

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

**January 1996**

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# 1. Renewable Fuels Module Introduction

## Purpose of This Report

This report documents the objectives, analytical approach, and design of the National Energy Modeling System (NEMS) Renewable Fuels Module (RFM) as it relates to the production of the 1996 *Annual Energy Outlook* (AEO96) 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 two 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)). Such documentation facilitates continuity in EIA model development by providing information sufficient to perform model enhancements and data updates as part of EIA's ongoing mission to provide analytical and forecasting information systems.

## Renewable Fuels Module Summary

The RFM consists of six analytical submodules that represent each of the major renewable energy resources—biomass, municipal solid waste (MSW), solar energy, wind energy, geothermal energy, and alcohol fuels.

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 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.

Currently, the RFM assigns technology and cost data for central station electric generation facilities. In addition, the RFM includes the Biofuels Submodule, which provides ethanol supply curves for the Petroleum Market Module (PMM).

Other renewables modeled elsewhere in NEMS include the biomass in the industrial sector, wood in the residential sector, geothermal heat pumps in the residential and commercial sectors, and solar hot water in the residential sector. In addition, there are several areas, primarily dispersed applications, that are not represented in NEMS. This includes direct applications of geothermal heat, several types of solar thermal use, and 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 "costless" 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 NEMS Electricity Market Module (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.

Several sources for the cost and performance characterization data were examined for use in the RFM. The primary source was the technology characterizations developed by the Electric Power Research Institute's 1993 *Technical Assessment Guide* (EPRI TAG). The EPRI TAG data were chosen as the most credible and consistent data for most technology characterizations.

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 for solar electric technologies, and construction lead times. All cost values are converted to real 1987 dollars.

Provided below are summaries of the six RFM submodules that are used for producing the AEO96 forecasts: the Municipal Solid Waste Submodule (MSW), the Wind Energy Submodule (WES), the Solar Energy Submodule (SOLES), the Biofuels Supply Submodule (BSS), 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.<sup>1</sup>

## Solar Submodule (SOLES)

The solar submodule defines the cost and performance characteristics of photovoltaic (PV) and solar thermal (ST) central station electric installations. (The submodule considers only grid-connected applications constructed by a utility or independent power producer.) This information is passed to the EMM for building these solar technologies in competition with other electricity generation technologies.

The required input information is similar for each type. Solar is a renewable energy form that requires a more detailed characterization to represent its intermittent nature and regionality. This is dealt with varying capacity factors for the regional load shapes used by the EMM and for different time segments to represent intermittency (for example, the absence of sunlight at night).

## Biofuels Supply Submodule (BSS)

This submodule produces annual supply functions (cost vs. quantity) by Petroleum Allocation for Defense Districts (PADD) and by Census division for corn-derived ethanol. The agricultural feedstock production quantities and costs are provided exogenously to NEMS from a U.S. Department of Agriculture linear programming model, Agricultural Resources Interregional Modeling System (ARIMS). The supply curves take into account feedstock costs, feedstock conversion costs, and energy prices. The supply functions are used by the Petroleum Market Module to compute regional demands for ethanol.

## 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 AEO96 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

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

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 four western EMM regions: 11, 12, 13, and 14. 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.

## **Hydroelectric Plant Data**

For AEO96, the assignment of hydroelectric plant data was transferred to the EMM without changing the fundamental approach. The hydroelectric power data, now assigned in EMM, 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.

## **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 six 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. 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 used to reduce the energy demand that is modeled in the NEMS end-use demand and utility modules (i.e., MSW energy is decremented from each sectoral electricity requirement; in the case of the electric utility sector, generating capacity is decremented). 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 bilinear 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 MSW definition 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 quantities reported in the annual Biocycle survey (Biocycle, 1993). The average difference between the EPA and Biocycle values for historical years was used as an 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 remain constant at the 5,569-Btu level, based on the expectation that the removal of low-Btu waste stream components (metal, glass, and yard waste) will be balanced by the removal of high-Btu components (paper and plastic). While these changes in MSW composition are significant, 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 requires the use of assumed fractions of MSW supplies combusted for energy recovery.

## **Disaggregation Rules**

National projections for energy from MSW are disaggregated into regional totals according to the geographical dispersion of current and planned WTE facilities, use of the MSW energy (electricity versus steam and heat), and sector (commercial, industrial, and utility). Information used for disaggregating MSW energy comes from the Government Advisory Associates (GAA) Resource Recovery Database. This proprietary database product includes information on locations, types of energy produced, ownership type, etc. for all existing U.S. WTE facilities, as well as those facilities in the construction, conceptual-planning, and advanced-planning stages.

For 1990 to 1996, the regional, usage, and sectoral totals are computed using GAA's site-level facility data. The Btu capacities of WTE facilities that are expected to come on-line before 1996 are assigned to the appropriate NEMS regions. Specifically, MSW electricity production for sales is disaggregated by NERC regions.

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 region, use, and sector 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 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 (SAIC, 1995). 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 LOTUS 1-2-3 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 included estimates of differing yields of methane as a function of time since disposal, further disaggregated for various waste types, produced the desired projections. Factors for portion of emissions converted to energy, 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. This capacity total is added to the capacity for MSW combustion before being shared out to the NEMS regions and passed to the EMM.

## Capital and Operating Costs

The MSW submodule supplies the EMM with capital and operating costs to help 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.<sup>3</sup> For both capital and operating costs, the TAG assumes a WTE plant size of 40 megawatts with a single combustion unit.

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

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<sup>3</sup>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.

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.

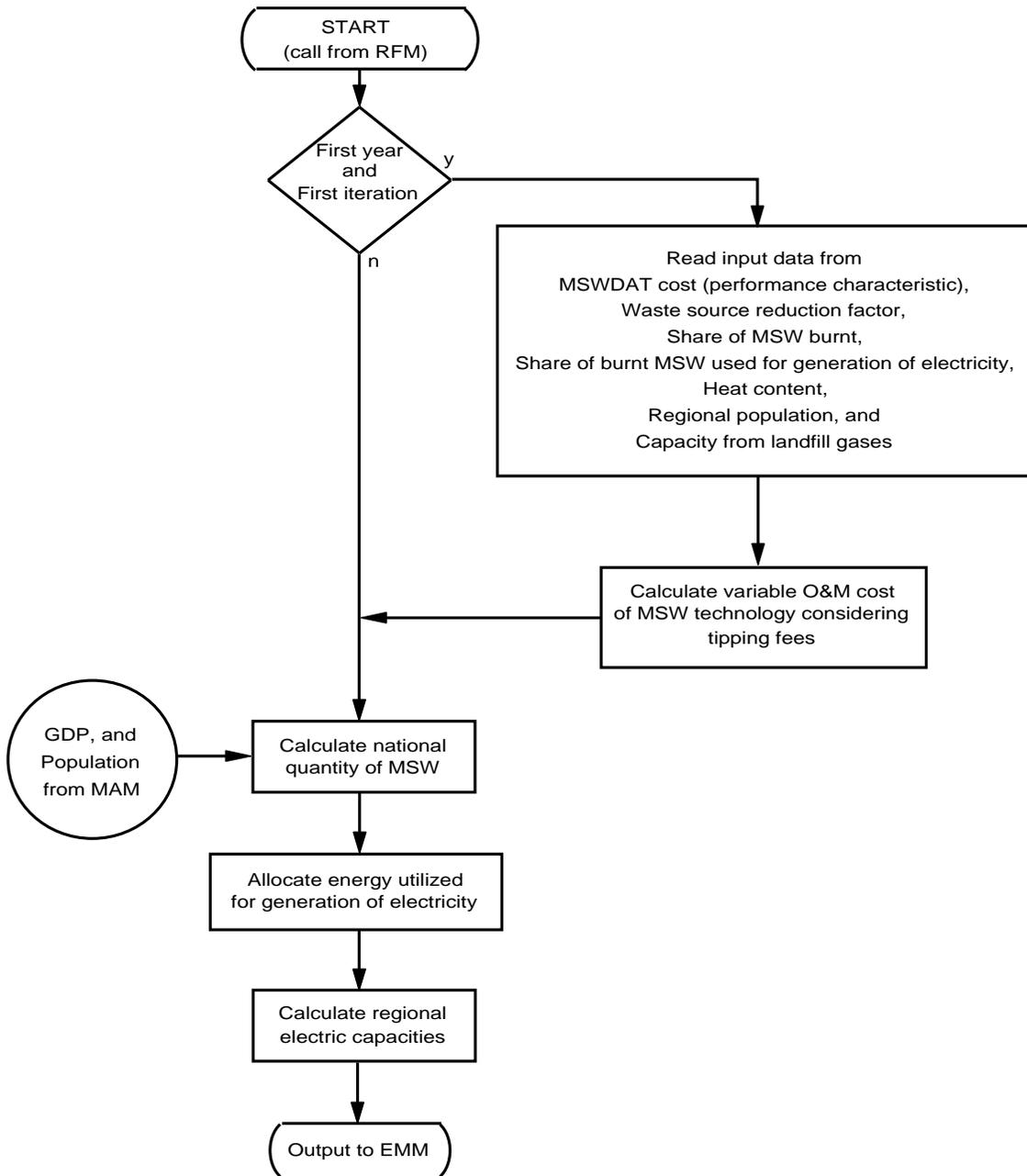
A key aspect of the selected modeling approach involves the application of expert judgement for specifying the projected regional fractions of MSW combusted for energy. (These fractions are multiplied by available MSW in order to determine the projected MSW quantities available for energy recovery.) 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 of the MSW Submodule that shows the Submodule's main computational steps and data relationships.

**Figure 1. Municipal Solid Waste Submodule Flowchart**



## Key Computations and Equations

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. The waste stream is adjusted to capture the efforts to reduce generation of MSW. The relation is expressed as:

$$QNAT_{yr} = (a_1 MC\_GDP_{yr} + a_2 MC\_POPAFO_{yr}) (1-(yr-1) SR) \alpha \quad (2-1)$$

where:

$QNAT_{yr}$	= national annual waste stream in year $yr$ , in [ $10^6$ ton]
$a_1$	= regression coef. representing GDP dependency ( $a_1=0.0334242$ [ $10^6$ ton/ $10^9$ \$])
$a_2$	= regression coef. representing population dependency ( $a_2=0.113202$ [ $10^6$ ton/ $10^6$ capita])
$MC\_GDP_{yr}$	= gross domestic product in year $yr$ , in [ $10^9$ \$]
$MC\_POPAFO_{yr}$	= national population in year $yr$ , in [ $10^6$ capita]
$yr$	= NEMS year
$SR$	= Reduction factor
$\alpha$	= waste stream adjustment factor - expands the EPA-defined MSW quantity to account for empirical information on other disposed materials.

Using the waste stream  $QNAT_{yr}$  in the equation (2-1), the energy utilized for the generation of electricity can be determined as:

$$Q_{nr,yr} = QNAT_{yr} PCC_{nr} F_{nr} HC_{yr} \beta WNRPOP_{nr} \quad (2-2)$$

where:

$Q_{nr,yr}$	= energy used for generation of electricity in region $nr$ in year $yr$ , in [ $10^6$ BTU],
$PCC_{nr}$	= share of total MSW burnt in region $nr$ , dimensionless,
$F_{nr}$	= share of burnt MSW used for generation of electricity in region $nr$ , dimensionless,
$HC_{yr}$	= heat content of MSW in year $yr$ , in [BTU/lb],
$\beta$	= conversion factor ( $\beta=2205$ [lb/ton]),
$WNRÉOP_{nr}$	= share of national population in region $nr$ , dimensionless.

The electricity capacity is then computed as:

$$WCAMSEL_{nr,yr} = \frac{Q_{nr,yr}}{WHRMSEL_{nr,yr} WCFMSEL_{nr,yr} 8760} + TCLANDF_{yr} LFSHR_{nr} \quad (2-3)$$

where:

$WCAMSEL_{nr,yr}$	=	MSW electric capacity in region $nr$ in year $yr$ , in [MW],
$WHRMSEL_{nr,yr}$	=	heat rate in region $nr$ in year $yr$ , in [BTU/kWh],
$WCFMSEL_{nr,yr}$	=	capacity factor for MSW incinerator in region $nr$ in year $yr$ , dimensionless,
$TCLANDF_{yr}$	=	total national electric capacity from landfill gas in year $yr$ , in [MW],
$LFSHR_{nr}$	=	share of total electric capacity fueled by landfill gas in region $nr$ , dimensionless.

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

## 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	Page Reference
<b>INPUT DATA</b>				
<i>F</i>	Fraction of MSW combusted for use <i>U</i> and sector <i>S</i> in Census division <i>RC</i>	Government Advisory Associates, processed using off-line Fortran program	Unitless	16
<i>HC</i>	MSW heat content values in Census division <i>RC</i> in year <i>T</i>	Franklin Associates and Office of Technology Assessment	Btu/lb of MSW	17
<i>WHRMSEL</i>	MSW heat rate for electricity production	Government Advisory Associates Oak Ridge	Btu/kWh	17
<i>PCC</i>	Percent combusted for Census division <i>RC</i> in year <i>T</i>	Franklin Associates and EIA staff Oak Ridge	unitless	13, 25
<i>WCFMSEL</i>	Capacity factor of a WTE plant	EPRI TAG	unitless	14
<i>WCCMSEL</i>	Capital cost for a WTE plant	EPRI TAG	\$/KW	27
<i>MSTIPPNR</i>	Tipping fee for MSW in Census division <i>RC</i>	Chupka, et al	\$/ton	26
<i>WOCMSEL</i>	Fixed O&M cost for a WTE plant	EPRI TAG	mills/kWh	27
<i>WVOMSEL</i>	Variable O&M cost for a WTE plant	EPRI TAG	mills/kWh	27
<i>SR</i>	Annual source reduction factor	Oak Ridge National Lab	Percentage	13
<i>TCLANDF</i>	Total national electric capacity from land fill in year <i>y</i>	determined by EIA	MW	25
<i>LFSHR</i>	Share of total electric capacity fueled by land fill gas in NERC Region <i>nr</i>	determined by EIA	unitless	25

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

Model Variable	Definition and Dimensions	Source	Units	Page Reference
$a_1$	Regression coeff. representing GDP dependency	regressed by EIA	$10^6$ ton/ $10^9$ \$	20
$a_2$	Regression coeff. representing population dependency	regressed by EIA	$10^6$ ton/ $10^6$ ca pita	21
$\alpha$	waste stream adjustment factor	determined by EIA	unitless	21
<b>CALCULATED VARIABLES</b>				
$MC\_GDP$	Real gross domestic product for year $y$	determined in MAM	Billion \$	13
$MC\_POPAFO$	U.S. Population incl. Overseas armed forces	determined in MAM	$10^6$	13
$Q$	Quantity of energy from municipal solid waste for generation of electric power in NERC Region $nr$		MMBtu per year	13
$QNAT$	Quantity of municipal solid waste produced in the U.S.		million tons per year	13
$WCAMSEL$	MSW electric capacity for utilities in NERC Region $nr$ in year $y$		Megawatts	14, 25
$WVCMSEL$	Variable O&M cost of MSW electric generating capacity in NERC Region $nr$ in year $y$ adjusted for tipping fees		mills/kWh	26

**MODEL INPUT:**  $F$

**DEFINITION:** Fraction of total MSW generated that is combusted for generation of electricity in NERC Region  $nr$

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 NERC 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:**    *WHRMSEL*

**DEFINITION:**        Heat rate for WTE plants in NERC Region *nr*, year *y*

The heat rate is assumed constant for all NERC Regions and years. The heat rate is calculated using Governmental Advisory Associates data and an off-line FORTRAN program. For those plants that cogenerate electricity and steam, the heat rate is assumed to equal the heat rate of facilities that generate only electricity.

**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. 15.

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

**MODEL INPUT:** PCC

**DEFINITION:** Percent MSW combusted NERC Region *nr*

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 the Oak Ridge National Laboratory and EIA staff.

**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. 12.

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:** WCFMSEL

**DEFINITION:** Capacity factor for a MSW incinerator in NERC Region *nr* and year *y*

**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:** WCCMSEL

**DEFINITION:** Capital cost of a MSW incinerator in NERC Region *nr* and year *y*

**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:** MSTIPPNR

**DEFINITION:** Tipping fee charged for MSW in NERC Region *nr*

The tipping fee is structured as a negative adjustment to the variable O&M cost, WVCMSSEL. 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 NERC Regions using MSW facility consumption weighting factors, converted to real 1987 dollars, and then transformed into mills-per-kilowatthour.

**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. 18.

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.

**MODEL INPUT:** WOCMSSEL

**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 an 85 percent capacity.

**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:** WVOMSSEL

**DEFINITION:** Variable O&M cost for a MSW incinerator in NERC Region *nr* and year *y*

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.

**SOURCE:** 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:**    *WVCMSEL*

**DEFINITION:**    Variable O&M cost for a MSW incinerator in NERC Region *nr* 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*.

**SOURCE:**    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 annual source reduction factor, based on expert judgement from Oak Ridge National Laboratory is 0.5 percent per year, or 0.005.

**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. 6.

**MODEL INPUT:**     $a_1$

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

**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.

**MODEL INPUT:**  $a_2$

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

**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.

**MODEL INPUT:**  $\alpha$

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

**SOURCES:** Biocycle, "The State of Garbage in America," 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 generation of MSW is postulated to be primarily a function of gross domestic product (GDP) and population. Empirical analysis shows that only GDP is necessary for a regression with a high coefficient of determination ( $R^2$ ). Therefore, a baseline amount of MSW generated nationally is computed in Equation 2B-1. This amount is further adjusted in the model in a manner discussed later. Therefore:

$$QNAT_{yr} = (a_1 GDP_{yr} + a_2 POP_{yr}) (1 - (yr-1) SR) \alpha \quad (2B-1)$$

where:

- $QNAT_{yr}$  = national annual waste stream in year  $yr$ , in [ $10^6$  ton]
- $a_1$  = regression coef. representing GDP dependency ( $a_1=0.0334242$  [ $10^6$  ton/ $10^9$  \$])
- $a_2$  = regression coef. representing population dependency ( $a_2=0.113202$  [ $10^6$  ton/ $10^6$  capita])
- $GDP_{yr}$  = gross domestic product in year  $yr$ , in [ $10^9$  \$]
- $POP_{yr}$  = national population in year  $yr$ , in [ $10^6$  capita]
- $yr$  = NEMS year
- $SR$  = Reduction factor
- $\alpha$  = waste stream adjustment factor - expands the EPA-defined MSW quantity to account for empirical information on other disposed materials.

### Source Reduction Factor

Projections of MSW generation quantities based on the above regression approach must be modified because of structural market changes that are occurring and are likely to occur in future years. Governments and businesses have adopted strategies to lessen the amount of waste generated without reducing economic output. The general term for these strategies is *source reduction*. An example of such a strategy is the local government trend toward unit-based disposal rates, which has brought about a reduction of generated waste where implemented. 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.

## 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 issues 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. Fourth, while recycling programs remain popular and continue to expand, there may be a practical upper limit to the share of the waste stream that can be recycled.

The current values for percent of waste combusted are calculated using a regional estimation procedure. First, the Franklin Associates/EPA/Biocyte value for total waste (280+ million tons per year) was proportionally disaggregated into Census divisions according to the populations in each Census division. This disaggregation assumes a constant per-capita MSW generation rate for all regions because there is no known data on regional MSW generation or rates.

The existing facility design capacity, in tons per day, is then identified and aggregated into Census divisions using information from Waste Age magazine (Waste Age, 1992). A value for tons of MSW combusted is estimated by applying a utilization factor of 0.88, which is consistent with the value derived from the EPA data. The estimated combusted-shares in each Census division is obtained by dividing the tons-combusted values by the total waste generated in Census division.

The regional combusted-shares for 2015 were established based on the following rules:

1. No regional share will be above 50 percent. Thus, combusted-share values for two regions (New England and Alaska-Hawaii) decline to 50 percent. This rule is based on the assumption of increased recycling, which is expected to grow to 40 percent in many jurisdictions. At least 10 percent is expected to be landfilled in any case since some material cannot be recycled or burned.
2. The Mid-Atlantic Census Division is assumed to be limited to a combusted-share of 40 percent, since those States have more robust recycling goals.
3. Combusted-shares for all other regions are assumed to increase at an annual rate of 5 percent from 1990 through 2015.

The average of the resulting values, weighted by waste generated, is about 30 percent for 2015, which is used as the national value. Use of regional shares directly would require that these values be derived by NERC regions, and data is not readily available for such a calculation. The interim values for shares combusted were linearly interpolated.

