

**EIA Model Documentation**

**NEMS Integrating Module**

**Documentation Report**

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May 1997

Office of Integrated Analysis and Forecasting  
Energy Information Administration  
U.S. Department of Energy  
Washington, DC 20585

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# **NEMS Integrating Module Documentation Report**

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# 1. Introduction

The National Energy Modeling System (NEMS) is a computer-based, energy-economy modeling system of U.S. energy markets for the midterm period. NEMS projects the production, imports, conversion, consumption, and prices of energy, subject to a variety of assumptions. The assumptions encompass macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, technology characteristics, and demographics. NEMS produces a general equilibrium solution for energy supply and demand in the U.S. energy markets on an annual basis through 2015.

Baseline forecasts from NEMS are published in the *Annual Energy Outlook*. Analyses are also prepared in response to requests by the U.S. Congress, the DOE Office of Policy, and others. NEMS was first used for forecasts presented in the *Annual Energy Outlook 1994*.

## Scope and Organization

Publication of this document is supported by Public Law 93-275, Federal Energy Administration Act of 1974, Section 57(B)(1) (as amended by Public Law 94-385, Energy Conservation and Production Act), which states in part

*...that adequate documentation for all statistical and forecast reports prepared...is made available to the public at the time of publication of such reports.*

In particular, this report is designed to meet EIA's model documentation standards established in accordance with these laws.

For documentation purposes, the individual components of NEMS are considered distinct models and documented individually. While the NEMS integrating module is a distinct component of NEMS, the integrating module is not by itself, a model. Rather, it is a component of the overall NEMS model and implements specific aspects of the overall modeling methodology that are not documented elsewhere. The documentation is organized accordingly.

Because the Integrating Module controls the solution process for all of NEMS, the second chapter summarizes NEMS as a whole, including some of the design considerations for the system. Chapter 3 briefly describes the individual component modules of NEMS. Readers interested in a more comprehensive summary of NEMS should see *The National Energy Model System: An Overview*, DOE/EIA-0581(96), March, 1996.

Chapter 4 describes the NEMS global data structure, used for inter-module communication, solution initialization and storage, and certain database operations.

Chapter 5, Integrating Module Solution Methodology, provides the mathematical specification for the solution algorithm and describes the convergence techniques used. Chapter 5 also documents other modeling functions of the integrating Module, include generation of foresight assumptions and carbon emission policy routines.

A bibliography is contained in Appendix A, and the model abstract is in Appendix B.

### **Model Archival Citation**

This documentation refers to the NEMS Integrating Module as archived for the *Annual Energy Outlook 1997*.

## **2. Overview of the Structure of NEMS**

NEMS is structured as a modular system. The modules include the Integrating Module and a series of relatively independent analytical modules that represent the domestic energy system, the international energy market, and the economy. The domestic energy system is decomposed into fuel supply markets, conversion activities, and end-use consumption sectors.

NEMS is a model of domestic energy markets. As such, the decisions to produce, convert, or consume energy products are presumed to serve the economic self-interest of those making the decisions. Many NEMS modules explicitly reproduce the economic decisionmaking involved in the portion of the energy system being modeled. In order to represent these decisions, NEMS is constructed in a reasonably fine detail of energy product categories and the regional locations of the sites of energy production and use. This detail is necessary since the economics of allocating energy products is strongly influenced by the product category at issue and regional differences in costs and other factors. Table 1 provides a summary of NEMS product and regional detail.

Table 1. Summary of NEMS Modeling Detail

| Energy System Activity                    | Categories  | Regions   |
|---|---|---|
| <b>Primary Supply</b>                     |   |   |
| Oil                                       | Conventional<br>Enhanced  | Six lower 48 onshore regions<br>Three lower 48 offshore regions<br>Three Alaska regions                             |
| Natural Gas                               | Conventional shallow<br>Conventional deep<br>Coalbed methane<br>Devonian shale<br>Tight sands                       | Six lower 48 onshore<br>Three lower 48 offshore<br>Three Alaska   |
| Natural Gas Transmission and Distribution | Firm vs. interruptible vs. competitive<br>Peak vs. offpeak  | Twelve regions<br>Nine pipeline border points<br>Five liquefied natural gas terminals                               |
| Coal                                      | Seven rank/compliance categories<br>Underground and surface mining types  | Eleven supply regions<br>Thirteen demand regions<br>Sixteen export regions<br>Twenty import regions                 |
| Renewables                                | Hydroelectric, wind-electric, geothermal-electric, solar-electric, municipal solid waste, ethanol, biomass-electric | Fifteen electricity supply regions<br>Five Petroleum Administration for Defense Districts,<br>Nine Census divisions |
| <b>Conversion</b>                         |   |   |
| Electricity                               | Utilities<br>Independent and small power producers  | Fifteen electricity supply regions<br>Nine Census divisions for demand  |
| Refining                                  | Five crude oil categories<br>Seven product categories   | Five Petroleum Administration for Defense Districts   |
| <b>Energy Demand</b>                      |   |   |
| Residential                               | Nine end-use services<br>Three housing types  | Nine census divisions   |
| Commercial                                | Ten end-use services<br>eleven building types   | Nine census divisions   |
| Transportation                            | Six car size categories<br>Six truck sizes<br>Ten vintages  | Nine census divisions   |
| Industrial                                | Fifteen industries groups<br>Cogeneration   | Four Census regions, shared to nine Census divisions  |



## Regional Detail

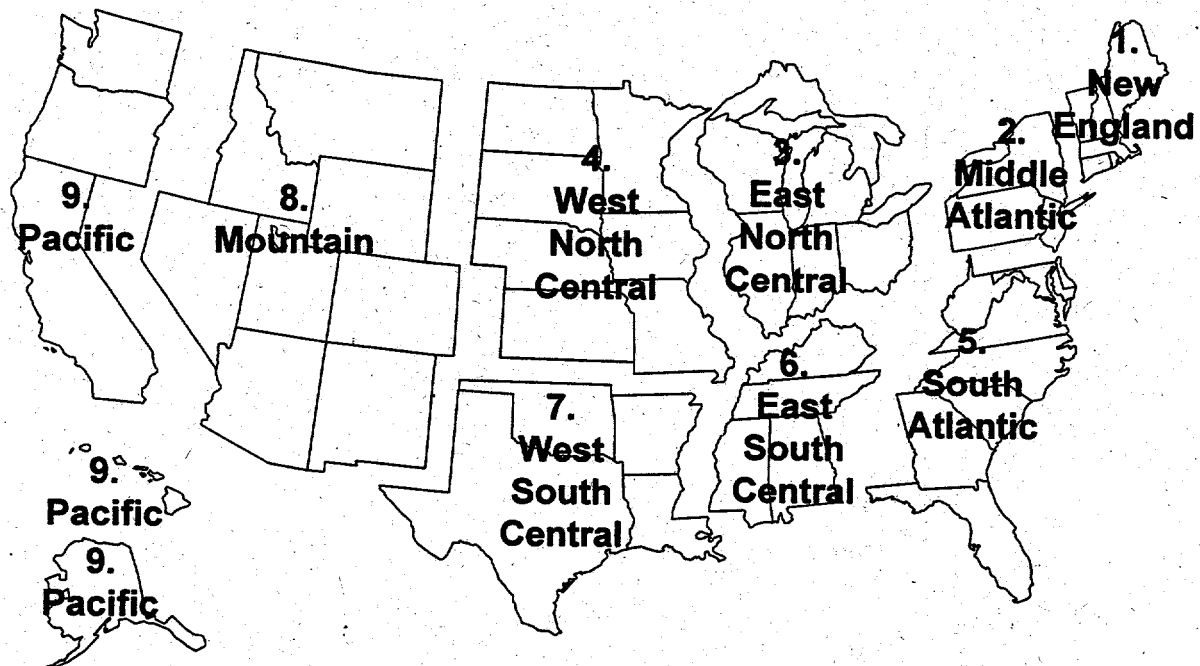
The Integrating Module of NEMS processes energy consumption and price information aggregated primarily at the Census division levels. The nine Census divisions are depicted in **Figure 1**. In addition, the integrating module processes some intermodule energy market data at regional levels tied to electricity supply regions. These alternative regional breakouts provide specific market feedbacks for consumption and prices of fuel used for electricity generation. While the NEMS modules use different regional structures as appropriate for their market segments, they aggregate (or disaggregate) their solutions to the Census Division structure for processing by the Integrating Module and by the reporting programs. Details of the conversion processes embedded in the modules are given in the individual *Model Documentation Reports* (see Appendix A, bibliography).

## Time Horizon

The horizon for the midterm model is 2015, covering that time period in which the structure of the economy, the nature of energy markets, and regional demographics are sufficiently well understood in structural and regional detail. The majority of policies proposed today can be expected to have their greatest impacts during the midterm years.

Rather than trying to attain some planned state of energy markets, NEMS attempts to simulate where the present state of energy markets and planned policies would take us. Therefore it solves forward in time year-by-year.

Figure 1. Census Divisions

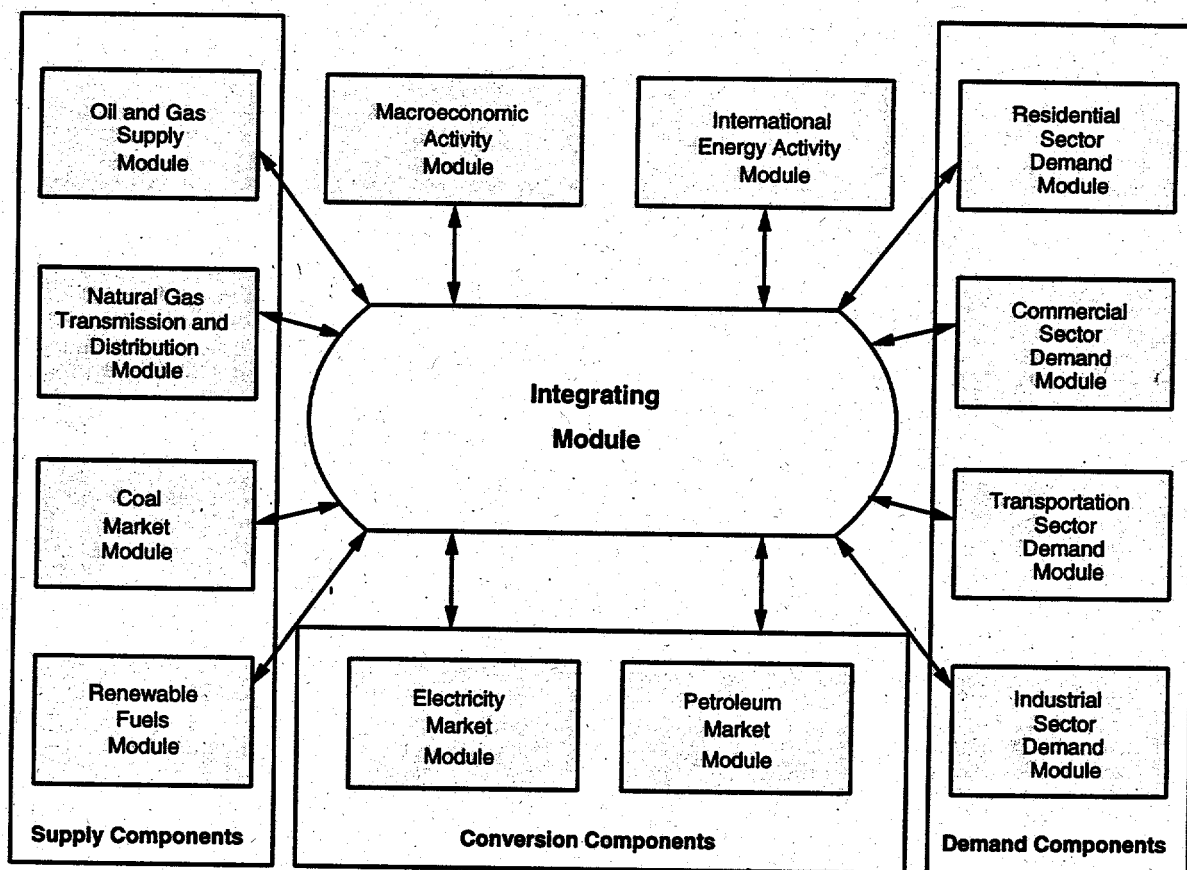


## **Major Assumptions**

Each module within NEMS embodies the many assumptions necessary to characterize the future production, conversion, and consumption of energy products in the U.S. NEMS' Integrating Module assumes that the individual modules can be integrated to provide a convergent process for the system as a whole. It makes use of the Gauss-Seidel algorithm for blocked non-linear simultaneous equations, interpreted for the characteristics of the national energy marketplace simulated here. Chapter 4 describes this approach in detail.

The NEMS algorithm and modeling approach worked successfully in the predecessor IFFS modeling system. Although the models differ, NEMS has not added obstacles to finding solutions and has retained the older model's overall structure. Experience has shown that this approach occasionally has difficulty converging on a final solution, due to two broad classes of discontinuities in the component modules: the linear programming solution methods used by some modules jump from one vertex to another of their polygonal solution space; and other modules use tabulated functions evaluated either as step functions or by linear interpolation. These issues are handled in NEMS by ensuring that the spacings between the modules' steps are reasonably small. Convergence issues are discussed in more detail in Chapter 5.

Figure 2. Basic NEMS Structure



## NEMS Modular Structure

As shown in **Figure 2**, NEMS consists of four supply modules (oil and gas, natural gas transmission and distribution, coal, and renewable fuels), two conversion modules (electricity and petroleum refineries), four demand modules (residential, commercial, transportation and industrial sectors), one module to simulate energy/economy interactions (macroeconomic activity), one to simulate world energy/domestic energy interactions (international energy activity), and one module to provide the mechanism that achieves a general market equilibrium among all the modules (the Integrating Module). The last of these is the focus of this document. **Figure 2** depicts the high level of modularity of NEMS.

## ***Modularity***

Model modularity implies a system of self-contained units, each performing a specific, well-defined function. This concept is generally consistent with the economic structure of energy markets, which can be represented by various supply, conversion, and demand components that are largely separable. Due to the heterogenous nature of energy markets, a single methodology cannot adequately represent all fuel supply, energy conversion, and end-use demand sectors. Modularity allows the flexibility to use the methodology and coverage that is most appropriate for each module. Furthermore, modularity provides the capability to execute the modules individually or to easily substitute alternative modules to represent a specific function, so long as the required interfaces are satisfied. The interactions among these modules are controlled by the integrating mechanism.

Table 2. NEMS Module Information Flows

| Module   | Inputs from Other NEMS Modules  | Inputs from Exogenous Sources  | Important Outputs  |
|--|---|--|--|
| <b>Oil and Gas Supply</b>                        | Oil and gas production by fuel type<br>Oil, gas, and electricity prices<br>Synthetic gas production<br>Canadian natural gas imports and production  | Resource levels<br>Initial finding rate parameters and costs<br>Production profiles<br>Tax parameters<br>Import capacity   | Domestic and Canadian supply curve parameters<br>Oil and gas financial data<br>Pipeline gas and liquefied natural gas imports (excluding Canada) and exports<br>Cogeneration from oil and gas production<br>Reserves and reserve additions<br>Annual drilling levels   |
| <b>Natural Gas Transmission and Distribution</b> | End-use natural gas demands<br>Natural gas domestic and Canadian supply parameters<br>Natural gas Mexican and LNG import parameters<br>Macroeconomic variables<br>Associated-dissolved natural gas production   | Historical consumption patterns<br>Historical flow patterns<br>Rate design specifications<br>Company-level financial data<br>Pipeline and storage capacity, utilization, and expansion cost data<br>Historical end-use prices<br>State and Federal tax parameters                                  | End-Use natural gas prices<br>Natural gas wellhead prices<br>Natural gas border crossing prices<br>Domestic natural gas production<br>Canadian natural gas imports and production<br>Lease and plant fuel consumption<br>Pipeline fuel use<br>Pipeline and distribution tariffs<br>Interregional natural gas flows<br>Investment for facilities expansion<br>Storage and pipeline capacity expansion |
| <b>Petroleum Market</b>                          | Petroleum product demand by sector<br>Domestic crude oil supply curves<br>World oil price<br>International crude oil supply curves<br>International product supply curves<br>International oxygenates supply curves<br>Ethanol supply curves<br>Natural gas and electricity prices<br>Natural gas production<br>Macroeconomic variables | Processing unit operating parameters<br>Processing unit capacities<br>Product specifications<br>Operating costs<br>Capital costs<br>Transmission and distribution costs<br>Federal and State taxes<br>Cogeneration unit capacity and operating parameters  | Petroleum product prices<br>Crude oil imports and exports<br>Crude oil production<br>Petroleum product imports and exports<br>Refinery activity and fuel use<br>Cogeneration<br>Natural gas plant liquids production<br>Processing gain<br>Capacity additions<br>Capital expenditures<br>Revenues  |
| <b>Coal Market</b>                               | Coal demand by sector<br>Interest rates<br>Price deflators<br>Diesel fuel prices  | Base year production<br>Contract quantities<br>Labor productivity<br>Labor costs<br>Transportation costs<br>Coal production capacity<br>International transportation costs<br>International supply curves<br>Labor cost escalators<br>Demand for U.S. coal exports<br>Demand for U.S. coal imports | Coal production and distribution<br>Minemouth coal prices<br>End-use coal prices<br>Coal exports<br>Transportation rates<br>Coal quality by source, destination, and end-use sector  |
| <b>Renewable Fuels</b>                           | Installed energy production capacity<br>Gross domestic product<br>Interest rates<br>Avoided cost of electricity   | Site-specific geothermal resource quality data<br>Agricultural feedstock data (biofuels submodule)<br>Site-specific wind resource quality data<br>Plant utilization (capacity factor)<br>Technology cost and performance parameters<br>Landfill gas capacity                                       | Energy production capacities<br>Capital costs<br>Operating costs (including wood supply prices for the wood submodule)<br>Ethanol supply curves<br>Capacity factors for solar-thermal, solar-photovoltaic, and wind-electric   |

Table 2. NEMS Module Information Flows (Continued)

| Module                               | Inputs from Other NEMS Modules   | Inputs from Exogenous Sources   | Important Outputs   |
|--------------------------------------|--|---|---|
| <b>Electricity Market</b>            | Electricity sales<br>Fuel prices<br>Cogeneration supply<br>Renewable technology characteristics and capacity<br>Renewable capacity factors<br>Gross domestic product<br>Interest rates | General financial data<br>Tax assumptions<br>Capital costs<br>Operation and maintenance costs<br>Operating parameters<br>Emissions rates<br>New technologies<br>Existing facilities<br>Transmission constraints   | Electricity prices and price components<br>Fuel demands<br>Capital requirements<br>Emissions  |
| <b>Residential</b>                   | Energy product prices<br>Housing starts<br>Population  | Current housing stocks, retirement rates<br>Current appliance stocks, life expectancy<br>New appliance types, efficiencies, costs<br>Housing shell retrofit indices, square footage<br>Unit energy consumptions<br>Square footage   | Energy product demand<br>Changes in housing and appliance stocks  |
| <b>Commercial</b>                    | Energy product prices<br>Interest rates<br>Floorspace additions  | Existing commercial floorspace<br>Floorspace survival rates<br>Appliance stocks and survival rates<br>New appliance types, efficiencies, costs<br>Energy use intensities  | Energy product demands<br>Changes in floorspace and appliance stocks  |
| <b>Industrial</b>                    | Energy product prices<br>Economic output by industry<br>Refinery fuel consumption<br>Cogeneration from refineries and oil and gas production   | Production stages in energy-intensive industries<br>Technology possibility curves<br>Unit energy consumption<br>Stock retirement rates  | Energy product demand<br>Electricity sales to the grid<br>Cogeneration output and fuel consumption  |
| <b>Transportation</b>                | Energy product prices<br>Gross domestic product<br>Disposable personal income<br>Industrial output<br>New car and light truck sales<br>International trade                             | Current and projected demographics<br>Existing vehicle stocks by vintage and fuel economy<br>Vehicle survival rates<br>New vehicle technologies and efficiencies, relative to conventional vehicles<br>Vehicle prices, fuel availability, and commercial availability<br>Vehicle safety and emissions regulations<br>Vehicle miles-per-gallon degradation rates | Fuel demand by mode<br>Sales, stocks and characteristics of vehicle types by size class<br>Vehicle-miles traveled<br>Fuel efficiencies by technology type<br>Alternative-fuel vehicle sales by technology type<br>Light-duty commercial fleet vehicle characteristics |
| <b>International Energy Activity</b> | U.S. Crude oil production and demand<br>U.S. product imports and exports   | OPEC Production Path<br>Reference non-U.S. oil supply and Demand<br>Product and oxygenate supply curves   | World oil price<br>Crude oil import supply<br>Product import supply curve<br>Methyl tertiary butyl ether and methanol supply<br>Other oxygenate prices  |
| <b>Macroeconomic Activity</b>        | Wholesale and retail prices for electricity<br>Wholesale and retail prices and production rates for oil, gas and coal<br>Level of oil refinery output<br>Investment                    | Macroeconomic growth cases  | Gross domestic product<br>Other economic activity measures<br>Price indices and deflators<br>Production rates for manufacturing<br>Production rates for nonmanufacturing<br>Interest rates  |

### *Coordination of Modules and Data*

Required linkages among modules are passed through common interfaces via the Integrating Module. The primary data flows among the major modules are the delivered prices of energy and

the quantities consumed by product, region, and sector. As shown in **Table 3**, the information flows are not limited to prices and quantities, but include other information such as economic activity, capital expenditures, and load curves. The delivered prices for a fuel include the costs of all the activities necessary to produce, import, and transport the fuel to the end user.

The NEMS user can modify input values and key assumptions for the modules through the user interface, thus facilitating analyses using individual modules. For example, the Electricity Market Module normally receives delivered prices of fuels from the fuel supply modules; however the user can specify those prices externally to allow greater flexibility in using individual modules of the system.

### ***Data Structure***

The concept of the NEMS Global Data Structure is central to the modular structure. The NEMS Global Data Structure is defined as the set of data communicated among any of the thirteen NEMS modules. The Global Data Structure includes the energy market prices and consumption, macroeconomic variables, energy production, transportation, and conversion information, as well as centralized model control variables, parameters, and assumptions. The Global Data Structure excludes variables that are defined locally within modules and not communicated to other modules.

An important subset of the Global Data Structure is the Energy Market Data, the energy market end-use-sector prices and quantities of fuels used for equilibration and the NEMS energy balance. The Energy Market Data are the principal variables used directly by the Integrating Module in its convergence algorithm. Additional macroeconomic and international trade variables are tested for convergence as well in the solution algorithm.

### **Alternative Approaches**

This section on alternative approaches to the integrating methodology for NEMS provides background on the research that preceded the overall system design. The discussion of methodologies is limited to those with which EIA has some familiarity and is intended to focus on the fundamental principles of the design rather than on the specifics of individual fuel or sector methodologies. This topic was also considered by the National Research Council Committee on NEMS.

Two primary requirements form the basis for discussion of the integrating framework of NEMS. First, NEMS is a tool for performing market-based integrated energy market analysis, but on a sector- and fuel-specific basis. Second, the NEMS design allows a high degree of modularity. The first goal implies that NEMS should be able to balance the supply of and demand for energy, taking into account the economic competition among energy sources. Economic principles for energy supply, consumption, and competition are the foundation of most EIA analysis. Although valuable insights can be derived from the analysis of a narrow sector-specific option, very often the policy discussions center on broad energy market impacts, such as energy security or economic impacts.

This is not to imply that all analyses need be done in an integrated framework, but rather that the capability should be in place.

