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Integrating Module of the National Energy Modeling System: Model Documentation 2014

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Update Information

This edition of the *Integrating Module of the National Energy Modeling System: Model Documentation 2014* reflects changes made to the integrating module over the past year for the *Annual Energy Outlook 2014*. These changes include:

- Updates to the summary descriptions of each NEMS module.
- Updates to the description and contents of the Global Data Structure.
- Description of parallel execution method.
- Updates to the carbon dioxide emissions factor table.

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1. Introduction

The National Energy Modeling System (NEMS) is an energy-economy modeling system of U.S. energy markets for the midterm period, extending through 2040, and currently being run on Windows-based personal computers and terminal servers. 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.

Baseline projections from NEMS are published in the U.S. Energy Information Administration's (EIA) Annual Energy Outlook. NEMS is developed and maintained by EIA's Office of Energy Analysis to provide projections of domestic energy-economy markets in the long term and perform policy analyses requested by decisionmakers in the White House; U.S. Congress; offices within the Department of Energy, including Program Offices; and other government agencies. NEMS was first used for projections 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 standard 2002-26, established in accordance with these laws.[1]

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 components of NEMS, Chapter 2 summarizes NEMS as a whole. Readers interested in a more comprehensive summary of NEMS should see The National Energy Modeling System: An Overview 2009, DOE/EIA-0581(2009), October 2009.[2]

Chapter 3 describes the NEMS global data structure, used for inter-module communication, solution initialization and storage, and certain database operations.

Chapter 4, Integrating Module Solution Methodology, provides the mathematical specification for the

[1] See http://www.eia.gov/about/eia_standards.cfm#standard26 .
[2] See http://www.eia.gov/forecasts/archive/0581(2009).pdf .

solution algorithm and describes the convergence techniques used. Chapter 4 also documents other modeling functions of the Integrating Module, including generation of foresight assumptions and carbon dioxide emission policy routines.

A bibliography is contained in Appendix A, and Appendix B describes some of the configuration management and other implementation practices used to coordinate NEMS software development.

Model archival citation

This documentation refers to the NEMS Integrating Module as archived for the *Annual Energy Outlook 2014 (AEO2014)*.

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 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.

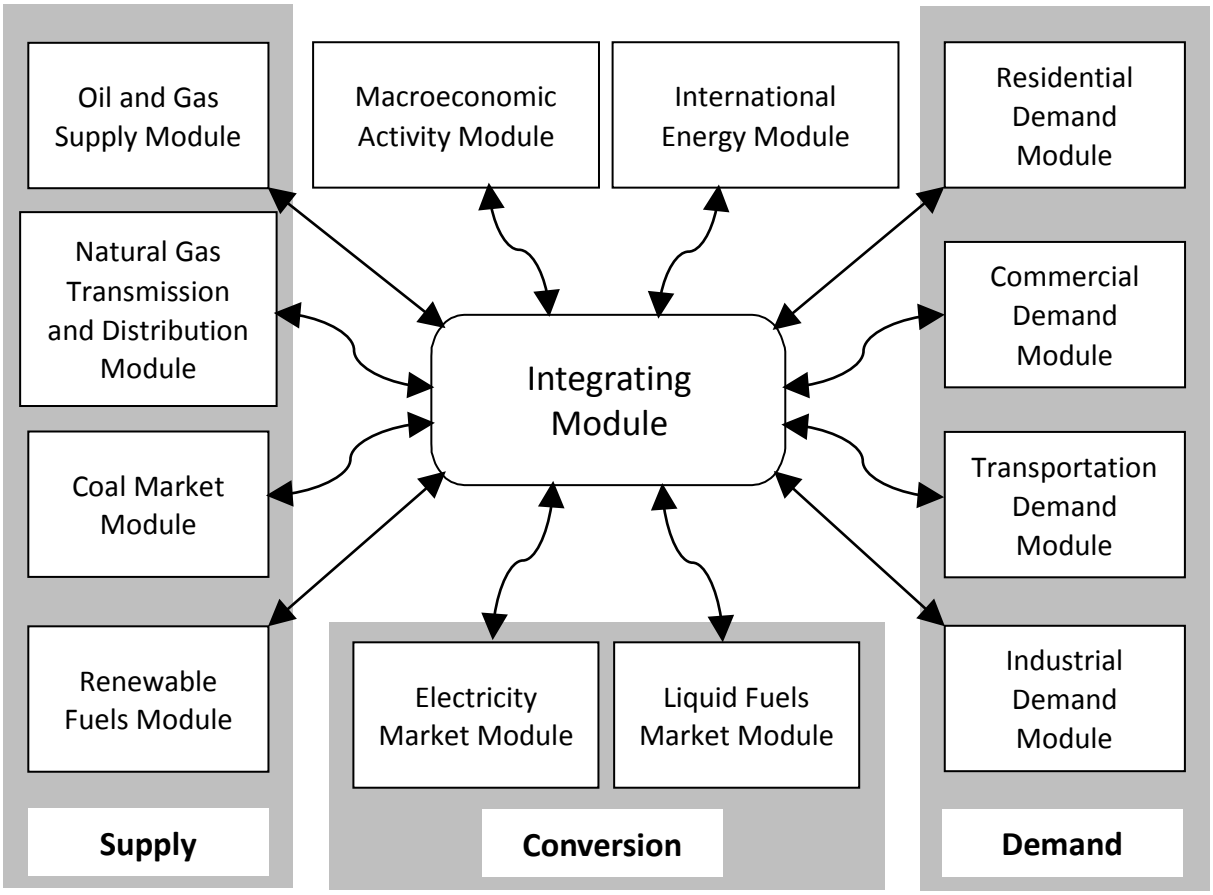
As shown in Figure 1, NEMS consists of four supply modules (oil and gas, natural gas transmission and distribution, coal, and renewable fuels), two conversion modules (electricity and petroleum refineries), four demand modules (residential, commercial, transportation and industrial sectors), one module to simulate energy/economy interactions (macroeconomic activity), one to simulate world/domestic liquids interactions (international energy), and one module that provides the mechanism to achieve a general market equilibrium among all the modules (integrating module). The last of these is the focus of this document.

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. Because energy markets are heterogeneous, a single methodology cannot adequately represent all supply, conversion, and end-use demand sectors. The modularity of the NEMS design provides the flexibility for each component to use the methodology and regional coverage that is most appropriate.

NEMS includes the capability to execute the modules individually or in subsets. This fosters independent module development, a distribution of model development work organized by energy market specialties, and incremental development of the system as a whole. Several modules are further decomposed into "submodules" for development and documentation purposes. While the submodules may not be executed individually, they constitute separable logical entities within a module. For example, the integrating module has an Emissions Policy Submodule (EPM) that is stored and maintained independently for programming and model management purposes, but is considered part of the integrating module because of its centralized functions that cut across all of NEMS.

To support modularity, the information flows between modules must be centralized in some way. The data linkages between modules are implemented through the NEMS Global Data Structure. The Global Data Structure (discussed in more detail in Chapter 3) is defined as the set of data communicated among any of the thirteen NEMS modules or used in the NEMS output reports. The global data is shared passively; the integrating module does not direct or control information flows, other than to manage the input and output of global data as a whole. Individual NEMS modules access the global data they need for input and must update the global variables storing their module's output.

Figure 1. Basis NEMS Structure and Information Flow



The primary data flows among the modules are the delivered prices of energy and the quantities consumed by product, region, and sector. As shown in Table 1, the information flows among modules are not limited to prices and quantities, but include other information such as economic activity, capital expenditures, and international energy supply curves.

Many NEMS modules simulate the economic decision-making involved in the portion of the energy system being modeled. In order to represent these decisions, NEMS is constructed with 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 2 provides a summary of NEMS product and regional detail.