Using the waste stream  $Q_{NAT_{yr}}$  in the equation (2B-1), the energy utilized for the generation of electricity can be determined as:

$$Q_{nr,yr} = Q_{NAT_{yr}} PCC_{nr} F_{nr} HC_{yr} \beta WNRPOP_{nr} \quad (2B-2)$$

where:

- $Q_{nr,yr}$  = energy used for generation of electricity in region  $nr$  in year  $yr$ , in [ $10^6$  BTU],
- $PCC_{nr}$  = share of total MSW burnt in region  $nr$ , dimensionless,
- $F_{nr}$  = share of burnt MSW used for generation of electricity in region  $nr$ , dimensionless,
- $HC_{yr}$  = heat content of MSW in year  $yr$ , in [BTU/lb],
- $\beta$  = conversion factor ( $\beta=2205$  [lb/ton]),
- $WNRPOP_{nr}$  = share of national population in region  $nr$ , dimensionless.

The electricity capacity is then computed as:

$$WCAMSEL_{nr,yr} = \frac{Q_{nr,yr}}{WHRMSWL_{nr,yr} WCFMSEL_{nr,yr} 8760} + TCLANDF_{yr} LFSHR_{nr} \quad (2B-3)$$

where:

- $WCAMSEL_{nr,yr}$  = MSW electric capacity in region  $nr$  in year  $yr$ , in [MW],
- $WHRMSEL_{nr,yr}$  = heat rate in region  $nr$  in year  $yr$ , in [BTU/kWh],
- $WCFMSEL_{nr,yr}$  = capacity factor for MSW incinerator in region  $nr$  in year  $yr$ , dimensionless,
- $TCLANDF_{yr}$  = total national electric capacity from land fill in year  $yr$ , in [MW],
- $LFSHR_{nr}$  = share of total electric capacity fueled by land fill gas in region  $nr$ , dimensionless.

Equation 2B-4 calculates WTE facility variable operating costs:

$$WVCMSEL_{nr,y} = WVOMSEL_{nr,y} - MSTIPPNR_{nr} \quad (2B-4)$$

where:

$WVCMSEL_{nr,y}$  = RFM variable operating cost common block variable for WTE facilities in NERC Region  $nr$  in year  $y$ ,

$WVOMSEL_{nr,y}$  = Variable operation & maintenance cost in mills per kilowatthour,

$MSTIPPNR_{nr}$  = Tipping fee in mills/kWh for a WTE plant for NERC Region  $nr$

## Appendix 2-C: Bibliography

- Biocycle, "*The State of Garbage in America*," April issue, 1993.
- Electric Power Research Institute, *Technical Assessment Guide*. EPRI TR-102276S, Vol. 1: Rev. 7, Palo Alto, CA, June 1993.
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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 and other energy forms (steam and direct heat). Forecasts are disaggregated by consuming sector (commercial, industrial, and electric utility) and region.

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

The MSW Submodule provides the NEMS commercial and industrial sector modules with annual regional projections of energy produced from the incineration of municipal solid waste. For the NEMS Electricity Market Module, 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 1995.

### **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*, March 1995.

### **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 NERC Regions.
- Time Unit/Frequency; Annual, 1990 through 2015
- Products: electricity
- 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
- Forecasted annual percentages of municipal solid waste combusted

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:**

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 2-E: Data Quality and Estimation Processes**

This Appendix discusses (1) 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, and (2) estimation methods used to derive parameters.

### **Governmental Advisory Associates Resource Recovery Database**

The original GAA data file consists of 20 columns of data items and 202 rows corresponding to each MSW facility in the GAA database. The 20 data items include the following: plant number, status, start month, start year, planned start month, planned start year, shutdown date, State, capacity, annual throughput of MSW, output type, gross capacity (2MW), net capacity (MW), gross kWh/ton, net kWh/ton, Btu/lb, Census division, NERC Region, sector, and a consuming sector code. Census division was determined by the State, and NERC Region was determined from a map of NERC Regions and the location of the facilities in the GAA data. Allocation by sector was determined according to the primary customer, not ownership of the facility. Military installations and sewage and water treatment facilities were assumed to be part of the industrial sector. Universities, prisons, police stations, and district heating facilities were included in the commercial sector. There was considerable missing data in the GAA database, particularly for electricity generation and energy content. Data were filled in using averages across WTE facilities.

## 3. Wind Energy Submodule (WES)

### Model Purpose

The objective 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 the building of new capacity in competition with other sources of electricity generation.

Projections are based on the performance of a "mix" of horizontal axis wind turbines (HAWTs) that have been installed and are currently operational.

The version of NEMS used in *AEO96* accounts for only grid-connected electricity generation. It does not consider dispersed, remote or any non-grid-connected applications. A portion of the transmission costs are accounted for by the EMM uniformly for all represented technologies. Furthermore, additional transmission cost unique to remote wind sites are estimated and passed to the EMM.

The EMM provides to the WES information on installed wind capacity after convergence is reached. WES then calculates the remaining wind resources available for future installations. This accounting of remaining resources is needed since wind energy consists of limited quantities of high-quality resources that are depleted as turbines are installed on windy sites.

### Relationship of the Wind Submodule to Other Models

As a submodule of the Renewable Fuels Module (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 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

WES produces energy supply curves from wind resource and wind turbine cost/performance data. This is accomplished by calculating the maximum conceivable turbine capacity that could be installed, given the available land area, wind resource, and the current year's turbine capacity factor. The available land area is subdivided into three zones defined as corridors with varying distances to existing transmission lines.

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.

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 Quantity Projections

The EMM requires capacity, performance, and cost data on the basis of NERC Regions. WES provides data by NERC Region based on 13 NERC Regions/Subregions with Alaska and Hawaii separated out, and not included in wind resources given to EMM.

Since horizontal-axis wind turbines are the predominant type in U.S. installations, accounting for over 95 percent of U.S. generating capacity, only this type is represented in the WES. No significant increase in accuracy or detail would be achieved by including vertical-axis designs as well. The most current, comprehensive and accurate knowledge exists for the horizontal types and there are limitations on the detail with which projections of cost and performance can be made. For a regional model, the appropriate level of detail assumes a hybrid of various horizontal-axis turbines.

## Land Use Estimates

It is assumed that wind turbines are installed in a grid pattern with spacing between them equal to five times the rotor diameter in one direction and ten times the rotor diameter in the other direction.

## Dispersed Penetration

It is assumed that penetration of dispersed wind energy systems will not impact the "learning curve" cost and performance changes of wind energy systems for central power generation. The two types of technologies are different in scale and therefore the learning in one is not applicable to the other.

## 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.

## 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.

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.

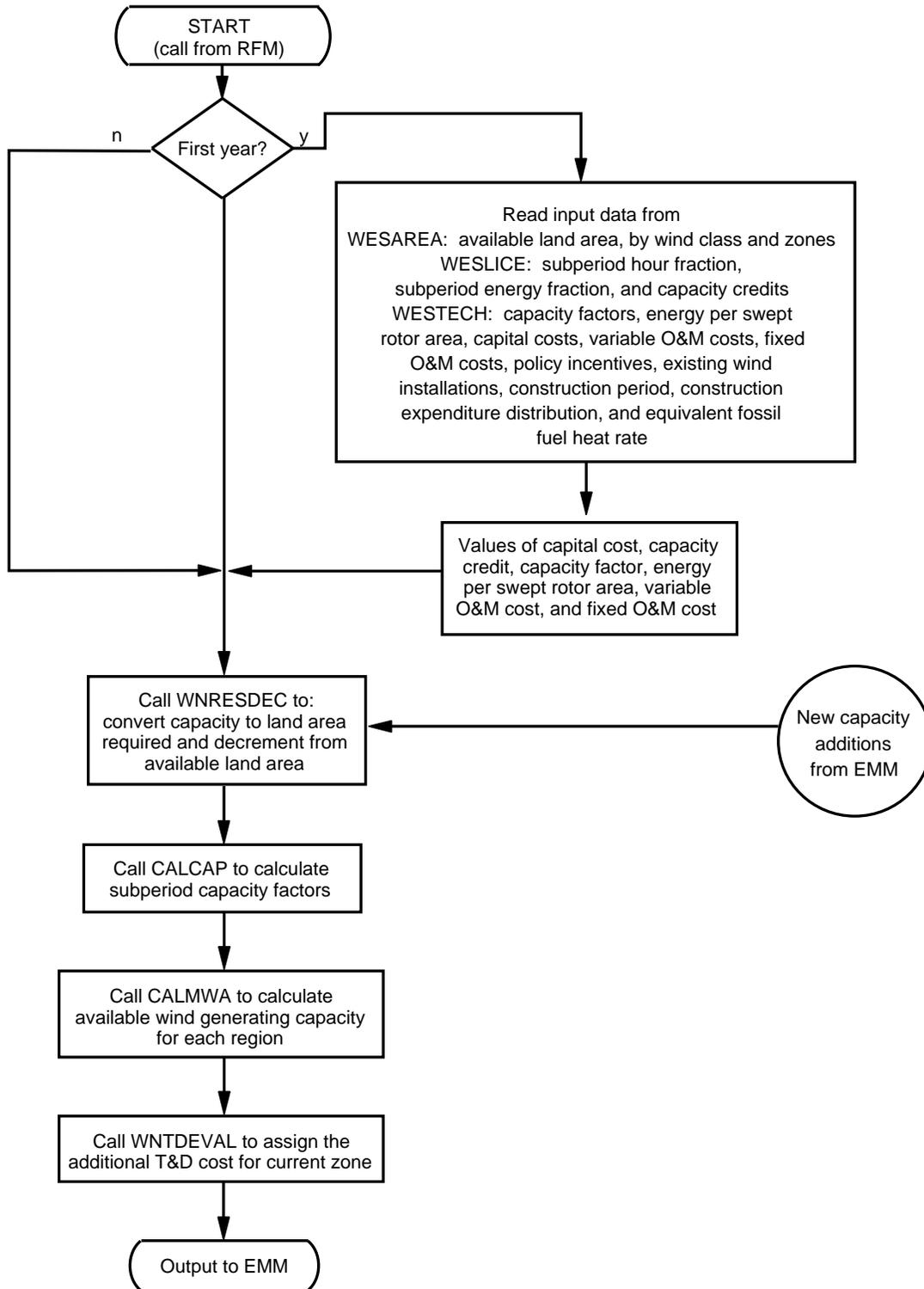
The model is built around concepts of new product diffusion into the marketplace. It is a spreadsheet-based tool that estimates market capture in competition with conventional fossil fuel-fired generating plants on a regional basis. It expands on previous techniques by incorporating a market acceptance 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, nonfinancial, 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 2.

**Figure 2. Wind Energy Submodule Flowchart**



## 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 WNREDEC 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 NERC Regions, 3 wind classes, and 3 zones (along existing transmission lines).

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  $5D \times 10D$ , 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	Page Reference
<b>INPUT DATA</b>				
<i>CAPCOS</i>	Installed capital cost of wind generation in NERC Region <i>n</i> in year <i>y</i> .	EPRI TAG™, 1993.	\$/kW	43
<i>OMFCOS</i>	Fixed O&M cost for NERC Region <i>n</i> in year <i>y</i> .	EPRI TAG™, 1993.	\$/kW	46
<i>OMVCOS</i>	Variable O&M cost for NERC Region <i>n</i> in year <i>y</i> .	EPRI TAG™, 1993.	mills/kWh	46
<i>CFANN</i>	Annual wind capacity factor for wind class <i>w</i> in year <i>y</i> .	SAIC, 1990.	Unitless	42, 43
<i>CREDIT</i>	Wind capacity credit for NERC Region <i>n</i> in year <i>y</i> .	Determined within EMM.	Unitless	44
<i>ENAREA</i>	Energy per swept rotor area for wind class <i>w</i> in year <i>y</i> .	SAIC, 1990.	kWh/m <sup>2</sup>	42, 44
<i>EXWIND</i>	Pre-existing total wind electric capacity installed in NERC Region <i>n</i> through year <i>y</i> .	EIA Form 860/867	MW	45
<i>HEAT</i>	Fossil fuel equivalent heat rate for wind.	EIA, 1992.	Btu/kWh	45
<i>LEAD*</i>	Construction lead time.	EPRI TAG™ + 1 year.	Years	46
<i>PERCON</i>	Fraction of construction completed in each year of construction.	EPRI TAG™, 1993.	Unitless	46
<i>POLICY</i>	Policy incentives for NERC Region <i>n</i> in year <i>y</i> .	Energy Policy Act of 1992.	mills/kWh	47
<i>SLICE</i>	Hour fraction for subperiod <i>l</i> in NERC Region <i>n</i> .	WNDSLICE preprocessing program (PERI).	Unitless	47

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

<b>Model Variable</b>	<b>Definition and Dimensions</b>	<b>Source</b>	<b>Units</b>	<b>Page Reference</b>
<i>WCRWIEL**</i>	Capacity credit for NERC Region <i>n</i> in year <i>y</i> .	EIA, expert judgement	Unitless	—
<i>STAREA</i>	Land area available for wind plant development in NERC Region <i>n</i> and wind class <i>w</i> .	Elliot 1991.	sq. km	47
<i>SUBPER</i>	Energy fraction for subperiod <i>l</i> in NERC Region <i>n</i> .	WNDSLICE preprocessing program (PERI).	Unitless	48
<i>AREA</i>	Energy per unit swept rotor area for wind class <i>w</i> in year <i>y</i> .	<i>ENAREA</i> , and interpolation for intermediate years.	kWh/m <sup>2</sup>	42, 44
<i>CF</i>	Annual capacity factor for wind class <i>w</i> in year <i>y</i> .	<i>CFANN</i> , and interpolation for intermediate years.	Unitless	42, 43
<i>UADDWNT</i>	Grid-connected wind electric capacity additions in NERC Region <i>n</i> in on-line year <i>y</i> .	EMM output variable in UECPOUT COMMON block.	MW	48
<i>WNTDBFCS</i>	Additional T&D cost for wind technology in NERC Region <i>n</i> and buffer zone <i>b</i>	Kintner-Meyer, SAIC, 1995	\$/kW	49, 54
<b>CALCULATED VARIABLE</b>				
<i>LDAREA</i>	Land area remaining for wind plant development in NERC Region <i>n</i> , in year <i>y</i> , for wind class <i>w</i> , in buffer zone <i>b</i>	model determined	sq. km	48
<i>LDUSED</i>	Land area needed to supply wind generating capacity in NERC Region <i>n</i> in year <i>y</i> , by wind class <i>l</i> .	model determined	sq. km	51
<i>SWAREA</i>	Swept rotor area available for wind class <i>w</i> in NERC Region <i>n</i> in year <i>y</i> , m <sup>2</sup> .	PERI, 1993	sq. m	53
<i>WCAWIEL</i>	Available capacity in NERC Region <i>n</i> in year <i>y</i> .	RFM output variable in WRENEW COMMON block.	MW	53
<i>WSFWIEL</i>	Capacity factor for NERC Region <i>n</i> in year <i>y</i> , wind class <i>w</i> , and subperiod <i>l</i> .	RFM output variable in WRENEW COMMON block.	Unitless	52
<i>WHRWIEL**</i>	Equivalent heat rate for wind in NERC Region <i>n</i> in year <i>y</i> .	<i>HEAT</i> . RFM output variable in WRENEW COMMON block.	Btu/kWh	—
<i>WCLT(9)**</i>	Construction lead time for wind.	<i>LEAD</i> . RFM output variable in WRENEW COMMON block.	Years	—

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

Model Variable	Definition and Dimensions	Source	Units	Page Reference
<i>WOCWIEL</i> **	Fixed O&M costs for NERC Region <i>n</i> in year <i>y</i> .	<i>OMFCOS</i> , and interpolation for intermediate years. RFM output variable in WRENEW COMMON block.	\$/kW	—
<i>WCPC(9,y)</i> **	Fraction of construction for wind completed in year <i>y</i> .	<i>PERCON</i> . RFM output variable in WRENEW COMMON block.	Unitless	—
<i>WCSU(9,y)</i> **	Policy incentives for wind in year <i>y</i> .	<i>POLICY(n,y)</i> . RFM output variable in WRENEW COMMON block.	mills/kWh	—
<i>WVCWIEL</i> **	Variable O&M costs for NERC Region <i>n</i> in year <i>y</i> .	<i>OMVCOS</i> , and interpolation for intermediate years. RFM output variable in WRENEW COMMON block.	mills/kWh	—
<i>WNNTD</i>	Additional T&D cost for wind technology in NERC Region <i>n</i> and year <i>y</i>	RFM output variable in WRENEW COMMON block.	\$/kW	54

\*Three years is minimum build time allowed for *AEO96*.

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

**MODEL INPUT:**     *CAPCOS*

**DEFINITION:**     Installed capital cost of wind generation in NERC Region *n* in year *y* at 5-year intervals; (\$/kW).

Values of capital cost are read into the WES from the WESTECH data file in 5 years intervals. Since passed to the EMM is a *n*<sup>th</sup>-of-a-kind value for the capital cost, this value is constant.

**SOURCE:**     Electric Power Research Institute, *TAG*<sup>TM</sup> — *Technical Assessment Guide*, 1993 with interpretation by EIA.

**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 NERC 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<sup>2</sup>).

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 NERC 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.

**SOURCE:** 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:** *HEAT*

**DEFINITION:** Fossil fuel equivalent heat rate for wind in NERC region *n* in year *y* in 5-year intervals, (Btu/kWh).

An equivalent fossil fuel displacement value of 10,280 Btu/kWh has been assigned, based on EIA data for 1994.

**SOURCE:** Energy Information Administration, *Annual Energy Review 1994*, DOE/EIA-0384(93), July 1995.

**MODEL INPUT:**    *LEAD*

**DEFINITION:**       Construction lead time at 5-year intervals; (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<sup>TM</sup> — Technical Assessment Guide*, 1993.

**MODEL INPUT:**    *OMFCOS*

**DEFINITION:**       Fixed O&M costs for NERC Region *n* in year *y* at 5-year intervals; (\$/kW).

Values of fixed O&M costs are read into the WES from the WESTECH data file. Fixed O&M costs are currently set in at \$20.86/kW (1987 dollars) for all years and all regions, based on the 1993 TAG<sup>TM</sup>.

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

**MODEL INPUT:**    *OMVCOS*

**DEFINITION:**       Variable O&M costs for NERC 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<sup>TM</sup>.

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

**MODEL INPUT:**    *PERCON*

**DEFINITION:**       Fraction of construction completed in each year of construction at 5-year intervals; (Unitless).

The construction period for a wind generating station is currently set at 3 years. The construction fraction is set at 0, 10 percent, and 90 percent, respectively.

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

**MODEL INPUT:**    *POLICY*

**DEFINITION:**       Policy incentives for NERC Region *n* in year *y* at 5-year intervals; (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 NERC 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 NERC Region *n* and wind class *w*; (sq. km).

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 areal assessments of available resource 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. Only land areas with average wind speeds above 12.5 mph are included in the WES input data. Land areas are separated into three classes, depending on the range of average wind speeds. WES class 1 is for average wind speeds above 14.3 mph, class 2 is for average wind speeds from 13.4 mph to 14.3 mph, and class 3 is for average wind speeds from 12.5 mph to 13.4 mph, all at a height of 10 meters.

**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.

**MODEL INPUT:** *SUBPER*

**DEFINITION:** Energy fraction for subperiod *l* in NERC Region *n*; (Unitless).

Values were calculated using WNDSLICE, a preprocessing program developed by Princeton 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 NERC 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 NERC Region *n*, in year *y*, of wind class *w*, in zone *b*; (km<sup>2</sup>).

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 NERC 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 NERC 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.

**SOURCE:** 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 NERC Region and current year:

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

where:

$LDUSED_{n,y}$	=	Land area used to supply EMM-called for wind generating capacity in NERC Region $n$ in year $y$ , $\text{km}^2$ ,
$UADDWNT_{n,y}$	=	Grid-connected wind electric capacity additions in NERC Region $n$ online year $y+Lead$ , (MW),
$Cf_{y,w}$	=	Annual capacity factor for wind class $w$ in year $y$ ,
$AREA_{y,w}$	=	Energy per unit swept rotor area for wind class $w$ in year $y$ , $\text{kwh/m}^2$ ,
$\pi$	=	3.141593,
$\alpha_{sp}$	=	Scalar derived from 5D x 10D grid spacing of wind generator ( $\alpha_{sp} = 50$ ).

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

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

where:

$LDAREA_{n,y,wc,bc}$  = land area available for wind development in NERC Region  $n$ , in year  $y$ , in currently offered wind class  $wc$  and buffer zone  $bc$ , (km<sup>2</sup>).

### Subroutine CALCAP

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

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

where:

$WSFWIEL_{n,y,w=1,l}$  = Capacity factor for wind class  $w$  in NERC 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 NERC Region  $n$ ,

$SLICE_{n,l}$  = Hour fraction for subperiod  $l$  in NERC 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, NERC Region and year:

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

where:

- $SWAREA_{n,y,wc}$  = Swept rotor area available for currently offered wind class  $wc$  in NERC Region  $n$  in year  $y$ , ( $m^2$ ),
- $LDAREA_{n,y,wc,bc}$  = land area available for wind development in NERC Region  $n$ , in year  $y$ , in currently offered wind class  $wc$  and buffer zone  $bc$ , ( $km^2$ ),
- $\alpha_{sp}$  = Scalar derived from 5D x 10D grid spacing of wind generator ( $\alpha_{sp} = 50$ ).