A fixed-shares approach to fuel competition or a system in which the energy sectors do not balance would add little information to the policy debates. A market-based approach, in which supplies and demands for energy respond to the costs and prices of energy, predominates as the underlying principle of the required energy policy analysis. Thus, NEMS must provide a framework in which the market-clearing prices and quantities of energy supply and demand can be derived, subject to other factors, such as regulatory and legislative conditions.

The second goal for NEMS development that directly affects the design of the integrating methodology is the requirement for modularity. Model modularity implies that the modules of NEMS that represent the various supply, conversion, and consumption components are separable in both their methodology and their implementation. Functionally, modularity allows the component modules to be tested and developed without running the entire system, which is necessarily faster, and allows problems to be isolated to particular sectors. In addition, individual fuel or sector studies can be conducted with all other components held constant. Finally, modularity readily allows for the inclusion of alternative modules that meet minimum interface requirements. This desired modularity or segmentation of the modeling system leads to the necessity for a methodology by which the various modules can interact—the integrating methodology. A discussion of various approaches used in earlier models follows.

## ***Approaches to an Integrating Methodology***

### ***Project Independence Evaluation System***

The Project Independence Evaluation System (PIES), later named the Midterm Energy Forecasting System (MEFS), is one example of a large-scale integrated energy modeling system. It was developed in 1974 by the Federal Energy Administration, a predecessor organization to the EIA. The core model of PIES/MEFS was a single linear program of fuel supply, transportation, conversion, and fixed demand activities, which optimized by solving for the least-cost combination of supply and transportation of fuel to meet end-use demand.

PIES/MEFS solved for a supply/demand equilibrium in one future period by iterating between the linear program and a reduced-form representation of demand models. After the linear program optimized the supply/conversion problem, the marginal, or shadow, prices for each fuel delivered to the end-users were taken from the linear program. The reduced-form demand models were evaluated at these marginal prices, giving revised demands for fuels that were entered into the linear program, which was then re-solved. This process of iterating between the linear program and demand models continued until the marginal prices and end-use demands between subsequent iterations were close within a convergence tolerance. Over the years, many special features were added to PIES/MEFS to reflect regulatory policies or to ensure that certain end-use prices from the linear program were average or regulated prices, rather than strict marginal prices. These features were



incorporated in either the linear program or in the program that controlled the equilibration and determined convergence.

As a modeling system, PIES/MEFS encompassed a host of satellite models—coal, oil, natural gas, synthetic fuels, refinery, electric utility, end-use demand, and macroeconomic. Each of these satellite models produced the necessary coefficients and objective function costs for the linear program and incorporated sector-specific features as required. This limited modular structure served to organize the data and allocate responsibilities for the modeling activities; however, there were several significant problems with PIES/MEFS as an integrating methodology.

First, the structure of the system required the entire linear program to be executed together without any means of decomposing the model. This was a serious problem in a testing and debugging mode since PIES/MEFS required several hours to execute, and the simplest changes could only be tested through an entire run of the model. The satellite models and preprocessor programs produced data for the linear program, but did not produce results that could be readily used for analysis or testing of the individual sector. Yet another difficulty with PIES/MEFS was the overarching optimization methodology, which was not suitable for all portions of all the supply sectors. Several special features were incorporated into the system to appropriately represent some regulatory or institutional features of various sectors; however, this became increasingly burdensome.

### *Intermediate Future Forecasting System*

The immediate predecessor to NEMS was the Intermediate Future Forecasting System (IFFS), an annual model that forecasted to a specified time horizon, the maximum finally set at 2010. IFFS partitioned the energy system into fuel supply, conversion, and end-use demand sectors, then solved for a supply/demand equilibrium by successively and repeatedly invoking these modules. This equilibration was performed one forecast year at a time, stepping forward to the next forecast year when the equilibrium for one year was complete.

The fuel supply modules in IFFS encompassed all the activities necessary to produce, import, and transport the fuel to the end user, thus computing the domestic production and the regional end-use prices necessary to meet end-use demand. Each of the end-use demand modules computed fuel requirements for the sector by region, based upon the regional end-use prices of all competing fuels, and other factors. The electricity module, as a conversion module, consumed fuel based on relative prices and then generated and priced electricity. The refinery module was also viewed as a conversion module, except that it used only a single primary input, crude oil, whose price was invariant, and its fuel use was represented in the industrial demand module with no direct linkage to refinery activity.

Within the IFFS framework, the primary interfaces among the modules were the regional end-use prices and demands for each fuel, although other information was passed among modules. Each fuel supply or end-use sector demand module was called in sequence, and each module solved assuming all other variables in the energy markets were held constant. That is, the coal module solved for the production and end-use prices of coal, assuming a slate of demands for coal and assuming that all other sectors were fixed. Any module that used the coal prices would then use these new prices to

compute demand the next time the module was executed. This process was equivalent to a Gauss-Seidel algorithm for solving a set of simultaneous equations.

The equilibration module of IFFS called the various modules in sequence and checked for convergence of the system by computing percentage differences between iterations for all end-use prices and demands in each region. When differences were within the user-specified tolerance, convergence was declared and the equilibrating module began solving the next forecast year. Some attempt was made in IFFS to speed convergence by using characteristics of particular modules. For example, the sensitivity of the natural gas price to the level of demand, and the concomitant sensitivity of gas demand in certain sectors to the price, was well recognized. To handle this, the electricity module computed a derived demand curve for natural gas, explicitly representing the demand for gas at a variety of prices, for both the electricity and gas modules to deal more effectively with convergence. This demand curve was part of the information passed from the electricity module to the gas module.

Due to the partitioning of the energy markets and the specific implementation of the modules and integrating methodology in IFFS, any subset of the modules could be executed, or any module that met a minimum interface requirement could be substituted. A key feature that was necessary to achieve the modularization was the means by which the modules passed information to each other. Within IFFS, none of the modules passed information directly to another module, but rather through a central data storage file. If a particular module was not included in a particular run of the system, the information it normally provided was located in the central data file. Thus, any other module could read that information and was oblivious to whether the module was included.

The modular nature of IFFS allowed for single-fuel studies, if desired. Such studies were conducted on the electricity and natural gas sectors. However, it was not easy to execute, for example, the electricity model with a specified demand or with fuel prices that were different from another instance of the model execution. These functions required explicit programming by someone familiar with IFFS, or adjusted assumptions in other modules to produce the desired input.

In addition, the modular nature of IFFS readily allowed each sector of the energy market to be represented with the methodology deemed most suitable to that sector, allowing for a more natural representation of each market. IFFS contained a mix of simulation, process, econometric, and optimization methods within the various sectors. It also allowed each module to vary the depth and breadth of its coverage of the sector. For example, the coal supply module of IFFS represented 32 coal production regions and a detailed transportation network delivering the coal to the end-use demand regions. By contrast, the petroleum product module computed the refinery gate prices of products at the national level and used regional, sectoral markups to derive end-use prices without an explicit transportation component.

The flexibility of IFFS came at some cost, however. A linear program, for example, is a highly structured approach to modeling. There is an ever-increasing set of software available to generate, debug, analyze, and report linear programs. In a less structured system with more diverse methodologies, many of these features are not available or must be programmed into individual modules.

The basic IFFS methodology was also employed in the PC-AEO, a simplified spreadsheet representation of the modeling system used by EIA for three years. PC-AEO decomposed the energy system into the same supply, conversion, and demand modules, representing each module in a separate spreadsheet. The interface variables among the modules upon which the system iterated were also the end-use prices and quantities by fuel. For easier file handling, each module of PC-AEO solved all years in the forecast horizon each time it was invoked. Thus, the order of looping over modules and forecast years was reversed from IFFS.

### ***Long-term Energy Analysis Package***

For three years, EIA used the Long-term Energy Analysis Package (LEAP) for long-range forecasting. LEAP was EIA's configuration of the Generalized Equilibrium Modeling System (GEMS), originally developed by the Stanford Research Institute and now with Decision Focus, Inc. Many organizations use GEMS, configured to suit their particular purposes.

LEAP segments the energy system by separating all supply, transportation, conversion, and end-use processes. Each of these activities is defined as a node, and a network describing the flows of all information between nodes must be explicitly drawn. Each regional activity, such as coal supply by region, would also be a separate node. At all decision points in the system, there are allocation nodes. Several examples of such allocations are:

- The coal transportation network might contain a centroid in the upper Great Plains that can be served by several production regions. An allocation node at that centroid determines how much production comes from each region.
- The decisions on how much natural gas goes to each of the gas technologies in the electricity generation sector or in any end-use sector would be allocation nodes.
- The amount of each competing technology used to satisfy residential heating needs would be an allocation node.
- The entrance of Alaskan North Slope gas into the supply system would be an allocation node.

Each allocation node is a market share algorithm that uses market share coefficients, price premium, behavioral lag coefficients, and initial year market shares. These data, though fundamental to the solution, are very difficult to derive empirically for each node in the system.

LEAP solved for a supply/demand equilibrium in a way fundamentally similar to IFFS, with prices and quantities of the various types of energy being computed by modules that represented production, raw material transportation, conversion, final product transportation, and end-use energy consumption. As a representation of the overall system, the order of solution was directional, prices flowing from supply to end-use demand and quantities flowing in reverse. Thus, it solved for an equilibrium by iteratively computing the network flows.

Like PC-AEO and unlike IFFS, each module of LEAP/GEMS solved for all forecast years at a time, coming to an equilibrium for all years simultaneously.

One feature of the GEMS system is a library of generic models, from which one can choose in building a representation of the energy system. These generic models include a simple and a complex conversion process, an allocation process, a primary resource process, an end-use demand process, and a transportation process. In building a model using GEMS, a user draws the network by selecting a generic model for each node, defining all the input and output links to other nodes, and specifying all necessary data. It is the data specification and the flows that distinguish, for example, a node representing the industrial sector demand for electricity for machine drive from a node for residential natural gas space heating demand. The value of the generic models depends on the view of the model builder. If the model builders think, for example, that the coal transportation system and the natural gas transportation system differ in their physical or economic characteristics, then a generic model cannot be used for both and separate models must be developed. One model builder might require only a simple energy market representation and therefore be comfortable with the generic models. Someone interested in more sophisticated representations of the different energy sectors for specific issues might be less comfortable with the generic model concept. As the model builder moves away from the generic model concept, the value of the GEMS system and its data structure diminishes.

A potential difficulty in using the GEMS-type approach is the application of methodologies that encompass several nodes. A model builder using GEMS would represent oil and gas production by a separate node for each region and each technology type, differentiated by oil and gas. This was done in LEAP, which made the model large and cumbersome. However, if EIA wished to incorporate a methodology such as an oil and gas industry-wide cash flow or other activity, this would become difficult. EIA has tended to take a wider market view of the various sectors, for example, representing coal supply and transportation in a unified way or natural gas production and transportation. GEMS could incorporate these market views if the model builder programmed larger, more specialized nodes, encompassing a larger number of individual activities, but diminishing the value of the generic module library.

### ***Optimization Methodologies***

Optimization models are often appropriate for simulating the behavior of a homogeneous industry or sector of the economy that typically has a single objective function. For example, the electric industry's plant dispatching decisions or the movements in the coal transportation sector can be represented appropriately as an optimization model. In such models, the objective is typically a cost minimization.

Optimization approaches can also be used to solve a market equilibrium problem for a competitive market. The mathematical equivalence between the competitive solution and the cost minimizing solution allows the use of optimization techniques to solve for the market equilibrium. For a competitive model, an equivalent supply side optimization problem is to provide customers with prespecified quantities of end-use fuels at minimum cost. Such a model ignores the fact that real-world markets are always suboptimal, as they are constantly in the process of optimizing to

constantly changing conditions. The integrating framework of the PIES model mentioned earlier was structured as an optimization problem.

While optimization methods could be used to determine a generalized market clearing solution, such an approach might prove too difficult or inflexible to apply to the complex U.S. energy economy. As discussed above, the experience with the PIES model cautions against using an overarching optimization approach as an integrating framework for NEMS. Model implementation and management are relatively difficult, as is the simulation of a diverse group of industries with a single modeling approach. A preferred approach combines a flexible integrating framework with a solution algorithm that yields equilibrium energy market forecasts.

### ***Other Methodologies***

All the above methodologies inherently assume a complex representation of the feedbacks and interrelationships of the energy system, as well as an ability to represent a system that evolves over time. Other methodologies that do not incorporate such features are possible.

EIA's *Short-Term Energy Outlook* is a 2-year, quarterly forecast of national energy supply and demand, produced using the Short-Term Integrated Forecasting System (STIFS). Given assumed crude oil and natural gas wellhead prices, STIFS computes delivered energy prices and the consumption of energy based upon relative prices and recent trends. Domestic crude oil and coal production are both projected based on the fuel prices. It achieves an energy balance using a simultaneous non-linear equations approach that adjusts production and import trends and stock levels, with limited feedback of energy prices and consumption on production. Being a short-term system, STIFS does not account for capital stock changes and investment decisions.

STIFS performs credibly for its intended purpose of providing short-term, non-equilibrium forecasts, although its limited structural representation and the lack of certain feedback effects restrict the types of scenarios it can address. In general, the STIFS integrating methodology, which does not allow for equilibration or market transition, would not be appropriate for a longer-term modeling system.

### ***Conclusions on Design Considerations***

Because of these considerations, NEMS adopted a system design and solution algorithm similar to that of the Intermediate Future Forecasting System (IFFS). The key features of this design are:

- The energy system is decomposed into fuel supply markets, conversion activities, and end-use consumption sectors, with explicitly defined flows among the components. The primary information flows among these major components are the delivered prices of energy and the quantities consumed by product, region, and sector. Other information such as economic activity, capital expenditures, and load curves is passed among the modules as well.

- To allow operational independence, the components do not pass information to each other directly but communicate through a global database structure.
- Solution is achieved by equilibrating on the delivered prices of energy and quantities demanded, which assures an economic equilibrium of supply and demand in each of the consuming sectors.
- Equilibration is achieved annually at least through the midterm.

Enhancements or improvements to the IFFS approaches implemented in NEMS are as follows:

- The convergence algorithm allows the use of relaxation techniques to ensure that the system achieves convergence as rapidly as possible.
- The integrating framework accounts for global system values, such as emissions and other toxics, capital requirements, and foreign trade, to allow for the representation of feedback effects of such values on the energy system.
- The structure of the integrating framework and data storage incorporate alternative assumptions about decision makers' foresight in the system.

### 3. Summary of the NEMS Component Modules

This chapter summarizes the components of NEMS, referred to as modules. For a more detailed description of the NEMS modules, the reader is referred to *The National Energy Modeling System--An Overview*, DOE/EIA-0581(96) and to the documentation reports for the individual NEMS modules, listed in the bibliography (Appendix A.)

The inputs for and outputs from the following modules are summarized in **Table 3** (previous chapter).

#### Integrating Module

**Figure 2** (previous chapter) depicts the relationship of the Integrating Module of NEMS with each of the component modules. The NEMS integrating module controls the NEMS solution process as it iterates to determine a general market equilibrium across all the NEMS modules.

The integrating module executes the system of modules iteratively until it achieves an economic equilibrium of supply and demand in all the consuming and producing sectors. Each module is called in sequence and solved, assuming that all other variables in the energy markets are fixed. The procedure continues until the specified convergence variables remain constant within a specified tolerance--a condition defined as convergence. Equilibration is achieved annually through the midterm period through 2015 for each of the nine Census divisions.

Any single module or subset of modules can be executed independently. Modules not executed are bypassed in the calling sequence, and the values they would calculate and provide to the other modules are held fixed at the values in the Global Data Structure, which would be the solution values from a previous run of NEMS.

The integrating module also includes an emissions policy module to calculate carbon emissions from energy use, and optionally, to impose carbon limits or emission fees on energy prices for potential policy analyses.

#### Macroeconomic Activity Module

The Macroeconomic Activity Module provides a set of essential macroeconomic drivers to the energy modules, macroeconomic feedback mechanism within NEMS, and a mechanism to evaluate detailed macroeconomic and interindustry impacts associated with energy events. Key macroeconomic variables include Gross Domestic Product (GDP), interest rates, disposable income, and employment. Industrial drivers are calculated for 35 industrial sectors. This module is a response surface representation of the Data Resources, Inc., Quarterly Model of the U.S. Economy.

## **International Module**

The International Module represents the world oil markets, calculating the average world oil price and computing supply curves for 5 categories of imported crude oil for the Petroleum Market Module of NEMS, in response to changes in U.S. import requirements. International petroleum product supply curves, including curves for oxygenates, are also calculated.

## **Household Expenditures Module**

The Household Expenditures Module provides estimates of average household direct expenditures for energy used in the home and in private motor vehicle transportation. The forecasts of expenditures reflect the projections from NEMS for the residential and transportation sectors. The projected household energy expenditures incorporate the changes in residential energy prices and motor gasoline price determined in NEMS, as well as the changes in the efficiency of energy use for residential end-uses and in light-duty vehicle fuel efficiency. Average expenditures estimates are provided for households by income group and Census division.

The Household Expenditures Module, unlike the other NEMS modules, does not execute within the overall solution algorithm and does not provide any outputs used by other NEMS modules. Instead, it is run after the NEMS has solved and at five-year intervals.

## **Residential and Commercial Demand Modules**

The Residential Demand Module forecasts consumption of residential sector energy by housing type and end use, subject to delivered energy prices, availability of renewable sources of energy, and housing starts. The Commercial Demand Module forecasts consumption of commercial sector energy by building types and nonbuilding uses of energy and by category of end use, subject to delivered prices of energy, availability of renewable sources of energy, and macroeconomic variables representing interest rates and floorspace construction. Both modules estimate the equipment stock for the major end-use services, incorporating assessments of advanced technologies, including representations of renewable energy technologies and effects of both building shell and appliance standards.

## **Industrial Demand Module**

The Industrial Demand Module forecasts the consumption of energy for heat and power and for feedstocks and raw materials in each of 16 industry groups, subject to the delivered prices of energy and macroeconomic variables representing employment and the value of output for each industry. The industries are classified into three groups—energy-intensive, non-energy-intensive, and nonmanufacturing. Of the 8 energy-intensive industries, 7 are modeled in the Industrial Demand Module with components for boiler/steam/cogeneration, buildings, and process/assembly use of



energy. A representation of cogeneration and a recycling component are also included. The use of energy for petroleum refining is modeled in the Petroleum Market Module, and the projected consumption is included in the industrial totals.

### **Transportation Demand Module**

The Transportation Demand Module forecasts consumption of transportation sector fuels, including petroleum products, electricity, methanol, ethanol, and compressed natural gas by transportation mode, vehicle vintage, and size class, subject to delivered prices of energy fuels and macroeconomic variables representing disposable personal income, GDP, population, interest rates, and the value of output for industries in the freight sector. Fleet vehicles are represented separately to allow analysis of CAAA90 and other legislative proposals, and the module includes a component to explicitly assess the penetration of alternatively-fueled vehicles.

### **Electricity Market Module**

The Electricity Market Module represents generation, transmission, and pricing of electricity, subject to delivered prices for coal, petroleum products, and natural gas; costs of generation by centralized renewables; macroeconomic variables for costs of capital and domestic investment; and electricity load shapes and demand. There are four primary submodules—capacity planning, fuel dispatching, finance and pricing, and load and demand-side management. Nonutility generation and transmission and trade are represented in the planning and dispatching submodules. The levelized fuel cost of uranium fuel for nuclear generation is directly incorporated into the Electricity Market Module. All CAAA90 compliance options are explicitly represented in the capacity expansion and dispatch decisions. Both new generating technologies and renewable technologies compete directly in these decisions. In addition, several options for wholesale pricing are included.

### **Renewable Fuels Module**

The Renewable Fuels Module includes submodules that provide explicit representation of the supply of wood, municipal solid waste, wind energy, solar thermal electric and photovoltaic energy, and geothermal energy. It provides cost and performance criteria to the Electricity Market Module. The Electricity Market Module represents market penetration of renewable technologies used for centralized electricity generation, and the end-use demand modules incorporate market penetration of selected off-grid electric and nonmarketed nonelectric renewables.

### **Oil and Gas Supply Module**

The Oil and Gas Supply Module represents domestic crude oil and natural gas supply within an integrated framework that captures the interrelationships between the various sources of supply: onshore, offshore, and Alaska by both conventional and nonconventional techniques, including enhanced oil recovery and unconventional gas recovery from tight gas formations, Devonian shale, and coalbeds.

This framework analyzes cash flow and profitability to compute investment and drilling in each of the supply sources, subject to the prices for crude oil and natural gas, the domestic recoverable resource base, and technology. Oil and gas production functions are computed at a level of 12 supply regions, including 3 offshore and 3 Alaskan regions. This module also represents foreign sources of natural gas, including pipeline imports and exports with Canada and Mexico and liquefied natural gas imports and exports. The crude oil supply curves are input to the Petroleum Market Module in NEMS for conversion and blending into refined petroleum products. The supply curves for natural gas are input to the Natural Gas Transmission and Distribution Module.

### **Natural Gas Transmission and Distribution Module**

The Natural Gas Transmission and Distribution Module represents the transmission, distribution, and pricing of natural gas, subject to end-use demand for natural gas and the availability of domestic natural gas and natural gas traded on the international market. The module tracks the flows of natural gas in an aggregate, domestic pipeline network, connecting the domestic and foreign supply regions with 12 demand regions. This capability allows the analysis of impacts of regional capacity constraints in the interstate natural gas pipeline network and the identification of pipeline capacity expansion requirements. Core and noncore markets are explicitly represented for natural gas transmission. Key components of pipeline and distributor tariffs are included in the pricing algorithms.

### **Petroleum Market Module**

The Petroleum Market Module forecasts prices of petroleum products, crude oil and product import activity, and domestic refinery operations, including fuel consumption, subject to the demand for petroleum products, availability and price of imported petroleum, and domestic production of crude oil, natural gas liquids, and alcohol fuels. The module represents refining activities for the 5 Petroleum Administration for Defense Districts, using the same crude oil types as the International Module. It explicitly models the requirements of CAAA90 and the costs of new automotive fuels, such as oxygenated and reformulated gasoline, and includes oxygenate production and blending for reformulated gasoline. Costs include capacity expansion for refinery processing units. End-use prices are based on the marginal costs of production, plus markups representing product distribution costs, State and Federal taxes, and environmental costs.

### **Coal Market Module**

The Coal Market Module simulates mining, transportation, and pricing of coal, subject to the end-use demand for coal differentiated by physical characteristics, such as the heat and sulfur content. The coal supply curves include a response to capacity utilization and fuel costs, as well as reserve depletion, labor productivity, and factor input costs. Thirteen coal types are represented, differentiated by coal rank, sulfur content, and mining process. Production and distribution are computed for 11 supply and 13 demand regions, using imputed coal transportation costs and trends in factor input costs. The Coal Market Module also forecasts the requirements for U.S. coal exports and imports. The international coal market component of the module computes trade in 4 types of coal for 16 export and 20 import regions. Both the domestic and international coal markets are simulated in a linear program.

## 4. Global Data Structure

The Global Data Structure defines the subset of NEMS variables used for intermodule communication and reporting. The variables consist of endogenous global variables shared among modules, such as prices, consumption, and macroeconomic information. The variables also include global reporting variables, as well as a subset of model control parameters and assumptions. The Global Data Structure excludes variables defined exclusively for use in a single module.

The variables in the Global Data Structure are defined and organized in a set of FORTRAN COMMON blocks that designate groups of global variables. During NEMS execution, each module accesses its global input and output variables through these NEMS COMMON blocks. Most modules also have other variables defined in common blocks for intra-module communication. However, such common blocks declared for a module's private use are not considered a part of the global data structure.