Table 1. Inputs and outputs of NEMS modules

Module	Outputs	Inputs from NEMS	Exogenous Inputs
Macroeconomic Activity	Gross domestic product Other economic activity measures, including housing starts, commercial floorspace growth, vehicle sales, and population Price indices and deflators Manufacturing and non-manufacturing sector production and employment Interest rates	Petroleum and other liquids, natural gas, coal and electricity prices Oil, natural gas, and coal production Electric power sector and natural gas industry output Natural gas processing plant output End-use energy consumption by fuel	Macroeconomic variables defining alternative economic growth cases
International Energy	World crude-like liquids supply curves World liquid fuels production and consumption by region Caribbean and Maritime Canada demand curves	Gross domestic product deflator U.S. and world crude-like liquids production and consumption	Expected U.S. and world crude-like liquids supply and demand curves Expected world liquid fuels production and consumption by region
Residential Demand	Energy demand by service and fuel type Changes in housing and appliance stocks Appliance stock efficiency Distributed electricity generation and capacity	Energy product prices Housing starts Population	Current housing stocks and retirement rates Current appliance stocks and life expectancy New appliance types, efficiencies, and costs Housing shell retrofit indices Unit energy consumption Square footage
Commercial Demand	Energy demand by service and fuel type Changes in floorspace and appliance stocks CHP and distributed electricity generation and capacity	Energy product prices Interest rates Floorspace growth	Existing commercial floorspace Floorspace survival rates Appliance stocks and survival rates New appliance types, efficiencies, and costs Energy use intensities

Table 1. Inputs and outputs of NEMS modules (continued)

Module	Outputs	Inputs from NEMS	Exogenous Inputs
Industrial Demand	Energy demand by service and fuel type Electricity sales to the grid CHP electricity generation and capacity	Energy product prices Economic output by industry Refinery fuel consumption Lease and plant fuel consumption CHP fuel consumption, electricity generation, and capacity from refineries and oil and gas production	Production stages in energy-intensive industries Technology possibility curves Unit energy consumption of outputs Capital stock retirement rates
Transportation Demand	Fuel demand by mode Sales, stocks and characteristics of vehicle types by size class Vehicle-miles traveled Fuel economy by technology type Alternative-fuel vehicle sales and stock by technology type Light-duty commercial fleet vehicle characteristics	Energy product prices Gross domestic product Disposable personal income Industrial output Vehicle sales International trade Natural gas pipeline consumption Population	Existing vehicle stocks by vintage and fuel economy, and vehicle survival rates New vehicle technology characteristics Fuel availability Commercial availability Vehicle safety and emissions regulations Vehicle degradation rates
Electricity Market	Electricity prices and price components Fuel demands Capacity additions Capital requirements Emissions Renewable capacity Avoided costs	Purchased electricity Fuel prices CHP supply and fuel consumption Electricity sales to the grid Renewable technology characteristics, allowable capacity, and costs Renewable capacity factors Interest rates	Financial data Tax assumptions Capital costs Operation and maintenance costs Operating parameters Emissions rates New technologies Existing facilities Transmission constraints
Renewable Fuels	Energy production capacities Capital costs Operating costs (including wood supply prices for the wood submodule) Capacity factors Available capacity Biomass fuel costs Biomass supply curves	Installed energy production capacity Gross domestic product Population Interest rates Avoided cost of electricity Discount rate Capacity additions Biomass consumption	Site-specific geothermal resource quality data Site-specific wind resource quality data Plant utilization (capacity factor) Technology cost and performance parameters Landfill gas capacity Biomass resource data, demand elasticities, and coefficients

Table 1. Inputs and outputs of NEMS modules (continued)

Module	Outputs	Inputs from NEMS	Exogenous Inputs
Oil and Gas Supply	Crude oil production U.S. nonassociated and Canadian conventional natural gas supply curves CHP from oil and gas production Reserves and reserve additions Drilling levels U.S. associated-dissolved gas production	U.S. and Canadian natural gas production and wellhead prices Crude oil demand World oil price Electricity price Gross domestic product Inflation rate	Resource levels Initial finding rate parameters and costs Production profiles Tax parameters
Natural Gas Transmission and Distribution	Natural gas delivered prices U.S. and Canadian natural gas wellhead prices U.S. natural gas production Canadian natural gas imports and production Lease and plant fuel consumption Pipeline fuel use Pipeline and distribution tariffs Interregional natural gas flows Storage and pipeline capacity expansion Supplemental gas production Imports and exports of liquefied natural gas Imports and exports of natural gas from Mexico and Canada	Natural gas demands U.S. and Canadian natural gas supply curves Macroeconomic variables Associated-dissolved natural gas production	Historical consumption, patterns, and supplies Pipeline company-level financial data Pipeline and storage capacity and utilization data Historical end-use citygate and wellhead prices State and federal tax parameters Pipeline and storage expansion cost data Liquefied natural gas supply curves Consumption projections for Canada and Mexico
Liquid Fuels Market	Petroleum product prices Crude oil imports and exports Imports and exports of liquid fuels Refinery activity, fuel use, and capacity additions Ethanol production, price, and motor gasoline blend percent Biodiesel production Liquids produced from coal, natural gas, and biomass Combined heat and power (CHP) Natural gas plant liquids production Processing gain Revenues and capital expenditures	Petroleum product demand by fuel and sector U.S. crude oil production Brent crude oil spot price International crude-like supply curves Natural gas prices Electricity prices Coal prices Natural gas production Macroeconomic variables Biomass supply curves	Processing unit operating parameters Processing unit capacities Product specifications Operating costs Capital costs Transmission and distribution costs Federal and state taxes Agricultural feedstock quantities and costs CHP unit capacities and operating parameters

Table 1. Inputs and outputs of NEMS modules (continued)

Module	Outputs	Inputs from NEMS	Exogenous Inputs
Coal Market	Coal production and distribution Minemouth coal prices End-use coal prices U.S. coal exports and imports Transportation rates Coal quality by source, destination, and end-use sector World coal flows	Coal demand Interest rates Price indices and deflators Diesel fuel prices Electricity prices	Base year production, prices, productive capacity, capacity utilization, and coal quality parameters Contract quantities Labor productivity Labor costs and cost escalators Domestic and international transportation costs International supply curves Demand for U.S. coal exports

Table 2. Summary of NEMS modeling detail

Energy Sector	Categories	Regions
Residential demand	Twenty-two end-use services Three housing types Forty-five end-use technologies	Nine Census divisions
Commercial demand	Ten end-use services Eleven building types Ten distributed generation technologies Sixty-four end-use technologies	Nine Census divisions
Industrial demand	Seven energy-intensive manufacturing industries Eight non-energy-intensive manufacturing industries Six non-manufacturing industries Combined heat and power	Four Census regions, shared to nine Census divisions
Transportation demand	Six car sizes Six light truck sizes Eighty-six conventional fuel-saving technologies for light-duty vehicles Gasoline, diesel, and fourteen alternative-fueled vehicle technologies for light-duty vehicles Twenty vintages for light-duty vehicles Regional, narrow-body, and wide-body aircraft Six advanced aircraft technologies Light-medium, heavy-medium, and heavy freight truck size classes Thirty-seven advanced freight truck technologies	Nine Census divisions
Electricity	Eleven fossil technologies Two distributed generation technologies Seven renewable technologies Conventional and advanced nuclear technologies Marginal and average cost pricing Generation capacity expansion Seven environmental control technologies	Twenty-two electricity supply regions, plus Alaska and Hawaii
Renewables	Wind, geothermal, solar thermal, solar photovoltaic, landfill gas, biomass, conventional hydropower	Twenty-two electricity supply regions
Oil supply	Onshore Deep and shallow offshore	Six lower-48 onshore regions Four lower-48 offshore regions Three Alaska regions

Table 2. Summary of NEMS modeling detail (continued)