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

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

where:

- $WCAWIEL_{n,y}$  = Available capacity in NERC Region  $n$  in year  $y$ , MW,

### Subroutine WNDECR

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

<u>Wind class</u>	<u>Buffer zone</u>
1	1 → 2 → 3 then
2	1 → 2 → 3 then
3	1 → 2 → 3.

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

The wind resource depletion scheme reflects an economic ranking based on 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

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

where:

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

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

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## 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, 1995.

### **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:**

Perry M. Lindstrom  
Coal, Uranium, and Renewable Fuels Analysis Branch  
Energy Information Administration  
(202) 586-0934

### **Documentation:**

NEMS Documentation Report: *Renewable Fuels Submodule*, May 1996

### **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 NERC 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 2015
- Products: Electricity
- Economic Sectors: Electric utility sector, nonutility generators (NUGS)
- Model Structure: Sequential calculation of available wind capacity by NERC 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 almost 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 emphases, 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.

The accelerated R&D scenario assumes that a significant portion of the "advanced turbine" technology is available by 1995, although scale-up to the complete 500 kW advanced turbine design is shown in year 2000. There is higher probability of success for the advanced turbine technology under the accelerated scenario because multiple designs will be able to be tested, resulting in lowered technical risk and multiple learning curves to prevent the problem of technological "lock-out" as discussed in the Technology Penetration CDR. In addition, technology transfer and design assistance programs could speed adoption and improve quality of the new technology. Further incremental improvements are experienced by the year 2005, and scale up to an optimum (1 MW) turbine, utilizing significantly better design tools developed by the basic science element of the program, should occur in the 2010 time frame. Small, incremental improvements should follow after 2010.

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.

## 4. Solar Submodule

### Model Purpose

The objective of the NEMS Solar Electric Submodule (SOLES) is to define the costs and performance characteristics of grid-connected Solar Thermal (ST) and Photovoltaic (PV) electricity generating technologies, and provide them to the Electricity Market Module (EMM) for capacity build decisions in competition with other sources of electricity generation for the purpose of capacity expansion. Costs and performance characteristics (including resource availabilities) are provided by EMM region. 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 SOLES. For ST technologies, however, only six selected regions are represented, since this technology will not compete in all regions of the country. The six selected regions with sufficient direct normal insolation (solar radiation) include essentially all land west of the Mississippi River. The available solar resource is well in excess of conceivable demand (2 orders of magnitude or more). Therefore the resource cost of an additional installation is not affected by the amount of existing capacity, and it is unnecessary for SOLES to keep track of the existing generating capacity.

SOLES passes the fixed operating and maintenance (O&M) costs, variable O&M costs, and capital costs as well as time-segment dependent capacity factors to the Electricity Capacity Planning (ECP) submodule of the EMM.

ST technologies concentrate direct normal sunlight onto a central receiver where the energy absorbed by a working fluid powers a thermal conversion-generator device. A storage of three hours is considered. PV technologies use silicon or some other semiconductor material to directly convert sunlight (direct normal and diffuse) into electricity in proportion to the quantity of sunlight received. Unlike both ST and conventional electric generation technologies, PV has no minimum system size.

### Relationship of the Solar Submodule to Other Models

SOLES assigns cost and performance data to global variables to be used by the EMM. SOLES 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, biomass, and hydro, 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 curve for solar is assumed to be perfectly elastic. 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.

Initially, data have been developed for a single type of each of the ST and PV technologies to be used for all regions. Accordingly, capital and O&M costs and the efficiency in converting sunlight into electric energy are held constant across regions. Any differences in regional resources are captured through the variable that represents the solar energy input to the technology.

ST technologies are composed of concentrators which can only use direct normal radiation. This resource is much more sensitive to cloud conditions than total (direct plus diffuse) solar radiation. Accordingly, for solar thermal, data are provided only for 6 of the 13 EMM Regions which have sufficiently intense insolation of this kind.

The default solar thermal electric technology is a central receiver with 3-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 flat-plate fixed axis array tilted at an angle equal to the site's latitude. The availability or energy output is represented as four values representing the average hourly output per unit of system capacity during daytime hours for each of the four seasons defined by the load duration curve of the EMM.

## Fundamental Assumptions

The regional classification plan is the same for both ST and PV. As an input to EMM, SOLES will operate on the same 13 regions plus Alaska and Hawaii. These correspond to the nine NERC 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.

## 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 NERC 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**

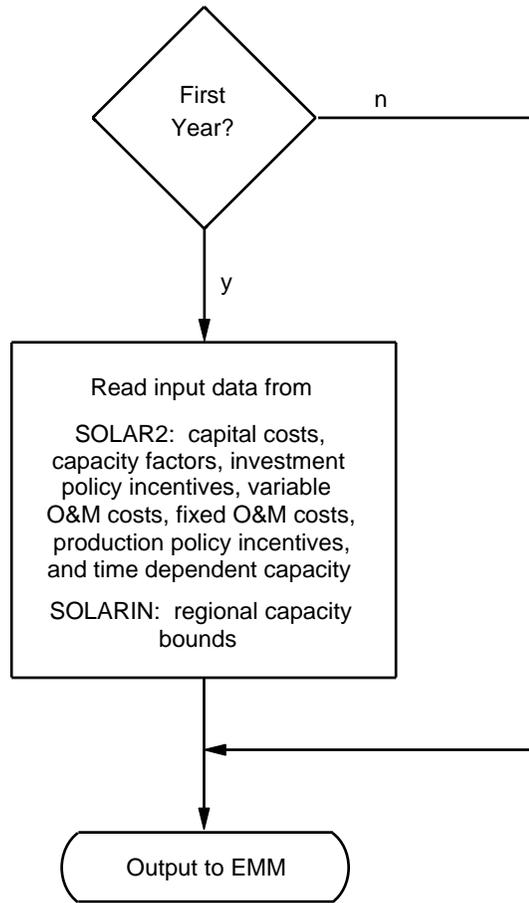
### **Submodule Flow Diagram**

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

### **Key Computations and Equations**

In its current embodiment, SOLES passes data directly, without any computations, through assignments to the appropriate COMMON variables. These are the utility generating capacities and capacity factors, capital costs, O&M costs, and subperiod capacity factors for each technology.

**Figure 3. Solar Energy Submodule Flowchart**



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

This Appendix describes the variables, data inputs, and parameter estimates associated with the Solar Submodule. 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	Page Reference
<b>INPUT DATA</b>				
<i>WCAPVEL</i>	Capacity constraints for photovoltaic technology in NERC Region <i>n</i> in year <i>y</i> .	EIA Estimates	MW	70
<i>WCASTEL</i>	Capacity constraints for photovoltaic technology in NERC Region <i>n</i> in year <i>y</i>	EIA Estimates	MW	70
<i>WCCPVEL</i>	Capital cost of photovoltaic technology in NERC Region <i>n</i> in year <i>y</i> .	EPRI TAG, 1993	\$/kW	71
<i>WCCSTEL</i>	Capital cost of solar thermal technology in NERC Region <i>n</i> in year <i>y</i> .	CEC, 1993..	\$/kW	70
<i>WCSI(t,y)</i>	Investment policy incentive as a fraction of capital cost for technology <i>t</i> ( <i>t</i> = ST, 8 = PV) in year <i>y</i> .	Energy Policy Act, 1992	Percent	72
<i>WCSU(t,y)</i>	Production policy incentive for technology <i>t</i> ( <i>t</i> = ST, 8 = PV) in year <i>y</i> .	Energy Policy Act, 1992.	mills/kWh	72
<i>WVCPVEL</i>	Variable O&M cost for photovoltaic technology in NERC Region <i>n</i> in year <i>y</i> .	CEC, 1993.	mills/kWh	71
<i>WVCSTEL</i>	Variable O&M cost for solar thermal technology in NERC Region <i>n</i> in year <i>y</i> .	.CEC, 1993.	mills/kWh	71
<i>WOCPVEL</i>	Fixed O&M cost for photovoltaic technology in NERC Region <i>n</i> in year <i>y</i> .	CEC, 1993.	mills/kW	71
<i>WOCSTEL</i>	Fixed O&M cost for solar thermal technology in NERC Region <i>n</i> in year <i>y</i> .	CEC, 1993.	mills/kW	71
<i>WSSPVEL</i>	Prototype photovoltaic system capacity factor for NERC Region <i>n</i> in time period <i>p</i> in year <i>y</i> .	NREL, 1995.	Percent	73

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

Model Variable	Definition and Dimensions	Source	Units	Page Reference
<i>WSSSTEL</i>	Prototype solar thermal system capacity factor for NERC Region <i>n</i> in time period <i>p</i> in year <i>y</i> .	CEC, 1993.	Unitless	73
<i>WCLT</i>	Construction period of technology <i>t</i> ( <i>7</i> = ST, <i>8</i> = PV).	CEC, 1993.	Years	72
<i>WCPC</i>	Completion fraction for technology <i>t</i> in each year of construction	CEC, 1993.	Percent	72

**MODEL INPUT:**     *WCAPVEL*

**DEFINITION:**       Constraint for PV capacity resource in NERC Region *n*; and year *y* (MW).

The variable is currently used to represent lower bounds on the capacity planning decisions in the EMM. EIA used off-line estimates to assign regional capacities that represent installations for experimental reasons or for commercial testing.

**SOURCE:**       EIA, Office of Integrated Analysis and Forecasting, off-line research.

**MODEL INPUT:**     *WCASTEL*

**DEFINITION:**       Constraint for solar thermal capacity resource in NERC Region *n*; and year *y* (MW).

The variable is currently used to represent lower bounds on the capacity planning decisions in the EMM. EIA used off-line estimates to assign regional capacities that represent future installations of other technologies (such as dish stirling and trough) and installations for experimental reasons or for commercial testing.

**SOURCE:**       EIA, Office of Integrated Analysis and Forecasting, off-line research.

**MODEL INPUT:**     *WCCPVEL*

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

**SOURCE:**       Electric Power Research Institute, “Technical Assessment Guide 1993 (TAG),” 1993.

**MODEL INPUT:**     *WCCSTEL*

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

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

**MODEL INPUT:**     *WCSI*

**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. (Solar Thermal: *t*=7; PV: *t*=8).

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

**MODEL INPUT:**     *WCSU*

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

A value of 15 mills per kilowatt hour for the years 1995 through 2004 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. (Solar Thermal: *t*=7; PV: *t*=8).

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

**MODEL INPUT:**     *WVCPVEL*

**DEFINITION:**       Variable O&M costs in NERC Region *n* and year *y*

The variable O&M costs for the PV technology are set to zero for all NERC 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:**     *WVCSTEL*

**DEFINITION:**     Variable O&M costs in NERC Region *n* and year *y*

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

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

**MODEL INPUT:**     *WOCPVEL*

**DEFINITION:**     Fixed O&M cost in NERC Region *n* and year *y*; (\$/kW).

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

**MODEL INPUT:**     *WOCSTEL*

**DEFINITION:**     Fixed O&M cost in NERC Region *n* and year *y*; (\$/kW).

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

**MODEL INPUT:**     *WSSPVEL*

**DEFINITION:**     Time segment system capacity factor for PV in NERC 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 NERC 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 (NERC 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:** *WCLT*

**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:** *WCPC*

**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.

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

The SOLES 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

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- 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:**

SOLES

### **Description:**

SOLES 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 SOLES. 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 Electric Submodule (SOLES) 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  
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(202) 586-6582

### **Documentation:**

NEMS Documentation Report: *Renewable Fuels Submodule*, May 1996.

### **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 NERC 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 2015
- 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:**

## **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.

### **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  $\text{W/m}^2$  divided by 1000.

## 5. Biofuels Supply Submodule

### Model Purpose

The objective of the Biofuels Supply Submodule (BSS) is to provide the NEMS Petroleum Market Module (PMM) with supply curves for corn-derived ethanol, thus allowing the PMM to forecast transportation ethanol demand through the year 2010. A secondary objective is to report the energy content of ethanol produced for transportation fuel.

To be consistent with the market clearing mechanism adopted for NEMS, the BSS provides ethanol prices in the form of annual price-quantity curves. The curves, derived from an ethanol production cost function, represent the prices of ethanol at which associated quantities of transportation ethanol are expected to be available to refineries for blending with gasoline.

### Relationship of the Biofuels Submodule to Other Models

The BSS's major NEMS linkages are with the Petroleum Market Module and the Coal Market Module (CMM). There is a two-way exchange of information between the BSS and PMM: the PMM provides the BSS with regional diesel fuel prices, while the BSS provides the PMM with delivered ethanol prices. The CMM serves as a source of energy price information for determining the total cost of converting corn into ethanol.

The delivered ethanol prices are provided to the PMM in the form of two supply curves, one for the East North Central Census Division (NEMS Region 3), and one for the West North Central Census Division (NEMS region 4).<sup>8</sup> These two Census divisions constitute the major ethanol producing regions in the United States, and are the only two Census divisions considered for the *AEO94* ethanol production forecasts.

To determine the delivered ethanol price, the contribution of the net cost of corn feedstock production must be factored in to the total unit price of ethanol. Diesel fuel prices, in dollars per gallon, are also considered as one of two energy cost variable inputs to the ethanol cost projected by the BSS. The other energy price input to the BSS's ethanol production cost function is the price of energy for corn feedstock processing and ethanol conversion. Coal prices are used as a proxy for industrial energy costs. Regional forecasts of energy prices (dollars per million Btu) to industrial consumers are supplied by the CMM.

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<sup>8</sup>All regional data inputs to the BSS ethanol production cost function are by Petroleum Administration for Defense Districts (PADDs). The calculated ethanol prices and quantities are mapped to the two Census divisions prior to being written to the NEMS price/quantity COMMON blocks.

Inputs from other NEMS modules are summarized as follows:

- Regional delivered price of diesel fuel to the agricultural/transportation sector. This is obtained from the Petroleum Market Module, and is used for computation of corn feedstock prices.
- Regional delivered price of process energy to industrial consumers, obtained from the Coal Market Module, are used to compute the conversion costs in the regional ethanol supply curves.
- Yield on AA utility bonds. This is obtained from the Macroeconomic Activity Module, and is used for calculating the capital cost factor. (See Appendix 5-B, "Mathematical Description," for the derivation of the capital cost factor.)

A major source of data supplied to the BSS comes from runs of a model external to the NEMS environment. This model, the Agricultural Resources Interregional Modeling System (ARIMS), was the source of the corn feedstock cost-supply relationships used in the BSS's ethanol cost function. ARIMS was developed at the U.S. Department of Agriculture in the 1980's. The ARIMS is a linear programming resource allocation model that was restructured to account for the value of the by-products produced in the corn-to-ethanol conversion process and to project the net cost of corn feedstocks.<sup>9</sup> In other words, the projected by-product values were credited against the price of corn. The variability of the market price for the feedstock corn and the conversion by-products and the variable influences of competitive uses for corn (e.g., for producing corn syrup) gives rise to broad fluctuations in net corn feedstock prices. All of these factors are considered in the ARIMS model.

ARIMS was run for 1995, 2005, and 2015 to provide price-quantity data for ethanol feedstocks. The changes in the competitive agricultural infrastructure modeled by ARIMS typically occur so slowly that the three years of model projections were deemed sufficient to bracket the behavior within the forecast horizon.<sup>10</sup> Interpolation was used to derive data points for the remaining *AEO94* forecast years. ARIMS is not integrated with NEMS, so that sensitivity analysis between NEMS and ARIMS is not currently feasible.

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<sup>9</sup>The net contribution of the cost of corn feedstocks to the price of ethanol is reduced over time by gradually improving conversion process yields. It is also affected by variations in the energy costs for producing corn. PDIESEL, the price of diesel fuel, was the proxy variable used to model the sensitivity of corn production costs to variable energy costs. Analyses were performed off-site and summary statistics are not currently available.

<sup>10</sup>Energy Information Administration, "Component Design Report for Biofuels (Ethanol) Supply Submodule - Renewable Fuels Model - National Energy Modeling System, Draft 7/2/92.

# Modeling Rationale

## Theoretical Approach

The BSS uses a process costing approach to model the impacts of net feedstock production costs plus the capital, operating, and process energy costs associated with converting the corn feedstocks to ethanol. In other words, each of the above factors contributes a part of the total price of ethanol projected by the BSS.

As mentioned above, the ARIMS supplied the data for the feedstock cost function variables. Since ethanol feedstock supply curves are a function of many factors (i.e., time, geographic location, demands for traditional agricultural commodities (domestic and foreign, crop and livestock), agricultural production technology, and land availability), the BSS needed the capability to relate such factors in a summary fashion to feedstock resource requirements under competitive agricultural market conditions. The ARIMS provides that capability with the use of a general equilibrium modeling framework.

The ARIMS was used to project corn crop demand and production resources and technology. Subject to constraints that were intended to capture the most important attributes of the agricultural market, the ARIMS model minimized the net cost of producing the specified quantities of corn produced as feedstock for ethanol, and the use of the feed by-products. The crop feedstock demand for ethanol production was set at various levels, with all other aspects of the model held constant. This allowed the linear program to develop sets of points that were used to estimate the step function feedstock supply curve.

Note that with this theoretical approach, only the agricultural, or feedstock production costs are modeled as a function of the total quantity of ethanol produced. The conversion plant process costs, (capital, operating, and process energy) are modeled as process cost which are independent of production quantities. The feedstock production cost components are estimated statistically, whereas the conversion process costs are determined from engineering concepts and data. Actual ethanol conversion process data are, for the most part, proprietary.

## Fundamental Assumptions

### Ethanol Production Capacity

An important modeling consideration is the imposition of a constraint on the amount of ethanol production capacity that can be added in any one year. Such a constraint would theoretically prevent unrealistically large increases in production capacity from occurring suddenly in response to potential structural market changes. On the other hand, our research determined that such capital expansion considerations are unnecessary for this modeling application because the lead time for capital expansion is very short and because the feedstock availability represents the major constraint to the expansion of ethanol production facilities.

For the *AEO94*, no structural changes to feedstock markets are assumed to occur during the forecast horizon. It is assumed that production capacity is utilized fully to meet refinery ethanol demand, and that there is sufficient ethanol production to meet refinery ethanol demand requirements.

## Ethanol Production Costs

The ethanol supply-price curve reflects offsetting influences stemming from the effects of increased corn production and improvements in corn-to-ethanol conversion technologies. Net feedstock prices are projected to increase as production increases due to two primary reasons. First, land becomes scarcer, causing both land and feedstock costs to increase, and second, feed by-products become less valuable as larger feedstock quantities are produced. Over time, however, the technologies for growing corn and converting it to ethanol are projected to improve, resulting in downward pressure on ethanol production prices. The BSS models the net effect of all of these factors.

In addition to feedstock prices and quantities derived from ARIMS, the BSS requires feedstock conversion and energy cost data. The conversion cost data were derived from the U.S. Department of Agriculture Report 585 *Ethanol: Economic and Policy Tradeoffs*, and the analytical judgment of Dr. Anthony Turhollow. These costs were developed for the two Census Divisions (3 and 4) that comprise PADD Region 2. Although the BSS has the ability to include ethanol production subsidies, they were set at zero for *AEO94*. The ethanol blender's excise tax credit, which is currently \$0.054 per gallon of gasohol (10 percent ethanol, 90 percent gasoline), is modeled in the PMM.

Quantities of energy needed to convert corn to ethanol are assumed to be a positive linear function of input values for years 1, 16, and 26, and to remain constant, at the year 26 value, for years 27, 28, and 29. (The *AEO94* runs utilized cost data only up to year 20.) Current facilities use 50,000 Btu per gallon of ethanol produced; while state-of-the-art plants run as low as 40,000 Btu per gallon. These two values are used as input values for years 1 and 16, respectively, with later years based on a linear trend of the first two values. This linear interpolation procedure was based on the assumption that, over time, ethanol facilities have become more energy efficient, and will continue to do so as they convert corn to ethanol at higher conversion rates and adopt technology improvements such as organisms with higher tolerances for sugars and ethanol, and molecular sieves to separate water from products. The feedstock conversion energy prices used to develop the feedstock cost function are national prices. Regional prices were not necessary since the relationship between feedstock production costs and energy prices is thought to be relatively constant across regions.

Operating costs for feedstock conversion are also assumed to be a positive linear function of input values for years 1 and 16, but remain constant at the year 16 value for the remaining forecast years. The first-year 1990 value of \$0.30 per gallon is an average plant cost for 1987, while the year 16 value of \$0.27 per gallon is a projected state-of-the-art plant cost.

## Treatment of Energy Crop Ethanol Feedstocks

Significant production of energy crops (e.g., grasses and short rotation trees) for ethanol production is not expected until about 2005. The conversion technology is at a stage wherein demonstration facilities for this technology are not expected to be operational until 1999, at the earliest. A few years of operating experience with the demonstration facilities will be required, and constructing the conversion facilities will also require several years time. Therefore, developing their supply functions for inclusion in the BSS will be deferred until a later *AEO*.

