitting H_2S to the atmosphere, an auxiliary abatement system is necessary at sites where such emissions would otherwise exceed regulatory limits. The costs for the abatement system are:

$$H_2S.COST = (3{,}010{,}000 * (SA / 2{,}000{,}000)^{0.60} + 230{,}000) * 1.643 / (PLANT.SIZE / 1000) \quad \text{(6E-23)}$$

$$H_2S.O\&M = 1.58 * [67{,}200 + RWF(211.18BTC + 173.44SRE)\ ] / (PLANT.SIZE / 1000) \quad \text{(6E-24)}$$

where:

$$SA = RWF * BTC = \text{steam flow from condenser (lb/hr)} \quad \text{(6E-25)}$$

where:

RWF = brine flow rate into plant (lb/hr)

BTC = fraction of brine flowing through condenser

PLANT.SIZE = net power output (MW)

The plant capital and O&M costs are then summed:

$$SCCPOWPL = \text{capital costs of plant + heat exchanger + cooling tower + auxiliaries (scaling, corrosion, clarifier) + } H_2S \text{ abatement system} \quad \text{(6E-26)}$$

$$SCCPOWPLOM = \text{O\&M costs of plant + heat exchanger + cooling tower + auxiliaries (scaling, corrosion, clarifier) + } H_2S \text{ abatement system} \quad \text{(6E-27)}$$

Emissions Rates

The CO_2 and H_2S emission rates for binary plants are zero.

The CO_2 emission rate for a flash plant is:

$$SCO2RATE = 1{,}000{,}000 / NETBE * X12 * NCG / 100 * 0.855 \quad \text{(6E-28)}$$

where:

NETBE = net brine effectiveness, watt-hour/lb. brine

X12 = steam total mass fraction to turbine

NCG = noncondensible gas content, percent (site data)

The H_2S emission rate for a flash plant is:

If the H_2S load is greater than the permissible rate then:

$$SH2SRATE = H2S.LIMIT / 453.6 * V.KWH.RATE / NETBE \quad \text{(6E-28)}$$

where:

H2S.LIMIT = regulatory limit for H_2S emission, gram/hr/MW (site data)

V.KWH.RATE = work rate across turbine, watt-hour/lb. brine

NETBE = net brine effectiveness, watt-hour/lb. brine

If the H_2S load is less than or equal to the permissible rate then:

$$SH2SRATE = H2S.LOAD / 453.6 * V.KWH.RATE / NETBE \quad \text{(6E-30)}$$

where:

H2S.LOAD = H_2S emission load, gram/hr/MW

V.KWH.RATE = work rate across turbine, watt-hour/lb. brine

NETBE = net brine effectiveness, watt-hour/lb. brine

Field Development Costs (GESDPP)

Geothermal field development consists of three phases - exploration, confirmation, and construction. Various well testing costs are added to the cost per well depending on which phase the well is drilled in. First, a base well cost is determined for both nominal diameter and slim diameter (used only in exploration phase) wells. Then, the cost of each of the three phases is determined.

Well Costs (GESDPP)

The cost per well (sans well testing costs) for nominal diameter wells is calculated by adding the three problem costs (loss circulation, cementing, miscellaneous) to the drilling cost (all of which are site data) and then adding additional costs to reflect that a percentage of wells will need to be either redrilled or extended:

$$WCPW = BASE.WELL.COST + COST.EXTND + COST.REDRILL = \quad \text{(6E-31)}$$

well cost per well

where:

BASE.WELL.COST = drilling cost + problems costs (all site data) (6E-32)

COST.EXTND = 0.75 * (0.8 - 0.25 * *WDRY*) * *WCEXTEND* (6E-33)

where:

WDRY = fraction of wells that are dry (from site data)

WCEXTEND = cost to extend one well (site data)

COST.REDRILL = 0.165 * ***WRED*** * ***WCBASE*** **(6E-34)**

where:

WRED = redrilling incidence fraction (site data)

WCBASE = drilling cost (site data)

The cost for slim diameter wells is:

SLIM.W.CPW = 0.5 * (drilling cost + 0.6 * lost circulation problem costs + miscellaneous problem costs (all from site data)) **(6E-35)**

Exploration Phase Cost (GESDPP)

C.EXPL.TOTAL = (***UCOST1*** + ***N.IDENT*** * (***UCOST2*** + ***WC.WILD***)) / ***UPROB.CONF*** **(6E-36)**

where:

UCOST1 = cost of geological and geophysical investigations

N.IDENT = number of wild cat wells required to get one good one

UCOST2 = cost of drilling shallow thermal gradient wells

WC.WILD = cost of drilling a slim diameter well
= ***SLIM.W.CPW*** + ***TEST.SL.EXPL***

where:

SLIM.W.CPW = (see Well Costs above)

TEST.SL.EXPL = cost to test a slim well

UPROB.CONF = probability of successful confirmation (site data)

Confirmation Phase Cost (GESDPP)

The cost of unsuccessful wells during the confirmation period is:

$$SCCDHCONF = ((GOOD.INJS + DRY.COUNT) * WC.GENL) + C.PERMITS \quad \text{(6E-37)}$$

where:

GOOD.INJS = number of failed confirmation wells that can become injection wells
= 1.5

DRY.COUNT = number of failed confirmation wells unsuitable for injection wells

WC.GENL = *WCPW + TEST.U.IJ* (6E-38)

where:

WCPW = (see Drilling Cost above)

TEST.U.IJ = cost of logging and 3 day flow test

C.PERMITS = cost of obtaining drilling permits = $ 179,200

The cost of successful production wells during the confirmation period is:

$$CONF.PROD = GOOD.PRODS * WC.CONF \quad \text{(6E-39)}$$

where:

GOOD.PRODS = number of successful confirmation production wells = 4

WC.CONF = cost per successful confirmation well
= *WCPW + TEST.U.CONF* (6E-40)

where:

WCPW = (see Well Costs above)

TEST.U.CONF = cost of logging, 3 day flow test and 21 day flow test

Construction Phase Cost (GESDPP)

The cost of injection wells, and successful and unsuccessful production wells during the construction phase is:

$$COST.INJ.WELLS = WC.GENL * (WIJN - GOOD.INJS) \quad \text{(6E-41)}$$

$$COST.PRO.WELLS = (WNUM + WPSPR - GOOD.PRODS) * WC.PROD * (1 + WRED) \quad \text{(6E-42)}$$

$$COST.DRY.WELLS = WC.GENL * WPDRY \quad \text{(6E-43)}$$

where:

WC.GENL	=	(see Confirmation Cost above)
WIJN	=	total number of injection wells needed
GOOD.INJS	=	number of injection wells from confirmation phase = 1.5
WNUM	=	number of production wells
WPSPR	=	number of spare production wells
GOOD.PRODS	=	number of good producers from confirmation phase = 4
WC.PROD	=	*WCPW*(see above) + cost of logging and 10-day flow tests
WRED	=	redrilling incidence fraction (from site data)
WPDRY	=	number of construction phase dry holes

Well Pump Cost (GESDPP)

The cost of downhole well pumps is:

$$DPTL = DPC * PNUM \quad \text{(6E-44)}$$

where:

DPC	=	deep pump cost, $ million
PNUM	=	number of pumps (including spares)

Gathering System Cost (GESDPP)

The cost of the surface gathering system for the production wells assumes a rectangular field, pipe cost of $50 per foot, and a $20,000 control valve for each well. The cost is:

$$CPRODGATH\ (\$\ \text{million}) = 1.120 * (50 * NFEET + 20{,}000 * WPRODSUM) / 1{,}000{,}000 \quad \text{(6E-45)}$$

where:

NFEET	=	length of pipe per production well, ft.
WPRODSUM	=	total number of production wells (including spares)

The cost of the surface gathering system for the injection wells assumes location of the injection wells in groups of 4, with total length of piping for each group equal to 6 times the distance between wells (site data), and a $20,000 control valve for each well. The cost is:

$$CINJGATH\ (\$\ \text{million}) = 1.120 * COSTPER4 * WIJN / 4 + 0.020 * WIJN \quad \text{(6E-46)}$$

where:

COSTPER4	=	surface pipe cost per group of 4 injection wells, $ million
WIJN	=	total number of injection wells needed

Field O&M Cost (GESDPP)

Operation and Maintenance costs ($ million/yr) associated with production wells and injection wells are:

$$WELL.O\&M = 0.506 + WNUM * V.PROD.REWORK + WIJN * V.INJ.REWORK \quad \text{(6E-47)}$$

where:

WNUM	=	total number of production wells
V.PROD.REWORK	=	unit annual cost for production well rework
WIJN	=	total number of injection wells
V.INJ.REWORK	=	unit annual cost of injection wells

Operation and maintenance costs ($ million/yr) for production well pumps are:

$$PUMP.O\&M = 0.0224 * WNUM \quad \text{(6E-48)}$$

where:

WNUM = total number of production wells

Operation and maintenance costs ($ million/yr) for the surface gathering system are:

$$GATHER.O\&M = 0.01 * BBB * SPTL \quad \text{(6E-49)}$$

where:

$$BBB = ZZB^2 - ZZB + 2 \quad \text{(6E-50)}$$

where:

ZZB = 0 if $TDS < 10$
= 1 if $TDS > 10$
= 2 if $TDS > 100$

where:

TDS = total dissolve solids (parts per thousand) (site data)

Injection Well Replacement Cost (GESDPP)

The proper location of injection wells is difficult. The objective is to locate them so that the injected cooled brine replenishes reservoir volume and pressure without cooling the brine coming up the production wells. It is not uncommon for initial injection wells to have to be relocated due to this "thermal breakthrough" of the cooled fluid into the production stream. The cost of relocating poorly located injection wells is:

$$COOLED.CAP.COST = (WIJN * WC.GENL + CINJGATH)(PERCENT.INJ.FAILED/100) \quad \text{(6E-51)}$$

where:

PERCENT.INJ.FAILED = percent of injectors to fail (site data)