Energy Sector	Categories	Regions
Natural gas supply	Conventional lower-48 onshore	Six lower-48 onshore regions
	Lower-48 deep and shallow offshore	Three lower-48 offshore regions
	Coalbed methane	Three Alaska regions
	Shale gas	Eight liquefied natural gas import regions
	Tight sands	
	Canadian, Mexican, and liquefied natural gas	
	Alaskan gas	
Natural gas transmission and distribution	Core *vs.* noncore	Twelve lower-48 regions
	Peak *vs.* offpeak	Ten pipeline border points
	Pipeline capacity expansion	
Refining	Nine crude oil categories	Eight refinery regions based on the Petroleum Administration for Defense Districts, plus one region representing the Caribbean and Maritime Canada
	Twenty product categories	
	More than 40 distinct technologies	
	Refinery capacity expansion	
Coal supply	Three sulfur categories	Fourteen domestic supply regions
	Four thermal categories	Sixteen domestic demand regions
	Underground and surface mining types	Seventeen international supply regions
	Imports and exports	Twenty international demand regions

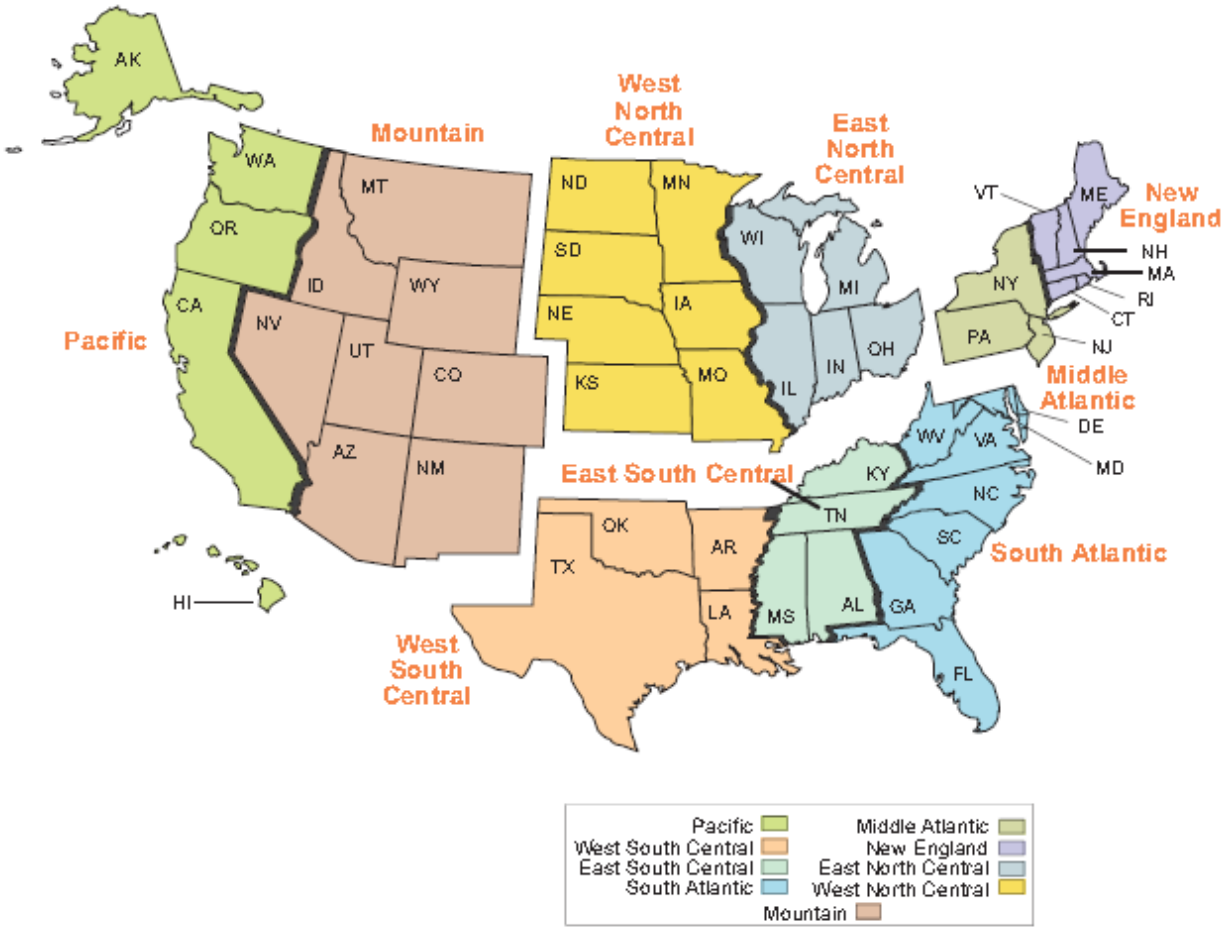
The Integrating Module of NEMS processes energy consumption and price information aggregated primarily at the Census division level. The nine Census divisions are depicted in Figure 2. In addition, the Integrating Module processes some intermodule energy market data at regional levels tied to electricity 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).

The projection horizon for NEMS is 2040, 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 that timeframe.

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.

The Integrating Module applies the Gauss-Seidel algorithm for solving simultaneous nonlinear equations as its solution methodology. Chapter 4 describes this approach in detail.

Figure 2. Census Divisions



The individual modules of NEMS are described briefly below:

Macroeconomic Activity Module

The Macroeconomic Activity Module provides a set of macroeconomic drivers to the energy modules and receives energy-related indicators from the NEMS energy components as part of the macroeconomic feedback mechanism within NEMS. Key macroeconomic variables include gross domestic product (GDP), disposable income, value of industrial shipments, new housing starts, sales of new light-duty vehicles, interest rates, and employment. Key energy indicators fed back to the MAM include aggregate energy prices and quantities. This module uses the following models from IHS Global Insight: Macroeconomic Model of the U.S. Economy, National Industrial Output Model, and the National Employment by Industry Model[3]. In addition, EIA has constructed a Regional Economic, Industrial Output and Employment by Industry Model to project regional economic drivers, and a

[3] IHS Global Insight long-term model, May 2013.

Commercial Floorspace Model to project 13 floorspace types in nine Census divisions. The accounting framework for industrial value of shipments uses the North American Industry Classification System (NAICS).

International Energy Module

The International Energy Module uses assumptions of economic growth and expectations of future U.S. and world petroleum and other liquids production and consumption, by year, to project the interaction of U.S. and international petroleum and other liquids markets. This module provides a world crude-like liquids supply curve and generates a worldwide oil supply/demand balance for each year of the projection period. The supply-curve calculations are based on historical market data and a world oil supply/demand balance, which is developed from reduced-form models of international petroleum and other liquids supply and demand, current investment trends in exploration and development, and long-term resource economics by country and territory. The oil production estimates include both petroleum and other liquids supply recovery technologies. The module also provides, for each year of the projection period, endogenous assumptions for petroleum products for import and export in the United States. A feedback mechanism changes Brent and West Texas Intermediate prices in response to changes in expected production and consumption of crude-like liquids in the United States.

Residential and Commercial Demand Modules

The Residential Demand Module projects energy consumption in the residential sector by Census division, housing type, and end use, based on delivered energy prices, the menu of equipment available, the availability of renewable sources of energy, and changes in the housing stock. The Commercial Demand Module projects energy consumption in the commercial sector by Census division, building type, and category of end use, and by nonbuilding uses of energy, based on delivered prices of energy, the menu of available equipment, availability of renewable sources of energy, and changes in commercial floorspace. Both modules estimate the equipment stock for the major end use services, incorporating assessments of advanced technologies, representations of renewable energy technologies, and the effects of both building shell and appliance standards. The modules also include projections of distributed generation. The Commercial Demand Module incorporates combined heat and power (CHP) technology. Both modules incorporate changes to “normal” heating and cooling degree-days by Census division, based on a 30-year historical trend and on state-level population projections. The Residential Demand Module projects an increase in the average square footage of both new construction and existing structures, based on trends in new construction and the remodeling of existing homes.