### Alternative Approaches

Prior to the BSS, the EIA had no in-house modeling system for forecasting alcohol fuel production and demand. The ethanol forecasts for previous *AEO* reports were consensus forecasts prepared by Oak Ridge National Laboratory (ORNL), based on the inter-laboratory renewable fuels energy white paper prepared in 1990. Subsequent to the *AEO92*, a prototype modeling system, utilizing other existing models and a simple supply representation for the production of ethanol, was developed by ORNL. The prototype model consisted of a supply component, a demand component, and a market-clearing process.<sup>11</sup>

For the demand component, an existing model, the Alternative Motor Fuel Use Model (AMFU) was adopted. AMFU is a model used to forecast fuel usage, vehicle usage, and vehicle stock for up to a 40-year horizon. It has the characteristics of both an accounting model for vehicle stocks, and an econometric model with economic activity and prices of fuels for forecasting total fuel demand. The fuel use portion of AMFU assumes that vehicle usage is a function of fuel cost and economic growth, as estimated by statistical models. The proportion of vehicles using any particular fuel (i.e., gasoline, diesel fuel, ethanol) is represented by an algebraic system that includes the relative prices of alternative fuels.

The supply component of the prototype model was represented by a step-function supply curve. The energy crops alternative was represented as a flat supply curve. The sources of these supply functions were Abt Associates (1991) and Tyson (1990), respectively.

Finally, a market-clearing process was used to find an equilibrium solution. The demand model was run for the lowest available price (as determined by the supply curve) of ethanol. If the demand for ethanol exceeded the available supply at that price, the next step of the supply curve was tried. When demand met the available supply, the solution was complete.

Unlike the prototype, the BSS analyzes supply factors only. Market penetration of alternative-fueled vehicles will be determined in the Transportation Demand Module, and the quantities of ethanol blended with gasoline will be determined by the Petroleum Market Module. No quantitative models

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<sup>11</sup>Lee, R., S.M. Cohn, and R.D. Perlack. 1991. *Prototype of an Integrated Model for Projecting Biofuels Consumption*. Draft report prepared for Energy Information Administration, U.S. Department of Energy. Oak Ridge National Laboratory, Oak Ridge, TN.

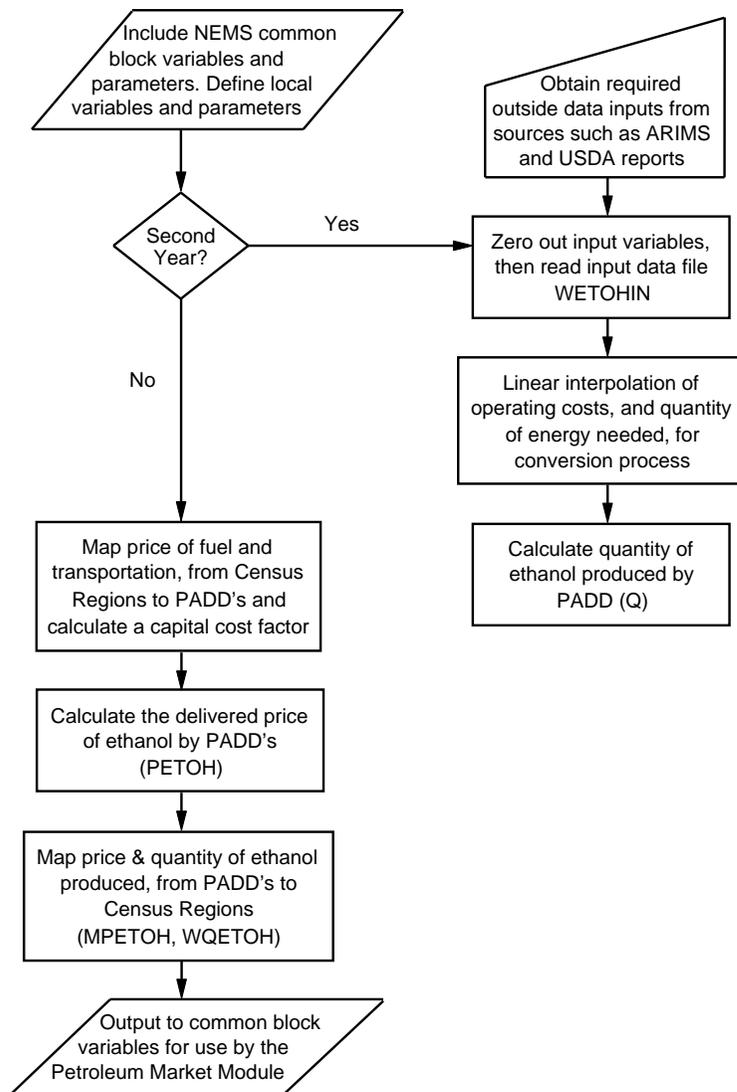
for forecasting the production or consumption of ethanol have been identified for application in the BSS.

## Biofuels Submodule Structure

### Submodule Flow Diagram

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

Figure 4. Biofuels Supply Submodule Flowchart



## Key Computations and Equations

The main computations performed by the BSS involve the derivation of a single ethanol supply-price curve. The computations consist of three major steps:

1. Reading in ethanol supply and component cost data, and performing annual interpolations of data values provided on a multi-year basis,
2. Computation of ethanol supply curve (price/quantity) coordinates.
3. Derivation of delivered ethanol prices, calculated as a function of the supply curve coordinates from step 2.

Each of these steps is described below.

After reading in the single input data file, (WETOHIN), the BSS performs a simple linear interpolation on two of the input data variables. These two variables, indexed in Table 5A-1, are *OPCST* (operating cost for feedstock conversion technologies, exclusive of energy) and *QEN* (quantity of energy needed for feedstock conversion). The BSS gets data values for these variables for 3 years, corresponding to years 1, 16, and 26. Linear interpolations are performed to calculate intermediate yearly values.

The next step involves the calculation of feedstock costs as a function of quantity and year. Readers should recognize this as a standard interpolation routine (Equation 5-1) supplied to the data in Table 3. The input data file supplies historical data on costs, as well as ARIMS forecasts, at selected quantities of ethanol production.<sup>12</sup> Because significant ethanol production is currently limited to PADD 2 (Census divisions 3 and 4), the BSS calculates ethanol supply quantities and prices only for Petroleum Administration for Defense District (PADD) 2; supply quantities and prices for the other four PADDs are fixed at zero. The input file therefore supplies the skeleton, for selected years, of the corn production costs  $COST_{p,t,e}$  at diesel price  $p$ , year  $t$  and production volume  $e$ . The input file also supplies the diesel price vector  $D_p$  and the vector  $Q_e$  that contains the quantities for each of the volume steps. Table 3 shows a the skeleton matrix used for *AEO96*. The BSS interpolates values for the  $COST_{p,t,e}$  matrix for years  $t$  not given in the input file, and fills in the same cost at all diesel price points in the historical years.

After the skeleton matrix  $COST_{p,t,e}$  has been filled in for all years, a supply curve for a given diesel price  $PDIESEL_{pr,t}$  is interpolated from the matrix using the formula:

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<sup>12</sup>All ethanol produced is assumed to be delivered to refineries.

**Table 5-1. Corn Production Cost Skeleton Matrix (\$/gal)**

Year	Diesel Price (\$/MMBtu)	Production Quantity Points (Billion gallons)					
		0	2.5	5	7.5	10	20
1995	6	0.214	0.315	0.346			
1995	8	0.233	0.336	0.372			
1995	10	0.250	0.359	0.402			
1995	12	0.272	0.378	0.425			
1995	14	0.279	0.408	0.454			
2005	6	0.266	0.301	0.331	0.371	0.420	
2005	8	0.279	0.327	0.347	0.383	0.435	
2005	10	0.306	0.379	0.379	0.407	0.466	
2005	12	0.333	0.394	0.412	0.431	0.488	
2005	14	0.351	0.415	0.436	0.470	0.514	
2015	6	0.255	0.281	0.300	0.326	0.351	0.442
2015	8	0.281	0.296	0.316	0.342	0.367	0.465
2015	10	0.307	0.327	0.349	0.374	0.400	0.511

$$\bar{C}_{pr,t,e} = COST_{p-1,t,e} + \frac{PDIESEL_{pr,t} - D_{p-1}}{D_p - D_{p-1}} (COST_{p,t,e} - COST_{p-1,t,e}) \quad (5-1)$$

where:

$FC_{pr,t,e}$  = Cost of producing corn in PADD  $pr=2$  in year  $t$  for volume step  $e$  (\$/gal),

$COST_{p,t,e}$  = Production cost matrix by diesel price step  $p$  in year  $t$  for volume step  $e$  (\$/gal),

$PDIESEL_{pr,t}$  = Price of diesel oil in PADD  $pr=2$  in year  $t$  (\$/MMBtu), and

$D_p$  = Diesel oil price step quantity for each step  $p$  (\$/MMBtu),

with

$$D_{p-1} < PDIESEL_{pr,t} < D_p.$$

## Indices

$e$	=	point on the supply curve, volume step 1 to 5
$f$	=	fuel (units in parentheses); 1=gasoline (gallons), 2=diesel (gallons), 3=LPG (gallons), 4=natural gas (MMBtu), 5=electricity (Kwh), 6=coal (MMBtu), 7=fuel for energy crop conversion (MMBtu).
$I$	=	crop; 1=corn, 2=energy crops
$sr$	=	Census Region, $sr=1$ to 9
$pr$	=	PADD, $pr=1$ to 5
$t$	=	year, $1990 \leq t \leq 2015$

The third major computational step involves the derivation of delivered ethanol prices for each PADD. The ethanol prices,  $PETOH$ , are calculated as a linear function of (1) the corn feedstock cost  $FC_{pr,t,e}$  shown above, (2) the price of diesel fuel, which serves as a proxy for all of the energy costs of producing the feedstock and transporting it to the conversion facility, and (3) corn-to-ethanol conversion facility process cost contributions, namely, capital, non-energy-related operating costs, and process energy costs.

The delivered ethanol price equation is as follows:

$$PETOH_{i,pr,t,e} = FC_{pr,t,e} + CAPCST_{i,t} * CCF + OPCST_{i,t} + QEN_{i,t} * PEN_{pr,t} - SUB \quad (5-2)$$

where:

$PETOH_{i,pr,t,e}$	=	Delivered price of ethanol produced from crop $I$ in PADD $pr$ in year $t$ for volume step $e$ for quantity of ethanol demand $Q$ (\$/gal),
$FC_{pr,t,e}$	=	Feedstock corn production cost for PADD $PR=2$ in year $t$ for volume step $e$ (\$/gal),
$CAPCST_{i,t}$	=	Capital cost for conversion technology for crop $I$ in year $t$ (\$/gal),
$CCF$	=	Capital cost factor (dimensionless),
$OPCST_{i,t}$	=	Operating costs, exclusive of energy, for crop $I$ conversion technology in year $t$ (\$/gal),
$QEN_{i,t}$	=	Quantity of energy needed to convert crop $I$ to ethanol in year $t$ (MMBtu/gal),
$PEN_{pr,t}$	=	Price of energy used in the corn-to-ethanol conversion process in PADD $pr$ in year $t$ (\$/MMBtu),
$SUB$	=	Subsidy for ethanol production (\$/gal)

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

This Appendix describes the variables, data inputs, and parameter estimates associated with the Biofuels Submodule. Table 5A-1 provides a tabular listing of model input data and input variable parameters. The table contains columns with information on item definitions, modeling dimensions, data sources, measurement units, and documentation page references. Similarly, Table 5A-2 provides an indexed listing of model output data and parameters.

The remainder of Appendix 5-A consists of detailed descriptions of data inputs and variables, including discussions on supporting data assumptions and transformations.

**Table 5A-1. NEMS Biofuels (Ethanol) Supply Submodule Inputs**

Model Variable	Definition and Dimensions	Source	Units	Page Reference
<i>CAPCST</i>	Capital cost for conversion technology for crop <i>I</i> in year <i>t</i>	USDA/ERS. 1988. Report #585	\$/gallon	96
<i>COST</i>	Cost of producing corn in PADD 2 at diesel price step <i>P</i> in year <i>t</i> at volume step <i>e</i>	ARIMS Output Trumble. 1994	\$/gallon	97
<i>D</i>	Values of diesel price steps <i>p</i>	Trumble. 1994	\$/MMBtu	97
<i>Q</i>	Quantity at each volume step <i>e</i>	Trumble. 1994	billion gallons	97, 102
<i>MC_RMPUAANS</i>	Yield on AA utility bonds for year <i>t</i>	Macroeconomic Market Module	Dimensionless	98
<i>OPCST</i>	Operating costs, exclusive of energy, for conversion technology of crop <i>I</i> in year <i>t</i>	USDA/ERS. 1988. Report 585	\$/gallon	98
<i>PADD2CR</i>	Conversion rates to convert from PADD <i>pr</i> to Census Region <i>sr</i>	A. Turhollow	Dimensionless	98
<i>PDSTR</i>	Price of diesel for transportation in Census Region <i>sr</i> in year <i>t</i>	Petroleum Market Module	\$/gallon	98
<i>PCLIN</i>	Price of coal for industrial use in Census Region <i>sr</i> in year <i>t</i>	Coal Market Module	\$/MMBtu	99
<i>QEN</i>	Quantity of energy needed to convert crop <i>I</i> to ethanol in year <i>t</i>	Marland & Turhollow. 1991	MMBtu/gallon	99
<i>QFUEL</i>	Quantity of fuel type <i>f</i> used in the production of crop <i>I</i> in year <i>t</i>	Marland & Turhollow. 1991	Gallons for f=1,2,3 MMBtu for f=4 kWh for f=5	99

**Table 5A-2. NEMS Biofuels (Ethanol) Supply Submodule Outputs**

Model Variable	Definition and Dimensions	Source	Units	Page Reference
<i>CCF</i>	Capital cost factor	Accounting Parameter	Dimensionless	101
<i>HEATCONT</i>	Heat content of ethanol	Value set to 3.5448	MMBtu/Bbl	99
<i>PDIESEL</i>	Price of diesel to industrial users in PADD <i>pr</i> in year <i>t</i>	Mapped from <i>PDSTR</i>	\$/gallon	101
<i>PEN</i>	Price of energy used in the corn to ethanol conversion process in PADD <i>pr</i> in year <i>t</i>	Mapped from <i>PNGIN</i>	\$/MMBtu	101
<i>PETOH</i>	Delivered price of ethanol produced from crop <i>I</i> in PADD <i>pr</i> in year <i>t</i> for volume step <i>e</i> for quantity of ethanol demand <i>Q</i>	Endogenous Variable	\$/gallon	101
<i>PETOHSRFACT</i>	Conversion factor to convert prices from \$/gallon to \$/barrel	42 gallons equals one barrel	Gallons/barrel	103
<i>Q</i>	Delivered quantity of ethanol produced from crop <i>I</i> in PADD <i>pr</i> in year <i>t</i> for volume step <i>e</i> for price of ethanol <i>PETOH</i>	Endogenous Variable	Billion gallons/year	97, 102
<i>QSRFACT</i>	Conversion factor to convert from million gallons per year to thousand barrels per day	set to value of 0.0652316, or $10^3/(42 * 365)$	Million bbl yrs/ billion gal days	102
<i>WPETOH</i>	Delivered price of ethanol produced from crop <i>I</i> in Census Region <i>sr</i> in year <i>t</i> for volume step <i>e</i> for quantity of ethanol demand <i>WQETOH</i>	Mapped from <i>PETOH</i> . Read to PETTR variable in WRENEW common block	\$/barrel	103
<i>WQETOH</i>	Delivered quantity of ethanol produced from crop <i>I</i> in Census Region <i>cr</i> in year <i>t</i> for volume step <i>e</i> for price of ethanol <i>WPETOH</i>	Read to QETTR variable in WRENEW common block	Million barrels/day	102

**MODEL INPUT:** *CAPCST*

**DEFINITION:** Capital cost for conversion technology for crop *I* in year *t*.

Given only for corn since the BSS is currently concerned only with corn as a feedstock. The current value is \$2.00 per gallon, and is the same for all years. Located in the WETOHIN input data file.

**SOURCE:** USDA/ERS. 1988. *Ethanol: Economic and Policy Tradeoffs*. Agricultural Economic Report No. 585. Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

**MODEL INPUT:**  $COST$

**DEFINITION:** Outputs from the ARIMS model from cases executed at each of the price steps  $p$  and each of the quantity steps  $e$ .

Values represent the cost of producing the corn necessary to produce  $Q_e$  billion gallons of ethanol if the price were  $D_p$  in year  $t$ .

Values are given only for PADD 2. Quantities of ethanol produced outside of PADD 2 are currently insignificant, so all production from ethanol is shown in PADD 2. Located in the WETOHIN input data file.

**SOURCE:** ARIMS model outputs. David A. Trumble. 1994. *Estimation of supply Curve for Ethanol with Corn as the Feedstock*. Oak Ridge National Laboratory.

**MODEL INPUT:**  $D$

**DEFINITION:** Diesel oil price steps  $p$ .

The diesel oil prices for which the ARIMS model was executed in each year. The BSS assumes that  $COST_{p,t,e}$  was generated from a matrix of ARIMS cases for each  $D_p$  and  $Q_e$ .

**SOURCE:** ARIMS model inputs. David A. Trumble. 1994. *Estimation of supply Curve for Ethanol with Corn as the Feedstock*. Oak Ridge National Laboratory.

**MODEL INPUT:**  $Q$

**DEFINITION:** Volume price steps  $e$ .

The ethanol volume steps for which the ARIMS model was executed in each year. The BSS assumes that  $COST_{p,t,e}$  was generated from a matrix of ARIMS cases for each  $D_p$  and  $Q_e$ .

**SOURCE:** ARIMS model inputs. David A. Trumble. 1994. *Estimation of supply Curve for Ethanol with Corn as the Feedstock*. Oak Ridge National Laboratory.

**MODEL INPUT:**     *MC\_RMPUAANS*

**DEFINITION:**       Yield on AA utility bonds for year *t*.

Located in the Macroeconomic common block, MACOUT.

**SOURCE:**       Generated by the Macroeconomic Activity Module.

**MODEL INPUT:**     *OPCST*

**DEFINITION:**       Operating costs, exclusive of energy, for conversion technology of crop *I* in year *t*.

Given only for corn since the BSS is currently modeling only corn-derived ethanol. Values are: \$0.30/gal. for 1990, \$0.27/gal. for 2005. \$0.27/gal. for 2015. Located in the WETOHIN input data file.

**SOURCE:**       USDA/ERS. 1988. *Ethanol: Economic and Policy Tradeoffs*. Agricultural Economic Report No. 585. Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

**MODEL INPUT:**     *PADD2CR*

**DEFINITION:**       Conversion rates to convert from PADD *pr* to Census Region *sr*.

Values are given for each PADD and Census Region. Most PADD's map one-to-one to a Census Region. Only PADD 2 maps into two different Census Regions. Located in the WETOHIN input data file.

**SOURCE:**       Generated by Dr. Anthony Turhollow, Oak Ridge National Laboratory, based on historical ethanol production from corn feedstocks.

**MODEL INPUT:**     *PDSTR*

**DEFINITION:**       Price of diesel for transportation in Census Region *sr* in year *t*.

Located in the NEMS Price common block (MPBLK).

**SOURCE:**       Generated by the Petroleum Market Module.

**MODEL INPUT:**     *PCLIN*

**DEFINITION:**       Price of coal for industrial use in Census Region *sr* in year *t*.

Located in the Price common block, (MPBLK).

**SOURCE:**       Generated by the Coal Market Module.

**MODEL INPUT:**     *QEN*

**DEFINITION:**       Quantity of energy needed to convert crop *I* to ethanol in year *t*.

Given only for corn since the BSS is currently concerned only with corn as a feedstock. Values, in million Btu per gallon, are as follows: 0.050 in 1990, 0.040 in 2005, 0.035 in 2015. This decreasing trend is based on the assumption that energy required decreases linearly over time. Located in the WETOHIN input data file.

**SOURCE:**       Marland, G. and A.F. Turhollow. 1991. "CO<sub>2</sub> Emissions From the Production and Combustion of Fuel Ethanol from Corn." *Energy*, 16(11/12):1307-1316.

**MODEL INPUT:**     *QFUEL*

**DEFINITION:**       Quantity of fuel type *f* used in the production of crop *I* in year *t*.

Given only for corn since the BSS is currently concerned only with corn as a feedstock. Values cover seven different fuel types and 20 forecasts, and remain constant for the duration of the forecast horizon. The values for fuel type six, coal, are all zero. Fuel type seven is reserved for fuel provided for the feedstock conversion process. Located in the WETOHIN input data file.

**SOURCE:**       Marland, G. and A.F. Turhollow. 1991. "CO<sub>2</sub> Emissions From the Production and Combustion of Fuel Ethanol from Corn." *Energy*, 16(11/12):1307-1316.