The NEMS COMMON block structure designed to store the Global Data Structure is displayed in Table 1. The specific elements of the COMMON block structure are defined in the "include" files containing declarations for variables. In addition, a data dictionary for the Global Data Structure includes definitions for each variable. The data dictionary is a text format input file to the NEMS data management routine, FILER. Generally, three COMMON blocks can be found in the Global Data Structure for each NEMS module, to hold three categories of information:

- The module's outputs used by other NEMS modules, exclusive of end-use consumption and prices. These common blocks are named to indicate the module and have a suffix "OUT."
- The module's outputs used only for reports (for some modules only). These common blocks are named with a suffix "REP."
- The module's input variables for its key parameters and assumptions (for some modules only). These common blocks are named with a suffix "PARAM."

**Table 3. Common Blocks in the NEMS Global Data Structure**

| <b>Module Creator</b>                            | <b>Common Block Names</b>   | <b>Description</b>   |
|--|---|--|
| Integrating, multiple contributors, or exogenous | QBLK<br>MPBLK<br>MXQBLK<br>MXPBLK<br>QSBLK<br>NCNTRL<br>EMISSION<br>CAPEXP<br>COGEN<br>DSM<br><br>CONVFACT<br>HEMREP<br>COALEMM | End-Use Sector Quantities (See Table 4)<br>End-Use Sector Prices (See Table 5)<br>Expected Quantities for foresight<br>Expected Prices for foresight<br>SEDS Historical data corresponding to QBLK<br>Control Variables<br>Pollution Emissions and related results<br>Capital Expenditures for Energy Equipment<br>Cogeneration<br>Demand-Side Management program savings (obsolete)<br><br>Global conversion factors<br>Household Expenditures report variables<br>Variables exchanged between the Coal Market Module and Electricity |
| Integrating, Emission Policy Submodule           | EMABLK<br>AMPBLK<br>ANGTDM<br>ACOAL<br>ACOALPRC   | Price adjustments associated with carbon fees, if any<br>Copies of MPBLK, NGTDMOUT, COALOUT, COALPRC but with prices to utilities adjusted with any carbon fees  |
| Macroeconomic                                    | MACPARMS<br>MACOUT<br>MACREP  | Control parameters, assumptions<br>Output variables<br>Reporting Variables   |
| Residential                                      | RESOUT<br>RESREP<br>(misc.)   | Output variables<br>Energy by end use stored in a series of small common blocks: HTCEN, CLCN, HWCN, CKCN, DRYCN, RFCN, FZCN, LTC, APC, SHC   |
| Commercial                                       | COMPARAM<br>COMOUT<br>COMMREP   | Control parameters, assumptions<br>Output variables<br>Reporting Variables   |

Table 3. Common Blocks in the NEMS Global Data Structure (continued)

| Module Creator    | Common Block Names  | Description  |
|-------------------|---|--|
| Transportation    | TRANREP   | Reporting Variables  |
| Industrial        | INDOUT<br>INDREP  | Natural Gas and LPG Feedstocks<br>Reporting Variables  |
| Electricity       | EMMOUT<br>UMMOUT<br>UEFPOUT<br>EFPOUT<br>UEFDOUT<br>UDATOUT<br>UECPOUT<br>DSMTFEFP<br>ULDSMOUT<br>UETTOUT<br>UGOILOUT | Electricity Market Outputs, General<br>Uranium outputs<br>Electricity pricing outputs<br>Electricity pricing outputs<br>Fuel-dispatch outputs<br>Electricity central data outputs<br>Capacity planning outputs<br>Demand side management /electricity pricing variables<br>Load and demand side management variables<br>Electricity trade outputs<br>Gas/Oil ("goil") Curve to NGTDM |
| Renewable         | WRENEW  | Output variables   |
| Coal              | COALOUT<br>COALREP<br>COALPRC   | Output variables<br>Reporting variables<br>Coal prices to utilities  |
| Petroleum         | PMMPARAM<br>PMMOUT<br>PMMRPT  | Control parameters, assumptions<br>Output variables<br>Reporting variables   |
| Oil & Gas Supply  | OGSMOUT   | Output variables   |
| Natural Gas T & D | NGTDMOUT<br>NGTDMREP<br>NGRPT   | Output variables<br>Reporting variables<br>Supplementary reporting variables   |
| International     | INTOUT<br>INTPMM  | Output variables<br>Variables for use with alternative integrated version of International and Petroleum Market Modules--now obsolete  |

In addition, a group of COMMON blocks called the Energy Market Data, hold data that are created by various modules. These are:

|        |  |
|--------|--|
| QBLK   | Sectoral end-use quantities  |
| MPBLK  | Sectoral end-use prices (prices omitting any carbon fees if effect)      |
| AMPBLK | Sectoral end-use prices (prices adjusted with any carbon fees in effect) |
| MXQBLK | Expectations for end-use quantities                                      |
| MXPBLK | Expectations for end-use prices  |
| CAPEXP | Capital Expenditures on Energy Equipment                                 |

## Energy Market Data Representation

The Energy Market Data define the energy consumption product and price details that are used for market definition in NEMS. These variables are the principal values necessary for convergence testing in the integrating algorithm. The Energy Market Data are just part of the NEMS Global Data Structure. The quantity and price structure does not attempt to represent all energy flows, but instead focuses on the primary variables necessary for the design of the NEMS equilibrating methodology. In addition, the Energy Market Data structure defines the end-use energy classification for the NEMS energy balance.

Table 4 presents a list of the consumption products in a grid depicting the sectoral detail. Each item in the grid represents the named variable in NEMS. The sectoral definitions include the four end-use sectors and three conversion sectors. The sectoral and fuel consumption detail is defined to meet several objectives, including energy accounting coverage and consistency, the structure of component modules, and the requirements for inter-module communications. Elements of this design requiring clarification are as follows:

- The electricity sector includes fuel used by electric utilities and independent power producers to generate electricity supplied to the grid. The industrial and commercial sectors include fuel used for on-site electricity generation, primarily in cogeneration applications. This breakout is consistent with the coverage of the Electricity Market Module and the demand modules.
- Fuel consumption in the refinery sector is broken out from the industrial sector for inter-module communication requirements. The Petroleum Market Module determines fuel use by the refinery sector. This information is passed to Industrial Demand Module, where fuel consumption for refining is added to other industrial fuel use. Thus, the industrial energy consumption product demands as defined in Table 4 *include* refinery consumption.
- The synthetic sector includes fuel consumed for conversion and omits energy products used solely as feedstocks in the synthesis itself.

Table 5 presents the prices in the Energy Market Data structure. In general, the energy prices match the corresponding consumption quantities. The exceptions are as follows:

- Detailed refinery sector prices are omitted even though refinery fuel consumption products are defined. This is because there is no corresponding need to break out refinery sector prices from the rest of the industrial sector. The industrial fuel prices are the delivered prices

to industrial fuel consumers, including refineries. As a result, the industrial sector prices match the coverage of the corresponding industrial consumption products.

- Prices for some industrial petroleum categories are combined in the industrial other petroleum category to eliminate unnecessary detail. That is, the industrial other petroleum price is defined as the average price of three consumption categories: still gas, petroleum coke, and other petroleum. The other petroleum price is not needed by any NEMS module but is required for reporting purposes to determine the average price of all petroleum products.
- Delivered prices for renewable energy categories are left undefined because there are no meaningful market prices for them. For example, there are no delivered prices associated with hydroelectric, geothermal, wind, solar thermal, and photovoltaic energy sources. In the case of biomass, the diverse nature of the product and the lack of organized market structures preclude the definition of a delivered price. Thus, there is no need to define end-use prices for renewables.

Table 4 and Table 5 also define the variable names for the NEMS consumption products and end-use prices along with the two-character product code mnemonic for each product. Each array is a two-dimensional, floating point array. The first dimension represents the nine Census Divisions, with a 10th position reserved for possible breakout of California and the 11th position reserved for the National total. The second dimension represents 26 years from 1990 to 2015, plus 3 additional positions reserved for future storage of 2020, 2025, and 2030 results. The space for the latter 3 years was reserved originally as a possible way of supporting the NEMS long-term modeling capability. Quantities are stored in trillions of Btu. Prices are stored in 1987 dollars per million Btu, as deflated by the implicit GDP price deflator.

A related part of the Energy Market Data structure comprises the variables to hold energy market expectations. The Integrating Module maintains a separate set of arrays to store consumption and price expectations. The expectations arrays are updated according to the foresight options under consideration. The expectations arrays are defined like the standard energy market arrays, each with an additional leading character, X. Not all energy product detail is duplicated.

Table 4. Energy Market Data Consumption Product Arrays

| Description                     | End-Use Sectors |                 |                |                  | Conversion Sectors |                  |                  | Totals        |
|---------------------------------|-----------------|-----------------|----------------|------------------|--------------------|------------------|------------------|---------------|
|                                 | Resd.<br>(Q_RS) | Comm.<br>(Q_CM) | Tran<br>(Q_TR) | Indus.<br>(Q_IN) | Refin.<br>(Q_RF)   | Elect.<br>(Q_EL) | Synth.<br>(Q_SY) | All<br>(Q_AS) |
| Purchased Electricity, Peak     | QEPRS           | QEPCM           | QEPTR          | QEPIN            | QEPRF              |                  |                  | QEPAS         |
| Purchased Electricity, Off-Peak | QENRS           | QENCM           | QENTR          | QENIN            | QENRF              |                  |                  | QENAS         |
| Purchased Electricity (total)   | QELRS           | QELCM           | QELTR          | QELIN            | QELRF              |                  |                  | QELAS         |
| Natural Gas, Firm               | QGFRS           | QGFCM           | QGFTTR         | QGFIN            | QGFRF              | QGFEL            |                  | QGFAS         |
| Natural Gas, Interrupt.         | QGIRS           | QGICM           | QGITR          | QGIIN            | QGIRF              | QGIEL            |                  | QGIAS         |
| Natural Gas (total)             | QNGRS           | QNGCM           | QNGTR          | QNGIN            | QNGRF              | QNGEL            |                  | QNGAS         |
| Natural Gas, Pipeline Fuel      |                 |                 | QGPTR          |                  |                    |                  |                  |               |
| Lease and Plant Fuel            |                 |                 |                | QLPIN            |                    |                  |                  |               |
| Steam Coal                      | QCLRS           |                 |                | QCLIN            | QCLRF              | QCLEL            | QCLSN            | QCLAS         |
| Metallurgical Coal              |                 |                 |                | QMCIN            |                    |                  |                  |               |
| Motor Gasoline                  |                 | QMPCM           | QMGTTR         | QMGIN            |                    |                  |                  | QM GAS        |
| Jet Fuel                        |                 |                 | QJFTR          |                  |                    |                  |                  |               |
| Distillate                      | QDSRS           | QDSCM           | QDSTR          | QDSIN            | QDSRF              | QDSEL            |                  | QDSAS         |
| Kerosene                        | QKSRS           | QKSCM           |                | QKSIN            |                    |                  |                  | QKSAS         |
| Liquid Petroleum Gas            | QLGRS           | QLGCM           | QLGTTR         | QLGIN            | QLGRF              |                  |                  | QL GAS        |
| Residual Fuel, Low Sulfur       |                 | QRLCM           | QRLTR          | QRLIN            | QRLRF              | QRL EL           |                  | QRLAS         |
| Residual Fuel, High Sulfur      |                 |                 | QRHTR          |                  |                    | QRHEL            |                  | QRHAS         |
| Residual Fuel (total)           |                 | QRSCM           | QRSTR          | QRSIN            | QRSRF              | QRSEL            |                  | QRSAS         |
| Petrochemical Feedstocks        |                 |                 |                | QPFIN            |                    |                  |                  |               |
| Still Gas                       |                 |                 |                | QSGIN            | QSGRF              |                  |                  |               |
| Petroleum Coke                  |                 |                 |                | QPCIN            | QPCRF              | QPC EL           |                  | QPCAS         |
| Asphalt and Road Oil            |                 |                 |                | QASIN            |                    |                  |                  |               |
| Other Petroleum                 |                 |                 | QOTTR          | QOTIN            | QOTRF              |                  |                  | QOTAS         |
| Total Petroleum                 | QTPRS           | QTPCM           | QTPTR          | QTPIN            | QTPRF              | QTP EL           |                  | QTPAS         |
| Methanol                        |                 |                 | QMETR          |                  |                    |                  |                  |               |
| Ethanol                         |                 |                 | QETTR          |                  |                    |                  |                  |               |
| Liquid Hydrogen                 |                 |                 | QHYTR          |                  |                    |                  |                  |               |
| Uranium                         |                 |                 |                |                  |                    | QUREL            |                  |               |
| Hydroelectric                   |                 |                 |                | QHOIN            |                    | QHOEL            |                  | QHOAS         |
| Geothermal                      |                 |                 |                | QGEIN            |                    | QGEEL            |                  | QGEAS         |
| Biomass                         | QBMRS           | QBMCM           |                | QBMIN            | QBMRF              | QBMEL            | QBMSN            | QB MAS        |
| Municipal Solid Waste           |                 |                 |                | QMSIN            |                    | QMS EL           |                  | QMSAS         |
| Solar Thermal                   | QSTRS           | QSTCM           |                | QSTIN            |                    | QST EL           |                  | QSTAS         |
| Photovoltaic                    | QPVRs           | QPVC M          |                | QPVIN            |                    | QPVEL            |                  | QP VAS        |
| Wind                            |                 |                 |                | QWIIN            |                    | QWIEL            |                  | QW IAS        |
| Total Renewable                 | QTRRS           | QTRCM           | QTRTR          | QTRIN            |                    | QTREL            | QTRSN            | QTRAS         |
| Net Electricity Imports         |                 |                 |                |                  |                    | QEIEL            |                  |               |
| Net Coal Coke Imports           |                 |                 |                | QCIIN            |                    |                  |                  |               |
| Total Sectoral Consumption      | QTSRS           | QTSCM           | QTSTR          | QTSIN            | QTSRF              | QTSEL            | QTSSN            | QTSAS         |



Table 5. Energy Market Data Price Product Arrays

| Description                     | Resd.<br>(P_RS) | Comm.<br>(P_CM) | Tran<br>(P_TR) | Indus.<br>(P_IN) | Elect.<br>(P_EL) | All<br>(P_AS) |
|---------------------------------|-----------------|-----------------|----------------|------------------|------------------|---------------|
| Purchased Electricity, Peak     | PEPRS           | PEPCM           | PEPTR          | PEPIN            |                  | PEPAS         |
| Purchased Electricity, Off-Peak | PENRS           | PENCM           | PENTR          | PENIN            |                  | PENAS         |
| Purchased Electricity (average) | PELRS           | PELCM           | PELTR          | PELIN            |                  | PELAS         |
| Natural Gas, Firm               | PGFRS           | PGFCM           | PGFTR          | PGFIN            | PGFEL            | PGFAS         |
| Natural Gas, Interruptible      | PGIRS           | PGICM           | PGITR          | PGIIN            | PGIEL            | PGIAS         |
| Natural Gas (average)           | PNGRS           | PNGCM           | PNGTR          | PNGIN            | PNGEL            | PNGAS         |
| Natural Gas, Pipeline Fuel      |                 |                 | PGPTR          |                  |                  |               |
| Lease and Plant Fuel            |                 |                 |                | PLPIN            |                  |               |
| Steam Coal                      | PCLRS           | PCLCM           |                | PCLIN            | PCELEL           | PCLAS         |
| Metallurgical Coal              |                 |                 |                | PMCIN            |                  |               |
| Motor Gasoline                  |                 | PMGCM           | PMGTR          | PMGIN            |                  | PMGAS         |
| Jet Fuel                        |                 |                 | PJFTR          |                  |                  |               |
| Distillate                      | PDSRS           | PDSCM           | PDSTR          | PDSIN            | PDSEL            | PDSAS         |
| Kerosene                        | PKSRS           | PKSCM           |                | PKSIN            |                  | PKSAS         |
| Liquid Petroleum Gas            | PLGRS           | PLGCM           | PLGTR          | PLGIN            |                  | PLGAS         |
| Residual Fuel, Low Sulfur       |                 | PRLCM           | PRLTR          | PRLIN            | PRLEL            | PRLAS         |
| Residual Fuel, High Sulfur      |                 |                 | PRHTR          |                  | PRHEL            | PRHAS         |
| Residual Fuel (average)         |                 | PRSCM           | PRSTR          | PRSIN            | PRSEL            | PRSAS         |
| Petrochemical Feedstocks        |                 |                 |                | PPFIN            |                  |               |
| Asphalt and Road Oil            |                 |                 |                | PASIN            |                  |               |
| Other Petroleum                 |                 |                 | POTTR          | POTIN            |                  | POTAS         |
| Petroleum(average)              | PTPRS           | PTPCM           | PTPTR          | PTPIN            | PTPEL            | PTPAS         |
| Methanol                        |                 |                 | PMETR          |                  |                  |               |
| Ethanol                         |                 |                 | PETTR          |                  |                  |               |
| Liquid Hydrogen                 |                 |                 | PHYTR          |                  |                  |               |
| Uranium                         |                 |                 |                |                  | PUREL            |               |

## **Other Variables in the Global Data Structure**

In addition to Energy Market Data, the Global Data Structure includes the following information:

- Model Control Variables
- Key parameters and Assumptions for each of the NEMS modules
- Macroeconomic variables, including energy demand drivers such as population
- Energy demand characteristics, including demand side management savings
- Energy production, conversion, and transportation activities
- International energy flows
- Emissions
- Renewable energy information
- Other data for inclusion in central report writing programs

These categories of data are those items necessary for inter-module communications and centralized report writing. There are also other COMMON blocks intended for communicating data within the subroutines of a module, but not between modules. This latter group of common data is not included in the NEMS Global Data Structure.

## **Restart File**

At the beginning of a run, the Integrating Module reads initial values for all data in the Global Data Structure from a user-specifiable version of a special file, called the Restart file. The Restart file contains a starting point for the scenario currently under consideration, that consists of results from a prior simulation. During the run, much of this data is updated and changed. For example, alternative values for key module parameters and input assumptions, read separately from the user interface file or other sources, override the values stored in the Restart file. At the end of the run, a new Restart file is created with all the data from the run. The file is available for future runs, as well as to link with reporting and database management routines.

This feature promotes modularity by supplying values for all shared variables, regardless of whether the module that creates them is active in the run. Prices, quantities demanded or supplied, and other variables normally generated by a module that is switched off for the current run, are provided instead by the Restart file.

## **Report Data**

NEMS contains several varieties of reporting functionality. While each module generates detailed, module-specific reports, there is also a central reporting feature that prepares reports that combine output from all of the modules and inputs to the models. A simple post-processing user interface is available to prepare standard reports and compose special reports.

A user interface also allows extraction of data and conversion to input for other types of analytic software, and facilitates transfer of output data between platforms. For example, selected output from

several NEMS runs may be extracted from the total results on the mainframe, reformatted into Lotus 1-2-3 format, and transferred to the PC for subsequent spreadsheet analysis.

## **Database Loading**

A database subroutine called FILER is used to store and retrieve the NEMS Global Data Structure. The global data is structured into groups of variables known as "common blocks." The FILER routine moves data between common block memory and disk storage. The NEMS modules may access data from, and write results to the common block variables once the data is loaded into memory. The basic capabilities of FILER are:

- To load data from a file into a standard NEMS COMMON block; and
- To write data from a standard NEMS COMMON block to a file.

This capability is constructed such that files created by FILER can also be read by FILER. In addition, FILER can be used to extract subsets of data and create text files or spreadsheets. It can also be used to initialize new global variables with starting values. Generally, FILER is not used for input of most exogenous data in NEMS. The procedure incorporates a data dictionary to define the variables in the Global Data Structure. User access to the FILER program is available outside NEMS through the NEMS macro command, TFILER.



## 5. Integrating Module Solution Methodology

The Integrating Module controls the overall flow of the NEMS solution algorithm, and provides the interface and control logic for scenario implementation and execution. In addition, it tests for convergence of the system during each year, as it controls the iteration process.

Using the Energy Market Data portions of the NEMS Global Data Structure as inputs, the Integrating Module measures whether convergence has occurred, and optionally adjusts the Energy Market Data values to accelerate the convergence process. By means of calls to the *FILER* and File Manager routines, the Integrating Module manages the flow of overall system data; however, beyond reading the user's parameter requests, it has no important input nor output functions of its own.

### Relationship of the Integrating Module to Other NEMS Modules

The modular structure of NEMS implies that little model structure resides within the Integrating Module. The component modules represent energy sectors and markets; the Integrating Module oversees the interactions among the various energy sectors, calling upon the component modules as needed. In a very real sense, the structure of the Integrating Module is therefore synonymous with the structure of NEMS, insofar as the Integrating Module defines a structure within which the analytical modules function.

The Integrating Module controls the execution of the other component modules as part of an iterative convergence algorithm. The objective is to equilibrate iteratively on the delivered prices and quantities of energy, thus assuring an economic equilibrium of supply and demand in the domestic energy markets, with feedbacks from the international markets and the U.S. economy as a whole.

The Integrating Module also coordinates communication among the other modules. The primary information flows among these major modules are the delivered prices and quantities of energy by product, region, and sector. However, the data flows are not limited to prices and quantities and include other information such as economic activity, capital expenditures, and impacts of demand side management programs.

### Integrating Module Inputs

Given its mediating role in the NEMS system, the Integrating Module has little input data of its own; the major model inputs are processed by each of the component modules. The Integrating Module reads user run description parameters and invokes a data base portion that reads the NEMS Global Data Structure.

As a body, all data used, either read or written, by more than one of the NEMS component modules are referred to as the *NEMS Global Data Structure*. For convenient sharing among the modules, all such variables are stored internally in FORTRAN COMMON blocks. At the end of each NEMS iteration, the Integrating Module invokes a process, called *FILER*, which stores the contents of the COMMON blocks that constitute the NEMS Global Data Structure into a single large file, called the

*RESTART* file. At the start of each NEMS run, the Integrating Module makes use of *FILER* to read an entire *RESTART* file to initialize the *COMMON* blocks. Thus, the NEMS Global Data Structure includes both the external file and its internal representation in *COMMON*.

Because all NEMS shared data are initialized from the *RESTART* file at the start of each run, it is not strictly necessary for the Integrating Module to invoke all of the component modules; if any module is omitted, its normal output variables can be found by the other modules in exactly the same places they would otherwise occupy, filled with values from the end of an earlier NEMS run. An important function of the Integrating Module is to ascertain which of the component modules are to be used in the current run, and to skip the others at times when they would otherwise be called.

## General Modeling Approach

EIA has taken the approach of developing models that characterize the natural decision making of each sector of the energy market, linking or integrating the models together in a simulation framework to represent the aggregate U.S. energy market response to basic assumptions and alternative policies. Optimization models are appropriate to simulate the behavior of a homogeneous industry or sector of the economy, and their use is a standard practice in economic policy analysis. For example, the electric industry's plant dispatch decisions or the movements in the coal transportation sector can be appropriately represented as an optimization model. Other sectors are better represented using simulations of the outcome of decision rather than modeling the decisions directly.

The fundamental integrating methodology used by NEMS involves a control program, the Integrating Module, that commences the solution process with an initial set of estimates of energy prices and quantities. It calls each of the modules in turn to generate new end-use demands for energy in the demand modules, and new end-use prices at which the demands can be satisfied in the supply and conversion modules. This new set of prices and quantities is then used for another round of calling the modules and so on, until the model has computed price estimates at which supply and demand are in balance.

NEMS design criteria do not specify the modeling approaches to be taken by the individual analytical modules. A variety of approaches can be found among the existing modules, ranging in complexity from simple accounting models through detailed mathematical optimization algorithms. Some sectors have implemented multiple approaches that the user can select by choosing alternative complete modules.

Figure 2 in Chapter 2 depicts the relationship of the Integrating Module of NEMS with each of the component modules. Generally, the component modules of NEMS do not interact with one another directly, but instead communicate through the Integrating Module. The organization has a number of benefits. It allows each module to be executed or omitted independently. More importantly, it provides centralized control over such Integrating Module functions as execution sequence, convergence checks, equilibration procedures, and data access. Finally, the organization promotes a division of labor for the development and maintenance of NEMS, as each module is the responsibility of a single team.