Industrial Demand Module

The Industrial Demand Module projects the consumption of energy for heat and power, feedstocks, and raw materials in each of 21 industry groups, subject to the delivered prices of energy and macroeconomic variables representing employment and the value of shipments for each industry. As noted in the description of the Macroeconomic Activity Module, the value of shipments is based on NAICS. The industries are classified into three categories: energy-intensive manufacturing, non-energy-intensive manufacturing, and non-manufacturing. Of the eight energy-intensive industries, seven are modeled in the Industrial Demand Module, with energy-consuming components for

boiler/steam/combined heat and power, buildings, and process/assembly use of energy. A generalized representation of combined heat and power is included based on historical utilization rates and driven by end-use electricity demand. The use of energy for petroleum refining and production of other liquids (the eighth energy-intensive manufacturing industry) is modeled in the Liquid Fuels Market Module, and the projected consumption is included in the industrial totals.

Transportation Demand Module

The Transportation Demand Module projects consumption of energy by mode and fuel—including petroleum products, electricity, methanol, ethanol, compressed natural gas, liquefied natural gas, and hydrogen—in the transportation sector, subject to delivered energy prices, macroeconomic variables such as gross domestic product, and other factors such as technology adoption and consumer behavior. Legislation and regulations are also included, such as the Energy Policy Act of 2005 (EPACT2005), the Energy Improvement and Extension Act of 2008 (EIEA2008), and the American Recovery and Reinvestment Act of 2009 (ARRA2009), which contain tax credits for the purchase of alternatively fueled vehicles. Representations of light-duty vehicle corporate average fuel economy and greenhouse gas emissions standards, heavy-duty vehicles fuel consumption and greenhouse gas emissions standards, and biofuels consumption reflect standards enacted by the National Highway Traffic Safety Administration and the U.S. Environmental Protection Agency (EPA), as well as provisions in the Energy Independence and Security Act of 2007 (EISA2007).

The air transportation component represents air travel in domestic and foreign markets and includes the industry practice of parking aircraft in both domestic and international markets to reduce operating costs, as well as the movement of aging aircraft from passenger to cargo markets. For passenger travel and air freight shipments, the module represents regional fuel use and travel demand for regional, narrow-body, and wide-body aircraft. An infrastructure constraint is also modeled and can potentially limit overall growth in passenger and freight air travel to levels commensurate with industry projected infrastructure expansion and capacity growth.

Energy consumption for freight and passenger rail and marine vessels is projected by mode and fuel, subject to macroeconomic variables such as the value and type of industrial shipments. Freight ton-miles and efficiency are also projected in the model.

Electricity Market Module

The Electricity Market Module (EMM) consists of three primary submodules: capacity planning, fuel dispatching, and finance and pricing. The capacity expansion submodule uses the stock of existing generation capacity, the expected cost and performance of future generation capacity, expected fuel prices, expected financial parameters, expected electricity demand, and known environmental regulations to project the optimal mix of new generation capacity that should be added in future years. The fuel dispatching submodule uses the existing stock of generation equipment, their operation and maintenance costs and performance, fuel prices to the electric power sector, electricity demand, and all applicable environmental regulations to determine the least-cost way to meet that demand. The submodule also determines transmission and pricing of electricity. The finance and pricing submodule uses capital costs, fuel costs, macroeconomic parameters, environmental regulations, and load shapes to estimate generation costs for each technology.

All specifically identified options promulgated by EPA for compliance with the Clean Air Act Amendments of 1990 are explicitly represented in the capacity expansion and dispatch decisions. All financial incentives for power generation expansion and dispatch specifically identified in EPACT2005 have been implemented. Several states, primarily in the Northeast, have enacted air emission regulations for carbon dioxide that affect the electric power sector, and those regulations are represented in *AEO2014*. A limit on electric power sector carbon dioxide emissions for plants serving California is imposed to represent California Assembly Bill 32. After the Cross-State Air Pollution Rule was vacated by the court in August 2012, the Clean Air Interstate Rule is in effect for *AEO2014*, incorporating a cap-and-trade program for annual emissions of sulfur dioxide and annual and seasonal emissions of nitrogen oxides from fossil fuel power plants. Reductions in hazardous air pollutant emissions from coal- and oil-fired steam electric power plants are reflected through inclusion of the Mercury and Air Toxics Standards for power plants, finalized by EPA on December 16, 2011.

Although federal legislation restricting greenhouse gas emissions is not currently in place, regulators and the investment community are continuing to push energy companies to invest in less greenhouse gas-intensive technologies. This trend is captured through a 3-percentage point increase in the cost of capital when evaluating investments in new coal-fired power plants, new coal-to-liquids plants without carbon capture and storage, and pollution control retrofits.

Renewable Fuels Module

The Renewable Fuels Module (RFM) includes submodules representing renewable resource supply and technology input information for central-station, grid-connected electricity generation technologies including conventional hydroelectricity, biomass (dedicated biomass plants and co-firing in existing coal plants), geothermal, landfill gas, solar thermal electricity, solar photovoltaics (PV), and wind energy (onshore and offshore). The RFM contains renewable resource supply estimates representing the regional opportunities for renewable energy development. Investment tax credits for renewable fuels are incorporated as currently enacted. This includes a permanent 10% tax credit for business investment in solar energy (thermal nonpower uses as well as power uses) and geothermal power (only available to those projects not accepting the production tax credit). In addition, the module reflects the increase in the tax credit to 30% for solar energy systems installed before January 1, 2017. The extension of the credit to individual homeowners under EIEA2008 is reflected in the Residential and Commercial Demand Modules.

Production tax credits for wind, geothermal, landfill gas, and some types of hydroelectric and biomass-fueled plants are also represented. They provide a tax credit of up to 2.3 cents per kilowatthour for electricity produced in the first 10 years of plant operation. The expiration of the PTC that occurred at the end of 2013 is represented, however, because the expiration date reflects an “under construction” versus “in service” deadline; the effective modeled eligibility deadline is extended to new wind and landfill gas plants coming on line by the end of 2015, and other eligible plants coming on line by the end of 2016. As part of ARRA2009, plants eligible for the production tax credit may instead elect to receive a 30% investment taxcredit. New renewable energy capacity resulting from state renewable portfolio standard programs, mandates, and goals are accounted for, but not those from unenforceable goals.

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 among the various sources of supply—onshore, offshore, and Alaska—by all production techniques, including natural gas recovery from coalbeds and low-permeability formations of sandstone and shale. The framework analyzes cash flow and profitability to compute investment and drilling for each of the supply sources, based on the prices for crude oil and natural gas, the domestic recoverable resource base, and the state of technology. Oil and natural gas production activities are modeled for 12 supply regions, including six onshore, three offshore and three Alaskan regions.

The Onshore Lower 48 Oil and Gas Supply Submodule evaluates the economics of future exploration and development projects for crude oil and natural gas at the play level. Crude oil resources include conventional, structurally reservoired resources as well as highly fractured continuous zones, such as the Austin chalk and Bakken shale formations. Production potential from advanced secondary recovery techniques (such as infill drilling, horizontal continuity, and horizontal profile) and enhanced oil recovery (such as carbon dioxide flooding, steam flooding, polymer flooding, and profile modification) are explicitly represented. Natural gas resources include high-permeability carbonate and sandstone, tight gas, shale gas, and coalbed methane. Crude oil production quantities are input to the Liquid Fuels Market Module in NEMS for conversion and blending into refined petroleum products. Supply curves for natural gas are input to the Natural Gas Transmission and Distribution Module for use in determining natural gas prices and domestic production.

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 and determines the associated capacity expansion requirements in an aggregate pipeline network, connecting the domestic and limited foreign supply sources with 12 U.S. lower 48 demand regions. The 12 regions align with the nine Census divisions, with three subdivided. Alaska is handled separately. The flow of natural gas is determined for both a peak and off-peak period in the year, assuming a historically based seasonal distribution of natural gas demand. Key components of pipeline and distributor tariffs are included in separate pricing algorithms. The primary outputs of the module are delivered natural gas prices by region and sector, supply prices, and realized domestic natural gas production. The module also projects natural gas pipeline imports and exports to Canada and Mexico, as well as LNG imports and exports.