**MODEL INPUT:**     *HEATCONT*

**DEFINITION:**       Heat content of ethanol in transportation fuel, high-heating value.

**SOURCE:**       Marland, G. and A.F. Turhollow. 1991. "CO<sub>2</sub> Emissions From the Production and Combustion of Fuel Ethanol from Corn." *Energy*, 16(11/12):1307-1316.

## Appendix 5-B: Mathematical Description

This Appendix provides the detailed mathematical specification of the Biofuels (Ethanol) Supply Submodule as presented in the RFM FORTRAN code execution sequence. Subscript definitions are also as they appear in the FORTRAN code.

The ARIMS model is executed for a series of cases defined at a series of ethanol production quantities  $Q_e$  and diesel fuel prices  $D$  and years  $t$ , to create a matrix of corn production cost solutions  $COST_{p,t,e}$  in \$/gal. These are input to the BSS, and interpolated over years.

For a given NEMS diesel price  $PDIESEL_{pr,p}$  where the PADD  $pr=2$ , the BSS interpolates a corn cost curve  $FC_{pr,t,e}$  for PADD 2 that gives the cost in that year to produce each of the ethanol quantities  $Q_e$  at that diesel price. Here,  $PDIESEL_{pr,t}$  represents the NEMS price of diesel fuel PDSTR, in \$/MMBtu.

The delivered price of ethanol is calculated with the following equation:

$$\begin{aligned}
 PETOH_{i,pr,t,e} = & FC_{pr,t,e} + CAPCST_{i,t} * CCF \\
 & + OPCST_{i,t} + QEN_{i,t} * PEN_{pr,t}
 \end{aligned}
 \tag{5B-1}$$

where:

$PETOH_{i,pr,t,e}$  = Delivered price of ethanol produced from crop  $I$  in PADD  $pr$  in year  $t$  for volume step  $e$  for quantity of ethanol demand  $Q$  (\$/gal)  
 Note: Since PETOH is given in \$/gallons, the product of  $B1 * Q$  is also \$/gallons. This is achieved by applying the unit ( $10^{-9}$ \$ year/gal<sup>2</sup>) to B1.

$PDIESEL_{pr,t}$  = price of diesel for PADD  $pr$  in year  $t$  (\$/MMBtu)

$CAPCST_{i,t}$  = capital cost for conversion technology for crop  $I$  in year  $t$  (\$/gal)

$CCF$  = Capital cost factor (dimensionless)

$OPCST_{i,t}$  = operating costs, exclusive of energy, for crop  $I$  conversion technology in year  $t$  (\$/gal)

$QEN_{i,t}$  = quantity of energy needed to convert crop  $I$  to ethanol in year  $t$  (MMBtu/gal)

$PEN_{pr,t}$  = price of energy used in the corn-to-ethanol conversion process in PADD  $pr$  in year  $t$  (\$/MMBtu)

## Indices

$e$	=	point on the supply curve, volume step 1 to 5
$f$	=	fuel (units in parentheses); 1=gasoline (gallons), 2=diesel (gallons), 3=LPG (gallons), 4=natural gas (MMBtu), 5=electricity (Kwh), 6=coal (MMBtu), 7=fuel for energy crop conversion (MMBtu).
$I$	=	crop; 1=corn, 2=energy crops
$sr$	=	Census Region, $sr=1$ to 9
$pr$	=	PADD, $pr=1$ to 5
$t$	=	year, $1990 \leq t \leq 2015$

The capital cost factor (CCF) used in equation 5B-2, which is based on a 30-year amortization period, is calculated as follows:

$$CFF = MC\_RMPUAANS_t * (1 + MC\_RMPUAANS_t)^{30} / ((1 + MC\_RMPUAANS_t)^{30} - 1) \quad (5B-2)$$

where:

$MC\_RMPUAANS$  = yield on AA-grade utility bonds (a Macroeconomic Activity Module output variable).

The quantity of ethanol used as a transportation fuel,  $WQETOH_{cr,t,e}$ , is derived from the following equation:

$$WQETOH_{(cr=3,4),t,e} = Q_e \cdot PADD2CR_{2,3} \cdot QSRFACT \quad (5B-3)$$

where:

$WQETOH$  = Quantity of ethanol used as a transportation fuel, in barrels per day, for Census division 3 and 4, year  $t$ , and supply step  $e$ ,

$Q_e$  = quantity of ethanol produced from crop  $I$  in PADD 2 in year  $t$  for volume step  $e$  (billion gallons/year),

$PADD2CR_{2,3}$  = Conversion factors to convert from PADD 2 to Census Regions 3 and 4,

$QSRFACT$  = Conversion factor to convert from million gallons per year to thousand barrels per day.

The price of ethanol used as a transportation fuel,  $WPETOH_{cr,t,e}$ , is derived from the following equation:

$$WPETOH_{(cr=3,4),t,e} = PETOH_{1,pr,t,e} \cdot PADD2CR_{2,3} \cdot PETOHSRFACT \quad (5B-4)$$

where:

*WPETOH* = Price of ethanol used as a transportation fuel, in \$ per barrel, for Census division 3 and 4, year *t*, and supply step *e*,

*PETOH<sub>e</sub>* = Price of ethanol produced from corn in PADD 2 in year *t* for volume step *e* (\$/gallon),

*PADD2CR<sub>2,3</sub>* = Conversion factors to convert from PADD 2 to Census Regions 3 and 4,

*PETOHSRFACT* = Conversion factor to convert from gallons to barrels.

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## Appendix 5-D: Model Abstract

### Model Name:

Biomass (Ethanol) Supply Submodule

### Model Acronym:

BSS

### Description:

The BSS is a supply curve model for ethanol used for transportation fuel. It utilizes an ethanol cost function, NEMS energy price data, and outputs from an exogenous agricultural resource allocation linear programming model, to produce ethanol supply curves. The ethanol cost function models the impact of corn feedstock prices and supplies, energy prices, and feedstock conversion costs on delivered ethanol prices. The BSS's primary interaction is with the NEMS Petroleum Market Module (PMM).

### Purpose of the Model:

The purpose of the Biofuels (Ethanol) Supply Submodule (BSS) is to provide annual corn-derived ethanol supply-cost curves for use by the Petroleum Market Module (PMM) in projecting ethanol requirements. For each year, the BSS calculates delivered ethanol prices for different ethanol demand levels. The ethanol supply/cost projection information by Petroleum Administration for Defense District (PADD) and by Census Region. These projections are made Through the year 2015. The BSS, as a part of NEMS, help the Energy Information Administration develop forecasts published in its *Annual Energy Outlook (AEO)*.

### Most Recent Model Update:

October 29, 1993

### Part of Another Model?:

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

### Official Model Representative:

Laurence Sanders  
Coal, Uranium, and Renewable Fuels Analysis Branch  
Energy Information Administration  
(202) 586-2049

### Documentation:

NEMS Documentation Report: *Renewable Fuels Submodule*, March 1994

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

Archived as part of the NEMS production runs.

## **Energy System Described:**

Agricultural sector—corn feedstock production net of byproducts; corn feedstock requirements for ethanol production; ethanol as a refinery input for gasoline blending.

## **Coverage:**

- Geographic: Nine Census Regions: New England, Mid Atlantic, South Atlantic, East North Central, West North Central, East South Central, West South Central, Mountain, and Pacific. Five PADDs: Atlantic Coast, North Central, South Central, Mountain, and Pacific.
- Time Unit/Frequency: Annual, 1990 through 2015
- Products: Motor Fuel/Additives

## **Modeling Features:**

NA

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

Omnibus Reconciliation Act of 1990

- \$0.54 per gallon subsidy for ethanol blenders

Marland & Turhollow, 1991

- Quantity of energy needed for process conversion
- Quantity of fuel used in the production of feedstocks

United States Department of Agriculture (USDA) - Report #585

- Capitol & operating costs for conversion technologies

United States Department of Agriculture (USDA) - (ARIMS)

- Percentage of ethanol produced by PADD's
- Feedstock cost data

Anthony Turhollow, Oak Ridge National Laboratory, Oak Ridge, Tennessee

- Beta coefficients derived from an analysis of ARIMS outputs

## **DOE Input Sources:**

- EIA coal prices
- EIA diesel prices

## **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

This Appendix provides an overview of the Agricultural Resources Interregional Modeling System (ARIMS), a main source of input data used in the BSS.

### Agricultural Resources Interregional Modeling System (ARIMS)

The primary purpose of the national Agricultural Resource Interregional Modeling System (ARIMS) is as a system to analyze agricultural policies. Because resources and agricultural production practices differ by region, numerous regional attributes and responses to agricultural and resource policies can be evaluated in ARIMS. For example, policies can be evaluated that impact regional resource availability, farming techniques, resource prices, input availability, alternative levels of demand, and environmental allowances. The foremost use of the ARIMS, however, is to appraise future agricultural resource requirements.

ARIMS is a large linear programming model that includes numerous input coefficients and constraints. The inputs include projections of future resource availability, future demand levels and regional distribution of those demands, future commodity yields, and future changes in the ability of farmers to produce agricultural commodities. These projections are then used in a programming model and the composite effect of these individual impacts and the policy provisions introduced is analyzed.

The linear programming model of the agricultural sector is a set of mathematical relationships incorporating characteristics most relevant to agricultural production. The model minimizes the cost of producing and transporting agricultural commodities as required to meet pre-specified demands.

ARIMS divides the Nation into eight economic sectors. These eight sectors, integrated by a linear programming framework, are designed to represent the production processes and driving forces of U.S. agriculture.

The modeling system incorporates three different regional definitions. Production of agricultural commodities includes 105 Crop Producing Areas and 31 Livestock Producing Areas. The grazing production sector is specified for a third set of regions—34 ecosystems. The 31 Livestock Producing Areas also serve as the regional structure for non-water input purchases. In addition to the regions explicitly contained in the model structure, coefficients are developed by county, State, USDA farm production region and Major Land Resource Area.

Livestock markets (cattle, hogs, and poultry) have an important role in determining the supply price of ethanol. The vast bulk of grain produced in the United States is fed to livestock, and the by-products of producing ethanol from corn (gluten meal, gluten feed, and distillers dried grains) are

either fed to domestic livestock or exported. The by-products, including corn oil, from converting corn into ethanol are typically valued at about 50 percent of the raw corn cost.

The value of the by-products is directly proportional to the caloric and protein values of the feed by-products. Gluten meal (60 percent protein) and gluten feed (20 percent or more protein) are high in protein relative to corn (9 percent protein) and thus have a strong impact on soybean meal prices and vice versa. Soybean meal is 44 percent or more protein and is the main protein supplement for livestock. This competitive interaction is captured in the ARIMS model. As ethanol production from corn increases, the unit value of the feed by-products tends to decrease.

As an example, with corn at \$2.50 per bushel the by-products are worth \$1.25 per bushel, so the net feedstock cost is only \$1.25 per bushel. At a conversion rate of 2.5 gallons of ethanol per bushel of corn, the net feedstock cost is only \$0.50 per gallon instead of \$1.00 per gallon.

The only use of ARIMS in this submodule is as a source of feedstock cost data. Regression equations relating the cost of corn to energy input prices were estimated from successive runs of the model. However, the summary statistics of those regressions are not currently available as they were conducted off-site and were not included in subsequent reports. For the next AEO, data will be obtained and analysis performed in order to estimate error terms and other relevant statistical information. ARIMS is run exogenously to NEMS, and is therefore not an integrated component of the BSS.

## 6. 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 Electric 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.

The submodule passes to the EMM cost and performance characteristics by NERC 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.

### 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 submodule provides regional biomass supply curves for noncaptive markets. The supply curves are based on a detailed analysis of historical biomass consumption for a set of biomass sources in the industrial, electric generating, and commercial sectors.

Prior to the development of NEMS, electricity from biomass was estimated by EIA as a series of econometric equations based on historical biomass use from various sources and the relationship between biomass consumption and key variables. For utilities, projections of biomass facility capacity and capacity utilization factors were made off-line and included in the EMM. No competition between biomass and other sources of electricity generation was modeled; rather, the use of biomass decreased the requirements from other sources of generation.

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 combust 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 noncaptive portion of 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 off-line analysis that includes data accounting procedure that aggregates supply/price information from U.S. Forest Service and forest product experts. In addition results from an U.S. Environmental Protection Agency study on the economic viability of energy crops are used.

## **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. Because no interregional biomass trade exists, it is assumed that no biomass is transported among NEMS regions.

## **Alternative Approaches**

As mentioned above, the Biomass Submodule is based on the simplifying assumption that a single regional supply schedule for all biomass resources is appropriate for the electric generating sector. However, this simplification may not be able to capture all of the important dynamics in biomass markets. Biomass costs increase rapidly as the distance transported increases. Biomass is used relatively near its source, unlike coal, gas, or oil. A concentrated use in a small area is difficult to represent in the large regions of NEMS, where the average biomass share of energy used could be quite small. Large-scale facilities could lead to transportation problems (e.g., too many trucks required for delivering biomass). While this submodule estimates supply curves for the production

of biomass, the transportation distance of a facility from the biomass supply can make up a significant share of the delivered cost. In this module, a typical transportation distance for each Census Division is assumed. A more complete representation would include transportation supply curves.

## **Biomass Submodule Structure**

### **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 other cost-performance figures (i.e. capital cost, fixed operation and maintenance cost, capacity factors, and heat rates).

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.

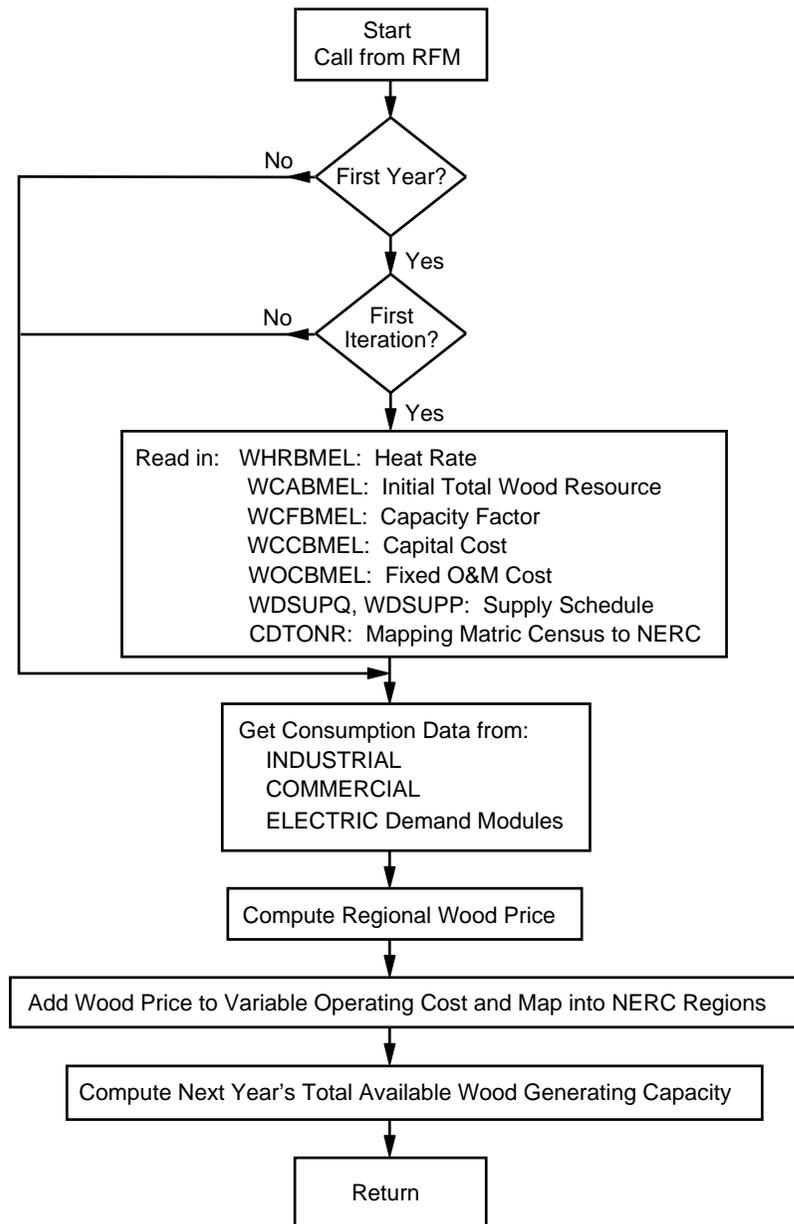
Since the quantity-price relations are established for Census regions, and the cost and performance characteristics of the biomass technology are defined for NERC regions, a geographic mapping was necessary to generate biomass prices by NERC regions.

In addition to the assignment of cost performance characteristics, the biomass submodule passes the maximum available electricity generating capacity using biomass to the ECP. This capacity limit is computed by decrementing the initial total potential by already installed capacity and for each subsequent year, decrementing the last year's unplanned new capacity from the previous limit. The initial total generating capacity for each region is determined by dividing the 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.

The procedural execution of the biomass subroutine is illustrated in Figure 5.

**Figure 5. Biomass Submodule Flowchart**



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

Appendix 6-A provides information on variables used in the Biomass Submodule. Table 6A-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 6A-1 are detailed descriptions of each input data item.

**Table 6A-1. NEMS Biomass Submodule Inputs and Variables**

Model Variable	Definition and Dimensions	Source	Units	Page Reference
<b>INPUTS</b>				
<i>CDTONR</i>	Conversion factors for converting Census division <i>R</i> to NERC Region <i>n</i>		Unitless	123
<i>WDSUPQ</i>	Biomass quantity step function in NERC Region <i>n</i> , year <i>y</i> , step <i>I</i>	DAC	trillion BTU	119
<i>WDSUPP</i>	Biomass price step function in year <i>y</i> , step <i>I</i>	DAC	\$/MMBTU	119
<i>WCCBMEL</i>	Capital cost for biomass technology in NERC Region <i>RN</i> in year <i>T</i>	NREL	\$/kW	120
<i>WCFBMEL</i>	Capacity factor for biomass technology electricity sector in NERC Region <i>RN</i> in year <i>T</i>	model determined	Unitless	120
<i>WVCBMEL</i>	Variable O&M costs for biomass technology electricity sector in NERC Region <i>RN</i> in year <i>T</i>	NREL	mills/KWh	120
<i>WOCBMEL</i>	Fixed O&M cost for biomass technology electricity sector in NERC Region <i>RN</i> in year <i>T</i>		\$/kW	120

**Table 6A-1. NEMS Wood Submodule Inputs and Variables (Continued)**

Model Variable	Definition and Dimensions	Source	Units	Page Reference
<b>VARIABLES</b>				
<i>QBMCM</i>	Quantity of biomass consumed in the commercial sector in Census division <i>R</i> in year <i>T</i>		MMBtu	123
<i>QBMEI</i>	Quantity of biomass consumed by utilities in Census division <i>R</i> in year <i>T</i>		MMBtu	123
<i>QBMIN</i>	Quantity of biomass consumed in the industrial sector in Census division <i>R</i> in year <i>T</i>		MMBtu	123
<b>OUTPUTS</b>				
<i>WCABMEL</i>	Capacity for utilities in NERC Region <i>RN</i> in year <i>T1</i>		MW	119
<i>WCCBMEL</i>	Capital cost for biomass technology in NERC Region <i>RN</i> in year <i>T</i>	NREL	\$/kW	120
<i>WCFBMEL</i>	Capacity factor for biomass technology electricity sector in NERC Region <i>RN</i> in year <i>T</i>	NREL	Unitless	120
<i>WVCBMEL</i>	Variable O&M costs for biomass technology electricity sector in NERC Region <i>RN</i> in year <i>T</i> . Incorporated the converted fuel cost for biomass.	NREL	mills/KWh	120
<i>WOCBMEL</i>	Fixed O&M cost for biomass technology electricity sector in NERC Region <i>RN</i> in year <i>T</i>	NREL	\$/kW	120

**MODEL INPUT:** *CDTONR*

**DEFINITION:** Conversion factors for converting Census division *R* to NERC Region *RN*

**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 NERC 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 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:**    *WCABMEL*

**DEFINITION:**        Available generating capacity [MW] in NERC 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.

**SOURCES:**        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.

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:**     *WCCBMEL*

**DEFINITION:**       Capital costs for electricity sector in NERC Region *n* in year *y*.

WCCBMEL represents the 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.

**SOURCES:**   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 INPUT:**     *WVCBMEL*

**DEFINITION:**       Variable costs for biomass electricity generation for the utility sector in NERC 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:**   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 INPUT:**     *WOCBMEL*

**DEFINITION:**       Fixed O&M costs for biomass technology in NERC region *n* and year *y*.

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

**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 INPUT:**     *WCFBMEL*

**DEFINITION:**       Capacity factor for the utility sector in NERC region *RN* in year *T*

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 NERC region *n* in year *y*

The heat rate represents the biomass gasification combined cycle technology. It is assumed that the heat rate will decrease 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 Region *r* and year *y*, trillion BTU.