The approach followed by NEMS is comparable to that followed by the predecessor Intermediate Future Forecasting System (IFFS). The model is entirely new, with additional features such as the

implementation of foresight throughout the model and the Global Data Structure. Improvements in the NEMS approach can be found more in the analytical modules than in the Integrating Module.

The following section provides a more explicit, detailed formulation of the Integrating Module solution algorithm. It includes a complete mathematical specification as well as a detailed flow chart of the algorithm.

## Mathematical Specification

In many ways, NEMS follows the standard structure of energy models. It has separate models for determining the supply of each fuel. These models are incorporated in the Oil and Gas Supply Module (OGSM), the Renewable Fuels Module, and the Coal Production Submodule. These modules produce supply curves. The supply curves consist of estimates of reserve additions that take account of the longer run effects of prices and the quality of the resource base followed by short-run supply curves that capture the short-run utilization of the reserves in clearing markets annually. The short-run supply curves are inserted into the fuel market models that determine the market clearing prices and quantities and distribution patterns. These models are contained in the Natural Gas Transmission and Distribution Module (NGTDM), the Coal Distribution submodule (CDS), and Coal Export submodule (CES). The transformation components model the conversion of fuel from one form to another. These include the Petroleum Marketing Module (PMM), which converts crude oil to refined products, and the Electricity Marketing Module (EMM), which converts natural gas, petroleum products, and other fuels to electricity. These modules consist of capacity expansion models and short-run capacity-utilization models. Finally, the demand models, including the Commercial, Residential, Industrial, and Transportation modules include short-run and long-run demand responses to price changes in fuels. The short-run response measures the effect of equipment utilization and the long-run response measures the change in energy-consuming capital stock.

The supply curves from the supply models provide prices for fuel quantity used. Although the demand models do not directly provide demand curves, their response to different input prices defines the inherent demand curves. These demand curves or demand model responses provide the quantities of fuels demanded for given fuel prices. The NEMS solution algorithm attempts to determine a vector of prices and quantities so that supply and demand are matched. Thus, the NEMS integrating algorithm must solve the set of simultaneous equations implied by the supply, demand, and conversion models.

### Equation Solving Techniques

The standard equation solving techniques are Jacobi and Gauss-Seidel algorithms. Suppose that a set of equations is defined

$$f_i(x_1, \dots, x_n) = 0 \text{ for } i = 1, \dots, n. \quad (1)$$

If one has a trial solution  $x_1^t, \dots, x_n^t$ , in a Jacobi iteration  $t$ , for each  $x_i$ , one solves for  $x_i^{t+1}$  in

$$f_i(x_1^t, \dots, x_{i-1}^t, x_i^{t+1}, x_{i+1}^t, \dots, x_n^t) = 0. \quad (2)$$

That is, one fixes all variables other than  $x_i$  at the previous trial solution and solves for a new  $x_i^{t+1}$  as a single dimensional line search. For example, if in iteration three of NEMS, the coal model is

called to determine the price of coal, the coal demand and all other inputs to the model would be obtained from iteration two of NEMS using the Jacobi method. This is the case even if, for example, the industrial model has already been called during the third NEMS iteration, and therefore, updated information on demand for coal from the industrial sector is available.

On the other hand, with the Gauss-Seidel algorithm one iterates sequentially through  $i$  and uses the most recent values for the  $x$ 's at each step. The equation solved at each step  $i$  looks as follows:

$$f_i(x_1^{t+1}, \dots, x_{i-1}^{t+1}, x_i^t, x_{i+1}^t, \dots, x_n^t) = 0. \quad (3)$$

Continuing the example introduced above with the Gauss-Seidel algorithm, when the coal model is called in iteration three of NEMS the results of any other models already run during iteration three are used. If inputs are required from other models that come after the coal model in the NEMS calling sequence, the results from iteration two of these models must be used.

Under certain conditions, it can be shown that the Jacobi iteration can never be faster than Gauss-Seidel and of course, could be considerably slower. It is intuitively more appealing to use the most recent information, which is why the NEMS uses the Gauss-Seidel algorithm.

### *Convergence Properties of the Jacobi and Gauss-Seidel Algorithms*

It is worth reviewing some of the general convergence properties of the Jacobi and Gauss-Seidel algorithms, especially their relationship to the convergence in NEMS. The matrix of first partial derivatives of equation (1), hereafter denoted  $J$ , is a square matrix known as the Jacobian. The spectral radius of a matrix is the largest absolute value of the eigenvalues associated with a matrix.<sup>1</sup> If the spectral radius of the iteration matrix derived from  $J$  is less than one, these algorithms converge to a solution. If not, then these algorithms do not necessarily converge. One can think of the spectral radius as the measure of the contractor in a contraction map, since the rate of convergence is inversely proportional to the spectral radius.

In situations where the spectral radius is greater than one, convergence can still be achieved by using relaxation techniques. That is, when the solution is oscillating and diverging, one can take a convex combination of the old and new solutions to dampen the oscillation. This technique, known as successive over relaxation, modifies the iteration matrix so that it has a spectral radius less than one. It can be shown that there is a sufficiently small  $w > 0$  such that when one uses  $(1-w)x_t + wx_{t+1}$  as the trial solution, a solution to the equations will be achieved. In complex models such as NEMS the parameter  $w$  must be determined empirically, and could impede convergence if the solution is monotonically converging and  $w$  is chosen less than one. The application of relaxation to the NEMS solution process is discussed in the section **Acceleration Techniques**.

With NEMS, however, there are solution points which are either nondifferentiable or for which there are no Jacobians because of the discontinuities caused by incorporating linear programs in the system. The presence of such points greatly complicates the solution procedure of the NEMS system.

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<sup>1</sup>Let  $Ax = \lambda x$  be a linear system of equations, with  $A$  a matrix,  $x$  a vector, and  $\lambda$  a scalar. The values of  $\lambda$  satisfying this equation are the eigenvalues of the matrix  $A$ .



## ***Discontinuities and Convergence in NEMS***

The existence of supply and demand curves in NEMS was discussed in the previous section. Though the supply and demand curves are generally treated as continuous functions, various models contain linear programs or their analogues that can only incorporate step functions. Any such continuous functions must be approximated by a series of discrete steps. The inclusion of such discrete functions leads to discontinuities in the representation of the supply and demand curves in NEMS. Such discontinuities cause significant problems in the solution process.

Several modules incorporate algorithms that yield these discontinuous results. For example, the petroleum refining and distribution model is a linear program that represents crude oil supply curves as discrete step functions. Similarly, the distribution model for natural gas is also a linear program that uses step-function approximations of the supply and demand curves. These step-function approximations are updated during each solution iteration, so that the model can be considered to be a nonlinear program which is solved by successive linear approximations. The electricity fuel dispatch (EFD) model, although not a linear program, contains discontinuities due to the discrete nature of the merit-order plant dispatch algorithm which determines the fuel mix required to produce electricity. The coal distribution model is a linear program. Thus, each of these models introduces discontinuities into the NEMS solution process.

The effect on the solution process of having discontinuities can be seen by using step function demand curves with continuous supply curves. The same conclusions may be drawn as long as either or both of the supply and demand curves are step functions. Figures 3a and 3b depict the two ways in which the continuous supply curve and step demand curves can intersect:

In these figures the supply curve determines the price used in the demand curves, which then feed back a quantity. The solution path resulting from application of the Gauss-Seidel algorithm is delineated by arrows: a horizontal arrow shows the quantity response from the demand curve and a vertical arrow shows the price response from the supply curve.

When the supply curve intersects the horizontal portion of the demand curve, there is an oscillation in the solution between quantities  $Q_0$  and  $Q_1$  and prices  $P_0$  and  $P_1$  (Figure 3a). When the intersection of the supply and demand curves is on the vertical portion of the demand curve, one can achieve the equilibrium with the Gauss-Seidel algorithm using relaxation, even if the unrelaxed algorithm yields an oscillation in the solution (Figure 3b). In Figure 3a there is no  $w$  for which convergence will occur. However, a value for  $w$  can always be found so that the oscillation occurs around no more than one (or possible two) steps. This is useful because if one can specify sufficiently small steps so that the entire step falls within the convergence tolerance, this oscillation is no longer a convergence problem.

## **Application of Gauss-Seidel to NEMS**

The NEMS integrating algorithm, similar to the approach used for the predecessor Intermediate Future Forecasting System (IFFS), is an application of the Gauss-Seidel algorithm designed to solve a set of simultaneous nonlinear equations.<sup>2</sup> The approach partitions the equations and variables into

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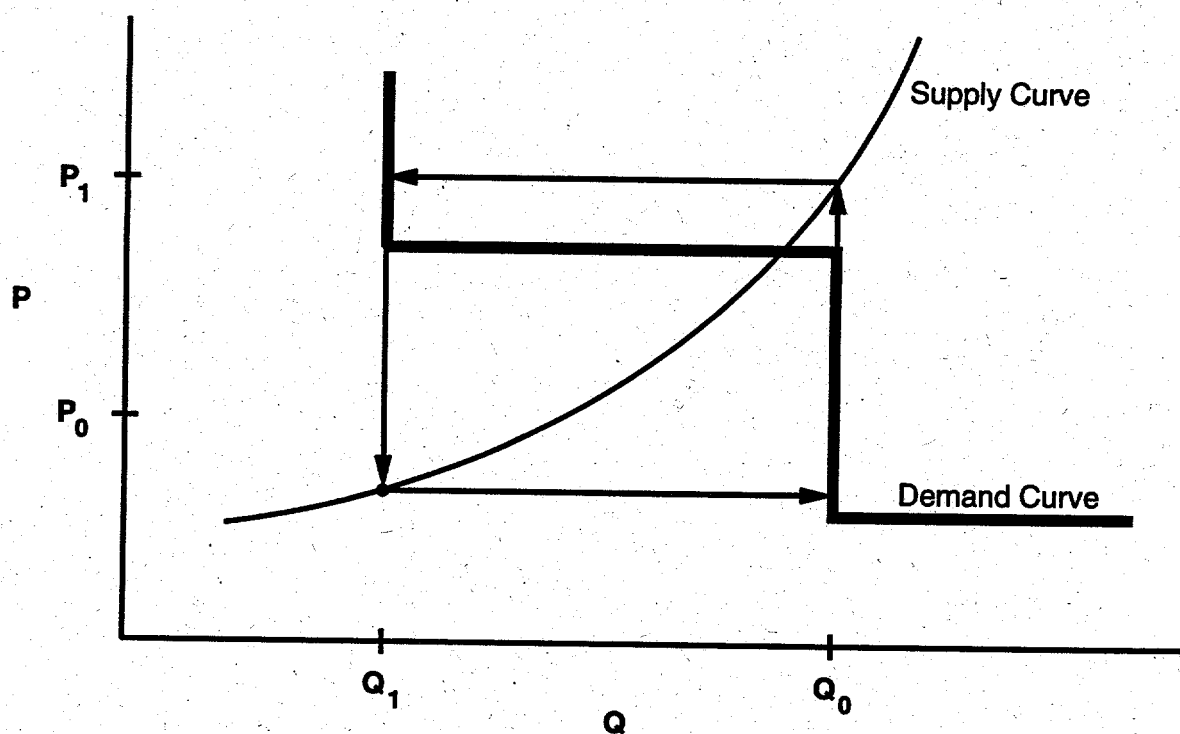
<sup>2</sup>Murphy, F., J. Conti, S. Shaw, and R. Sanders, "Modeling and Forecasting Energy Markets with the Intermediate Future Forecasting System," *Operations Research*, Vol. 36, No. 3, May-June 1988.

subsets. For NEMS, the subsets consist of predefined fuel supply, energy conversion, and sectoral demand modules. Each subset of equations is solved keeping the other variables constant at their trial values and ignoring the effects of current variables on equations in other subsets. The process is repeated for each subset, updating the trial values for each variable from the prior solution.

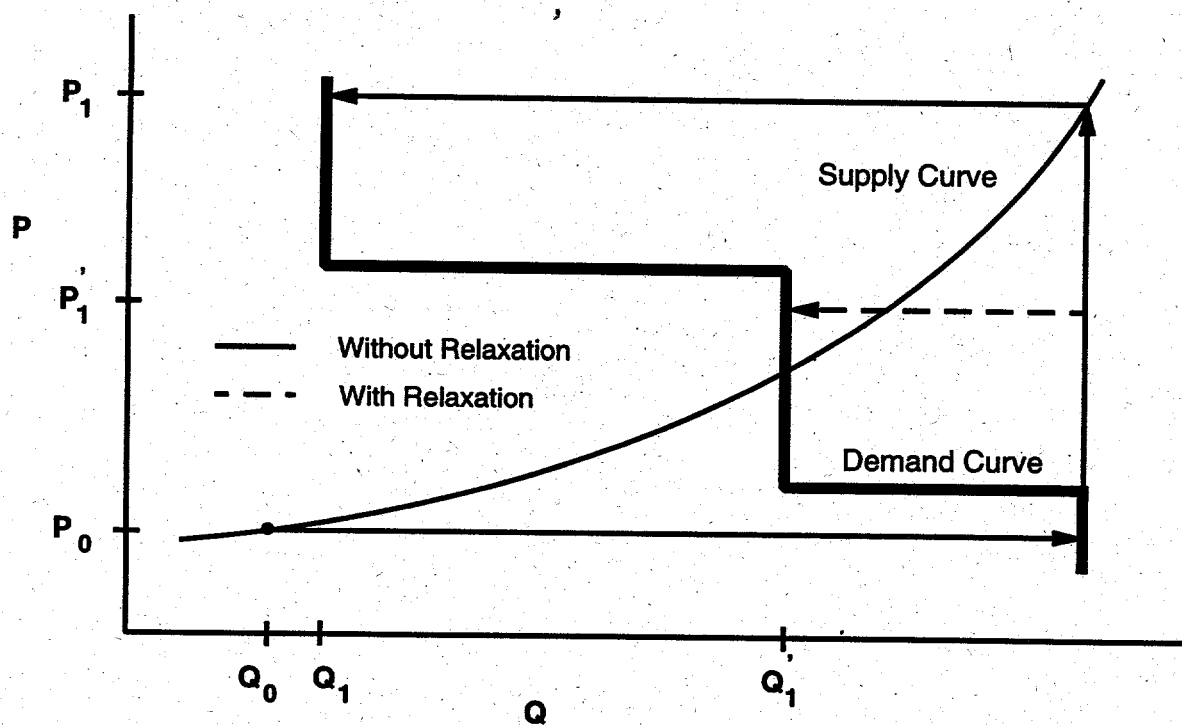
More formally, for a stylized NEMS, the nonlinear system of equations could be represented by

$$x_i = g_i(x) \quad \text{for } i = 1, \dots, n \quad (4)$$

**Figure 3A. The Supply Curve Cuts Across the Horizontal Portion of the Demand Curve**



**Figure 3B. The Supply Curve Cuts Across the Vertical Portion of the Demand Curve**



having the market clearing or equilibrium solution vector

$$x = (x_1, \dots, x_n).$$

Here, each  $x_i$  is a single variable. A trial solution for iteration  $k$  for a certain year is denoted by  $x^k$ , where

$$x^k = (x_1^k, \dots, x_n^k).$$

Each  $g_i(x)$  uses one or more of the elements of the trial solution vector  $x^k$ , excluding its own solution,  $x_i^k$ .

Further, we define a series of nonlinear equations  $f_i(x^k)$  that represent the amount by which any trial solution  $g_i(x^k)$  deviates from an equilibrium solution:

$$f_i(x^k) = x_i^k - g_i(x^k).$$

To reiterate, the solution vector  $x$  represents the set of solutions to the model: prices of energy products, quantities of energy products demanded, and certain key economic quantities. The functions  $g_i(x)$  represent the formulas by which the  $x$  are calculated, and  $f(x)$  represent the discrepancies between the calculated values for the solution vector and the solution vector itself. The  $g_i(x)$  represent the relationships in the modules between prices and demands: for those  $i$  that correspond to supply modules and conversion markets the  $g_i(x)$  are prices, for demand modules the  $g_i(x)$  are quantities.

At the end of iteration  $k$  for a certain year, the discrepancy  $f_i(x^k)$  from the equilibrium solution can be estimated as follows:

$$f_i(x^k) = x_i^{k-1} - g_i(x^{k-1}), \quad (5)$$

$$f_i(x^k) = x_i^{k-1} - x_i^k. \quad (6)$$

where  $x^{k-1}$  is the trial solution vector from the previous iteration for the same year.

In the block Gauss-Seidel scheme, unknowns are grouped together in such a way that a subsystem (e.g., a NEMS module) must be solved before any of the unknowns can be determined. The NEMS equations are divided into  $n$  groups (modules) and the subsystem of equations belonging to a given group is solved for the corresponding unknowns using approximate values for the other unknowns. For example, suppose the unknowns are divided into groups  $(x_1, \dots, x_n)$  such that  $X_1, X_2, \dots, X_{m1}$  belong to group  $x_1$ ;  $X_{m1+1}, X_{m1+2}, \dots, X_{m2}$  belong to group  $x_2$ ;  $X_{m(k-1)+1}, X_{m(k-1)+2}, \dots, X_{mk}$  belong to group  $x_k$  etc. In our case,  $n$  corresponds to the number of separate modules in NEMS (residential demand, commercial, industrial, transportation, petroleum markets, electric generation, oil and gas supply, etc.) In the NEMS context each  $x_i$  represents the set of *outputs* from the module  $(g(x))$ , given approximate values for the other unknowns in the remaining NEMS modules. Consequently, there are  $n$  blocks of variables to be solved for as groups using each of the  $n$  model blocks,  $g_i(x)$ . At iteration  $k+1$ , the solution can be represented by

$$x_1^{k+1}, x_2^{k+1}, \dots, x_{i-1}^{k+1}, x_i^k, \dots, x_n^k$$

In the above representation of the solution, the first  $i-1$  groups of unknowns ( $x$ 's) have been solved for in iteration  $k+1$  and the other groups remain to be determined. The  $i$ -th group will be solved for next in the scheme. To solve for the next estimate of  $x_i$ , we determine  $x_i$  in the functional relationship

$$(g_i(x_1^{k+1}, x_2^{k+1}, \dots, x_{i-1}^{k+1}, x_i^k, x_{i+1}^k, \dots, x_n^k)) = (x_1^{k+1}, x_2^{k+1}, \dots, x_{i-1}^{k+1}, x_i^{k+1}, x_{i+1}^k, \dots, x_n^k)$$

Notice that  $x_i^k$  is usually not used to solve module  $i$  but is included here for completeness. Starting at the beginning of iteration  $(k+1)$ , the algorithm proceeds as follows:

Step 0: Start with  $x = (x_1^k, x_2^k, \dots, x_n^k)$ .

Step 1: Solve the first module in iteration  $(k+1)$

Solve for  $x_1^{k+1}$  by solving for  $x_1$  in the nonlinear system

$$g_1(x_1^{k+1}, x_2^k, \dots, x_n^k) = (x_1^{k+1}, x_2^k, \dots, x_n^k).$$

The solution yields a new estimate of the unknowns  $x = (x_1^{k+1}, x_2^k, \dots, x_n^k)$ .

Step 2: Solve the second module in iteration  $(k+1)$ .

Solve for  $x_2^{k+1}$  by solving for  $x_2$  in the nonlinear system

$$g_2(x_1^{k+1}, x_2^{k+1}, x_3^k, \dots, x_n^k) = (x_1^{k+1}, x_2^{k+1}, x_3^k, \dots, x_n^k).$$

The solution yields a new estimate of the unknowns  $x = (x_1^{k+1}, x_2^{k+1}, x_3^k, \dots, x_n^k)$ .

In general, when solving for the  $i$ -th group of variables,

Step  $i$ : Solve the  $i$ -th module in iteration  $(k+1)$ .

Solve for  $x_i^{k+1}$  by solving for  $x_i$  in the nonlinear system

$$g_i(x_1^{k+1}, x_2^{k+1}, x_{i-1}^{k+1}, x_i^k, x_{i+1}^k, \dots, x_n^k) = (x_1^{k+1}, x_2^{k+1}, \dots, x_{i-1}^{k+1}, x_i^{k+1}, x_{i+1}^k, \dots, x_n^k).$$

The solution for  $x_i$  above in  $g_i$  updates the solution estimate to

$$x = (x_1^{k+1}, x_2^{k+1}, \dots, x_{i-1}^{k+1}, x_i^{k+1}, x_{i+1}^k, \dots, x_n^k).$$

The process continues until a  $k+1$  iteration estimate is derived for all groups of  $x_j$ .

At the end of the  $k+1$  iteration, we compare, pointwise, every component of every group of variables in the  $k+1$  iteration versus the  $k$ -th iteration values. A final solution,  $x^{k+1}$ , has been achieved if, after all modules have been executed, the absolute values of the proportional changes in the  $x_i$  remain smaller than a specified tolerance,  $\epsilon$ :

$$\left| \frac{x_i^{k+1} - x_i^k}{(x_i^{k+1} + x_i^k)/2} \right| < \epsilon$$

for  $i = 1, \dots, n$ . Values of  $\epsilon$  can be chosen on a variable-specific basis. Defaults are in the range of 5 percent for the Census Division variables, less for the national macroeconomic variables.

After the convergence criterion has been met, another iteration is performed to test whether a true equilibrium has been reached, and to allow the modules to perform final processing for the year; so that the final converged solution vector for the year is  $x^{k+1}$ .

To handle cases where the procedure does not converge on a solution or does not achieve the specified tolerance, a limit on the number of iterations terminates the algorithm for the current year. In such cases, the model performs the additional iteration mentioned in the previous paragraph, reports the convergence status with a list of the variables failing to converge, and then proceeds to the next projection year. The final solution for the year is therefore the result of one iteration beyond the non-converged trial solution.

The equations are partitioned in the fuel supply and sectoral demand modules, with the  $x_i$  consisting primarily of quantities and prices of fuels by region and consuming sector. These variables are defined as

$P_{f,s,r,y}^k$  = Energy product price (current iteration)

$P_{f,s,r,y}^{k-1}$  = Energy product price (previous iteration)

$Q_{f,s,r,y}^k$  = Energy product quantity consumed (current iteration)

$Q_{f,s,r,y}^{k-1}$  = Energy product quantity consumed (previous iteration)

indices:

$f$  fuel/energy product (natural gas, coal, petroleum products, electricity, etc)

$s$  consuming sector (residential, commercial, industrial, transportation, electric utility, refinery, synthetic)

$r$  region (census divisions)

$y$  year

In several modules, planning decisions must be made to acquire additional capacity which will be required in future years. These include the Electricity Capacity Expansion (ECP) submodule, the Capacity Expansion Module for natural gas, the Oil and Gas Supply module.