Liquid Fuels Market Module

The Liquid Fuels Market Module (LFMM) projects prices of petroleum products, crude oil and product import activity, and domestic refinery operations (including fuel consumption), subject to the demand for petroleum products, the availability and price of imported petroleum, and the domestic production of crude oil, natural gas liquids, biofuels (ethanol, biodiesel, and biomass-to-liquids), coal-to-liquids, gas-to-liquids, and coal-and-biomass-to-liquids. The module represents refining activities in eight domestic U.S. regions (which align with the five U.S. Petroleum Administration for Defense Districts, with three

subdivided) and a Maritime Canada/Caribbean region created to represent short-haul international refineries that predominantly serve U.S. markets. It models the costs of automotive fuels, such as conventional and reformulated gasoline, and includes production of biofuels for blending in gasoline and diesel. Fuel ethanol and biodiesel are included because they are commonly blended into petroleum products. The module allows ethanol blending into gasoline at 10% or less by volume (E10), 15% by volume (E15) in states that lack explicit language capping ethanol volume or oxygen content, and up to 85 % by volume (E85) for use in flex-fuel vehicles. The module also includes a 16% by volume biobutanol/gasoline blend.

Fuels produced by Fischer-Tropsch synthesis and through a pyrolysis process are also modeled in the LFMM, based on their economics relative to competing feedstocks and products. The five processes modeled are coal-to-liquids, gas-to-liquids, biomass-to-liquids, coal-and-biomass-to-liquids, and pyrolysis.

The renewable fuels standard is represented as specified in EISA2007, which mandates the use of 36 billion gallons of ethanol equivalent renewable fuel by 2022. Two California-specific policies targeting carbon dioxide emissions are also represented: the low carbon fuel standard and the California Assembly Bill 32 cap-and-trade program.

Coal Market Module

The Coal Market Module (CMM) simulates mining, transportation, and pricing of coal, subject to the end-use demand for coal differentiated by heat and sulfur content. U.S. coal production is represented by 41 separate supply curves—differentiated by region, mine type, coal rank, and sulfur content. The coal supply curves include a response to capacity utilization of mines, mining capacity, labor productivity, and factor input costs (mining equipment, mining labor, and fuel requirements). Projections of U.S. coal distribution are determined by minimizing the cost of coal supplied, given coal demands by demand region and sector, environmental restrictions, and accounting for minemouth prices, transportation costs, and coal supply contracts. Over the projection horizon, coal transportation costs in the CMM vary in response to changes in the cost of rail investments and diesel fuel prices.

The CMM produces projections of U.S. steam and metallurgical coal exports and imports in the context of world coal trade, determining the pattern of world coal trade flows that minimizes production and transportation costs while meeting a specified set of regional world coal import demands, subject to constraints on export capacities and trade flows. The international coal market component of the module computes trade for steam and metallurgical coal for 17 export regions and 20 import regions. U.S. coal production and distribution are computed for 14 supply regions and 16 demand regions.

3. 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 and their storage locations in the program.

> *A **Fortran common block** is a named data storage area in a program containing the contents of one or more program variables. In a Fortran program, any subroutine or function can access and change the contents of variables in a common block, provided the common block and variable declarations are repeated within the subroutine's declarations. The global variables can be organized into common blocks of named variables so as to limit access within a subroutine to only those parts of the global data that are needed. The common block storage area is initialized with zeroes when the program begins, and the variables are filled through assignment statements and "read" statements during program execution.*

The Global Data Structure can be thought of as defining a data storage area within NEMS. It is not specifically a part of the integrating module or any other module of NEMS, but rather exists in program memory during NEMS execution. During NEMS execution, each module accesses the global input and output variables it needs through these 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 in NEMS.

The common block structure designed to store the NEMS Global Data Structure is displayed in Table 3. 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.

Table 3. Common Blocks in the NEMS global data structure

Module(s) Filling the Common Block	Common Block Names	Description
Integrating, multiple contributors, or exogenous	QBLK	End-use sector quantities (See Table 4)
	QMORE	Additional end-use sector quantities
	MPBLK	End-use sector prices (See Table 5)
	PMORE	Additional end-use sector prices
	MXQBLK	Expected quantities for foresight
	MXPBLK	Expected prices for foresight
	QSBLK	State Energy Data System historical data corresponding to QBLK
	NCNTRL	Control variables
	COGEN	Combined heat and power
	CONVFACT	Thermal conversion factors
	CONVERGE	Convergence variable data and reporting summary
	COALEMM	Variables exchanged between the Coal Market Module and the Electricity Market Module
	HMMBLK	Hydrogen module variables (future use)
	CYCLEINFO	Current cycle number and total cycles in overall run
	CONTINEW	Information related to continuation of cycling
	NCHAR	Character variables such as scenario name or module names
Integrating (Emission Policy Submodule)	EMABLK	Price adjustments for carbon dioxide fees, if any
	EMEBLK	Carbon dioxide emissions factors by fuel/sector
	EPMBANK	Parameters for an emissions constraint banking option
	REGCO2	Regional carbon dioxide emissions by fuel and sector
	GHGREP	Greenhouse gas abatement costs and offsets
	EMISSION	Emissions and related results
	AMPBLK, ANGTDM, ACOALPRC, APONROAD, APMORE, AEUSPRC	Copies of MPBLK, NGTDMOUT, COALPRC, PONROAD, PMORE, EUSPRC, and PCDR with prices adjusted by any energy tax or emission allowance fees
	AB32	California Assembly Bill 32 cap and trade variables
	RGGI	Regional Greenhouse Gas Initiative variables
	CSAPR	Cross-State Air Pollution Rule variables
Macroeconomic	MACOUT	Output variables
	MCDETAIL	Reporting Variables
International Energy	INTOUT	All International Energy Module global variables
Residential Demand	RESDREP	Reporting variables
	RSCON	Energy consumption by end use
	RSEFF	Energy efficiency by end use

Table 3. Common Blocks in the NEMS global data structure (continued)

Module(s) Filling the Common Block	Common Block Names	Description
Commercial Demand	COMPARAM	Control parameters, assumptions
	COMMREP	Reporting Variables
	BLDGLRN	Cumulative shipments of distributed generation technologies for "learning" curves
Industrial Demand	INDOUT	Industrial variables for use in other modules
	INDREP	Industry-level consumption reporting variables
	INDREP2	Industry-level combined heat and power reporting variables
	BIFURC	Energy by fuel/region classified by covered and uncovered industry groups for emission cap and trade analysis
Transportation Demand	TRANREP	All global transportation variables
Electricity Market	UEFPOUT	Electricity pricing outputs
	EFPOUT	Electricity pricing outputs
	UEFDOUT	Fuel-dispatch outputs
	UDATOUT	Electricity central data outputs
	UECPOUT	Capacity planning outputs
	DSMTFEFP	Demand side management /electricity pricing
	UETTOUT	Electricity trade outputs
	EUSPRC	Electricity prices for end uses by sector
	CAPEXP	Capital expenditures
Renewable Fuels	WRENEW	All Renewable Fuel Module global variables
Oil and Gas Supply	OGSMOUT	All Oil and Gas Supply Module global variables
Natural Gas Transmission and Distribution	NGTDMOUT	Output variables
	NGTDMREP	Reporting variables
	NGRPT	Supplementary reporting variables
Liquid Fuels Market	PMMOUT	Output variables
	PMMRPT	Output variables
	PMMFTAB	Reporting variables
	QONROAD	On-road distillate quantity, conversion factor
	PONROAD	On-road distillate price
	LFMMOUT	Output variables
Coal Market	COALOUT	Output variables
	COALREP	Reporting variables
	COALPRC	Electric power sector coal prices at the coal demand region level
	USO2GRP	Coal output by emission categories for ECP interface

Energy market data representation

The Energy Market Data define the energy quantity and price variables for NEMS. These variables are the principal values subject to convergence testing in the integrating algorithm. The Energy Market Data are part of the NEMS Global Data Structure and are stored in the following common blocks:

QBLK	Energy consumption quantities by fuel and sector
MPBLK	Energy prices by fuel and sector, excluding any carbon dioxide fees in effect
AMPBLK	Energy prices by fuel and sector, including any carbon dioxide fees in effect
MXQBLK	Expectations for energy consumption quantities
MXPBLK	Expectations for energy prices

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 fuel and sectoral energy classification for the NEMS energy balance.