NEMS variable, calculated in the commercial demand model.

**SOURCE:** None.

**MODEL INPUT:** *QBMIN*

**DEFINITION:** Biomass/wood consumption in industrial sector in Census Region *r* and year *y*, trillion BTU.

NEMS variable, calculated in the industrial demand model.

**SOURCE:** None.

**MODEL INPUT:** *QB MEL*

**DEFINITION:** Biomass/wood consumption in electric power sector in Census Region *r* and year *y*, trillion BTU.

NEMS variable, calculated in the EMM model.

**SOURCE:** None.

## Appendix 6-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 regions. They are mapped to NERC Regions using the following mapping:

commercial sector: 
$$WDQNR_{CM_{n,y}} = \sum_{r=1}^{R=9} \sum_{n=1}^{N=13} CDTONR_{n,r} \quad QB_{MCM_{n,y}}$$

industrial sector: 
$$WDQNR_{IN_{n,y}} = \sum_{r=1}^{R=9} \sum_{n=1}^{N=13} CDTONR_{n,r} \quad QB_{MIN_{n,y}}$$

electric power sector: 
$$WDQNR_{EL_{n,y}} = \sum_{r=1}^{R=9} \sum_{n=1}^{N=13} CDTONR_{n,r} \quad QB_{MEL_{n,y}}$$

where:

- $CDTONR_{n,r}$  = mapping matrix to map Census regions into NERC regions,
- $QB_{MCM_{r,y}}$  = biomass/wood consumption in commercial sector in Census Region  $r$  and year  $y$ , trillion BTU,
- $QB_{MIN_{r,y}}$  = biomass/wood consumption in industrial sector in Census Region  $r$  and year  $y$ , trillion BTU,
- $QB_{MEL_{r,y}}$  = biomass/wood consumption in electric power sector in Census Region  $r$  and year  $y$ , trillion BTU,
- $WDNRCM_{r,y}$  = biomass/wood consumption in commercial sector in NERC Region  $n$  and year  $y$ , trillion BTU,
- $WDNRIN_{r,y}$  = biomass/wood consumption in industrial sector in NERC Region  $n$  and year  $y$ , trillion BTU,

$WDNREL_{r,y}$  = biomass/wood consumption in electric power sector in NERC 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 NERC Region is:

$$CURWDCON_{n,y} = WDQNRCM_{n,y} + WDQNRIN_{n,y} + 0.03 WDQNREL_{n,y} \quad (6B-1)$$

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 on the supply curve to determine the price of biomass given a quantity. The interpolation is expressed as:

$$CURWDPR_{n,y} = WDSUPR_{y,i} + \left[ \frac{CURWDCON_{n,y} - WDSUPQ_{n,i}}{WDSUPQ_{n,y,i+1} - WDSUPQ_{n,y,i}} \right] (WDSUPR_{y,i+1} - WDSUPR_{y,i}) \quad (6B-2)$$

where:

$CURWDPRT_{n,y}$  = price of biomass energy from the all-sector supply schedule, NERC Region  $n$ , year  $y$ , \$/MMBTU.

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:

$$WVCBMEL_{n,y} = WVC_{n,y} + CURWDPR_{n,y} \cdot WHRBMEL_{n,y} \cdot C_1 \quad (6B-3)$$

where:

$WVC_{RN,T}$  = Constant variable O&M cost component in NERC region  $n$  and year  $y$ .

$WHRBMEL_{RN,T}$  = Heat rate for biomass technology in NERC region  $n$  and year  $y$ .

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

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## Appendix 6-D: Model Abstract

**Model Name:**

Biomass Submodule.

**Model Acronym:**

None.

**Description:**

The submodule passes to the EMM cost and performance characteristics by NERC 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 1995.

**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, EI-822  
202-586-0829.

**Documentation:****Archive Media and Installation Manual(s):****Energy System Described:**

Non-captive biomass supply and associated price.

**Coverage:**

USA.

**Modeling Features:**

Nine separate 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 6-E: Data Quality and Estimation Processes

## Derivation of the All-Sector Biomass Supply Curve Logging Residue and Whole Tree Data

### Data Sources and Methodology

#### *Mill Residues*

Estimates for quantities of mill residues available for fuel are based on data obtained from the U.S. Forest Service (U.S. Department of Agriculture). Figures on bark and wood residue generated from primary wood-using mills were provided by Joanne Faulkner of the Southern Forest Experiment Station in Starkville, Mississippi. Only a portion of this resource is available to the noncaptive market. Assumptions on availability are based on conversations with Kenneth Skog of the Forest Products Laboratory and end-use information published in Tables 33 and 34 of the USDA Forest Service 1989 Timber Analysis publication. As no updates are available for the above tables according to the coordinator of the publication, this study assumed that "35.71 percent of all coarse mill residues and 10 percent of fine and bark mill residues are available for use as energy in non-captive markets. Of residues not used, 50 percent of any type (coarse, fine, or bark, and hard or soft) are available for use as energy in noncaptive markets" (Turhollow et al., 1993).

The mill residue data was provided by the Forest Service by type of material and use for all states. For the cost-supply schedule calculations, mill residues going to fiber products and "other uses" were excluded. The above end-use percentages were applied to the mill residues available for fuel and those not used. The data was provided in dry tons and converted to trillion Btu based on the assumption of  $17 \times 10^6$  Btu per dry ton. Totals were then aggregated for each Census Division.

Estimates for mill residue prices are based on information obtained from Timber Mart-South and Timber-Mart North for the East North Central, West North Central, South Atlantic, East South Central, and West South Central Census Divisions. To estimate prices for the other Census Divisions, telephone calls were made to State utilization and marketing foresters, utilities using wood fuel, mills selling residues, State energy offices, and trade associations.

Based on the prices obtained from Timber Mart for mill residues, the low end of the range was used as an approximation for fine and bark mill residues. It should be noted that prices for these types of residues vary greatly with local conditions and that in some cases these residues are made available by mills at a nominal fee or even at no charge. The upper end of the range of prices provided by Timber Mart was used to approximate the price for coarse mill residues that could be purchased for fuel. Prices for residues were provided in dollars per green ton, delivered. In order to calculate the price per million Btu, an average moisture content of 50 percent (wet basis) was assumed.

The average prices for mill residues in each of the Census Divisions were calculated as weighted averages. Due to lack of data, prices for the Pacific Census Division were extended to the Mountain Census Division, and prices for New England extended to the Middle Atlantic.

### ***Logging Residues***

Attempts were made to use the latest U.S. Forest Service logging residue estimates. However, the current high cost of logging residues has precluded their widespread use. Research and contacts with utilization and marketing foresters in numerous states could not supply enough information on logging residue prices and utilization to construct cost-supply schedules using the Forest Service data. This study therefore relied on data from the report by McQuillan et al. to estimate prices and quantities of logging residues (McQuillan, 1984).

The data from the study by McQuillan et al. was provided in million cubic feet and was as converted to trillion Btu assuming average weights of 35 pounds per cubic foot for softwood, 40 pounds per cubic foot for hardwood, 15 percent moisture content (U.S. Forest Service, Turhollow), and  $17 \times 10^6$  Btu per dry ton. For the sake of consistency with recent practices, Gross Domestic Product (GDP) rather than Gross National Product price deflators were used for price conversions. Logging residue prices were converted from 1980 dollars to 1987 dollars using the GDP price deflator of 1.39. Totals of available residues by Census Division were calculated using a series of mapping factors to convert the data from the regions used in the McQuillan report (see DAC, 1995).

### ***Whole Tree Chips***

According to the U.S. Forest Service, data on whole tree chips is just beginning to be collected. Several states have data on whole tree chip utilization, but national figures are not available at this time. Discussions were held with numerous U.S. Forest Service and Forest Products Laboratory personnel, as well as chipping equipment manufacturers, to arrive at an approximation of whole tree chip supplies. Although some data was available, no satisfactory estimates or estimation methodologies could be established on a consistent basis for all regions. (The Forest Products Laboratory deemed its own estimates too tentative for release.)

A number of "local market" simulation studies were examined for applicability as well. For example, the Tennessee Valley Authority (TVA) conducted studies in 1989 and 1990 on tree chip markets using the Industrial Fuel Chip Supply Simulator (IFCHIPSS), a deterministic model that calculates cost-supply curves for a single harvesting operation in a predefined whole tree chip procurement area. However, price elasticities for the McQuillan and TVA studies are not comparable. The IFCHIPSS cost estimates have only been validated for production levels up to 200,000 tons per year. On the other hand, the McQuillan report looked at region-wide production economics; consequently, cost estimates are only valid for much greater production quantities (at least 93 million tons for the South East Census Division). Finally, the studies used different indicators of economic availability for wood chips, as well as different data sources.

Based on the lack of comprehensive data, and the fact that resource constraints precluded conducting a new and thorough study to develop cost curves for whole tree chips, the 1990 estimates by McQuillan et al. were used. Although the McQuillan study has neither been peer reviewed nor

updated since its completion in early 1984, an assessment of the study by DAC indicates that its results are acceptable given that the wood chip fuel market remains largely undeveloped. In particular, price/quantity relationships are generally in line with the limited findings of DAC's price and resource utilization research.

The McQuillan report estimates the inventory available for whole tree chips and logging residues. Since logging residues were treated separately, they were subtracted from the inventory total to avoid double counting. It is assumed that one-twentieth (1/20) of the inventory can be harvested annually on a sustainable basis (Turhollow et al., 1993).

The data by McQuillan et al. was reported in million cubic feet, and was converted to trillion Btu assuming average weights of 35 pounds per cubic foot of softwood, 40 pounds per cubic foot of softwood, 15 percent moisture, and  $17 \times 10^6$  Btu per dry ton. Prices were converted from 1980 to 1987 prices using the GDP deflator of 1.39. Totals of available whole tree chips by Census Division were calculated using a series of mapping factors to convert the data from the regions used in the McQuillan report (McQuillan, 1984).

### ***Other Wood***

Included in the wood resource cost-supply schedule estimates is a category referred to as *other wood*. In comparison with the ORNL/Turhollow study, these estimates reflect more recent market conditions in which more wood from pallets, reels, containers, construction and demolition waste is available as a resource. The Forest Products Laboratory estimates that the wood pallet, reel, and container industries annually produce the equivalent of 9 million dry tons of wood (MLSE & Associates). Based on EPA data, it is estimated that approximately 33 million tons of construction and demolition waste were generated in 1990 (McElvenny, 1994). It is unknown exactly how much "other wood" is processed for fuel. Therefore, it was decided that an availability estimate of 10 percent for pallets, reels and wood containers, and construction and demolition waste, would be a reasonable assumption.

There was insufficient data on prices and quantities of other wood resources in each of the Census Divisions. Therefore, this study allocated the 10-percent of "other wood" deemed available for fuel nationally according to 1990 Census Division population figures. Other wood resources were converted from tons into trillion Btu, assuming a moisture content of 15 percent for construction and demolition waste and  $17 \times 10^6$  Btu per dry ton. The study used a 1994 price of \$26.50/ton for these materials and a GDP deflator of 0.793 to convert to 1987 prices. Due to the lack of regional price information, this price was applied to all Census Divisions.

One category of wood waste not included in this study were urban forestry residues. Although some information was available for several states, not enough data could be located to include this resource in a national study. Certainly this resource should be considered in future updates of the estimates.

## ***Energy Crops***

The energy crop portion of the biomass cost-supply schedule was developed from a base case run of the Forest and Agricultural Sector Optimization Model (FASOM).<sup>13</sup> The FASOM is a dynamic, nonlinear programming model of the domestic forest and agricultural sectors. It was developed for the U.S. Environmental Protection Agency (EPA) as an aid in studying carbon sequestration policies and other land use issues.

The model solves for the optimum sum of the net present value of producer and consumer welfare surplus, and allows the agricultural and forest sectors to compete for land acreage. Transfers of land between sectors, as well as prices for agricultural goods and forest products (sawlogs, pulpwood, and fuelwood) are solved endogenously. FASOM can simulate market behavior over a 100-year period with model accounting accomplished at ten-year time intervals, starting at year 1990. Eleven supply regions<sup>14</sup> and one "national demand" region are modeled.

In late 1994, FASOM was modified to include biomass energy market activities. The purpose of the modification was to conduct an interagency biomass energy assessment study, sponsored by the EPA and DOE Office of Policy, Planning and Evaluation. For the supply side, two types of feedstocks are modeled as the primary biomass energy resources : mill residues and energy crops.<sup>15</sup> The energy crops and their FASOM supply regions are as follows: willow - Northeast (NE), poplar - Lake States (LS), switchgrass - Southeast (SE) and Southcentral (SC). Although other energy crop species can be used for dedicated feedstock production systems, willow, switchgrass, and poplar are good representative species that are considered the most promising at this time. For the demand side, a biomass integrated gasification/combined cycle (IGCC) technology scenario, based on a 100 megawatt plant, was assumed.

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<sup>13</sup>The run was made by Bruce McCarl of Texas A&M University, February 22, 1995. DAC considers the FASOM results for wood waste resources to be unreliable because of internal model accounting problems. The extent to which these problems affect the energy crop portion of the simulation is unknown.

<sup>14</sup>The supply regions are as follows: Northeast, Southeast, South Central, Corn Belt, Lake States, Southern Plains, Northern Plains, Rocky Mountains, Pacific Northwest (Western), Pacific Northwest (Eastern), and Pacific Southwest.

<sup>15</sup>Potential biomass feedstocks include resources besides mill residues and energy crops. Examples include urban wood wastes, logging residues, and wood chips/wastes from tree harvesting operations.

## 7. Geothermal Electric 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.

## Model 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 regions defined by the North American Electric Reliability Council (NERC). Supply curves are modeled for NERC 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.<sup>16</sup> 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<sup>17</sup>, using U.S. Geological Survey data and other sources. The data include potential site capacity; reservoir parameters such as temperature, depth, salinity, noncondensable 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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<sup>16</sup>Entigh, D., Livesay, B. and Petty, S., *Geothermal Cost of Power Model IM-GEO Version 3.05: User's Manual*, February 1989.

<sup>17</sup>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 220° F to 700° F. 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)<sup>18</sup> 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.<sup>19</sup>

## 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<sup>20</sup> (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 7-E for further details on the GESDPP.

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<sup>18</sup>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).

<sup>19</sup>EIA, *Annual Energy Review*, DOE/EIA 0384(93), Washington, DC, July 1994.

<sup>20</sup>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

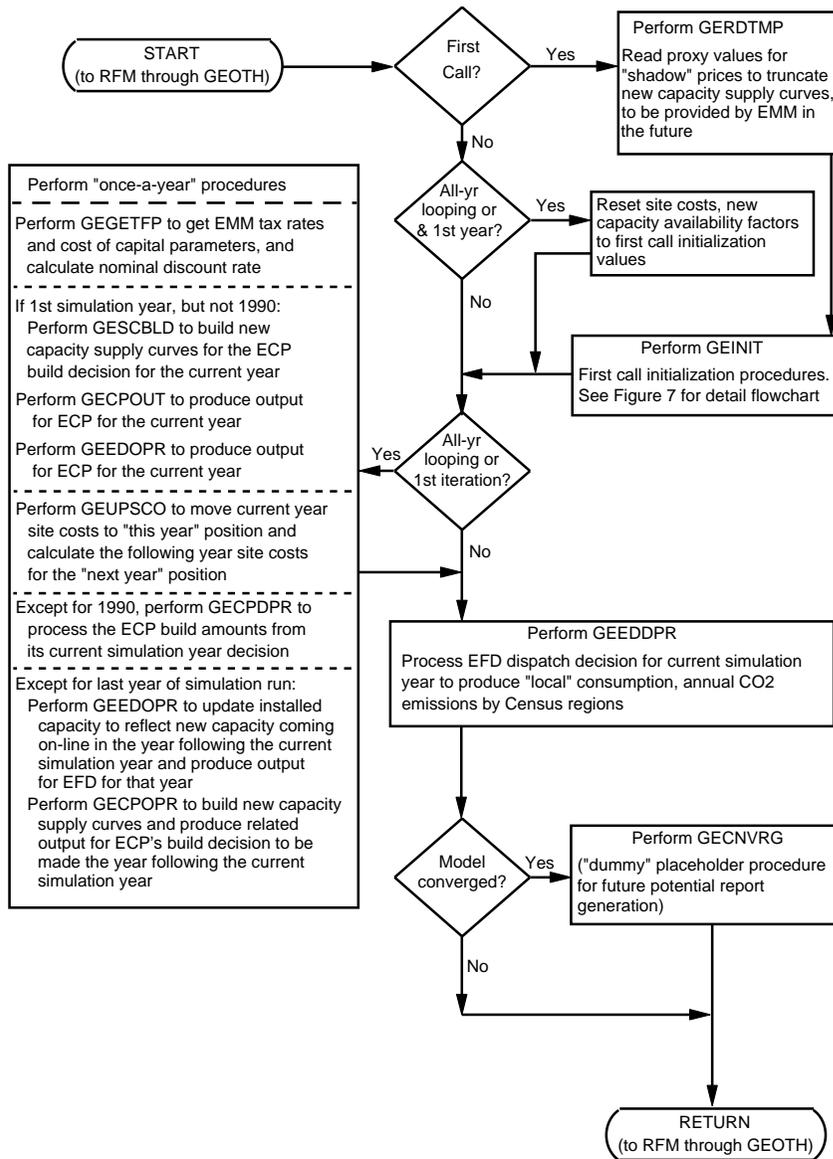
### Submodule Flow Diagrams

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

Figure 6 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 7. 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. *GECPPDR* 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 aggregations, and produces output for use by the EFD submodule of the EMM. *GECPOPR* uses a set of procedures to build new capacity supply

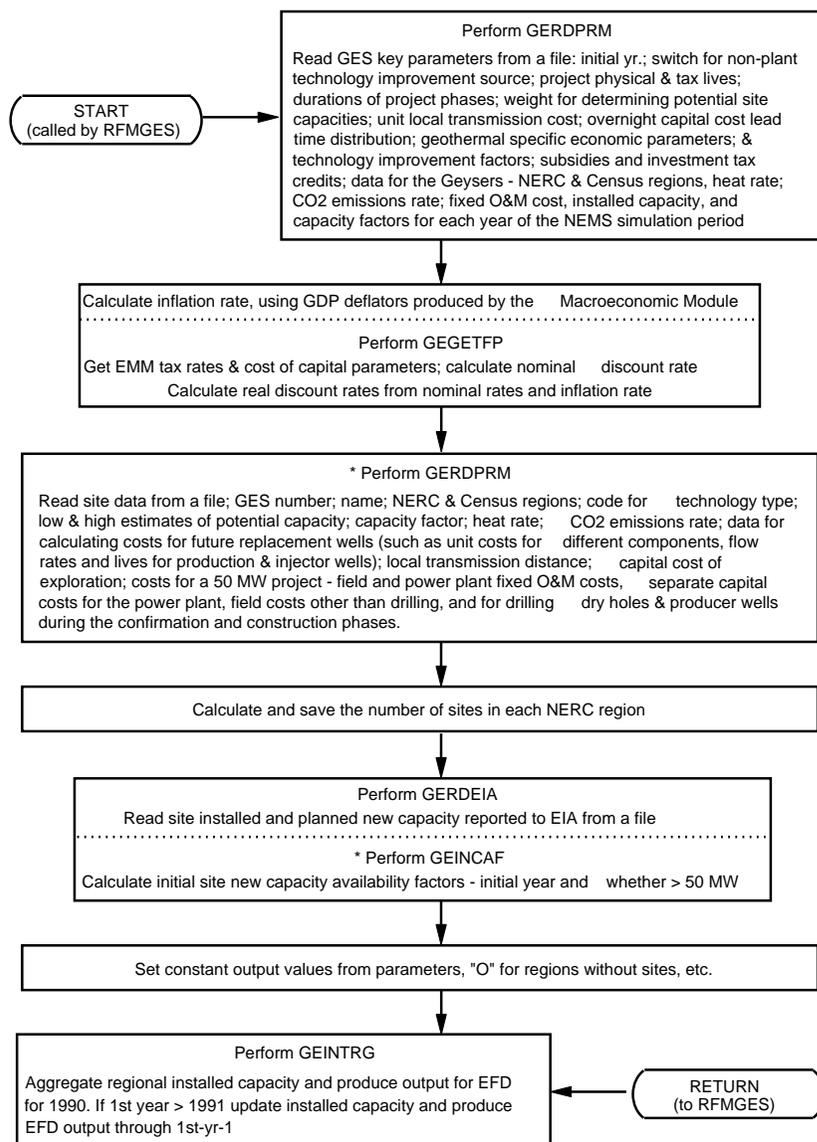
**Figure 6. Geothermal Electricity Submodule Overview Flowchart**



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<sub>2</sub> emissions by Census region from the dispatch amount 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.

**Figure 7. GES First Call Initialization Overview Flowchart**



- (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 7 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 7.