In order to make such decisions, information on future demands, prices, and macroeconomic variables such as interest rates must be provided. While each module solves one year at a time, their simulations of planning activities involve an extrapolation of energy market conditions. Those modules making new capacity construction decisions apply an assumption about foresight in their expectations of future energy prices and quantities. In NEMS, a set of price and quantity variables is defined to store expectations:

$XP_{f,s,r,y}$  = Expected prices of energy products beyond the current forecast year (for  $y > y$ )

$XQ_{f,s,r,y}$  = Expected consumption of energy products beyond the current forecast year

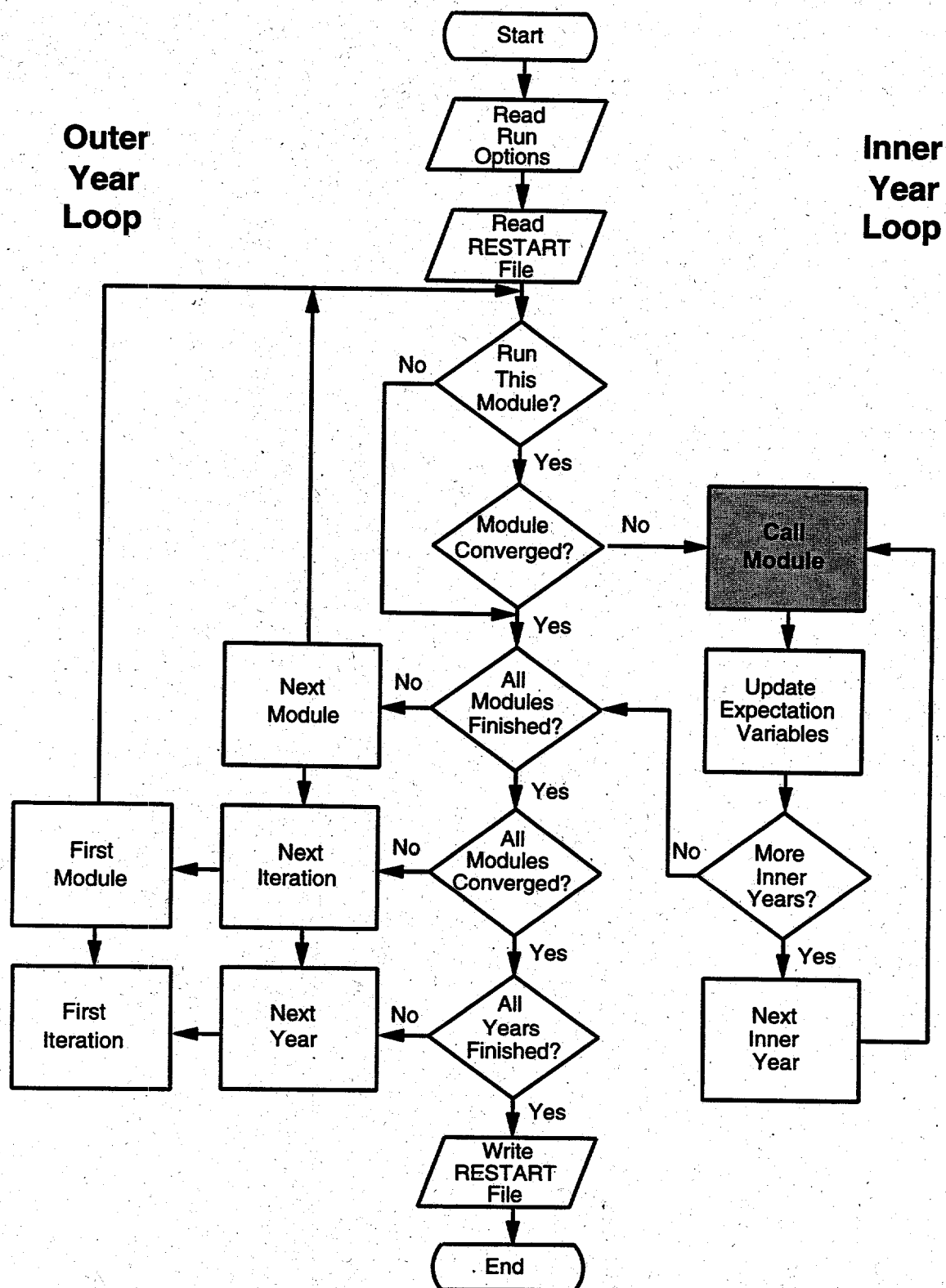
The foresight mode determines how the expectation variables are to be calculated: under perfect foresight, the various NEMS modules are invoked for years beyond the current iteration year; otherwise, the Integrating Module calculates minor extrapolations of present-year conditions. Foresight is therefore always calculated by looking forward to the consequences of conditions in the present iteration year, not by attempting to reach some end state determined *a priori*. The treatment of expectations is discussed in greater detail under **Expected Value Foresight**, on page 54.

Additional variables, representing such values as macroeconomic activity, world oil prices and trade, and emissions, may be added to the convergence algorithm, but are omitted here for clarity. In terms of the energy market interactions, the sectoral demand models estimate current-year energy demands  $Q_{f,s,r,y}$  and energy-related capital stock additions as functions of current and expected energy prices. The supply models estimate end-use prices  $P_{f,s,r,y}$  and capacity additions as functions of current and expected energy demands. The conversion modules (electricity, refinery, and synthetics) are viewed primarily as supply components, but they are both consumers of primary energy and suppliers of energy products.

### Solution Algorithm Flow Chart

Figure 4 presents a detailed flow of the Integrating Module solution algorithm. The objective of the algorithm is to execute the system of component modules repeatedly until convergence is reached. The solution procedure for one iterative cycle involves execution of the component modules, as well as updating expectation variables. The component modules include the International Energy Activity Module, the Macroeconomic Activity Module, the sectoral demand models, the conversion models, and the supply models.

Figure 4. Integrating Module Flow Chart





Through program control options, the looping over years takes place either within an iterative cycle (Inner Year Loop) or outside the iterative cycle (Outer Year Loop). That is, component modules may either be called repeatedly to execute for all years in a given iteration, or may be executed one year at a time. The flexible year looping was designed to support different approaches for foresight, as discussed in detail under **Expected Value Foresight** below. However, the looping for all years at a time, for the perfect foresight approach, has never been exercised for the system as a whole and is now considered obsolete. The solution of each module one year at a time is the only solution method in use.

In Figure 4, the *Outer Year Loop* is executed once for each year in the forecast horizon when all modules are being executed for one year during each iteration. In that case, the *Inner Year Loop* executes for a single year as well. When modules execute for all years during each iteration, the *Inner Year Loop* controls the year indexing, and the *Outer Year Loop* is entered only once.

To accommodate flexible year looping, the solution procedure for a given iteration begins with the establishment of starting and ending year index ranges for the inner year loop. The next step is to update the expectation variables over the specified inner year range (either a single year or all years):

$$\begin{aligned} XP_{f,s,r,y}^k &= f(P_{f,s,r,y}^{k-1}) && \text{(update price expectations from previous iteration prices)} \\ XQ_{f,s,r,y}^k &= f(Q_{f,s,r,y}^{k-1}) && \text{(update quantity expectations from previous iteration quantities)} \end{aligned}$$

Next, each of the modules is executed in turn. Normally, for each year in the inner year range, the International Energy Module and the Macroeconomic Module are called first, followed by the sectoral demand models.

$$Q_{f,s,r,y}^k = f(P_{f,s,r,y}^{k-1}, XP_{f,s,r,y}^k, \text{macroeconomic, other variables})$$

The conversion and supply models are then called, using updated demand quantities, to return prices:

$$P_{f,s,r,y}^k = f(Q_{f,s,r,y}^k, XQ_{f,s,r,y}^k, \text{macroeconomic, other variables})$$

After all modules have been executed for an inner year, the next inner year is begun. The order of calling the modules is flexible.

## Convergence

After a module has been called, a check for convergence for that specific module is made, and the storage of previous iteration values is performed. Modules that had converged on an earlier iteration in the current year are bypassed. These intervening convergence checks isolate the specific modules that are not converging. An additional global convergence check requires all submodules to have converged. A separate convergence check is made for prices and quantities, consisting of a comparison of the absolute value of the percent changes to an assumed tolerance,  $\epsilon$ , as follows:

$$\left| \frac{Q_{f,s,r,y}^k - Q_{f,s,r,y}^{k-1}}{(Q_{f,s,r,y}^k + Q_{f,s,r,y}^{k-1}) / 2} \right| < \epsilon$$

$$\left| \frac{P_{f,s,r,y}^k - P_{f,s,r,y}^{k-1}}{(P_{f,s,r,y}^k + P_{f,s,r,y}^{k-1}) / 2} \right| < \epsilon$$

Here, the denominators use an average to avoid convergence difficulties if either the starting value or a trial solution value is equal to zero. To avoid unnecessary iterations for changes in insignificant values, the quantity convergence check is omitted for changes less than a user-specified minimum level.

The last step is to store the current quantities and prices for the next iteration's convergence check:

$$\begin{aligned} Q_{f,s,r,y}^{k+1} &= Q_{f,s,r,y}^k \\ P_{f,s,r,y}^{k+1} &= P_{f,s,r,y}^k \end{aligned}$$

The cycle is repeated until convergence is achieved for all submodules over the specified inner year range or until the maximum number of iterations is reached. When one of these two conditions occurs, an additional iteration, referred to as the "Final Convergence and Reporting Loop" is executed. This has several purposes. First, it is used to test whether a solution meeting the convergence criteria is maintained on two successive iterations. If so, there is a greater likelihood that the solution is an equilibrium solution. Second, it provides a signal for each module to write any reporting data out to disk, thus saving resources on intermediate iterations. Third, it provides a signal to the Integrating Module that all modules are to be executed, even if they had already converged on prior iterations. If the modules fail to converge on the Final Convergence and Reporting Loop, the convergence algorithm is repeated. In such cases, the model may converge on a subsequent iteration, thus triggering the Final Convergence and Reporting Loop a second time.

Once the model completes the Final Convergence and Reporting Loop, or when the maximum number of iterations is reached, the cycle for the current inner year range is completed. If the specified inner year range is only one year, the outer year index is incremented and the algorithm is repeated for the next year.

Whenever a year fails to converge within the user-specified number of iterations, the model completes the Final Convergence and Reporting Loop, accepts the resulting solution as the final solution, and proceeds to the next model year. The unconverged final solution should be examined in detail by the user, to verify its validity. Furthermore, later years' solutions in modules that refer to earlier years' solutions in their formulations can be affected adversely by the data in the unconverged final solution.

A model "execution log" is generated to record the progress of the model as it proceeds from one iteration to the next. The convergence status after execution of each module is reported in the log. Also reported are the names of any variables failing to converge, along with their values on the current and previous iterations, and their fractional changes. If the values of any tested variables fail to converge within the specified number of iterations, a message is written to the execution log, and execution continues with the next year. During or after a model run, the user may review the execution log to examine the convergence status.

When a nonconvergent situation arises, the results of the run must be viewed with caution. An assessment should be made as to the type of convergence problem and its effect on the results. A failure to converge may indicate a programming error, or it may be an accurate reflection of the modeling configuration. Generally, convergence problems must be evaluated on a case-by-case basis.

Other than specifying the run options through the run submission user interface, and substituting modified files containing data upon which the NEMS modules depend, there is no intervention required of the user to ensure a successful model run. The user should examine the execution run log and other output reports to ensure that convergence has been achieved, and that the results are credible. In the case of a problem with convergence, appropriate modules may be "switched off," the allowable number of iterations may be increased, or other such parameters may be adjusted through the user interface and the simulation resubmitted.

## **Summary of Convergence Problems and Resolution**

Integrated developmental testing of NEMS revealed a number of convergence problems. Factors leading to convergence problems were assessed and changes were made as needed to the individual NEMS modules. In a few cases, provisions to pass additional information between modules were required to develop stable convergence properties. Many of the convergence problems involved interactions between the Electricity Market Module (EMM) and the three supply modules providing it with fuel prices: the Natural Gas Transmission and Distribution Module (NGTDM), the Petroleum Market Module (PMM), and the Coal Market Module (CMM). The primary convergence problems and their resolutions are summarized below.

### ***Merit Order Switching***

The major function of the Electricity Fuel Dispatch (EFD), a submodule of the EMM, is to determine what generating capacity should be running at a particular time to meet the demand for electricity. The type of capacity used (fossil fuel, nuclear, renewables) and the manner in which it is deployed (base load, intermediate load, or peak) determines the fuel demands for the EFD. The objective of the EFD is to provide a least cost solution while meeting environmental requirements. In the merit order dispatching methodology, the marginal source of electricity is selected to react to each load change. One effect of this methodology is that step changes in the quantity of fuels required occur; the resulting discontinuities occasionally yielded nonconvergence.

Merit order switching in the utility market commonly occurred between natural gas and other fuels, between types of coal (graded by sulfur content), and sometimes between types of natural gas (competitive versus firm). Several techniques were used to reduce this effect, depending on the specific cause of the switch. These included incorporating demand curves in the PMM and NGTDM modules, price relaxation, and other modifications discussed later in this section.

### ***NGTDM/EMM Interactions***

Since NEMS is an extension and elaboration of IFFS, the experience gained with achieving convergence while incorporating step functions in IFFS was relevant. Consequently, the first step towards convergence in NEMS was to extend the IFFS approach to addressing the natural gas/utility interactions. As described above, the step functions for utility demand for natural gas come from merit order switches in the utilities model. When gas is cheaper than oil, the gas plants are dispatched with a higher capacity factor than the oil plants, and dual-fired plants switch to gas. When gas is more expensive, the reverse occurs and the gas plants operate with a lower capacity factor and consume less gas even though total electricity demand has not changed. If, when in the gas model, one were to take the utility gas demand as fixed, one would have an oscillation as in Figure 3a. This was known from the beginning of the design of IFFS.

Because of the similarity in the structures of NEMS and IFFS, the first step in achieving convergence was to focus on gas/utility interactions. Using a derived demand curve to encompass all the natural gas consumed by the utilities was not possible due to the greater complexity of the models in NEMS than the ones in IFFS. For example, allowing electricity trade meant that the utility model in each region was no longer an isolated consumer of natural gas and the full derived demand curve could not be constructed in each region without considering the interregional interactions. Consequently, the curve constructed in NEMS looks at fuel switching in dual-fired plants only.

In the EMM, the fuel choice decision is made for each capacity subunit based on a gas/oil sharing function. This function relates the ratio of prices of competitive gas to residual fuel oil to the quantity of gas required by the utilities. The vertical portions of the curve represent minimum and maximum quantities of gas needed by the utility respectively. An aggregate curve for each region is generated in the NGTDM. In order to use the information from the gas/oil sharing function, the oil price provided by the PMM is used as the denominator for the gas/oil price ratio, and a portion of the demand curve is created around the average of the trial prices from the last two iterations. Since a continuous demand curve cannot be implemented in a linear program, the three line segments constructed with the four points shown in the figure are approximated by a step function for inclusion in the NGTDM. This approach operated with relatively few problems and stabilized the fuel switching in the dual-fired plants.<sup>3</sup>

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<sup>3</sup>There are two ways of interpreting the use of this step function. One is to view this approach as a partition in which the natural gas demand in utilities is determined in the natural gas model. The alternative is to view the utility gas demand as being determined in both the gas and utilities model. This is a departure from traditional equation solving, for in the traditional approach one constructs a partition of the equations, where each equation appears in only one grouping.

Additional merit order switching between categories of gas also occurred for which the gas/oil sharing function did not compensate. Gas is categorized as firm, interruptible, and competitive. Firm gas delivery is guaranteed in that the pipeline capacity is allocated to these customers first. These customers pay a reservation charge to reserve the capacity. Interruptible customers pay a lower price, essentially the marginal cost of delivery plus purchase costs, and face the risk of having gas supplies curtailed if delivery capacity is insufficient. Competitive customers have the ability to switch between gas and oil. Their gas is assumed to be priced as the maximum of either the residual oil price or the city gate price plus \$.10 per MMBtu, with a ceiling at the interruptible price.

Because of the differences in the three gas prices, it was thought that the merit order would not change between iterations. However, this was not the case. Firm gas in utilities is burned in combined cycle plants that are more efficient than steam plants. Although the firm price remained above the competitive price, given the heat rate advantages, in some iterations the usual merit order switched. That is, instead of the steam plants being dispatched ahead of the combined cycle plants, the reverse occurred. With the higher operating rates for the combined cycle plants and the correspondingly lower operating rates for the steam plants, less gas was consumed overall, reflecting the greater efficiencies of the combined cycle plants over the steam plants in electricity production. The effect was to lower the wellhead price of gas. The economics of steam versus combined cycle depend more on the ratio of prices. Given the wellhead price drop and a constant difference between the different gas prices, the merit order switched back and forth because the percentage differences in the prices increased.

The solution to this problem involves changing the representation in the model. Firm gas to utilities needs to be marginally priced at the competitive price for dispatching purposes and priced at the full firm rate (including reservation rates) for calculating electricity rates and capacity expansion planning. The rationale is that the reservation charge is a sunk cost; that is, the charge must be paid whether gas is purchased or not. In general, this puts combined-cycle plants ahead of steam plants in the merit order, thus reducing the potential for these merit order switches. However, in Texas certain steam plants had better heat rates than combined cycle plants, though they had higher operating costs. Consequently, when the price of gas reached a threshold merit order switches still occurred. This was resolved by equalizing the operating costs of the two types of plants.

### ***Other Natural Gas Convergence Issues***

An aspect of the solution procedure that never caused a problem on its own, but did aggravate other problems, was the way the linear program approximations to the supply curves are constructed in the NGTDM. The underlying supply curve is a continuous function, which is approximated with a step function by constructing steps around the trial solution. The same increment to the price was used in all regions. In the solution to successive transportation linear programs, given the basis did not change, all prices changed the same amount for supply and demand nodes connected by any path of basic variables.<sup>4</sup>

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<sup>4</sup>Murphy, F.H., and H. Greenberg, "Computing Regulated Equilibria with Mathematical Programming," *Operations Research*, Vol. 33, No. 5, 1985, pp 935-955.

In the case of the natural gas model transmission and distribution problem, almost all the supply and demand nodes and their associated prices are connected in this way. The only demand region not usually connected is the Northwest, because this region is supplied by Canadian gas. Consequently, when the equilibrium price changes, the gas prices in almost all regions change the same amount. Since all of the supply curve steps were based on the same price differences, they coincided with each other for changes in the equilibrium price. Essentially, the gas model had only six national steps because of this property of the solution. The solution was to ensure that step sizes were not absolute but based on a fraction of each regional price. This approach operated with relatively few problems and stabilized the fuel switching in the dual-fired plants. In addition, an oscillation in gas prices occurred because the price used to construct the supply curve was not relaxed, but the demand curve starting price was. The solution was to apply the same relaxation to the supply price as was used for the demand price.

Another natural gas convergence problem occurred when the short run supply curves hit the maximum production-to-reserves ratio at a low price. In this situation, the NGTDM had vertical supply curves. The resulting oscillations in the trial solutions were quite large in price with little quantity movement. The oscillations were aggravated because there were demand curves only for competitive gas to the utilities and not for the other gas demands. Since much of the response to the perturbations in price occurred with other types of gas and by other sectors, these demand curves did not sufficiently reflect the total demand response. This problem was resolved by including the demand response of end-use consumption of natural gas in the NGTDM.

The final convergence problems of note with natural gas involved the linear program defining the end-use prices and flow patterns for movements of natural gas through the regional interstate network. Because of the nature of the linear program, as the full capacity of a pipeline or storage facility would be reached, the price response would be disproportionate, leading to a drop in demand and an oscillation on the price. The solution to this problem also required the incorporation of an approximation of end-use demands within the natural gas distribution model.

### ***Coal/EMM Interactions***

The Electricity Market Module of NEMS was designed to represent environmental constraints, including the Clean Air Act Amendments of 1990 (CAAA 1990). The Act established a national cap for sulfur dioxide (SO<sub>2</sub>) emissions by utilities and a market for trading allowances, or rights to emit one ton of SO<sub>2</sub> over the course of one year.

In model versions used up through the *Annual Energy Outlook 1996* (AEO96), this national cap was represented as a constraint in the least cost dispatch heuristic used by the EMM to determine fuel requirements. A trial least cost dispatch was determined and the sulfur emissions totaled. A penalty was added to the price of each fuel proportional to the sulfur allowances needed for its consumption, and the merit order was re-evaluated. A scalar search was then performed on the penalty cost to find the least penalty for which the total sulfur emissions were below the cap. If one views the merit order dispatch as a constrained minimization program, the penalty cost reflected the dual value of the national cap constraint.

However, this penalty must also reflect the price differential between low and high-sulfur coal, which was in fact determined from the supply curves in the NEMS Coal Market Module. Since the penalty was calculated in the EMM but depended upon factors in both the EMM and the coal module, significant convergence problems resulted. Various heuristic schemes were examined but did not resolve the problem.

The solution, implemented in the AEO97 version for NEMS, was to move the penalty calculation from the EMM to the coal module. This was accomplished through the addition of a constraint row in the linear program of the Coal Distribution submodule to limit the level of sulfur credits expended to meet the CAAA regulations. The dual variable for this constraint represents the penalty level.

In order for this algorithm to be valid two conditions must be met: the coal module must have an accurate representation of the number of allowances needed for a particular level of coal consumption, and variations in SO<sub>2</sub> emissions from the other fuels may be ignored. Since the former quantity is actually a function of both the coal and plant type (primarily the use of scrubbers), the specifications for coal demands in the EMM were also modified. In particular demand was specified by plant type rather than rank and sulfur level. The latter condition is met because natural gas has essentially no sulfur, and the sulfur emitted from the consumption of residual fuel is minimal compared to that from coal.

As a result of these changes, the coal module now determines the least cost sulfur penalty as well as the mix of coals necessary to meet the EMM demand; the EMM determines only the total demand (in BTUs) for each plant type. In theory, convergence problems could still arise as merit order changes would adjust the consumption of each plant type. In practice, since coal plants typically meet base-load demand, any change in the merit order due to changes in the coal price or sulfur penalty typically move various plants up or down in the merit order but leaves overall coal consumption essentially unchanged. This results in an algorithm that is very robust and significantly improved convergence.

### ***Convergence Issues and the PMM***

Since refineries in the Texas/Louisiana area can burn both natural gas and residual oil for heat, the linear program in the PMM allows both fuels to be consumed. This caused an oscillation between gas and residual fuel oil in the Southwest. This problem was resolved by taking the slope of the Texas supply curve for natural gas and using it to generate a step function supply curve for natural gas in the PMM. Since this supply curve is less elastic than the derived supply curve from NGTDM, it has the property that the model would converge monotonically if there were no other adjustments made. Both the base price and quantity are derived from the trial price and quantity determined in the previous iteration.

Demand curves were added for the following imported products: liquid propane gas (LPG), heating oil, high and low sulfur residual fuel, petrochemical feedstocks and other petroleum products. The purpose of these curves is to reduce the oscillation in prices caused by imports. These curves are implemented with three steps in the linear program used by the PMM. All curves except residual

have three steps; high and low-sulfur residual were modeled with a nine step curve. This was required because of a convergence problem that occurred in the Northern Great Plains. In this case the high and low-sulfur residual oil prices oscillated to such an extreme that the high-sulfur residual was more expensive than the low-sulfur residual, the opposite of what should occur. With only three steps, the representation of the import supply curve is necessarily crude. In this case this representation was sufficient to cause slight changes in demand to shift the solution from one step to another and back, causing an oscillation. This was resolved by taking the import points and connecting them with line segments. That is, the curves were made continuous, which better matched the underlying economics. These line segments were then dynamically approximated by the nine steps. This eliminated any major price moves unaccompanied by quantity moves.

### ***Summary of Convergence Issues***

Three basic techniques were used to enhance convergence in NEMS. The first was to incorporate a representation of the demand response in the supply and pricing modules, as was done in the NGTDM to capture the behavior of dual-fired power plants. Secondly, when the slope of the supply curve for natural gas was incorporated in the PMM, an approximation was created of the first order effects of a change in gas consumption caused by a change in the demands by the PMM. To some extent, these two techniques are reflections of the same principle: a particular set of price-quantity relationships are incorporated in two distinct modules. The final convergence technique involved passing additional information besides just price and quantity signals between the coal and utility modules to compensate for the convergence problems caused by the CAAA requirements.

### **Acceleration Techniques**

The NEMS Integrating Module incorporates a number of features that provide the user some amount of control over the speed with which the equilibration process converges on a final solution. Foremost among such features in terms of accelerating convergence while at the same time increasing the overall robustness of the solution process is a user-controllable feature known as *relaxation*.