Table 4 presents a list of the arrays storing the energy consumption quantities by fuel and sector. Each item in the table represents a named variable in NEMS. The sectoral definitions include the four end-use sectors and two 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 electric power sector includes fuel used by electric-only and combined heat and power plants that have a regulatory status. The industrial and commercial sectors include fuel used for electricity generation, by combined heat and power plants and electricity-only plants that have a non-regulatory status and by small on-site generating systems, some of which may be sold to the grid. This breakout is consistent with the coverage of the Electricity Market Module and the demand modules.
- The Liquid Fuels Market Module determines fuel use by the refinery sector, which in NEMS includes ethanol and biobutanol plants, pyrolysis plants, and plants that convert other hydrocarbon compounds into liquid fuels via the Fischer-Tropsch process. Fuel consumption in the refinery sector is broken out from the industrial sector for inter-module communication requirements. This information is passed to the Industrial Demand Module, where it is added to other industrial fuel use. Thus, the industrial energy consumption product demands as defined in column 5 of Table 4 include refinery consumption.

Table 5 presents a list of arrays storing 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 quantities 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 quantities.

- 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, supply curves for four different feedstocks (forestry residues, urban wood waste and mill residues, agricultural residues, and energy crops) are generated for the Liquid Fuels Market Module and the Electricity Market Module and a composite average price is calculated.

Table 4 and **Table 5** also define the variable names for the NEMS consumption quantities and 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 tenth position originally reserved for possible breakout of California, and an eleventh position reserved for the National total. The second dimension represents 51 years from 1990 to 2040 (with space for years 2041 to 2050 reserved for future use). Quantities are stored in trillions of Btu. Prices are stored in 1987 dollars per million Btu, as deflated by the chain-weighted price deflator for gross domestic product.

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 fuel price and demand quantity detail is represented in the expectation arrays.

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, consisting of results from a prior simulation. During the run, much of these data are 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.

A database subroutine called FILER is used to store and retrieve the NEMS Global Data Structure as represented in the NEMS Restart file. The global data are separated 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.

Table 4. Arrays storing quantities of energy consumed by fuel and sector

	End-Use Sectors				Conversion Sectors				Totals
Description	Resd. (Q_RS)	Comm. (Q_CM)	Tran. (Q_TR)	Indus. (Q_IN)	Refin. (Q_RF)	Elect. (Q_EL)	Synth. (Q_SN)	Hydrog.[1] (Q_HM)	All (Q_AS)
Purchased Electricity	QELRS	QELCM	QELTR	QELIN	QELRF			QELHM	QELAS
Natural Gas, Firm	QGFRS	QGFCM	QGFTR	QGFIN	QGFRF	QGFEL		QGFHM	QGFAS
Natural Gas, Interruptible	QGIRS	QGICM	QGITR	QGIIN	QGIRF	QGIEL		QGIHM	QGIAS
Natural Gas (Total)	QNGRS	QNGCM	QNGTR	QNGIN	QNGRF	QNGEL		QNGHM	QNGAS
Natural Gas, Pipeline			QGPTR						
Lease and Plant Fuel				QLPIN					
Steam Coal	QCLRS	QCLCM		QCLIN	QCLRF	QCLEL	QCLSN	QCLHM	QCLAS
Metallurgical Coal				QMCIN					
Motor Gasoline		QMGCM	QMGTR	QMGIN					QMGAS
Jet Fuel			QJFTR						
Distillate	QDSRS	QDSCM	QDSTR	QDSIN	QDSRF	QDSEL			QDSAS
Kerosene	QKSRS	QKSCM		QKSIN					QKSAS
Liquefied Petroleum Gases	QLGRS	QLGCM	QLGTR	QLGIN	QLGRF				QLGAS
Residual Fuel, Low Sulfur		QRLCM	QRLTR	QRLIN	QRLRF	QRLEL			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	QPCEL			QPCAS
Asphalt and Road Oil				QASIN					
Other Petroleum			QOTTR	QOTIN	QOTRF				QOTAS
Total Petroleum	QTPRS	QTPCM	QTPTR	QTPIN	QTPRF	QTPEL			QTPAS

Table 4. Arrays storing quantities of energy consumed by fuel and sector (continued)

	End-Use Sectors					Conversion Sectors			Totals
Description	Resd. (Q_RS)	Comm. (Q_CM)	Tran. (Q_TR)	Indus. (Q_IN)	Refin. (Q_RF)	Elect. (Q_EL)	Synth. (Q_SN)	Hydrog.[1] (Q_HM)	All (Q_AS)
Methanol			QMETR						
Ethanol			QETTR					QETHM	
Hydrogen [1]			QHYTR						
Uranium						QUREL		QURHM	
Hydroelectric				QHOIN		QHOEL			QHOAS
Geothermal	QGERS			QGEIN		QGEEL			QGEAS
Biomass	QBMRS	QBMCM		QBMIN	QBMRF	QBMEL	QBMSN	QBMHM	QBMAS
Municipal Solid Waste				QMSIN		QMSEL			QMSAS
Solar Thermal	QSTRS	QSTCM		QSTIN		QSTEL			QSTAS
Photovoltaic	QPVRS	QPVCM		QPVIN		QPVEL			QPVAS
Wind				QWIIN		QWIEL			QWIAS
Total Renewable	QTRRS	QTRCM	QTRTR	QTRIN		QTREL	QTRSN	QTRHM	QTRAS
Net Electricity Imports						QEIEL			
Net Coal Coke Imports				QCIIN					
Total Sector Consumption	QTSRS	QTSCM	QTSTR	QTSIN	QTSRF	QTSEL	QTSSN	QTSHM	QTSAS

[1] The hydrogen variables are placeholders for a future hydrogen market module for NEMS, represented as a new conversion sector. On the demand side, QHYTR is the total hydrogen consumed in three classes (not shown): large cities (QH1TR), small cities (QH2TR), and rural (QH3TR).

Table 5. Arrays storing prices of energy by fuel and sector

Description	Resd. (P_RS)	Comm. (P_CM)	Tran. (P_TR)	Indus. (P_IN)	Elect. (P_EL)	All (P_AS)
Purchased Electricity	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	PCLEL	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
Liquefied Petroleum Gases	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			
Hydrogen—Large Cities[1]			PH1TR			
Hydrogen—Small Cities[1]			PH2TR			
Hydrogen—Rural[1]			PH3TR			
Hydrogen—Average[1]			PHYTR			
Uranium					PUREL	

[1] The hydrogen variables are placeholders for a future hydrogen market module for NEMS, represented as a new conversion sector. On the price side, PHYTR is the total hydrogen price in three classes: large cities (PH1TR), small cities (PH2TR), and rural (PH3TR).

This capability is constructed such that files created by FILER (Restart files) 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 script command TFILER.

4. Integrating Module Solution Methodology

The Integrating Module controls the NEMS solution algorithm, executing the NEMS component modules iteratively in an attempt to achieve energy market equilibrium in each projection year. Using the Energy Market Data portions of the NEMS Global Data Structure as its inputs, the Integrating Module tests whether convergence has occurred, and optionally adjusts the solution values to aid the convergence process. The Integrating Module also manages the storage of global data and the access to input and output files. Finally, the integrating module includes an emission policy submodule to calculate carbon dioxide emissions and implement some emissions control options that cut across all of NEMS.