## 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 7-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.**  $WGESNCA_{v_{PS,PY}}$  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  $WGESNCA_{v}$  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,  $WGESPt_{PS}$ . Local, undimensioned variables are used for intermediate computations.

$$WGESNCA_{v_{PS,PY}} = 0 \quad \text{for } PY < IAY$$

$$WGESNCA_{v_{PS,PY}} = AvVAL \quad \text{for } PY = IAY \text{ and } > IAY$$

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":

$$DV = (TIC + TP) / WGESPtIPS \quad (7-1)$$

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**

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

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

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

*IAY* is computed as follows:

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

$$IAY = \max(9, Y + WGEPLEAD) \quad (7-2)$$

where:

*Y* = the index for the first year of the run

*WGEPLEAD* = the lead time for new capacity

**CASE 2 -  $DV > 0$**

$$IAY = \max(LPY + BDCOn, Y + WGEPLD) \quad (7-3)$$

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 7-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<sub>2,PS</sub>*.

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 AEO96, the power plant capital cost improvements have been changed to conform with the EMM learning curve approach. According to 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).

$$WGESFIOC_{2,PS} = WGESFIOC_{1,PS} * WGEPIGOT_{NY} \quad (7-4)$$

$$WGESPIOC_{2,PS} = WGESPIOC_{1,PS} * WGEPIGOT_{PT,NY} \quad (7-5)$$

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

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

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

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

The factors used for updating power plant capital and O&M costs are always those input as GES key parameters. However, when the key parameter  $WGETSW = 1$ , the key parameters input for drilling and field cost update factors are replaced by Oil & Gas Supply Submodule factors. Using an OGSM algorithm, these are 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 are replaced as follows:

$$WGE PGDCT_{NY} = 2. - OGF_1 \quad \text{for updating drilling capital cost}$$

$$WGE PGFCT_{NY} = 2. - OGF_2 \quad \text{for updating other field capital cost}$$

$$WGE PGFOT_{NY} = 2. - OGF_3 \quad \text{for updating field O&M cost}$$

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:

$$\begin{aligned} DY &= Y + 1 && \text{if } PY > Y + WGEPL\text{EAD} \text{ and } Y < 26 \\ DY &= Y && \text{if } PY \text{ not } > Y + WGEPL\text{EAD} \text{ or } Y = 26 \end{aligned}$$

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

$$SRDFct = \frac{1.}{(1. - WGEPROY_{DY} - WGEPS\text{EV}_{DY} + CTXR * WGEPP\text{D}pA_{DY})} \quad (7-9)$$

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

$$LACC_1 = WGESXSS_{PS} * IntFct_1 * SRDFct \quad (7-10)$$

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

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

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:

$$IntFct_{CC} = 1. - (WGEPI\text{NXP}_{DY} * WGEPP\text{ct}X_{CC} * CTXR) \quad (7-13)$$

For O&M costs,

$$LAFOC = WGESFIOC_{CI,PS} * SRDFct \quad (7-14)$$

$$LAPOC = WGESPIOC_{CI,PS} \quad (7-15)$$

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:

$$PSF = PQCAP / 50 \quad \text{if } PQCAP < 50 \quad (7-16)$$

$$PSF = 1 \quad \text{if } PQCAP \text{ not } < 50 \quad (7-17)$$

$$PCSF = PSF^{0.7} \quad \text{if } PQCAP < 50 \text{ and } WGESPTyp_{PS} = 2 \quad (7-18)$$

(flash technology site)

$$PCSF = 1 \quad \text{if } PQCAP \text{ not } < 50 \text{ or } WGESPTyp_{PS} = 1 \quad (7-19)$$

*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:

$$LACC_{CC} * PSF \quad \text{for } CC = 4, 5, 6, 8 \quad (7-20)$$

$$LACC_7 * PSF \quad \text{if } PCSF = 1 \quad (7-21)$$

$$LACC_7 * PCSF \quad \text{if } PCSF < 1 \quad (7-22)$$

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:

$$WGEAdXCC = LACC_1 \quad (7-23)$$

$$WGEAdFCC = (LACC_2 + LACC_3) / 50 \quad (7-24)$$

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

$$WGEAdSCC = LACC_4 + LACC_5 + LACC_6 + LACC_8 \quad (7-25)$$

$$WGEAdOC = LAFOC \quad (7-26)$$

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:

$$WGEAdICC = TRIC / 50 \quad \text{if } PSF = 1 \text{ (} QCAP \text{ is 50 or more)} \quad (7-27)$$

$$WGEAdICC = TRIC / PQCAP \quad \text{if } PSF < 1 \quad (7-28)$$

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

$$WGEAdSCC = (WGEAdSCC + LACC_7) / 50 \quad \text{if } PSF = 1 \quad (7-29)$$

$$WGEAdOC = (WGEAdOC + LAPOC) / 50 \quad (7-30)$$

$$WGEAdSCC = (WGEAdSCC + LACC_7 * PSF) / PQCAP \quad (7-31)$$

if  $PSF < 1$  and  $PCSF = 1$

$$WGEAdOC = (WGEAdOC + LAPOC * PSF) / PQCAP \quad (7-32)$$

$$WGEAdSCC = (WGEAdSCC + LACC_7 * PCSF) / PQCAP \quad (7-33)$$

if  $PSF < 1$  and  $PCSF < 1$

$$WGEAdOC = (WGEAdOC + LAPOC * PCSF) / PQCAP \quad (7-34)$$

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:

$$WGEAdXCC = 0 \quad \text{if } WGESPl_{PS} \text{ not } > 300 \text{ and } TIC > 0 \quad (7-35)$$

$$WGEAdXCC = (PQCAP / 250) * WGEAdXCC \quad (7-36)$$

if  $WGESPl_{PS} > 300$  and  $TIC \text{ not } > 250$  and  $TIC + PQCAP \text{ not } > 250$

$$WGEAdXCC = ((250 - TIC) / 250) * WGEAdXCC \quad (7-37)$$

if  $WGESPl_{PS} > 300$  and  $TIC \text{ not } > 250$  and  $TIC + PQCAP > 250$

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 than 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:

$$LCOST = ADJ * (TFVCC * (LAFCR/GLVL) + WGEAdOC) \quad (7-38)$$

where:

$$ADJ = \text{factor for conversion from annual \$/kW to cents per kWh.}$$

**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 (*WGESNCA<sub>v<sub>PS,PY</sub></sub>*). For these sites, a preliminary project size is computed as a percentage of total potential capacity as follows:

$$NCQ = WGESPl_{PS} * .01 \quad \text{if } DV = 0 \quad (7-39)$$

$$NCQ = WGESPl_{PS} * (.01 + (.14/.15)*DV) \quad \text{if } DV > 0 \text{ and } DV \text{ not } > .15 \quad (7-40)$$

$$NCQ = WGESPl_{PS} * .15 \quad \text{if } DV > .15 \text{ and } DV \text{ not } > .8 \quad (7-41)$$

$$NCQ = 0.75 * (WGESPl_{PS} - TIC) \quad \text{if } DV > .8 \quad (7-42)$$

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):

$$NCQ = 20 \quad \text{if } WGESNCA_{v_{PS,PY}} = 1 \text{ and } DV = 0 \text{ and } NCQ^* > 20$$

$$NCQ = 50 \quad \text{if } WGESNCA_{v_{PS,PY}} = 1 \text{ and } DV > 0 \text{ and } NCQ^* > 50$$

$$NCQ = 10 \quad \text{if } WGESNCA_{v_{PS,PY}} = 1 \text{ and } DV > 0 \text{ and } NCQ^* < 10$$

$$NCQ = 200 \quad \text{if } WGESNCA_{v_{PS,PY}} = 2 \text{ and } NCQ^* > 200$$

$$NCQ = 10 \quad \text{if } WGESNCA_{v_{PS,PY}} = 2 \text{ and } NCQ^* < 10$$

$$NCQ = 50 \quad \text{if } WGESNCA_{v_{PS,PY}} = 2 \text{ and } NCQ^* > 50 \text{ and } NCQ^* < 70$$

$$NCQ = 100 \quad \text{if } WGESNCA_{v_{PS,PY}} = 2 \text{ and } NCQ^* > 100 \text{ and } NCQ^* < 120$$

$$NCQ = 150 \quad \text{if } WGESNCA_{v_{PS,PY}} = 2 \text{ and } NCQ^* > 150 \text{ and } NCQ^* < 170$$

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:

$$PQCAP = NCQ - \text{MOD}(NCQ, 50) \quad \text{for the multiple of 50 MW project} \quad (7-43)$$

$$PQCAP = \text{MOD}(NCQ, 50) \quad \text{for the "residual" project} \quad (7-44)$$

### Computations for NEMS Regions

Most GES regional computations are for NERC 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 NERC 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 NERC region with geothermal sites:

Set NERC 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 regions, which are performed within the repetitive NERC region computational structure. Specifically,:

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

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

After end of NERC region repetitions: Perform final computations for all Census regions

**New Capacity Supply Curve Computations.** For given year of availability,  $PY$ , new capacity supply curves are generated for each NERC region with geothermal sites. A supply curve's index,  $SC$ , is related to the corresponding NERC 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 NERC region and availability year,  $WELSCST_{PN, PY}$ , data characterizing the project are saved with the next "step" index, *NS*.

$$\begin{aligned} NDX_{NS} &= NS \\ WID_{NS} &= PS \\ WLC_{NS} &= LCOST \\ WSQ_{NS} &= PQCAP \end{aligned}$$

For AEO96, the methodology for the supply curve truncation has been 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<sub>ST</sub>," which is the project with original step index *NX*, where:

$$NX = NDX_{ST}$$

Computations are performed sequentially for Project<sub>1</sub>, Project<sub>2</sub>, etc., through Project<sub>NS</sub>. Data for step 1 of the supply curve is for Project<sub>1</sub> only; step 2 data is for Project<sub>1</sub> and Project<sub>2</sub> combined; and so on, through the last step with data for all *NS* projects combined. The site index and size for Project<sub>ST</sub> are:

$$\begin{aligned} PS &= WID_{NX} \\ PQCAP &= WSQ_{NX} \end{aligned}$$

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<sub>ST</sub>

$CC_{ST}$  (for **WGEAdXCC** + **WGEAdFCC** + **WGEAdSCC** + **WGEAdICC**) is the total overnight capital cost for Project<sub>ST</sub>

Other variables for the project are similarly subscripted here.

$PQCAP_{ST}$  is the size of Project<sub>ST</sub>

$CF_{ST} = WGESCfct_{PS}$  is the capacity factor for Project<sub>ST</sub>

$HR_{ST} = WGESHtRt_{PS}$  is the heat rate for Project<sub>ST</sub>

$CO2R_{ST} = WGESCO2R_{PS}$  is the CO<sub>2</sub> emissions rate for Project<sub>ST</sub>

The site index for step  $ST^*$  of supply curve  $SC$  (for NERC region **WGEUNRgn<sub>SC</sub>**) is set as:

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

In all of the following computations, summations are over all projects from Project<sub>1</sub> through Project<sub>ST<sup>\*</sup></sub>, and the computations are made for all values of  $ST^*$  from 1 through  $NS$ .

$$WGEVNCCQ_{SC,ST^*} = \sum PQCAP_{ST} \quad (7-45)$$

$$WGEVCFct_{SC,ST^*} = \sum (PQCAP_{ST} * CF_{ST}) / \sum PQCAP_{ST} \quad (7-46)$$

$$WGEVOVCC_{SC,ST^*} = \sum (PQCAP_{ST} * OC_{ST}) / \sum PQCAP_{ST} \quad (7-47)$$

$$WGEVFOC_{SC,ST^*} = \sum (PQCAP_{ST} * CF_{ST}) / \sum PQCAP_{ST} \quad (7-48)$$

$$WGEVHtRt_{SC,ST^*} = \sum (PQCAP_{ST} * CF_{ST} * HR_{ST}) / \sum (PQCAP_{ST} * CF_{ST}) \quad (7-49)$$

$$WGEVCO2R_{SC,ST^*} = \sum (PQCAP_{ST} * CF_{ST} * CO2R_{ST}) / \sum (PQCAP_{ST} * CF_{ST}) \quad (7-50)$$

**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 NERC 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<sub>SC</sub>* supply curves. For the supply curve with index *ST*, the region and number of steps are set as follows:

$$\begin{aligned} PN &= WGEUNRgn_{SC} \\ RS &= WGEUNRgn_{SC} \end{aligned}$$

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.

$$WCAGPEL_{PN,PY-5} = WGEPCMAXC_{PN,PY} = WGEVNCCQ_{SC,RS} \quad (7-51)$$

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 than 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:

$$WCFGPEL_{PN,PY-5} = WGEPCF_{PN,PY} = WGEVCFct_{SC,RS} \quad (7-52)$$

$$WCCGPEL_{PN,PY-5} = WGEPC_{PN,PY} = WGEVOVCC_{SC,RS} \quad (7-53)$$

$$WOCGPEL_{PN,PY-5} = WGEPCFXOC_{PN,PY} = WGEVFOC_{SC,RS} \quad (7-54)$$

$$WHRGPEL_{PN,PY-5} = WGEPCPHtRt_{PN,PY} = WGEVHtRt_{SC,RS} \quad (7-55)$$

$$WEMGPEL_{3,PN,PY-5} = WGEPCO2R_{PN,PY} = WGEVCO2R_{SC,RS} \quad (7-56)$$

**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 NERC 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 *GECPPDR*. 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.

$$CPQ = WGEVNCCQ_{SC,CP} \quad (7-57)$$

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:

$$PS = WGEVSI_{SC,ST} \quad (7-58)$$

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

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

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 than 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<sub>SC,CP</sub>**:

$$\begin{aligned} PQCAP &= WGEVNCCQ_{SC,CP} && \text{if } CP = 1 \\ UCCADJ &= WGEVOVCC_{SC,SP} \end{aligned}$$

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

$$UCCADJ = \frac{(WGEVNCCQ_{SC,CP} * WGEVOVCC_{SC,CP}) - (WGEVNCCQ_{SC,CP-1} * WGEVOVCC_{SC,CP-1})}{PQCAP} \quad (7-59)$$

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.

$$WGEVOVCC_{SC,CP} = UCCADJ + WGEAdSCC + WGEAdIOC \quad (7-60)$$

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

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:

$$WGEVOVCC_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{OVCC}_{SC,CP-1}) + PQCAP * (UCCADJ + WGEAdSCC + WGEAdIOC)}{WELRQCA} \quad (7-61)$$

$$WGEVFOC_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{VFOC}_{SC,CP-1}) + (PQCAP * WGEAdOC)}{WELRQCA} \quad (7-62)$$

$$WGEVCFct_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{CFct}_{SC,CP-1}) + (PQCAP * WGESCFct_{PS})}{WELRQCA} \quad (7-63)$$

$$WGEVHtRt_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{CFct}_{SC,CP-1} * WGEV^{HtRt}_{SC,CP-1}) + (PQCAP * WGESCFct_{PS} * WGESHtRt_{PS})}{(WELRQCA * WGEVCFct_{SC,CP})} \quad (7-64)$$

$$WGEVCO2R_{SC,CP} = \frac{(WGEVNCCQ_{SC,CP-1} * WGEV^{CFct}_{SC,CP-1} * WGEV^{CO2R}_{SC,CP-1}) + (PQCAP * WGESCFct_{PS} * WGESCO2R_{PS})}{(WELRQCA * WGEVCFct_{SC,CP})} \quad (7-65)$$

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 NERC region  $PN$  with initial availability in year  $PY$  is saved for later use in computing output for all installed capacity for year  $PY$ .

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

**Dispatch Related Output Computations for All Installed Capacity.** Regional (NERC 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 NERC region, with the initial computations performed sequentially for the sites in the region. Totals are aggregated for both NERC regions and Census regions.

Except for fixed O&M cost, by NERC 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 NERC region and Census region. Initial computations when processing each site in successive NERC regions are identical.

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

$$NRCRFCT = \sum (WGESICap_{PS,PY} * WGESCFct_{PS}) \quad (7-66)$$

For the Census region computations, summation for region **CI** is over all sites in all NERC regions such that **WGESCR<sub>PS</sub> = CI**.

$$CRCRFCT_{CI} = \sum (WGESICap_{PS,PY} * WGESCFct_{PS}) \quad (7-67)$$

$$CRHtRt_{CI} = \sum (WGESICap_{PS,PY} * WGESCFct_{PS} * WGESHtRt_{PS}) \quad (7-68)$$

$$CRECO2_{CI} = \sum (WGESICap_{PS,PY} * WGESCFct_{PS} * WGESCO2R_{PS}) \quad (7-69)$$

NERC 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 = WGEENR**

No computations, output value remains 0.

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

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

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

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

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

$$WCFGIEL_{PN,PY} = \frac{(NRCFCT + WGE GICAP_{PY} * WGEGCFct_{PY})}{(NRICAP + WGE GICAP_{PY})}$$

Census region output is produced after all sites in all regions have been processed. Total installed capacity in Census region  $CI$  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  $CI = WGEGCR$**

$$\begin{aligned} WHRGIEL_{CI,PY} &= WGEGHtRt \\ WEMGIEL_{3,CI,PY} &= WGEGCO2R \end{aligned}$$

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

$$WHRGIEL_{CI,PY} = CRHTRT_{CI} / CRCFCT_{CI} \quad (7-70)$$

$$WEMGIEL_{3,CI,PY} = CRECO2_{CI} / CRCFCT_{CI} \quad (7-71)$$

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

$$WHRGIEL_{CI,PY} = \frac{(CRHTRT_{CI} + WGE GICAP_{PY} * WGEGCFct_{PY} * WGEGHtRt)}{(CRCFCT_{CI} + WGE GICAP_{PY} * WGEGCFct_{PY})} \quad (7-72)$$

$$WEMGIEL_{3,CI,PY} = \frac{(CRECO2_{CI} + WGE GICAP_{PY} * WGEGCFct_{PY} * WGEGCO2R)}{(CRCFCT_{CI} + WGE GICAP_{PY} * WGEGCFct_{PY})} \quad (7-73)$$

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  $PN = WGEGNR$**

$$WCFGIEL_{PN,PY} = \frac{(NRFXOC + WEGEGICAP_{PY} * WGEGOC)}{(NRICAP + WEGEGICAP_{PY})} \quad (7-74)$$

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  $WEGEGPCap_{PS,PY}$ , so that the computation for  $NRFXOC$  produces total O&M costs of all planned capacity additions for the region.

If 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 Geysers' region; or, for that region,  $WGEGOC$ . For "CASE 3" and "CASE 4":

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

$$WOCGIEL_{PN,PY} = \frac{(NRFXOC + WOCGIEL_{PN,PY-1} * WGENICap_{PN,PY-1})}{WGENICAP_{PN,PY}} \quad (7-75)$$

**CASE 4 -  $WGENICAP > 0$  and  $PN = WEGENR$**

$WOCGIEL_{PN,PY} =$

$$\frac{(NRFXOC + WOCGIEL_{PN,PY-1} * (WGENICap_{PN,PY-1} + WEGEGICAP_{PY-1})) + A}{(WGENICAP_{PN,PY} + WEGEGICAP_{PY})} \quad (7-76)$$

where:

$$A = WEGEOC * (WEGEGICAP_{PY} - WEGEGICAP_{PY-1}) \quad (7-77)$$

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:

$$NRUFOC = NRUCAP * WGENUOC_{PN,PY} \quad (7-78)$$

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 7-A: Inventory of Variables, Data and Parameters**

Due to its size, Appendix 7-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 7-B: Mathematical Description

Due to its size, Appendix 7-B has not been included here. For Appendix 7-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.

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- Petty, S., Livesay, B., Long, W. and Geyer, J., Contractor Report, "Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power in 20 to 40 Years," (June 21, 1991).
- White, D. and Williams, D., Eds., "Assessment of Geothermal Resources of the United States - 1975," United States Geological Survey Circular 726 (1975).
- McLarty, L., "Geothermal Electric Supply Data Pre-Processor: Model Documentation," (November 1994 Draft).

# Appendix 7-D: Model Abstract

**Model Name:**

Geothermal Electric Submodule

**Model Acronym:**

GES

**Description:**

The GES models economic supply curves, aggregated by NERC 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 1995

**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:**

Model Documentation: Renewable Fuels Module of the National Energy Modeling System, 1995.

**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: NERC regions 11, 12, 13, and 15
- Time Unit/Frequency: Annual, 1990 through 2015
- 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 7-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<sup>21</sup>, 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<sup>22</sup>, 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 7E-1, 7E-2, and 7E-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 7-A. A description of the output file, WGESITE, which serves as the main input file for GES can also be found in Appendix 7-A.

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<sup>21</sup>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.