As the Integrating Module iteratively directs the energy supply, demand, and other modules to recalculate the energy market data, the calculated prices and quantities can be expected to oscillate about the equilibrium solution as they converge on the supply and demand equilibrium for the current year. If the relaxation option is selected for the run by the user, then these swings from iteration to iteration are dampened by a user-specified factor, which may accelerate convergence and lead to a more stable and robust solution process. Using the notation developed above,

$$x^{k+1} = x^k + r (x^{k-1} - x^k)$$

where  $r$  = relaxation factor.



Another acceleration technique is the selection of the appropriate initial solution. As many runs are simulations of alternative scenarios to a prior run, an appropriate choice of initial solution will speed convergence significantly.

### ***Initial Solution Selection***

At the start of a NEMS run, initial values for all years for all variables in the Global Data Structure, including the energy market data, are read from a user-specified version of the RESTART file. In turn, the final solution for all years at the end of the NEMS run is stored and becomes available for use as the initial solution for subsequent runs.

The choice of restart files may have an affect on the speed of convergence. A restart file provides an initial set of demands and prices for the modules to use as input. In addition, for those modules employing linear programs, the restart file is associated with a set of initial bases. The restart file based on the last iteration of the same year of another run provided the most efficient initial point for the starting iteration.

### **Expected Value Foresight**

Approaches to foresight ( $XP_{f,s,r,y}$  and  $XQ_{f,s,r,y}$ ) are important for theoretical and practical reasons. Mid- and long-term energy forecasting involves assessing changes in energy-using capital stocks and choices among energy supply alternatives. This analysis requires simulation of such decisions as the selection of durable appliances, planning electricity-generating capacity additions, and building gas pipelines. The economic evaluation of these decisions requires energy demand and price expectations for life-cycle cost and capacity addition calculations. An objective in this aspect of the modeling is to simulate such decision making in the aggregate for predictive and analytical purposes, representing how players in the energy marketplace make long term planning decisions, rather than by deriving the theoretically optimal long-term expansion path. As a result, the formulation of foresight assumptions is open to alternative approaches based on observed industry practices.

NEMS could, in principle, approach the issue of foresight by prescribing a desirable end state for the energy marketplace, and calculating backwards in time to prescribe how best to arrive there. However, as a simulation, NEMS calculates foresight as an extrapolation of the present state of energy markets, subject to announced policies. Rather than determining how to arrive at the planned future, NEMS can evaluate whether present plans could result in the desired end state.

In reality, different methodologies for treating foresight are used in different sectors and supply areas, and alternate approaches to representing expectations may yield significantly different planning decisions. Consequently, treatment of foresight becomes an important modeling decision.

There is no one best approach to treating foresight. The National Research Council Committee on NEMS recommended that several options for modeling foresight be developed.<sup>5</sup> As a result, an objective in NEMS was to build the flexibility to support different approaches to foresight to allow for experimentation and future modeling changes. In addition, it is desirable to have the option to treat foresight consistently throughout the modeling system.

The purpose of dealing with foresight and expectations in the Integrating Module is to be able to represent different types of foresight consistently. At the same time the Integrating Module allows individual modules to handle foresight independently, should industry practice require different approaches. To achieve this flexibility, each NEMS module is intended to be constructed so that an on-off switch is examined to determine whether the module uses the system-generated expectations or not. If this central-control switch is turned on, the module uses system expectations; otherwise, the module uses expectations it generates for itself.

The system-generated expectations include several types:

- The “myopic expectations” option is one in which expected prices for any forecast period are assumed to be constant in real dollar terms relative to the current period in which decisions are being made. Generally, this case applies only to expected prices because an assumption of constant energy demands would rarely be assumed.
- “Adaptive expectations,” also known as “extrapolative expectations,” is an approach that assumes planners extrapolate recent trends when making long-term decisions. For the system-generated expectations, this assumption about foresight is implemented by extrapolating the current projection year prices and quantities using the average annual growth over the previous few projection years. For example, the expectations generated in model year 2000 for use in 2001 would be determined from the growth over the last few model years (e.g., 1998 to 2000), with the number of years being a model option. For expectations generated within individual modules, more elaborate behavioral models, or adaptive expectations, are used.
- The “perfect foresight” approach is based on rational expectations theory. The approach generates an internally consistent scenario for which the formation of expectations is consistent with the projections realized in the model. In practice, perfect foresight describes the configuration and solution algorithm that achieves the convergence of expected values and realized values. A variation in the integrating algorithm is required to implement perfect foresight. Instead of solving for an equilibrium for each year, the Integrating Module calls each model for all years of the forecast horizon during each iteration. The objective is to converge across all years simultaneously rather than solving one year at a time. While the perfect foresight algorithm is included in the integrating module, the procedure has never been exercised for the entire system and is considered obsolete.

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<sup>5</sup>National Research Council, *The National Energy Modeling System*, Washington D.C.: National Academy Press, 1992.

Among those modules using alternative expectations is the Electricity Market Module (EMM). The EMM requires fuel price expectations for natural gas, oil, and coal for use in its capacity planning submodule. The capacity planning submodule also requires expectations for electricity demand. The approaches for generating oil, gas, and coal prices and electricity demand for the EMM are summarized below:

- Coal price expectation equations were developed using a regression approach on a NERC region basis. This methodology is implemented directly in the EMM.
- Oil product price expectations are generated in the Integrating Module. The prices are calculated from an external forecast of world oil prices, assuming a constant markup between the regional product price and the world oil price. In each forecast year, the assumed markup is derived from the prior forecast year:

$$P_{c+k} = (P_c - W_c) + W_{c+k} \quad \text{for } k=1, \dots, 40$$

where  $P_c$  and  $W_c$  are the product price and the exogenous world oil price from the previous forecast year, and  $P_{c+k}$  and  $W_{c+k}$  are the prices in the expectation years.

- Delivered natural gas prices are derived from expected wellhead prices, assuming a constant markup between the delivered prices and the wellhead price. The wellhead price expectations are based on a simple, nonlinear function which relates the expected wellhead gas price to cumulative domestic gas production. The equation is of the following form:

$$P_k = A * Q_k^{1.5} + B,$$

where  $P$  is the wellhead price,  $Q$  is the cumulative production from 1991 to year  $k$ , and  $A$  and  $B$  are determined each year, as explained below.

The approach was developed to have the following properties:

- Prices should be upward sloping as a function of cumulative gas production.
- The rate of change in wellhead prices should increase as fewer economical reserves remain to be discovered and produced.

The approach assumes that at some point in the future a given target price,  $PF$ , results when cumulative gas production reaches a given level,  $QF$ . Thus, the target values  $PF$  and  $QF$  are assumed inputs to the approach. For simplicity, the annual production is assumed to be constant at the prior year's level. The parameters of the price equation,  $A$  and  $B$ , are determined each projection year such that the price equation will intersect the future target point. That is:

- let  $D$  = Last year's gas production
- let  $PS$  = Last year's wellhead gas price
- let  $QS$  = Last year's cumulative gas production since 1991

$$A = (PF - PS) / (QF^{1.5} - QS^{1.5})$$

$$B = PF - A * QF^{1.5}$$

Extrapolate cumulative production for future years  $k = 1, \dots, 40$ :

$$Q_k = Q_{k-1} + D$$

Generate expected well-head prices:

$$P_k = A * Q_k^{1.5} + B$$

- The electricity demand expectations determine how much generating capacity will be needed in subsequent years and when new capacity will be scheduled. Expectations for electricity demand growth are generated through the adaptive expectations approach, constrained by lower and upper limits on growth. The lower limit is zero growth. The upper limit on the regional growth of electricity demand was assumed to be five percent a year for the 1997 Annual Energy Outlook. The upper limit on electricity demand expectations was established to neutralize any tendencies for the capacity planning module to favor technologies with either short or long construction lead times, particularly early in the simulation period.

## Carbon Emission Calculations

The Integrating Module calculates carbon emissions associated with the use of energy. Carbon emissions are dependent on the carbon content of the fuel and the fraction of the fuel consumed in combustion. The product of the carbon coefficient and the combustion fraction yields a carbon emission factor. The emissions factors are expressed in millions of metric tons of carbon emitted per quadrillion Btu of energy use, or equivalently, in kilograms of carbon per million Btu.

For fuel uses of energy, the combustion fractions are assumed to be .99 for liquid fuels and .995 for gaseous fuels. The carbon in nonfuel use of energy, such as for asphalt and petrochemical feedstocks, is assumed to be sequestered in the product and not released to the atmosphere. For energy categories that are mixes of fuel and nonfuel uses, the combustion fractions are based on the proportion of fuel use.

Table 6 presents the carbon coefficients, combustion fractions, and emission fractions for 1995. The adjusted emission factors are input into the emission policy submodule through a file ("epmdata"). Because some of the factors have varied over time, factors for each history year in NEMS, 1990 to 1995, are entered separately. Factors for the last available year, 1995, apply for all projection years.

Any carbon emitted by renewable sources is considered balanced by the carbon sequestration that occurred in its creation. Therefore, following convention, net emissions of carbon from renewable sources is taken as zero, and no emission coefficient is reported. Renewable fuels include hydroelectric power, biomass, photovoltaic, geothermal, ethanol, and wind energy.

**Table 7 lists the NEMS variables used to calculate the carbon emissions.**

Table 6. Carbon Emissions Factors (Kilograms-carbon per million Btu)

| Fuel Type                        | Carbon Coefficient at Full Combustion | Combustion Fraction | Adjusted Emissions Factor (Model Input) |
|----------------------------------|---------------------------------------|---------------------|---|
| <b>Petroleum</b>                 |                                       |                     |   |
| Motor Gasoline .....             | 19.38                                 | 0.990               | 19.20                                   |
| Liquefied Petroleum Gas          |                                       |                     |   |
| Used as Fuel .....               | 17.01                                 | 0.995               | 16.92                                   |
| Used as Feedstock .....          | 17.01                                 | 0.194               | 3.30                                    |
| Jet Fuel .....                   | 19.34                                 | 0.990               | 19.14                                   |
| Distillate Fuel .....            | 19.95                                 | 0.990               | 19.75                                   |
| Residual Fuel .....              | 21.49                                 | 0.990               | 21.28                                   |
| Asphalt and Road Oil .....       | 20.62                                 | 0.000               | 0.00                                    |
| Lubricants .....                 | 20.24                                 | 0.600               | 12.14                                   |
| Petrochemical Feedstock .....    | 19.37                                 | 0.200               | 3.84                                    |
| Kerosene .....                   | 19.72                                 | 0.990               | 12.92                                   |
| Petroleum Coke .....             | 27.85                                 | 0.500               | 13.93                                   |
| Petroleum Still Gas .....        | 17.51                                 | 0.995               | 17.42                                   |
| Other Industrial .....           | 20.31                                 | 0.990               | 20.11                                   |
| <b>Coal</b>                      |                                       |                     |   |
| Residential and Commercial ..    | 25.95                                 | 0.990               | 25.69                                   |
| Metallurgical .....              | 25.52                                 | 0.990               | 25.25                                   |
| Industrial Other .....           | 25.63                                 | 0.990               | 25.38                                   |
| Electric Utility .....           | 25.72                                 | 0.990               | 25.46                                   |
| Electric Utility by Sulfur Class |                                       |                     |   |
| Existing Units, Low Sulfur ..    | 26.61                                 | 0.990               | 25.35                                   |
| Existing Units, Mid Sulfur ..    | 25.64                                 | 0.990               | 25.38                                   |
| Existing Units, High Sulfur ..   | 25.62                                 | 0.990               | 25.37                                   |
| New Units, Low Sulfur ....       | 26.17                                 | 0.990               | 25.91                                   |
| New Units, Mid Sulfur ....       | 26.00                                 | 0.990               | 25.74                                   |
| New Units, High Sulfur ....      | 25.90                                 | 0.990               | 25.65                                   |
| Units with Scrubbers .....       | 26.04                                 | 0.990               | 25.78                                   |
| <b>Natural Gas</b>               |                                       |                     |   |
| Used as Fuel .....               | 14.47                                 | 0.995               | 14.40                                   |
| Used as Feedstock .....          | 14.47                                 | 0.774               | 11.20                                   |

Table 7. Energy Consumption and Emissions Factor Variables for Carbon Emissions

| Fuel Type by Sector             | Energy Consumption Variable | Emission Factor Variable |
|---------------------------------|-----------------------------|--------------------------|
| <b>Residential</b>              |                             |                          |
| Distillate Fuel .....           | QDSRS                       | EDSRS                    |
| Kerosene .....                  | QKSRS                       | EKSRS                    |
| Liquefied Petroleum Gas .....   | QLGRS                       | ELGRS                    |
| Natural Gas .....               | QNGRS                       | ENGRS                    |
| Coal .....                      | QCLRS                       | ECLRS                    |
| <b>Commercial</b>               |                             |                          |
| Motor Gasoline .....            | QMGCN                       | EMGCN                    |
| Liquefied Petroleum Gas .....   | QLGCM                       | ELGCM                    |
| Distillate Fuel .....           | QDSCM                       | EDSCM                    |
| Residual Fuel .....             | QRSCM                       | ERSCM                    |
| Coal .....                      | QCLCM                       | ECLCM                    |
| Natural Gas .....               | QNGCM                       | ENGCM                    |
| <b>Industrial</b>               |                             |                          |
| Distillate Fuel .....           | QDSIN                       | EDSIN                    |
| Kerosene .....                  | QKSIN                       | EKSIN                    |
| Liquefied Petroleum Gas .....   | QLGIN                       | ELGIN                    |
| Natural Gas .....               | QNGIN                       | ENGIN                    |
| Lease and Plant Fuel .....      | QLPIN                       | ELPIN                    |
| Steam Coal .....                | QCLIN                       | ECLIN                    |
| Motor Gasoline .....            | QMGIN                       | EMGIN                    |
| Petroleum Feedstock .....       | QPFIN                       | EPFIN                    |
| Petroleum Coke .....            | QPCIN                       | EPCIN                    |
| Still Gas .....                 | QSGIN                       | ESGIN                    |
| Asphalt and Road Oil .....      | QASIN                       | EASIN                    |
| Other Petroleum .....           | QOTIN                       | EOTIN                    |
| Metallurgical Coal .....        | QMCIN                       | EMCIN                    |
| <b>Transportation</b>           |                             |                          |
| Compressed Natural Gas .....    | QNGTR                       | ENGTR                    |
| Pipeline Fuel Natural Gas ..... | QGPTR                       | EGPTR                    |
| Motor Gasoline .....            | QMGTR                       | EMGTR                    |
| Jet Fuel .....                  | QJFTR                       | EJFTR                    |
| Distillate .....                | QDSTR                       | EDSTR                    |
| Liquid Petroleum Gas .....      | QLGTR                       | ELGTR                    |
| Methanol .....                  | QMETR                       | EMETR                    |
| Other Petroleum .....           | QOTIN                       | EOTIN                    |
| <b>Electric Generators</b>      |                             |                          |
| Distillate .....                | QDSEL                       | EDSEL                    |
| Petroleum Coke .....            | QPCEL                       | EPCEL                    |
| Natural Gas - Core .....        | QGFEL                       | EGFEL                    |
| Natural Gas - Non-Core .....    | QGIEL                       | EGIEL                    |
| Residual - High Sulfur .....    | QRHEL                       | ERHEL                    |
| Residual - Low Sulfur .....     | QRLEL                       | ERLEL                    |

Table 7. Energy Consumption and Emission Factor Variables for Carbon Emissions (continued)

| Fuel Type by Sector                         | Energy Consumption Variable | Emission Factor Variable |
|---|-----------------------------|--------------------------|
| <b>Electric Generators (cont'd)</b>         |                             |                          |
| Coal By Plant Type and EMM Region:          |                             |                          |
| Old Plants, Low Emission Standards .....    | QCLOLNR                     | CCLOLNR                  |
| Old Plants, Medium Emission Standards ..... | QCLOMNR                     | CCLOMNR                  |
| Old Plants, High Emission Standards .....   | QCLOHNR                     | CCLOHNR                  |
| New Plants, Low Emission Standards .....    | QCLNLNR                     | CCLNLNR                  |
| New Plants, Medium Emission Standards ..... | QCLNMNR                     | CCLNMNR                  |
| New Plants, High Emission Standards .....   | QCLNHNR                     | CCLNHNR                  |
| Plants with Flue Gas Scrubbers .....        | QCLSBNR                     | CCLSBNR                  |

Several adjustments to the carbon calculations are made in the industrial, transportation, and electricity generation sectors, as follows.

**Industrial:** The use of fossil fuels for non-fuel use of certain end-use products such as feedstocks for chemical production causes a significant amount of carbon to be sequestered in the product and not released to the atmosphere. Technically, the amount of carbon sequestered depends on product characteristics that are not defined explicitly in NEMS. Following standard practice, an average sequestration fraction is used for each nonfuel use.<sup>6</sup> In the Industrial Module, the two major feedstocks are liquified petroleum gases (LPG) and natural gas. Consumption of these fuels is divided into feedstock and combustion categories. For the feedstock uses, an appropriate sequestration rate is applied to account for the average proportion of carbon sequestered among products in this category. "Other" petroleum products consist of lubricants and miscellaneous petroleum products.

**Transportation:** The total consumption of motor gasoline reported by the Transportation module includes both gasoline, gasoline-ethanol mixtures, and gasoline containing oxygenates with ethanol precursors. Since ethanol is considered a renewable fuel with zero net carbon emissions, the total consumption of motor gasoline was reduced by the amount of ethanol used in its production before multiplication by the emission coefficient. This modification represents less than one million metric tons of carbon. Furthermore, since "other" petroleum was considered

<sup>6</sup>Energy Information Administration, *Emissions of Greenhouse Gases in the United States; 1987-1992*, DOE/EIA-0573 (Washington, DC, 1994), pg 14.



primarily lubricants, the emission coefficient and sequestration rate for lubricants was used for all of "other" petroleum.

**Electricity Generation Market:** Carbon emissions for coal are computed for each of seven categories of coal, as determined in the Electricity Market Module and Coal Market Module. The carbon emissions factors each coal category are provided by the Coal Market Module. This methodology incorporates changes in the mix of coal types used over time.

## **Emissions Policy Submodule**

The Emissions Policy Submodule (EPM) implements four carbon policy evaluation options. None of the policy options are assumed to take place in runs for the *Annual Energy Outlook 1997*. However, the options could be used to simulate potential market-based approaches to meet National carbon emission objectives. The four policy options are as follows:

- 1) **Carbon Tax.** A nominal or real dollar tax per kilogram of carbon for fossil fuels is converted to a dollar-per-Btu tax for each fuel/sector based on the carbon emission factor.<sup>7</sup> A different tax may be set for each year. Fossil fuel prices are adjusted to include the tax. The demand and conversion models respond to the adjusted fossil fuel prices to induce carbon reductions. Revenue from the tax is passed to the macroeconomic module. There, treatment of such revenue (e.g., reducing the deficit or reducing other taxes), depends on option settings in the macroeconomic module. Generally, large changes in government revenue would require additional offline analysis to assess macroeconomic feedbacks.
- 2) **Auction of Permits.** An auction to distribute emissions permits is simulated. The total number of permits sold corresponds to the total carbon emission goal as set by the user. A different goal may be set for each year. Essentially, this option determines the permit fee necessary to achieve the carbon goal by clearing the auction market. The permit fee is treated as a carbon tax and used as an adjustment to the fossil fuel prices. A new auction price is set each NEMS iteration until the emissions reach the goal. The permit auction is assumed to operate with no initial allocation of emission permits. As in Option 1, Carbon Tax, revenue from the auction is passed to the macroeconomic module where its effect may require additional analysis.
- 3) **Market For Permits.** A market for tradable carbon emissions permits is simulated assuming that an initial distribution of marketable permits to emission sources takes place. The permits are transferable but are not banked between years. As with the carbon tax and auction options, the full market price of the permits is added to the energy prices on a dollar-per-Btu basis. The system of marketable permits is implemented in the same way as the permit auction, with the exception of the calculation of revenues from permit sales. Similar treatment is warranted because the marginal cost of a "free" permit is equivalent to one purchased at auction, given the opportunity cost of holding the distributed permit.

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<sup>7</sup>A single tax rate applies to all categories of carbon use. A switch in the control file allows the tax rate to be treated as either a carbon tax (\$ per kilogram carbon) or as a Btu tax (\$ per million Btu). This flexibility allows the emissions policy module to be used to analyze simple energy tax policies as well.

In an open, competitive permit market, the permit will tend to be priced at the marginal cost of reducing carbon emissions, regardless of the initial distribution of permits. If permits are purchased by suppliers and passed through to the fuel price, the marginal cost of the carbon emission by a particular sector in a region will be reflected in the individual end-use fuel cost for that sector.

The evaluation of the initial distribution of permits depends on the sector. For those sectors in which the product prices are based on marginal cost, as modeled in the Petroleum Marketing Module, the value of the initial distribution of permits may be ignored; it does not affect the price of products. However, in the regulated electricity sector, where the average cost is used to determine price, the revenue attributed to the free use or sales of the initially distributed permits would possibly be passed through to the consumers. The value of the initial distribution of permits is calculated, but it is not used for electricity pricing purposes. Instead, the full cost of the permits, as though there were no initial distribution, is reflected in the electricity price.

As with the auction, a new permit fee is set each iteration. The fee is adjusted once each iteration in response to the total carbon emissions obtained. The price of an allowance is adjusted until the total carbon produced is within a tolerance of the goal for that year.

4) Market for Permits with Emission Offsets. The offset option allows for the goal on tradeable emissions permits to increase through a user-specified supply of offsets. Part of a greenhouse gas emission reduction strategy may be an offset policy. An offset policy gives credit to reductions in emissions from sources whose total emissions would be difficult to quantify precisely, such as the capture of coal bed methane. Offsets could also be available from activities like reforestation, to reflect the increase in carbon sequestration. The amount of offsets for reforestation and coal bed methane capture must be specified at various permit prices; the higher the price, the greater the assumed offsets. The offset, in millions of tons available at a given allowance price, is added to the carbon goal. While some test values for offsets are available, any formal use of this option would require additional research to arrive at appropriate assumptions. Another possible use of this option would be to simulate the availability of international carbon emission allowances.

## **Emissions Policy Submodule Implementation and Mathematical Specification**

The Emissions Policy Submodule (EPM) is called at the end of each NEMS iteration, after all the other modules have been called. With all four of the EPM options, some form of energy price adjustment is calculated to account for the carbon tax, or permit fee, for the next iteration. The carbon fee is either fixed (for a straight carbon tax) or is varied each NEMS iteration until a carbon goal is met (for the permit auction and permit market options).

The fee on carbon emissions is modeled as an adjustment on the end-use price of the fuel. Two sets of end-use price variables are maintained in NEMS: an *unadjusted* set of prices without any carbon fee added, and an *adjusted* set of prices that includes the carbon fee. The *unadjusted* prices are those determined by the NEMS supply and conversion modules. The *adjusted* prices, with the carbon fee included, are the prices variables actually used by the demand models. In the

integrating module, after each module is executed, the adjusted fuel prices are reassigned based on the current carbon fee.

### ***Input-Output Linkages***

The input data for EPM comes primarily from other modules of NEMS. The only other exogenous data are the policy options to be implemented and the carbon emissions factors. If a carbon tax scenario is to be implemented, the tax rate must also be specified. Alternatively, a carbon goal may be specified, and the carbon tax to meet that goal will be set in the EPM once each iteration of the NEMS solution algorithm. Output from the EPM consists of adjustments of the end-use prices of fuels consumed by the demand and conversion modules. The adjustments are additions to prices in dollars per million Btu. Revenue, in billions, from the carbon penalty is also calculated, where it can be used by the Macroeconomic module or for offline analysis of macroeconomic feedbacks.