Solution algorithm

The modules in NEMS represent the demand, supply, and conversion segments of the energy market, as well as modules to provide economic and international oil market feedbacks. In effect, these modules can be thought of as representing a set of energy supply and demand curves. That is, the supply and conversion modules determine prices and sources of supply, given the quantity of fuel demanded. The demand and conversion models determine the fuel demands, given the prices of those fuels. The solution algorithm attempts to determine a vector of fuel prices and quantities so that supply and demand curves in all fuel markets equilibrate. That is, a solution occurs when energy demands and prices, along with the macroeconomic variables, reach stable, convergent values.

To reach such a solution, the integrating module is essentially solving a set of simultaneous equations implied by the supply, demand, and conversion modules. The approach used is an application of the Gauss-Seidel algorithm designed to solve a set of simultaneous equations. Gauss-Seidel is an iterative method of solving simultaneous linear equations by replacing the independent variables with their previous solved-for values. While the equations within NEMS are non-linear, this method is expected to still provide an equilibrium solution since the equations are either monotonically increasing (as are the supply curves) or monotonically decreasing (as are the demand curves).

In effect, the approach partitions the equations and variables into 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

$$x_i = g_i(x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_n) \quad \text{for} \quad i = 1, \ldots, n, \quad (1)$$

having the market clearing or equilibrium solution vector

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

The solution process assumes a set of initial values, denoted x^0, where

$$x^0 = (x_1^0, \ldots, x_n^0).$$

A trial solution for iteration *k* for a certain year is denoted by x^k, where

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

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.

A solution iteration *k* begins with the evaluation of g_1 and continues solving each g_i, ending with g_n. The solution of g_i in iteration *k* updates the solution estimate to

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

The updating process continues until an iteration-*k* trial solution is derived for all x_i.

After evaluating g_i^k, the values of the solution variables are compared to the values from iteration *k-1*. A final solution, x^k, 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, ε :

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

for *i* = 1, ..., *n*. Values of ε can be chosen on a variable-specific basis. The typical values used are in the range of 1% for the Census division variables, less for the national macroeconomic variables.

After the convergence criteria have been met, another iteration is performed to test whether the solution is stable and to allow the modules to perform final processing for the year. As a result, the final converged solution vector for the year is x^{k+1}, where k is the first iteration for which the solution meets the convergence criterion.

A procedure referred to as "relaxation" is used to control the equilibration process and aid in resolving some convergence problems. If the relaxation option is selected, changes in values of convergence variables between iterations are dampened by a user-specified factor. The selection of appropriate relaxation parameters may speed convergence and lead to a more stable and robust solution process. The relaxation *assignment statement* is of the form:

$$x_i^k = x_i^{k-1} + r_i^k (x_i^k - x_i^{k-1})$$

where r^k_i = relaxation factor for a convergence variable *i* for iteration *k*. Note that the specification of relaxation factors is variable-specific and iteration-specific. The capability to specify varying relaxation fractions, depending on the iteration number, is available as an option. This feature is used to allow greater dampening after the first few iterations. Convergence parameters, including the tolerances and relaxation fractions for each variable, are specified through the input file **mncnvrg.txt**.

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 one iteration beyond the non-converged trial solution.

The equations are partitioned in the fuel supply and sectoral demand modules, with the solution variables (x_i) consisting primarily of quantities and prices of fuels by region and consuming sector. To illustrate the regional and sectoral detail, these variables are redefined as follows:

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

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

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

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

indices:

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

s consuming sector (residential, commercial, industrial, transportation, electric power, refining)

r region (nine Census divisions)

y year

Several modules simulate planning decisions to acquire additional capacity that will be required in future years. These include the Electricity Capacity Expansion submodule, the pipeline capacity decisions for natural gas in the Natural Gas Transmission and Distribution Module, and the refinery capacity decisions in the Liquid Fuels Market Module.

To simulate such decisions, information on future demands and prices must be assumed. 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:

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

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

The foresight mode determines how the expectation variables are to be calculated: under myopic foresight, the expected values are simply held constant at their current trial values. For adaptive expectations, 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**.

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 modules estimate end-use prices $P_{f,s,r,y}$ and capacity additions as functions of current and expected energy demands. The conversion modules (electricity and refinery) are viewed primarily as supply components, but they are both consumers of primary energy and suppliers of energy products.

For some model components, a rational expectations, or "perfect foresight" approach is used implicitly or explicitly. Where these approaches are used, expectations for future years are defined by the realized solution values for these years in a prior run. This approach is used, for example, for the energy demand expectations used for capacity planning of energy infrastructure (pipelines and refineries). The other area is for market-based approaches to limit carbon dioxide emissions, where knowledge of future emission taxes or permit prices is assumed to be known in advance.

Cycles. To solve NEMS with perfect foresight structures, an added dimension, or super loop, to the convergence procedure was developed. This extension to the solution algorithm involves the iterative execution of complete NEMS runs (i.e., single passes through all of the projection years). Each such pass through NEMS is referred to as a cycle. Previously, a NEMS run was initiated from some prior run's restart file, and a series of individual runs was made by "cycling" the output restart from one run as the input restart file for the next run. This process improved convergence and was used to resolve perfect foresight expectations. When this process became routine, the cycling of runs was automated as part of a single NEMS "batch job." Now, a NEMS batch job consists of a multiple set of individual runs of NEMS, with the output restart file of each run used as the input restart file to the next run. Each such run in the series is referred to as a "cycle."

Cycles are analogous to the convergence iterations used to solve NEMS for a single year. Solution values for successive cycles are compared to determine if expected values (from the prior cycle) and realized values (from the current cycle) converge. This procedure has been implemented through a run-cycling option, controlled by an "intercycle convergence check." Operationally, this involves a Korn shell script (or batch command process) that repeatedly executes NEMS, automatically cycling the output restart file for one run to be used as the input restart file for the next run. A program (outside of NEMS, per se),

known as “intercv” performs the intercycle convergence checks and scores the degree of intercycle convergence using a qualitative metric (discussed more below). It is typical, then, to run NEMS in sets of 4-to-10 cycles to achieve intercycle convergence. In addition, a relaxation procedure, similar to the single-year relaxation procedure, can be applied to speed up convergence between cycles. Parameters for testing convergence between cycles are separate from those for testing convergence between iterations, and are specified through the input file **iccnvrg.txt**.

Another reason for introducing this run-cycling loop to NEMS runs was the need to implement a direct link to an external macroeconomic model purchased from IHS Global Insight. The IHS Global Insight model, written using the “Eviews” modeling software, could not be integrated into NEMS, nor could it be configured to execute for a single projection year. As a result, the IHS Global Insight model is launched from NEMS as a separate, executable process (known as a “child process” in operating system terminology) during the first simulation year of NEMS. The IHS Global Insight model executes for the entire projection period, using as its energy inputs the NEMS results from the input restart file. While the IHS Global Insight model executes, NEMS execution is suspended and resumes when the IHS Global Insight model finishes. NEMS then captures IHS Global Insight macroeconomic outputs for the entire projection period and applies them within the current NEMS cycle.

Speeding solution times. For *AEO2014* developmental runs, the execution time for one cycle was approximately four hours. With runs requiring six or more cycles, results would not be available until a full day after the run was submitted. To speed runs, an option was introduced to reduce the number of iterations of early cycles to three (maximum iterations are set to two with the final convergence and reporting loop, executed as an extra iteration when NEMS fails to converge on the two iterations, making the third). This run-time option can be enabled in the user scenario descriptor file, setting CUTITR=1. It pairs with another run-time option (DOAMINOF) that specifies a minimum number of cycles to be executed, so that any cycle that could possibly be the final cycle (i.e., the cycle number is equal to or greater than the number specified for DOAMINOF) reverts to the normal number of iterations. The reasoning behind this approach is that the results in the early cycles need not be as precise, as they are used to establish the long-term trends for expectation purposes. Once established, a finer-converged solution can be sought. The shorter cycles save about 40% of the run time from the traditional cycles, completing in about two and a half hours each.