<sup>22</sup>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 7E-1. Main Flow Chart of GESDPP

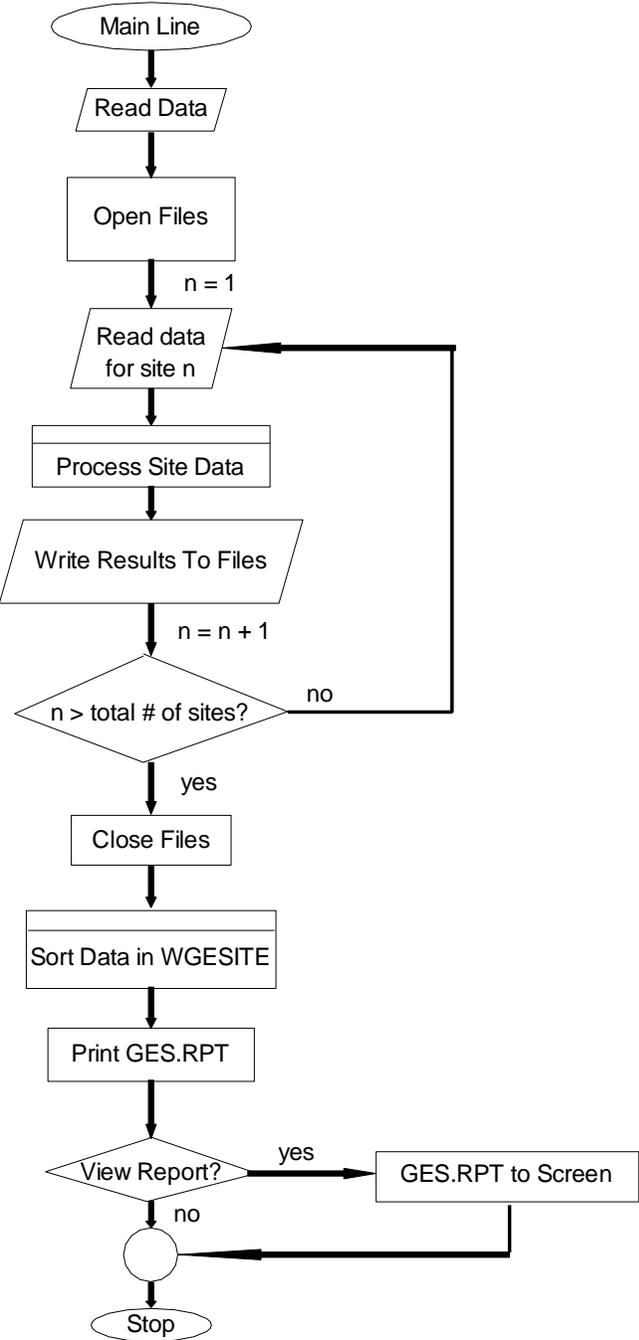


Figure 7E-2. Flow Diagram for Process Site Data Routine

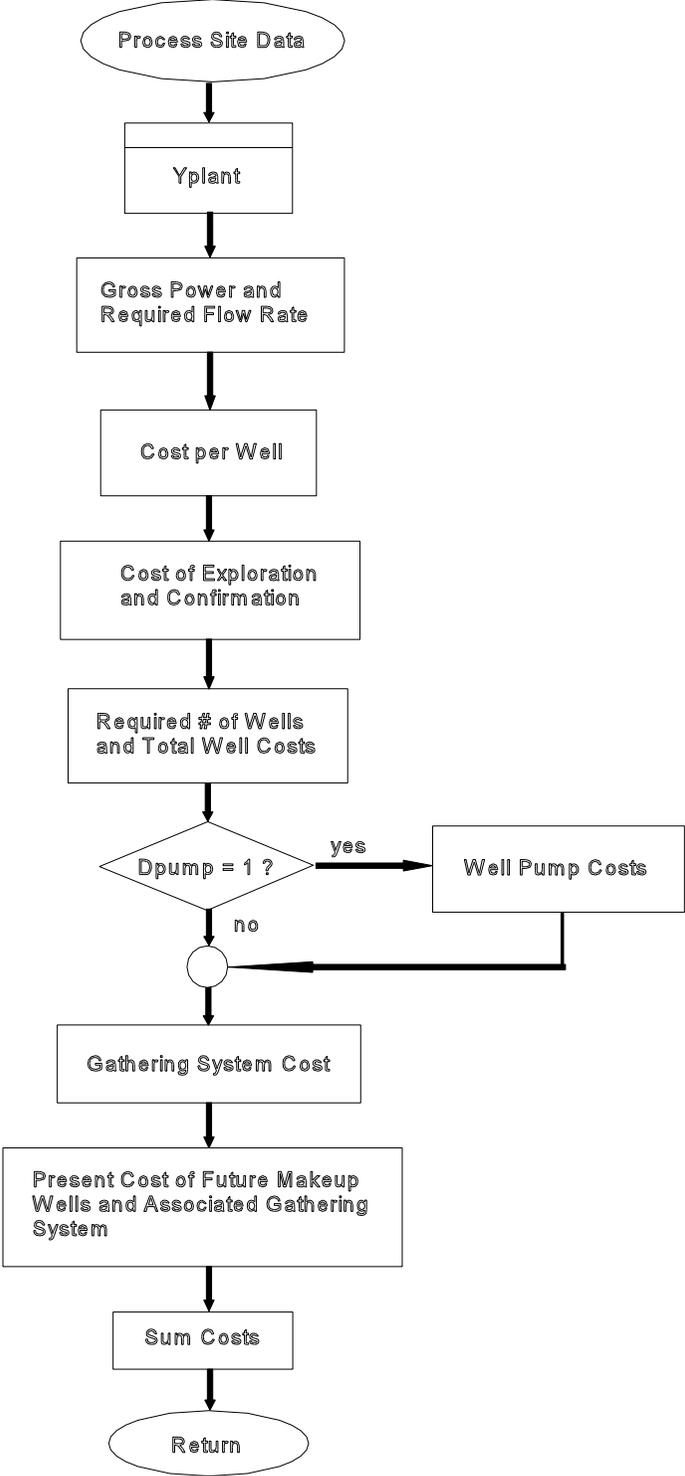
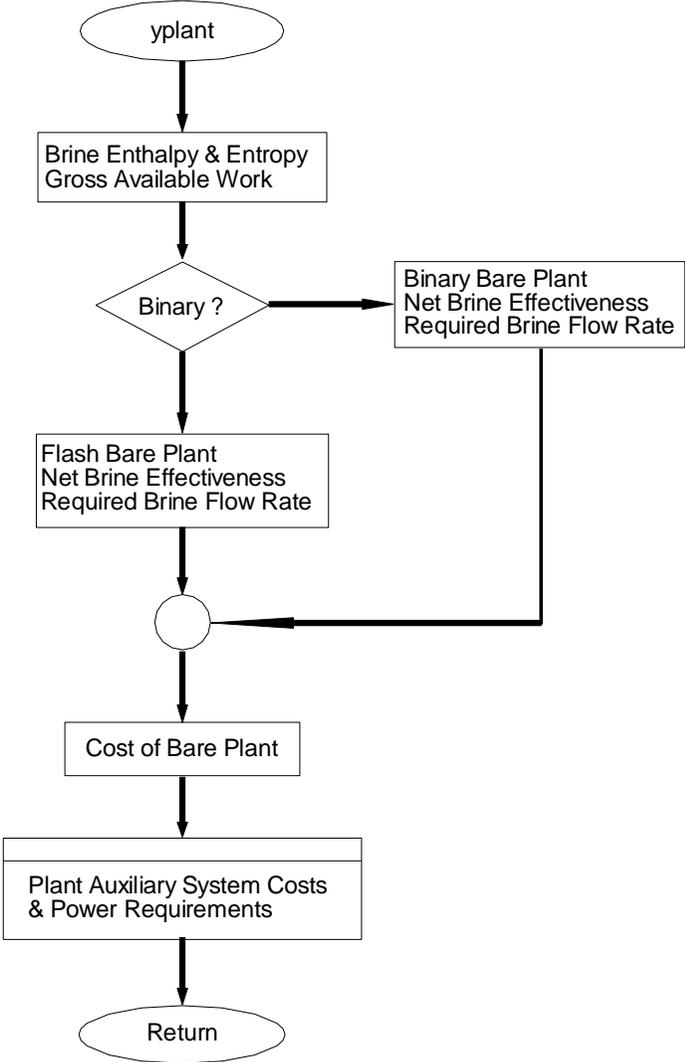


Figure 7E-3. Flow Chart for Yplant Routine



# Mathematical Descriptions of Key Algorithms

## Heat Rate (GESDPP)

$$HEAT.RATE \text{ (BTU/kWh)} = 1000 * (H.IN - H.COND) / NETBE \quad (7E-1)$$

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

$$COST.FLASH = 0.75 * (1.3336 - 5.4308 * TX + 0.013179 * TX^2 + 1.0752 * (EFFIC - 30)) \quad (7E-2)$$

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:

$$COST.BINARY = 1.06 * (1595 - 4.9836 * TX + 0.0087648 * TX^2 + 3.4082 * (EFFIC - 40) ) \quad (7E-3)$$

where:

$$TX = RESERVOIR.TEMPERATURE - 260$$

$$EFFIC = \text{same as above}$$

### **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:

$$COST.HXC = HXF * COST.BINARY \quad (7E-4)$$

where:

$$HXF = \begin{aligned} &= \text{the fraction of the bare plant cost attributable to the HXC} \\ &= 0.2 - 0.1 * (RESERVOIR.TEMPERATURE - 250) / 150 \end{aligned}$$

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

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

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

$$HXC.O\&M = 0.030 * COST.HXC \quad (7E-5)$$

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

$$FLASH.INJ.POWER = 100.3774 - 0.7504002 * T.IN + 2.116543^{-3} * T.IN^2 - 2.638822^{-6} * T.IN^3 + 1.220977^{-9} * T.IN^4 \quad (7E-6)$$

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

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

$$BINARY.INJ.PUMP.COST (\$/kW) = 230 * BINARY.INJ.POWER \quad (7E-9)$$

where:

$$T.IN = \text{plant inlet temperature (degrees F)}$$

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:

$$\mathbf{WATER.LOSS} \text{ (acre-ft/kW/yr)} = 2300 / (\mathbf{RESERVOIR.TEMPERATURE} * 1234) \quad \mathbf{(7E-10)}$$

where:

$$\mathbf{RESERVOIR.TEMPERATURE} = \text{reservoir temperature (degrees F)}$$

The annual cost of the water is calculated by

$$\mathbf{TOTAL.WATER.COST} \text{ (\$/kW)} = \mathbf{WATER.LOSS} * \mathbf{WATER.COST} \quad \mathbf{(7E-11)}$$

where:

$$\mathbf{WATER.COST} = \text{cost of water (\$/acre-ft) (from site data)}$$

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:

$$\mathbf{CLARIFIER.COST} \text{ (\$/kW)} = 140 * \mathbf{B} \quad \mathbf{(7E-12)}$$

$$\mathbf{CLARIFIER.O\&M} \text{ (\$/kW/yr)} = 3 * \mathbf{B} \quad \mathbf{(7E-13)}$$

where:

$$\begin{aligned} \mathbf{B} &= 0 && \text{if total dissolved solids} < 0.5 \text{ percent} \\ &= 1 && \text{if total dissolved solids} \geq 0.5 \text{ percent} \\ &= 2 && \text{if total dissolved solids} \geq 10 \text{ percent} \end{aligned}$$

$$\mathbf{CLARIFIER.WASTE.DISPOSAL} \text{ (\$/kW/yr)} = \mathbf{SLUDGE} * \mathbf{(137.50) / PLANT.SIZE / 1000} \quad \mathbf{(7E-14)}$$

where:

$$\mathbf{SLUDGE} \text{ (tons/yr)} = 57.2769 * \mathbf{TFLIN} * \mathbf{TDS} * (\mathbf{CAP.FAC} + 1) \quad \mathbf{(7E-15)}$$

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:

$$FLASH.SCALE.O\&M = 0.002 * (TDS/15) * (COST.FLASH + INJ.PUMP.COST) \quad (7E-16)$$

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:

$$BINARY.SCALE.COST = 0.50 * (TDS/15) * COST.HXC \quad (7E-17)$$

$$BINARY.SCALE.O\&M = 0.015 * (TDS/15) * COST.HXC \quad (7E-18)$$

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

$$FLASH.CORROSION.COST = 0.03 * (TDS/15) * (COST.FLASH + INJ.PUMP.COST) \quad (7E-19)$$

$$BINARY.CORROSION.COST = 0.015 * (TDS/15) * (COST.BINARY + INJ.PUMP.COST) \quad (7E-20)$$

The existence of noncondensable 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:

$$FLASH.NCG.COST (\$/kW) = 13.5 * NCG \quad (7E-21)$$

$$FLASH.NCG.O\&M (\$/kW/yr) = 0.02 * 13.5 * NCG \quad (7E-22)$$

where:

*NCG* = per cent noncondensable gas content of brine

The existence of hydrogen sulphide (H<sub>2</sub>S) 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<sub>2</sub>S 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:

$$H_2S.COST = (3,010,000 * (SA / 2,000,000)^{0.60} + 230,000) * 1.643 / (PLANT.SIZE / 1000) \quad (7E-23)$$

$$H_2S.O\&M = 1.58 * [67,200 + RWF(211.18BTC + 173.44SRE) ] / (PLANT.SIZE / 1000) \quad (7E-24)$$

where:

$$SA = RWF * BTC = \text{steam flow from condenser (lb/hr)} \quad (7E-25)$$

where:

$$RWF = \text{brine flow rate into plant (lb/hr)}$$

$$BTC = \text{fraction of brine flowing through condenser}$$

$$PLANT.SIZE = \text{net power output (MW)}$$

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

$$SCCPOWPL = \text{capital costs of plant + heat exchanger + cooling tower + auxiliaries (scaling, corrosion, clarifier) + H}_2\text{S abatement system} \quad (7E-26)$$

$$SCCPOWPLOM = \text{O\&M costs of plant + heat exchanger + cooling tower + auxiliaries (scaling, corrosion, clarifier) + H}_2\text{S abatement system} \quad (7E-27)$$

### **Emissions Rates**

The CO<sub>2</sub> and H<sub>2</sub>S emission rates for binary plants are zero.

The CO<sub>2</sub> emission rate for a flash plant is:

$$SCO2RATE = 1,000,000 / NETBE * X12 * NCG / 100 * 0.855 \quad (7E-28)$$

where:

$$NETBE = \text{net brine effectiveness, watt-hour/lb. brine}$$

$$X12 = \text{steam total mass fraction to turbine}$$

$$NCG = \text{noncondensable gas content, percent (site data)}$$

The H<sub>2</sub>S emission rate for a flash plant is:

If the H<sub>2</sub>S load is greater than the permissible rate then:

$$SH2SRATE = H2S.LIMIT / 453.6 * V.KWH.RATE / NETBE \quad (7E-28)$$

where:

<i>H2S.LIMIT</i>	=	regulatory limit for H <sub>2</sub> S emission, gram/hr/MW (site data)
<i>V.KWH.RATE</i>	=	work rate across turbine, watt-hour/lb. brine
<i>NETBE</i>	=	net brine effectiveness, watt-hour/lb. brine

If the H<sub>2</sub>S load is less than or equal to the permissible rate then:

$$SH2SRATE = H2S.LOAD / 453.6 * V.KWH.RATE / NETBE \quad (7E-30)$$

where:

<i>H2S.LOAD</i>	=	H <sub>2</sub> S emission load, gram/hr/MW
<i>V.KWH.RATE</i>	=	work rate across turbine, watt-hour/lb. brine
<i>NETBE</i>	=	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 3 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:

$$WCPW = BASE.WELL.COST + COST.EXTND + COST.REDRILL = \quad (7E-31)$$

well cost per well

where:

$$BASE.WELL.COST = \text{drilling cost} + \text{problems costs (all site data)} \quad (7E-32)$$

$$COST.EXTND = 0.75 * (0.8 - 0.25 * WDRY) * WCEXTEND \quad (7E-33)$$

where:

$$\begin{aligned} WDRY &= \text{fraction of wells that are dry (from site data)} \\ WCEXTEND &= \text{cost to extend one well (site data)} \\ \mathbf{COST.REDRILL} &= \mathbf{0.165 * WRED * WCBASE} \end{aligned} \tag{7E-34}$$

where:

$$\begin{aligned} WRED &= \text{redrilling incidence fraction (site data)} \\ WCBASE &= \text{drilling cost (site data)} \end{aligned}$$

The cost for slim diameter wells is:

$$\mathbf{SLIM.W.CPW} = 0.5 * (\text{drilling cost} + 0.6 * \text{lost circulation problem costs} + \text{miscellaneous problem costs (all from site data)}) \tag{7E-35}$$

### **Exploration Phase Cost (GESDPP)**

$$\mathbf{C.EXPL.TOTAL} = (\mathbf{UCOST1} + \mathbf{N.IDENT} * (\mathbf{UCOST2} + \mathbf{WC.WILD})) / \mathbf{UPROB.CONF} \tag{7E-36}$$

where:

$$\begin{aligned} UCOST1 &= \text{cost of geological and geophysical investigations} \\ N.IDENT &= \text{number of wild cat wells required to get one good one} \\ UCOST2 &= \text{cost of drilling shallow thermal gradient wells} \\ WC.WILD &= \text{cost of drilling a slim diameter well} \\ &= \mathbf{SLIM.W.CPW} + \mathbf{TEST.SL.EXPL} \end{aligned}$$

where:

$$\begin{aligned} \mathbf{SLIM.W.CPW} &= \text{(see Well Costs above)} \\ \mathbf{TEST.SL.EXPL} &= \text{cost to test a slim well} \\ \mathbf{UPROB.CONF} &= \text{probability of successful confirmation (site data)} \end{aligned}$$

### **Confirmation Phase Cost (GESDPP)**

The cost of unsuccessful wells during the confirmation period is:

$$SCCDHCONF = ((GOOD.INJS + DRY.COUNT) * WC.GENL) + C.PERMITS \quad (7E-37)$$

where:

$$\begin{aligned} GOOD.INJS &= \text{number of failed confirmation wells that can become} \\ & \text{injection wells} \\ &= 1.5 \end{aligned}$$

$$DRY.COUNT = \text{number of failed confirmation wells unsuitable for injection wells}$$

$$WC.GENL = WCPW + TEST.U.IJ \quad (7E-38)$$

where:

$$WCPW = \text{(see Drilling Cost above)}$$

$$TEST.U.IJ = \text{cost of logging and 3 day flow test}$$

$$C.PERMITS = \text{cost of obtaining drilling permits} = \$ 179,200$$

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

$$CONF.PROD = GOOD.PRODS * WC.CONF \quad (7E-39)$$

where:

$$GOOD.PRODS = \text{number of successful confirmation production wells} = 4$$

$$\begin{aligned} WC.CONF &= \text{cost per successful confirmation well} \\ &= WCPW + TEST.U.CONF \end{aligned} \quad (7E-40)$$

where:

$$WCPW = \text{(see Well Costs above)}$$

$$TEST.U.CONF = \text{cost of logging, 3 day flow test and 21 day flow test}$$

### **Construction Phase Cost (GESDPP)**

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

$$COST.INJ.WELLS = WC.GENL * (WIJN - GOOD.INJS) \quad (7E-41)$$

$$COST.PRO.WELLS = (WNUM + WSPR - GOOD.PRODS) * WC.PROD * (1 + WRED) \quad (7E-42)$$

$$COST.DRY.WELLS = WC.GENL * WPDRY \quad (7E-43)$$

where:

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

### **Well Pump Cost (GESDPP)**

The cost of downhole well pumps is:

$$DPTL = DPC * PNUM \quad (7E-44)$$

where:

<i>DPC</i>	=	deep pump cost, \$ million
<i>PNUM</i>	=	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:

$$CPROD GATH (\$ \text{ million}) = 1.120 * (50 * NFEET + 20,000 * WPRODSUM) / 1,000,000 \quad (7E-45)$$

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:

$$CINJ GATH (\$ \text{ million}) = 1.120 * COSTPER4 * WIJN / 4 + 0.020 * WIJN \quad (7E-46)$$

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:

$$WELL.O\&M = 0.506 + WNUM * V.PROD.REWORK + WIJN * V.INJ.REWORK \quad (7E-47)$$

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:

$$PUMP.O\&M = 0.0224 * WNUM \quad (7E-48)$$

where:

$WNUM$  = total number of production wells

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

$$GATHER.O\&M = 0.01 * BBB * SPTL \quad (7E-49)$$

where:

$$BBB = ZZB^2 - ZZB + 2 \quad (7E-50)$$

where:

$$\begin{aligned} ZZB &= 0 \text{ if } TDS < 10 \\ &= 1 \text{ if } TDS > 10 \\ &= 2 \text{ if } TDS > 100 \end{aligned}$$

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 injectate into the production stream. The cost of relocating poorly located injection wells is:

$$COOLED.CAP.COST = (WIJN * WC.GENL + CINJGATH)(PERCENT.INJ.FAILED/100) \quad (7E-51)$$

where:

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