The EPM inputs and outputs are stored in the NEMS global data structure. As input, three common blocks contain the NEMS end-use fuel prices: MPBLK, NGTDMOUT and COALPRC. These prices, established in the NEMS supply and conversion modules, are the input prices to the EPM. As output, EPM determines a dollar-per-Btu adjustment to each product-sector price to reflect any carbon tax or allowance fee. EPM adds the adjustment to the NEMS end-use fuel prices and stores them in a parallel set of price common blocks: AMPBLK, ANGTDM, and ACOALPRC. When no carbon policy options are in effect, the adjusted price common blocks (AMPBLK, ANGTDM, ACOALPRC) match the unadjusted price common blocks from the supply modules (MPBLK, NGTDMOUT, and COALPRC). The energy price adjustments, equal to the difference between the two sets of prices, are stored in the EMABLK common block. If nonzero, these prices adjustments are used as starting values when either of the carbon goal options (auction or permit market) are in effect.

The total carbon emission from both combustion and non-combustion sources is calculated in the EPM from information in the common blocks QBLK, INDOUT, EMMOUT, and COALEMM. The common QBLK contains the quantities of end-use fuels consumed. In QBLK, feedstock uses of liquid gas and natural gas are not broken out separately from total industrial liquid gas and natural gas, respectively. The feedstock portion of these fuels is obtained from two variables, INQLGPF and INQNGPF, in the common block INDOUT. The EMMOUT common has natural gas consumption reported by EMM region for firm, interruptible, and competitive categories. The COALEMM block contains coal consumption by SO<sub>2</sub> classification category and emissions factors for coal aggregated to those same categories. Several policy options result in revenue from the carbon penalty flowing to the government. This revenue is furnished to the MACRO module through the EMISSION common block.

### ***Emissions Policy Submodule Algorithm***

The EPM is executed once each iteration to determine total carbon emissions produced, the revenue created by any tax or permit fees for carbon emissions, and, depending upon the scenario, the level of offsets produced. For the carbon goal policy options, a heuristic algorithm

(subroutine REGFALSI) sets a new carbon fee to bring the carbon emissions closer to the carbon goal.

The following outline depicts the steps in the submodule flow, showing subroutine calls and variable names in parentheses.

- I. First Year, First Iteration Processing
  - A. Read control file, "epmctl," to get settings for the four policy options (TAX\_FLAG, PERMIT\_FLAG, MARKET\_FLAG, OFFSET\_FLAG)
  - B. Read emissions policy data file "epmdata" (Call EPM\_READ).
    - 1) Read yearly arrays with the emission tax (EMTAX), carbon goal (EMISSIONS\_GOAL), and maximum tax (MAX\_TAX).
    - 2) Read coal region mapping variable (obsolete).
    - 3) Read yearly arrays with emission factors for each fuel/sector product (variable names are the same as the corresponding NEMS energy consumption variables but start with "E" instead of "Q").
    - 4) Read supply curve prices, quantities for reforestation offsets (PREF, OFFSETREF).
    - 5) Read supply curve prices and quantities for coal bed methane offsets (PCB, OFFSETCB).
- II. Calculate carbon emissions and sum to a national total (Call SUM\_EMISSIONS).
- III. Calculate revenues from carbon tax or carbon permit fees (Call ACCNTREV).
- IV. Under a market permit system, allocate revenue to end-use sectors based on initial sector shares of carbon emissions (Call INITREV).
- V. Under a market permit system with offsets, determine what level of emission offsets are available to raise the carbon cap, given the current carbon tax (Call OFFSETS).
- VI. With a permit auction or market, assign a new carbon tax to reduce the absolute difference between the carbon emissions and the carbon goal (Call REGFALSI)
- VII. Calculate energy price adjustments of end-use fuels from the carbon tax by multiplying the carbon tax by the fuels' emission factors (Call PRICE\_ADJUST).
- VIII. After every NEMS module called, reassign the adjusted prices by adding the carbon tax price adjustments to the unadjusted prices (Call COPY\_ADJUST).

### ***Emission Policy Submodule Mathematical Specification***

The following subroutine descriptions provide the mathematical specifications for these calculations.

## SUBROUTINE EPM

This subroutine is the main controlling subroutine for the Emissions Policy Submodule. Initially, the subroutine reads flags to determine the scenario type: carbon tax, auction of permits, market for permits, and permit market with offsets. Based on these flags, the module calls the appropriate subroutines. For all options, carbon emissions are estimated (SUM\_EMISSIONS), and the revenue from any carbon fee, regardless of whether it is from a carbon tax, auction, or permit trading policy is calculated (ACCNTREV). For the permit trading policy, a routine is called to distribute an initial allocation of the revenues, equivalent to distributing "free" permits to the consuming sectors in proportion to their base year carbon emissions (INITREV). For an auction or permit market policy, a new permit fee is established each NEMS iteration, such that the emissions goal is met within a given tolerance level (REGFALSI). For the carbon emissions offset option, the offsets that would be created at the previous market clearing price are added to the emissions goal (OFFSETS).

Called by: Integrating Module, Subroutine NSOLVE

Calls:  
EPM\_READ  
SUM\_EMISSIONS  
ACCNTREV  
INITREV  
REGFALSI  
OFFSETS  
PRICE\_ADJUST

Equations: None.

## SUBROUTINE SUM\_EMISSIONS

**Description:** This subroutine calculates carbon emissions by sector and returns to national total, AMTPOL. Carbon emissions are the product of end use fuel consumption and the corresponding emissions factor. The emissions are aggregated by Census region and sector. The variables for fuel quantities are defined in the common blocks QBLK and EMMOUT.

**Called by:** EPM

**Calls:** None

**Equations:**

$$AMTPOL = \sum_i \sum_j \sum_k Em(ik) * Qf(ijk)$$

where

AMTPOL = Total carbon emissions from all fuel i (billion kilogram-carbon) from all regions j in year k,

Em(ik) = Carbon emission factor for fuel i (kilogram-carbon /million-Btu) in year k,

Qf(ijk) = Quantity of fuel i consumed (trillion-Btu) in region j and year k.

SUBROUTINE ACCNTREV

Description: This subroutine calculates the total revenue raised from each sector by the emissions fee (tax or permit fee). Revenue is calculated by multiplying the quantity of end-use fuel consumption by an emissions factor and the emissions fee.

Called by: EPM

Calls: None

Equations:

$$REV(l) = \sum_{i=1} \sum_j \sum_k EMTAX(k) Em(ik) Qf(ijk) / 1000$$

where

REV(l) = Total revenue collected in sector l from all fuel i from all regions j and in year k (Billion 1987 \$),  
Em(ik) = Emission factor for fuel i (kilograms-carbon /million-Btu) in year k,  
EMTAX(k)= Carbon tax or permit fee (87\$/kilogram carbon) in year k  
Qf(ijk) = Quantity of fuel i consumed in region j and year k (trillion-Btu)

## SUBROUTINE INTREV

**Description:** If a marketable permit system is being modeled, a given number of permits will be distributed initially to the affected sources. This subroutine calculates the value of this initial allocation of permits by multiplying the number of permits by the carbon permit fee.

**Called by:** EPM

**Calls:** None.

**Equations:**

$$CallocInit = Sallocinit * Palloc$$

where

CallocInit = Total value of initial allocation of permits (billion 1987 \$),  
SallocInit = Permits allocated initially (billion kilograms-carbon)  
Palloc = Price of a permit (87\$/kilograms-carbon).



## SUBROUTINE OFFSETS

**Description:** Offsets may be used to credit reductions in greenhouse gas emissions against the emissions goal. This subroutine uses linear interpolation to determine from an ordered price schedule, or offset supply curve, the offsets that would be made available at a particular permit price.

**Called by:** EPM

**Calls:** none

$$OFFST = OFFSET(I) + \frac{OFFSET(I+1) - OFFSET(I)}{PRICE(I+1) - PRICE(I)}$$

where

OFFST = Total offsets (billion-kilogram-carbon),  
PRICE(I) = Highest price on the offset supply schedule that is less than the current (or trial) emissions fee (87\$/kilogram),  
PRICE(I+1) = Lowest price on the offset supply schedule that is greater than the current emissions fee (87\$/kilogram),  
OFFSET(I) = Offset quantity corresponding to PRICE(I) (billion-kilogram-carbon),  
OFFSET(I+1) = Offset quantity corresponding to PRICE(I+1) (billion-kilogram-carbon.)

**SUBROUTINE: PRICE\_ADJUST**

**Description:** This subroutine assigns the price adjustment of each fuel to reflect the carbon emissions tax of permit fee by multiplying it by the fuel's emission factor. These price adjustments are used in subroutine COPY\_ADJUST to establish adjusted fuel prices that include the carbon tax or permit fee.

**Called by:** EPM

**Calls:** None.

**Equations:**

$$Eadj(ik) = Em(ik) * EMTAX(k)$$

where

|            |   |   |
|------------|---|---|
| $Em(ik)$   | = | Emission factor for fuel i (kilograms-carbon /million-Btu) in year k, |
| $EMTAX(k)$ | = | Carbon tax (\$/kilogram-carbon) in year k                             |
| $Eadj(ik)$ | = | Price adjustment of fuel i (\$/million-Btu) in year k.                |

SUBROUTINE: REGFALSI

**Description:** This subroutine adjusts the carbon tax (or carbon permit fee) such that the carbon emission goal is met. In general, the routine will increase the tax if the carbon emissions exceed the goal and decrease the tax if the emissions fall below the goal.

The routine first establishes a tax range to try to bracket emissions within an interval around the goal. Let  $f(x)$  be the difference between the carbon emissions and the carbon goal for a carbon tax of  $x$ . Note the  $f(x) > 0$  implies the tax is too low, while  $f(x) < 0$  implies the tax is too high. The objective is to find  $x$ , where  $f(x) = 0$ . Initially, the subroutine must adjust the value of  $x$  to find two values of the carbon penalty,  $x_i$  and  $a_i$ , where  $x_i < a_i$ ,  $f(x_i) < 0$ , and  $f(a_i) > 0$ . Once these conditions hold, a new trial tax,  $u$ , is established within the interval between  $x_i$  and  $a_i$  using the equation below.

This interpolation method to find the root is known as *the method of false position*, or *regula falsi*.

**Called by:** EPM

**Calls:** None.

**Equations:**

$$u = \frac{[a_i f(x_i) - x_i f(a_i)]}{f(x_i) - f(a_i)}$$

where

$a_i$  = Carbon tax on some previous iteration  $i$  such that  $f(a_i) < 0$ ,  
 $x_i$  = Carbon tax on some previous iteration  $i$  such that  $f(x_i) > 0$ ,  
 $u$  = New carbon tax.

In the next iteration,  $x_i$  is replaced with  $u$  if  $f(u) < 0$ , or  $a_i$  is replaced with  $u$  if  $f(u) > 0$ . Using this procedure, the value of  $u$  is found such that  $f(u) = 0$  to some tolerance.

**SUBROUTINE: COPY\_ADJUSTED**

**Description:** This subroutine updates the adjusted price common blocks, adding a fuel-specific cost adjustment to reflect a carbon tax or permit fee on each fuel. All of the prices in the unadjusted price common blocks MPBLK, COALOUT and NGDTMOUT, are copied to the corresponding adjusted price common blocks AMPBLK, ACOAL and ANGTFM each time a NEMS module is executed, and the fuel-specific price adjustments for specific variables calculated in subroutine PRICE\_ADJUST are added.

**Called By:** NSOLVE

**Calls:** none

**Equations:**

$$Padj(ijk) = Pbase(ijk) + Eadj(ik)$$

where

$Padj(ijk)$  = Adjusted price of fuel i in region j and year k (87\$/million-Btu),  
 $Pbase(ijk)$  = Unadjusted price of fuel i (87\$/million-Btu) in region j and year k.  
 $Eadj(ik)$  = Price adjustment of fuel i (87\$/million-Btu) in year k.

**SUBROUTINE: EPM\_READ**

**Description:** This subroutine reads the initial carbon penalty, emissions factors, and offset curves for the EPM.

**Called by:** EPM

**Calls:** None.

**Equations:** None.

## Emission-Related Variable Listing

### EMISSIONS Common Block

| Description                                   | Variable        | Type   | Units             | Indices     |
|---|-----------------|--------|-------------------|-------------|
| Coalbed Recovery Offset Prices                | PCB             | REAL*4 | 87\$/kg Carbon    | (MAX_INDEX) |
| Reforestation Offset Prices                   | PREF4           | REAL*4 | 87\$/kg Carbon    | (MAX_INDEX) |
| Offset for coalbed methane                    | OFFSETCB        | REAL*4 | billion kg Carbon | (MAX_INDEX) |
| Offset for Reforestation                      | OFFSETREF       | REAL*4 | billion kg Carbon | (MAX_INDEX) |
| Tax or Permit Price                           | EMTAX           | REAL*4 | 87\$/kg Carbon    | (Year)      |
| National carbon emissions                     | TOTAL_EMISSIONS | REAL*4 | billion kg Carbon | (Year)      |
| Carbon emissions Goal                         | EMISSIONS_GOAL  | REAL*4 | billion kg Carbon | (Year)      |
| Initial carbon permit allocation by 5 sectors | INIT_ALLOC      | REAL*4 | billion kg Carbon | (5,Year)    |

## Adjusted Price Common Block

| Description                     | Variable | Type | Units      | Indices  |
|---------------------------------|----------|------|------------|----------|
| Purch. Elec. Peak. Resid        | AEPRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Peak. Comm         | AEPCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Peak. Trans        | AEPTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Peak. Indust       | AEPIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Peak. Refinery     | AEPAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Nonpeak. Resid     | AENRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Nonpeak. Comm      | AENCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Nonpeak. Trans     | AENTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Nonpeak. Indust    | AENIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Nonpeak. All Sect  | AENAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Resid              | AELRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Comm               | AELCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Trans              | AELTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. Indust             | AELIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Purch. Elec. All Sectors        | AELAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Core. Resid        | AGFRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Core. Comm         | AGFCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Core. Trans        | AGFTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Core. Indust       | AGFIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Core. Electr       | AGFEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Core. All Sect     | AGFAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Noncore. Resid     | AGIRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Noncore. Comm      | AGICM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Noncore. Trans     | AGITR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Noncore. Indust    | AGIIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Noncore. Electr    | AGIEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Noncore. All Sect  | AGIAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Residential        | ANGRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Commercial         | ANGCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Transportation     | ANGTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Industrial         | ANGIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Electricity        | ANGEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. All Sectors        | ANGAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Natural Gas. Pipeline           | AGPTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Lease and Plant Fuel            | ALPIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Coal. Residential               | ACLRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Coal. Commercial                | ACLCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Coal. Industrial                | ACLIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Coal. Electricity               | ACLEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Coal. Synthetics                | ACLSN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Coal. All Sectors               | ACLAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Metallurgical Coal. Industrial  | AMCIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Motor Gasoline. Commercial      | AMGCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Motor Gasoline. Trans           | AMGTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Motor Gasoline. Industrial      | AMGIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Motor Gasoline. All Sectors     | AMGAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Jet Fuel. Transportation        | AJFTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Distillate. Residential         | ADSRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Distillate. Commercial          | ADSCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Distillate. Transportation      | ADSTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Distillate. Industrial          | ADSIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Distillate. Electric-Petro Coke | ADSEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Distillate. All Sectors         | ADSAS    | REAL | 87\$/MMBTU | (Reg,Yr) |

| Description                     | Variable | Type | Units      | Indices  |
|---------------------------------|----------|------|------------|----------|
| Kerosene. Residential           | AKSRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Kerosene. Commercial            | AKSCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Kerosene. Industrial            | AKSIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Kerosene. All Sectors           | AKSAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Liquid Petroleum Gases. Resid   | ALGRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Liquid Petroleum Gases. Comm    | ALGCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Liquid Petroleum Gases. Trans   | ALGTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Liquid Petroleum Gases. Indust  | ALGIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Liquid Petroleum Gases.All Sect | ALGAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,Low Sulfur. Comm  | ARLCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,Low Sulfur.Trans  | ARLTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,Low Sulfur.Ind    | ARLIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,Low Sulfur.Ele    | ARLEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,Low Sul. All Sec  | ARLAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,High Sul. Trans   | ARHTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,High Sul. Electr  | ARHEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel,High Sul. All Sec | ARHAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel. Commercial       | ARSCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel. Transportation   | ARSTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel. Industrial       | ARSIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel. Electricity      | ARSEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Residual Fuel. All Sectors      | ARSAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Petrochemical Feedstocks. Ind   | APFIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Asphalt, Road Oil. Indust       | AASIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Other Petroleum. Trans          | AOTTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Other Petroleum. Indust         | AOTIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Other Petroleum. Indust         | AOTAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Total Petroleum. Resid          | ATPRS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Total Petroleum. Comm           | ATPCM    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Total Petroleum. Trans          | ATPTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Total Petroleum. Indust         | ATPIN    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Total Petroleum. Refinery       | ATPRF    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Total Petroleum. Electr         | ATPEL    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Total Petroleum. All Sectors    | ATPAS    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Methanol. Transportation        | AMETR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Ethanol. Transportation         | AETTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Liquid Hydrogen. Transporation  | AHYTR    | REAL | 87\$/MMBTU | (Reg,Yr) |
| Uranium. Electricity            | AUREL    | REAL | 87\$/MMBTU | (Reg,Yr) |

## Emissions Factors Common Block

| Description                    | Variable | Type | Units      | Indices |
|--------------------------------|----------|------|------------|---------|
| Natural Gas, Core. Residential | EGFRS    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Core. Commercial  | EGFCM    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Core. Transport   | EGFTR    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Core. Industrial  | EGFIN    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Core. Electricity | EGFEL    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Noncore. Resid    | EGIRS    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Noncore. Comm     | EGICM    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Noncore. Transp   | EGITR    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Noncore. Indust   | EGIIN    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas, Noncore. Electr   | EGIEL    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas. Residential       | ENGRS    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas. Commercial        | ENGCM    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas. Transportation    | ENGTR    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas. Industrial        | ENGIN    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas. Electricity       | ENGEL    | REAL | Kg C/MMBtu | (Year)  |
| Natural Gas. Pipeline          | EGPTR    | REAL | Kg C/MMBtu | (Year)  |
| Lease and Plant Fuel           | ELPIN    | REAL | Kg C/MMBtu | (Year)  |
| Coal. Residential              | ECLRS    | REAL | Kg C/MMBtu | (Year)  |
| Coal. Commercial               | ECLCM    | REAL | Kg C/MMBtu | (Year)  |
| Coal. Industrial               | ECLIN    | REAL | Kg C/MMBtu | (Year)  |
| Coal. Electricity              | ECLEL    | REAL | Kg C/MMBtu | (Year)  |
| Metallurgical Coal. Industrial | EMCIN    | REAL | Kg C/MMBtu | (Year)  |
| Motor Gasoline. Commercial     | EMGCM    | REAL | Kg C/MMBtu | (Year)  |
| Motor Gasoline. Transportation | EMGTR    | REAL | Kg C/MMBtu | (Year)  |
| Motor Gasoline. Industrial     | EMGIN    | REAL | Kg C/MMBtu | (Year)  |
| Jet Fuel. Transportation       | EJFTR    | REAL | Kg C/MMBtu | (Year)  |
| Distillate. Residential        | EDSRS    | REAL | Kg C/MMBtu | (Year)  |
| Distillate. Commercial         | EDSCM    | REAL | Kg C/MMBtu | (Year)  |
| Distillate. Transportation     | EDSTR    | REAL | Kg C/MMBtu | (Year)  |
| Distillate. Industrial         | EDSIN    | REAL | Kg C/MMBtu | (Year)  |
| Distillate. Elect(+Petro Coke) | EDSEL    | REAL | Kg C/MMBtu | (Year)  |
| Kerosene. Residential          | EKSRS    | REAL | Kg C/MMBtu | (Year)  |
| Kerosene. Commercial           | EKSCM    | REAL | Kg C/MMBtu | (Year)  |
| Kerosene. Industrial           | EKSIN    | REAL | Kg C/MMBtu | (Year)  |
| Liquid Petroleum Gases. Resid  | ELGRS    | REAL | Kg C/MMBtu | (Year)  |
| Liquid Petroleum Gases. Comm   | ELGCM    | REAL | Kg C/MMBtu | (Year)  |
| Liquid Petroleum Gases. Trans  | ELGTR    | REAL | Kg C/MMBtu | (Year)  |
| Liquid Petroleum Gases. Indust | ELGIN    | REAL | Kg C/MMBtu | (Year)  |



| Description                    | Variable | Type   | Units      | Indices |
|--------------------------------|----------|--------|------------|---------|
| Residual Fuel,Low Sulfur.Comm  | ERLCM    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel,Low Sulfur.Tran  | ERLTR    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel,Low Sulfur.Ind   | ERLIN    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel,Low Sulfur.Ele   | ERLEL    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel,High Sul.Trans   | ERHTR    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel,High Sul.Elect   | ERHEL    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel. Commercial      | ERSCM    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel. Transportation  | ERSTR    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel. Industrial      | ERSIN    | REAL   | Kg C/MMBtu | (Year)  |
| Residual Fuel. Electricity     | ERSEL    | REAL   | Kg C/MMBtu | (Year)  |
| Methanol. Transportation       | EMETR    | REAL   | Kg C/MMBtu | (Year)  |
| Ethanol. Transportation        | EETTR    | REAL   | Kg C/MMBtu | (Year)  |
| Pet Feedstocks Industrial      | EPFIN    | REAL   | Kg C/MMBtu | (Year)  |
| Pet Code Industrial            | EPCIN    | REAL   | Kg C/MMBtu | (Year)  |
| Still Gas Industrial           | ESGIN    | REAL   | Kg C/MMBtu | (Year)  |
| Other Pet Industrial           | EOTIN    | REAL   | Kg C/MMBtu | (Year)  |
| Pet Coke Electricity           | EPCEL    | REAL   | Kg C/MMBtu | (Year)  |
| VLS Bit Coal Emissions By NERC | EBCELNR  | REAL   | Kg C/MMBtu | (Year)  |
| LS Bit Coal Emissions By NERC  | EBDELNR  | REAL   | Kg C/MMBtu | (Year)  |
| MS Bit Coal Emissions By NERC  | EBMELNR  | REAL   | Kg C/MMBtu | (Year)  |
| HS Bit Coal Emissions By NERC  | EBHELNR  | REAL   | Kg C/MMBtu | (Year)  |
| VLS Sub Coal Emissions By NERC | ESCELNR  | REAL   | Kg C/MMBtu | (Year)  |
| LS Sub Coal Emissions By NERC  | ESDELNR  | REAL   | Kg C/MMBtu | (Year)  |
| MS Sub Coal Emissions By NERC  | ESMELNR  | REAL   | Kg C/MMBtu | (Year)  |
| HS Sub Coal Emissions By NERC  | ESHELNR  | REAL   | Kg C/MMBtu | (Year)  |
| VLS Lig Coal Emissions By NERC | ELCELNR  | REAL   | Kg C/MMBtu | (Year)  |
| LS Lig Coal Emissions By NERC  | ELDELNR  | REAL   | Kg C/MMBtu | (Year)  |
| MS Lig Coal Emissions By NERC  | ELMELNR  | REAL   | Kg C/MMBtu | (Year)  |
| HS Lig Coal Emissions By NERC  | ELHELNR  | REAL   | Kg C/MMBtu | (Year)  |
| E Util Firm NG Emissions       | EGFELGR  | REAL*4 | Kg C/MMBtu | (Year)  |
| E Util Inter NG Emissions      | EGIELGR  | REAL*4 | Kg C/MMBtu | (Year)  |
| E Util Compet NG Emissions     | EGCELGR  | REAL*4 | Kg C/MMBtu | (Year)  |

## Quantity Common Block

| Description                    | Variable | Type | Units     | Indices  |
|--------------------------------|----------|------|-----------|----------|
| Purch Elec, Peak. Residential  | QEPRS    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Peak. Comm         | QEPCM    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Peak. Trans        | QEPTR    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Peak. Industrial   | QEPIN    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Peak. Refinery     | QEPRF    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Peak. All Sectors  | QEPAS    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Nonpeak. Resid     | QENRS    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Nonpeak. Comm      | QENCM    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Nonpeak. Trans     | QENTR    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Nonpeak. Ind       | QENIN    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Nonpeak. Refinery  | QENRF    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec, Nonpeak. All Sect  | QENAS    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec. Residential        | QELRS    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec. Commercial         | QELCM    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec. Transportation     | QELTR    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec. Industrial         | QELIN    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec. Refinery           | QELRF    | REAL | Trill Btu | (Reg,Yr) |
| Purch Elec. All Sectors        | QELAS    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Core. Residential  | QGFRS    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Core. Commercial   | QGFCM    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Core. Trans        | QGFTR    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Core. Industrial   | QGFIN    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Core. Refinery     | QGFRF    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Core. Electr       | QGFEL    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Core. All Sect     | QGFAS    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Noncore. Resid     | QGIRS    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Noncore. Comm      | QGICM    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Noncore. Trans     | QGITR    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Noncore. Indust    | QGIIN    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Noncore. Refinery  | QGIRF    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Noncore. Electr    | QGIEL    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Noncore. All Sect  | QGIAS    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Residential        | QNGRS    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Commercial         | QNGCM    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Transportation     | QNGTR    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Industrial         | QNGIN    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Refinery           | QNGRF    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Electricity        | QNGEL    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas All Sectors        | QNGAS    | REAL | Trill Btu | (Reg,Yr) |
| Natural Gas Pipeline           | QGPTR    | REAL | Trill Btu | (Reg,Yr) |
| Lease and Plant Fuel           | QLPIN    | REAL | Trill Btu | (Reg,Yr) |
| Coal. Residential              | QCLRS    | REAL | Trill Btu | (Reg,Yr) |
| Coal. Commercial               | QCLCM    | REAL | Trill Btu | (Reg,Yr) |
| Coal. Industrial               | QCLIN    | REAL | Trill Btu | (Reg,Yr) |
| Coal. Refinery                 | QCLRF    | REAL | Trill Btu | (Reg,Yr) |
| Coal. Electricity              | QCLEL    | REAL | Trill Btu | (Reg,Yr) |
| Coal. Synthetics               | QCLSN    | REAL | Trill Btu | (Reg,Yr) |
| Coal. All Sectors              | QCLAS    | REAL | Trill Btu | (Reg,Yr) |
| Metallurgical Coal Industrial  | QMCIN    | REAL | Trill Btu | (Reg,Yr) |
| Motor Gasoline. Commercial     | QMPCM    | REAL | Trill Btu | (Reg,Yr) |
| Motor Gasoline. Transportation | QMGTTR   | REAL | Trill Btu | (Reg,Yr) |
| Motor Gasoline. Industrial     | QMGIN    | REAL | Trill Btu | (Reg,Yr) |
| Motor Gasoline. All Sectors    | QMGAS    | REAL | Trill Btu | (Reg,Yr) |

| Description                      | Variable | Type | Units     | Indices  |
|----------------------------------|----------|------|-----------|----------|
| Jet Fuel Transportation          | QJFTR    | REAL | Trill Btu | (Reg,Yr) |
| Distillate Residential           | QDSRS    | REAL | Trill Btu | (Reg,Yr) |
| Distillate Commercial            | QDSCM    | REAL | Trill Btu | (Reg,Yr) |
| Distillate Transportation        | QDSTR    | REAL | Trill Btu | (Reg,Yr) |
| Distillate Industrial            | QDSIN    | REAL | Trill Btu | (Reg,Yr) |
| Distillate Refinery              | QDSRF    | REAL | Trill Btu | (Reg,Yr) |
| Distillate Electr(+petro coke)   | QDSEL    | REAL | Trill Btu | (Reg,Yr) |
| Distillate All Sectors           | QDSAS    | REAL | Trill Btu | (Reg,Yr) |
| Kerosene. Residential            | QKSRS    | REAL | Trill Btu | (Reg,Yr) |
| Kerosene. Commercial             | QKSCM    | REAL | Trill Btu | (Reg,Yr) |
| Kerosene. Industrial             | QKSIN    | REAL | Trill Btu | (Reg,Yr) |
| Kerosene. All Sectors            | QKSAS    | REAL | Trill Btu | (Reg,Yr) |
| Liquid Petroleum Gases Resid     | QLGRS    | REAL | Trill Btu | (Reg,Yr) |
| Liquid Petroleum Gases Comm      | QLGCM    | REAL | Trill Btu | (Reg,Yr) |
| Liquid Petroleum Gases Trans     | QLGTR    | REAL | Trill Btu | (Reg,Yr) |
| Liquid Petroleum Gases Ind       | QLGIN    | REAL | Trill Btu | (Reg,Yr) |
| Liquid Petroleum Gases Refine    | QLGRF    | REAL | Trill Btu | (Reg,Yr) |
| Liquid Petroleum Gases All Sec   | QLGAS    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel Low Sulfur Comm    | QRLCM    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel Low Sulfur Trans   | QRLTR    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel Low Sulfur Ind     | QRLIN    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel Low Sulfur Refine  | QRLRF    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel Low Sulfur Electr  | QRLEL    | REAL | Trill Btu | (Reg,Yr) |
| Resid Fuel Low Sulfur All Sec    | QRLAS    | REAL | Trill Btu | (Reg,Yr) |
| Resid Fuel High Sulfur Trans     | QRHTR    | REAL | Trill Btu | (Reg,Yr) |
| Resid Fuel High Sulfur Electr    | QRHEL    | REAL | Trill Btu | (Reg,Yr) |
| Resid Fuel High Sulfur All Sec   | QRHAS    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel. Commercial        | QRSCM    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel. Transportation    | QRSTR    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel. Industrial        | QRSIN    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel. Refinery          | QRSRF    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel. Electricity       | QRSEL    | REAL | Trill Btu | (Reg,Yr) |
| Residual Fuel. All Sectors       | QRSAS    | REAL | Trill Btu | (Reg,Yr) |
| Petrochemical Feedstocks. Ind    | QPFIN    | REAL | Trill Btu | (Reg,Yr) |
| Still Gas. Industrial            | QSGIN    | REAL | Trill Btu | (Reg,Yr) |
| Still Gas. Refinery              | QSGRF    | REAL | Trill Btu | (Reg,Yr) |
| Petroleum Coke. Industrial       | QPCIN    | REAL | Trill Btu | (Reg,Yr) |
| Petroleum Coke. Refinery         | QPCRF    | REAL | Trill Btu | (Reg,Yr) |
| Petroleum Coke. Electricity      | QPCEL    | REAL | Trill Btu | (Reg,Yr) |
| Petroleum Coke. All Sectors      | QPCAS    | REAL | Trill Btu | (Reg,Yr) |
| Asphalt and Road Oil Ind         | QASIN    | REAL | Trill Btu | (Reg,Yr) |
| Other Petr Trans-lubes,aviat gas | QOTTR    | REAL | Trill Btu | (Reg,Yr) |
| Other Petroleum. Industrial      | QOTIN    | REAL | Trill Btu | (Reg,Yr) |
| Other Petroleum. Refinery        | QOTRF    | REAL | Trill Btu | (Reg,Yr) |
| Other Petroleum. All Sectors     | QOTAS    | REAL | Trill Btu | (Reg,Yr) |
| Total Petroleum. Residential     | QTPRS    | REAL | Trill Btu | (Reg,Yr) |
| Total Petroleum. Commercial      | QTPCM    | REAL | Trill Btu | (Reg,Yr) |
| Total Petroleum. Trans           | QTPTR    | REAL | Trill Btu | (Reg,Yr) |
| Total Petroleum. Industrial      | QTPIN    | REAL | Trill Btu | (Reg,Yr) |
| Total Petroleum. Refinery        | QTPRF    | REAL | Trill Btu | (Reg,Yr) |
| Total Petroleum. Electricity     | QTPEL    | REAL | Trill Btu | (Reg,Yr) |
| Total Petroleum. All Sectors     | QTPAS    | REAL | Trill Btu | (Reg,Yr) |

| Description                       | Variable | Type | Units     | Indices  |
|-----------------------------------|----------|------|-----------|----------|
| Methanol. Transporation           | QMETR    | REAL | Trill Btu | (Reg,Yr) |
| Ethanol. Transporation            | QETTR    | REAL | Trill Btu | (Reg,Yr) |
| Liquid Hydrogen. Trans            | QHYTR    | REAL | Trill Btu | (Reg,Yr) |
| Uranium. Electricity              | QUREL    | REAL | Trill Btu | (Reg,Yr) |
| Hydropower. Industrial            | QHOIN    | REAL | Trill Btu | (Reg,Yr) |
| Hydropower. Electricity           | QHOEL    | REAL | Trill Btu | (Reg,Yr) |
| Hydropower. All Sectors           | QHOAS    | REAL | Trill Btu | (Reg,Yr) |
| Geothermal. Industrial            | QGEIN    | REAL | Trill Btu | (Reg,Yr) |
| Geothermal. Electricity           | QGEEL    | REAL | Trill Btu | (Reg,Yr) |
| Geothermal. All Sectors           | QGEAS    | REAL | Trill Btu | (Reg,Yr) |
| Biomass. Residential              | QBMRS    | REAL | Trill Btu | (Reg,Yr) |
| Biomass. Commercial               | QBMCM    | REAL | Trill Btu | (Reg,Yr) |
| Biomass. Industrial               | QBMIN    | REAL | Trill Btu | (Reg,Yr) |
| Biomass. Refinery                 | QBMRF    | REAL | Trill Btu | (Reg,Yr) |
| Biomass. Electricity              | QBMEL    | REAL | Trill Btu | (Reg,Yr) |
| Biomass. Synthetics               | QBMSN    | REAL | Trill Btu | (Reg,Yr) |
| Biomass. All Sectors              | QBMAS    | REAL | Trill Btu | (Reg,Yr) |
| Municipal Solid Waste Ind         | QMSIN    | REAL | Trill Btu | (Reg,Yr) |
| Municipal Solid Waste Electr      | QMSEL    | REAL | Trill Btu | (Reg,Yr) |
| Municipal Solid Waste All Sec     | QMSAS    | REAL | Trill Btu | (Reg,Yr) |
| Solar Thermal. Residential        | QSTRS    | REAL | Trill Btu | (Reg,Yr) |
| Solar Thermal. Commercial         | QSTCM    | REAL | Trill Btu | (Reg,Yr) |
| Solar Thermal. Industrial         | QSTIN    | REAL | Trill Btu | (Reg,Yr) |
| Solar Thermal. Electricity        | QSTEL    | REAL | Trill Btu | (Reg,Yr) |
| Solar Thermal. All Sectors        | QSTAS    | REAL | Trill Btu | (Reg,Yr) |
| Photovoltaic. Residential         | QPVRs    | REAL | Trill Btu | (Reg,Yr) |
| Photovoltaic. Commercial          | QPVCM    | REAL | Trill Btu | (Reg,Yr) |
| Photovoltaic. Industrial          | QPVIN    | REAL | Trill Btu | (Reg,Yr) |
| Photovoltaic. Electricity         | QPVEL    | REAL | Trill Btu | (Reg,Yr) |
| Photovoltaic. All Sectors         | QPVAS    | REAL | Trill Btu | (Reg,Yr) |
| Wind. Industrial                  | QWIIN    | REAL | Trill Btu | (Reg,Yr) |
| Wind. Electricity                 | QWIEL    | REAL | Trill Btu | (Reg,Yr) |
| Wind. All Sectors                 | QWIAS    | REAL | Trill Btu | (Reg,Yr) |
| Total Renewables. Residential     | QTRRS    | REAL | Trill Btu | (Reg,Yr) |
| Total Renewables. Commercial      | QTRCM    | REAL | Trill Btu | (Reg,Yr) |
| Total Renewables. Trans           | QTRTR    | REAL | Trill Btu | (Reg,Yr) |
| Total Renewables. Industrial      | QTRIN    | REAL | Trill Btu | (Reg,Yr) |
| Total Renewables. Electricity     | QTREL    | REAL | Trill Btu | (Reg,Yr) |
| Total Renewables. Synthetics      | QTRSN    | REAL | Trill Btu | (Reg,Yr) |
| Total Renewables. All Sectors     | QTRAS    | REAL | Trill Btu | (Reg,Yr) |
| Net Electricity Imports Electr    | QEIEL    | REAL | Trill Btu | (Reg,Yr) |
| Net Coal Coke Imports Ind         | QCIIN    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. Resid       | QTSRS    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. Comm        | QTSCM    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. Trans       | QTSTR    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. Ind         | QTSIN    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. Refine      | QTSRF    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. Electr      | QTSEL    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. Synthet     | QTSSN    | REAL | Trill Btu | (Reg,Yr) |
| Total Energy Consump. All Sec     | QTSAS    | REAL | Trill Btu | (Reg,Yr) |
| Breakout of natural gas feedstock | INQNGPF  | REAL | Trill Btu | (Reg,Yr) |
| Breakout of LPG feedstock         | INQLGPF  | REAL | Trill Btu | (Reg,Yr) |

## Appendix A. Bibliography

The National Energy Modeling System is documented in a series of model documentation reports, available by contacting the National Energy Information Center (202/586-8800). The first section of this Bibliography lists these documentation reports and their publication numbers. The second section lists other reports cited in this report. All reports listed in this appendix, unless cited otherwise, were produced by the Energy Information Administration.

### Model Documentation Reports

*Model Documentation Report: Macroeconomic Activity Module (MAM) of the National Energy Modeling System*, DOE/EIA-M065 (Washington, DC, 1997).

*Model Developer's Appendix to the Model Documentation Report: NEMS Macroeconomic Activity Module*, DOE/EIA-M065A(95) (Washington, DC, July 1994).

*Documentation of the DRI Model of the U.S. Economy*, DOE/EIA-M061 (Washington, DC, December 1993).

*NEMS International Energy Module, Model Documentation Report*, DOE/EIA-M071 (Washington, DC, April 1994).

*EIA Model Documentation: World Oil Refining Logistics Demand Model "World" Reference Manual*, DOE/EIA-M058 (Washington, DC, March 1994).

*Model Documentation Report: Residential Sector Demand Module of the National Energy Model System*, DOE/EIA-M067(97) (Washington, DC, 1997).

*Model Documentation Report: Commercial Sector Demand Module of the National Energy Modeling System*, DOE/EIA-M066(97) (Washington, DC, 1997).

*National Energy Modeling System Industrial Demand Module Documentation Report*, DOE/EIA-M064 (Washington, DC, 1997).

*Model Documentation Report: Transportation Sector Model of the National Energy Modeling System*, DOE/EIA-M070 (Washington, DC, March 1997).

*Model Documentation: Electricity Market Module, Load and Demand-Side Management Submodule. Volume 1: Model Description, DOE/EIA-M068-A/1 (Washington, DC, March 1994).*

*Model Documentation: Electricity Market Module, Load and Demand-Side Management Submodule. Volume 2: Model Code Listing, DOE/EIA-M068-A/2 (Washington, DC, March 1994).*

*Model Documentation: Electricity Market Module, Electricity Capacity Planning Submodule, DOE/EIA-M068-B (Washington, DC, March 1994).*

*Model Documentation: Electricity Market Module, Modifications to the Electricity Capacity Planning Submodule, DOE/EIA-M068-B/1 (Washington, DC, April 1995).*

*Model Documentation: Electricity Market Module, Electricity Finance and Pricing Submodule, DOE/EIA-M068-C (Washington, DC, March 1994).*

*Model Documentation: Electricity Market Module, Electricity Fuel Dispatch Submodule, DOE/EIA-M068-D(97) (Washington, DC, 1997).*

*Documentation of the Electricity Market Module (EMM). Appendix: Model Developer's Report, DOE/EIA-M068(95) (Washington, DC, February 1995).*

*Documentation of the Oil and Gas Supply Module (OGSM), DOE/EIA-M063(97) (Washington, DC, October 1997).*

*Documentation of the Oil and Gas Supply Module (OGSM). Appendix: Model Developer's Report, DOE/EIA-M063A(95) (Washington, DC, July 1994).*

*Model Documentation: Natural Gas Transmission and Distribution Model of the National Energy Modeling System. Volume 1, DOE/EIA-M062/1(97) (Washington, DC, 1997).*

*Model Documentation: Natural Gas Transmission and Distribution Model (NGTDM) of the National Energy Modeling System. Volume 2: Model Developer's Report, DOE/EIA-M062/2 (Washington, DC, January 1995).*

*EIA Model Documentation: Petroleum Market Model of the National Energy Modeling System, DOE/EIA-M059(97) (Washington, DC, 1997).*

*Documentation of the Petroleum Market Model (PMM). Appendix: Model Developer's Report, DOE/EIA-M095/A (Washington, DC, December 1994).*

*Model Documentation: Coal Market Module of the National Energy Modeling System, DOE/EIA-M060(97) (Washington, DC, 1997).*

*Model Documentation: Renewable Fuels Module of the National Energy Modeling System, DOE/EIA-M069(97) (Washington, DC, 1997).*

*Model Documentation: Renewable Fuels Module of the National Energy Modeling System. Appendix: Model Performance, DOE/EIA-M069/A (Washington, DC, September 1994).*

### **Other Documents**

Energy Information Administration, *The National Energy Modeling System: An Overview*, DOE/EIA-0581(96), (Washington, DC, March 1996).

Energy Information Administration, *Documentation of the Integrating Module of the Intermediate Future Forecasting System*, (Washington, DC, May 1991).

Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1995*, DOE/EIA-0573 (95) (Washington, DC, October 1996).

Energy Information Administration, *The Integrating Model of the Project Independence Evaluation System, Volume 3: User's Guide*, (Washington, DC, March 1979).

Energy Information Administration, *The Integrating Model of the Project Independence Evaluation System, Volume 5: Code Documentation*, (Washington, DC, July 1978).

Energy Information Administration, *The Integrating Model of the Project Independence Evaluation System, Volume 6: Data Documentation, Part 1*, (Washington, DC, February 1979).

Federal Energy Administration, *Project Independence Report*, (Washington, DC, November 1974).

Energy Information Administration, *Research into the Methodology of the LEAP Model*, (Washington, DC, December 1979).





## Appendix B. Model Abstract

**Model Name:** National Energy Modeling System, Integrating Module

**Acronym:** NEMS

**Description:** NEMS represents a general equilibrium solution of the interactions between the U.S. energy markets and the economy. The model achieves a supply and demand balance in the end-use demand regions, defined as the nine Census Divisions, by solving for the prices of each energy type such that the quantities producers are willing to supply equal the quantities consumers wish to consume. The system reflects market economics, industry structure, and energy policies and regulations that influence market behavior.

**Last Model Update:** October 1996

**Part of Another Model?** Part of the National Energy Modeling System.

**Model Interfaces:** NEMS integrates the efforts of the following modules, with model contacts as indicated:

|   |                                  |
|---|----------------------------------|
| Integrating Module                                  | Dan Skelly, 202-586-1722         |
| Residential Sector Demand Module                    | John H. Cymbalsky, 202-586-4815  |
| Commercial Sector Demand Module                     | Erin Boedecker, 202-586-4791     |
| Transportation Sector Demand Module                 | David M. Chien, 202-586-3994     |
| Industrial Sector Demand Module                     | Crawford Honeycutt, 202-586-1420 |
| Macroeconomic Activity Module                       | Kay Smith, 202-586-1455          |
| International Energy Activity Module                | Dan Butler, 202-586-9503         |
| Coal Market Module                                  |                                  |
| Coal Production                                     | Mike Mellish, 202-586-2136       |
| Coal Export   | Melinda Hobbs, 202-586-0012      |
| Coal Distribution                                   | Richard Newcombe, 202-586-2415   |
| Renewable Fuels Module                              | Tom Petersik, 202-586-6582       |
| Electricity Market Module                           | Jeffrey Jones, 202-586-2038      |
| Natural Gas Transmission and<br>Distribution Module | Joseph Benneche, 202-586-6132    |
| Oil and Gas Market Module                           | Ted McCallister, 202-586-4820    |
| Petroleum Market Module                             | Tom White, 202-586-1393          |

**Sponsor:** Office of Integrated Analysis and Forecasting, Energy Demand and Integration Division, National Energy Modeling System Branch, EI-811.

**Model Contact:** Dan Skelly (202) 586-1722

**Documentation:**

- Energy Information Administration, *NEMS Integrating Module Documentation Report*, DOE/EIA-M057(97) (Washington, DC, March, 1997).
- Energy Information Administration, *The National Energy Modeling System: An Overview*, DOE/EIA-0581(96) (Washington, DC, March 1996).

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

- NEMS-94 archive package for the *Annual Energy Outlook 1994*, DOE/EIA-0383(94).
- NEMS-95 archive package for the *Annual Energy Outlook 1995*, DOE/EIA-0383(95).
- NEMS-96 archive package for the *Annual Energy Outlook 1996*, DOE/EIA-0383(96).
- NEMS-97 archive package for the *Annual Energy Outlook 1997*, DOE/EIA-0383(97).

**Purpose:** The objective of NEMS is to account for the many interactions of the different segments of the energy industries and to provide an internally consistent forecast of prices and quantities for which supply equals demand. This equilibrium solution accounts for the main economic factors that affect supply and demand, allows price competition of fuels, and accounts for policies and regulations that cause deviations from purely economic behavior.

**Energy System Described by Model:** NEMS is a general equilibrium model of domestic energy supply and demand. It represents the domestic production of oil natural gas, refined petroleum products, coal and electricity. It also represents the two major energy conversion activities, the refining of crude oil into petroleum products and the conversion of fossil fuels, nuclear power, hydropower, and other renewable sources into electricity. Consumption of energy is represented by four end-use sectors: residential, commercial, industrial, and transportation.

**Coverage:**

- **Geographic:** Nine Bureau of Census Divisions. Some component analytical modules represent energy production or conversion at different levels of regional detail. All equilibration takes place at the Census Division level.
- **Time Unit/Frequency:** Annual through 2015
- **Product(s):** Natural gas, electricity, coal, steam coal, metallurgical coal, distillate fuel oil, residual fuel oil, motor gasoline, jet fuel, liquefied petroleum gases, petrochemical feedstocks, kerosene, other petroleum products, hydropower, and other renewable sources.
- **Economic Sector(s):** Residential, commercial, industrial, and transportation end-use consumption; coal supply; oil and gas production and natural gas markets; utility and nonutility capacity, and generation of electricity; oil product pricing.

### **Modeling Features:**

- **Model Structure:** NEMS provides an equilibrium framework in which the economic forces of supply and demand can be simulated. Its modular structure allows each individual module to be represented in a different fashion if desired.
- **Modeling Technique:** NEMS is a simulation of the impacts of present and planned energy market conditions upon the supplies of and demands for energy products. Different techniques are applied in different sectors, as appropriate.
- **Special Features:** The primary design feature of NEMS is its modularity. That is, the model is organized by fuel production—oil, natural gas, coal, and electricity—and by end-use consumption sector. Any of these modules can be replaced by a simple representation when detailed results are not required. The modularity also allows any single module or group of modules to be run independently as a debugging aid or for stand-alone analysis. Furthermore, modularity also allows the flexibility for each sector to be represented in the most appropriate way, highlighting the particular issues important for the sector, including the most appropriate regional structure.

**Non-DOE Input Sources:** All data sources are listed under the appropriate modules of NEMS, which are listed in the Model Interfaces section.

**DOE Data Input Sources:** All data sources are listed under the appropriate modules of NEMS, which are listed in the Model Interfaces section.