Parallel run approach. The modularity of NEMS allows for each module to be run alone, paired with the integrating module in what we refer to as “standalone” mode. Thus, the Jacobi approach towards convergence could be used, with each NEMS module run using the same input and the results merged together. This would be repeated until the results were within a specified tolerance. Since two NEMS modules, the Electricity Market Module and the Liquid Fuels Market Module, account for more than half of the execution time of NEMS, and most of the rest of the modules run much more quickly, modules can be grouped together reducing the number of parallel processes, with a combination of the Jacobi and Gauss-Seidel methods used. Due to the degree of connectivity between the Electricity Market Module, the Coal Market Module, and the Renewable Fuels Module, these are run together. The rest of the modules, along with the Renewable Fuels Module, run in a second process. After these two processes complete, the results are merged together, and another cycle is run.

Solution algorithm—detailed flow outline

Figure 3 presents an outline of the Integrating Module algorithm to illustrate the logical organization and flow.[4]

Figure 3. NEMS Integrating Module Outline

I. Read run options.

II. Read Global Data from a prior run via the run's RESTART file.

III. Year Loop – "DO CURIYR = FIRSYR, LASTYR" (e.g., year index CURIYR goes from 1 to 51 usually, representing calendar years from 1990 to 2040; however, most models bypass history years prior to their base year.)

A. Set Maximum Convergence Iterations (MAXITR) for Current Year (CURIYR).

1. MAXITR = MAXITRJR (History years)
2. MAXITR = MAXITRSR (Projection years)

B. Convergence/Iteration Loop – "WHILE CURITR <= MAXITR & CTEST = 0" (i.e., while iteration count CURITR is less than or equal to the maximum, MAXITR, and the global convergence test has failed)

1. Store the convergence variable values for post-run convergence checks and reporting.
2. Model Loop – "DO IMODEL = 1, NMODEL (model number goes from 1 to 12)

   The usual model execution order is:

   1. International
   2. Macroeconomic
   3. Coal
   4. Residential
   5. Commercial
   6. Industrial
   7. Transportation
   8. Electricity
   9. Oil and Gas Supply
   10. Natural Gas Transmission and Distribution
   11. Refinery
   12. Renewables

   Is the model switched on? If "yes":

   i. Update the expectation variables.
   ii. Replace "previous values" with "current values" to prepare for model-specific convergence check
   iii. Call model's main subroutine (e.g., CALL WELL for the Oil and Gas Supply module)
   iv. Check convergence. Do "current values" differ from "previous values" by more than the allowed tolerance? If "yes," assign 0 to CNVTEST(IMODEL); otherwise assign 1.
   v. Perform relaxation. If the relaxation option is on (IRELAX = 1) and this model is not converged (CNVTST(IMODEL) = 0), then relax convergence variables by setting values between current and previous values based on the relaxation fraction.
   vi. Apply the carbon price to adjusted end-use energy prices (if applicable).
3. Run the Emissions Module. Calculate carbon emissions and set a new carbon price (if applicable).
4. Did all Models pass the Convergence Test (CNVTST(IMODEL) = 1 for IMODEL = 1 to 12)? If "yes," set CTEST to 1 to trigger an exit from the Convergence/Iteration Loop.

C. Final Convergence and Reporting Loop (FCRL) – Set FCRL = 1 and run all the models one more time to ensure solution remains converged, and to allow the models to generate summary results and reports.

1. Model Loop – "DO IMODEL = 1, NMODEL" (see details above)
2. Run the Emissions Module.

D. Optional Reporting Loop – Run any models that store or write results without resolving the model.

IV. Write Global Data to new RESTART file.

[4] Not reflected is the run-cycling that is used to resolve perfect foresight expectations and to integrate the external IHS Global Insight model with NEMS.

The outline depicts the three nested levels of looping to implement the convergence algorithm within a single run or cycle. Looping over the projection years takes place in the outer-most of these loops (see **Section III** in Figure 3). The objective of the algorithm is to execute the system of component modules repeatedly until convergence is reached in a given year and the solution remains converged for a subsequent iteration. This is reflected in the convergence iteration loop (see **Section III.B** in Figure 3).[5]

The solution procedure for one convergence iteration involves looping over the twelve component modules (see **Section III.B.2** in Figure 3). If a module is switched on, six steps are executed. (See items **III.B.2.i to III.B.2.vi** in Figure 3). The component modules include the International Energy Module, the Macroeconomic Activity Module, the four sectoral demand modules, the conversion modules, and the supply modules. The order of execution of the modules was designed to be flexible; in practice, however, the execution sequence has remained as indicated in the outline.

Before a module is executed, the current quantities and prices (denoted k) are stored as the previous iteration values (denoted k-1) in preparation for the post-module convergence test (outline **Section III.B.2.ii** in Figure 3):

$$Q^{k-1}_{f,s,r,y} = Q^{k}_{f,s,r,y}$$

$$P^{k-1}_{f,s,r,y} = P^{k}_{f,s,r,y}$$

The post-module convergence test (see outline Section **III.B.2.v** in Figure 3) identifies the specific modules whose output variables are not converged. While a single convergence test could be made after all modules were executed, these intervening, or post-module checks are used to determine whether the relaxation algorithm for the modules' output variables is performed. Once all modules are finished, an additional global convergence check examines the test results for all of the individual modules (outline **Section III.B.4** in Figure 3). If this global convergence test passes, the trial solution is considered converged pending a final iteration to test stability.

Separate convergence tests are made for prices and quantities, consisting of a comparison of the absolute value of the percentage changes to an assumed tolerance, ε, as follows:

$$\left| \frac{Q^{k}_{f,s,r,y} - Q^{k1}_{f,s,r,y}}{(Q^{k}_{f,s,r,y} + Q^{k1}_{f,s,r,y})/2} \right| < \varepsilon$$

$$\left| \frac{P^{k}_{f,s,r,y} - P^{k1}_{f,s,r,y}}{(P^{k}_{f,s,r,y} + P^{k1}_{f,s,r,y})/2} \right| < \varepsilon$$

In the convergence tests, 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 ignored for changes less than a user-specified minimum level (normally set at 10 trillion Btu).

[5]For simplicity, the outline omits a convergence stability "while" loop that continues processing until the solution remains converged for two iterations or the maximum iterations is reached.

If the post-module convergence test fails, an optional relaxation of the variables is performed (outline **Section III.B.v** in Figure 3), meaning that the variables are reset part way between the current and previous iterations' values.

The convergence iteration loop (outline **Section III.B** in Figure 3) is repeated until convergence is achieved or until the maximum number of iterations is reached.[6] When one of these two conditions occurs, an additional iteration, referred to as the "Final Convergence and Reporting Loop" is executed (outline **Section III.C** in Figure 3). 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 summarize final results and write reporting data to disk. If variables fail to converge on the Final Convergence and Reporting Loop, the convergence algorithm continues. In such cases, the model may converge on a subsequent iteration, thus triggering the Final Convergence and Reporting Loop a second time. Because of this, an optional reporting-only loop was added (see end of outline **Section III.D** in Figure 3) to call modules that have independent reporting routines that do not require model re-execution. This also allows modules to access the final solution variables from all other modules to use in their reports.

Whenever convergence fails to occur 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 projection year. A nonconverged final solution should be examined to assess its validity.

Several information sources are generated to aid in convergence analysis. The NEMS console output, directed to a file "**nohup.out**," constitutes an execution log for the run. This log records the progress of the model and the convergence status after execution of each module. 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.

A summary log (named "**maindbug**") is written to show the convergence status for each projection year, along with up to 25 variables that failed to converge. In addition, a database of values by iteration is generated optionally in a direct-access, binary format for all variables subject to convergence testing. That file (**mnpqit.daf**) can be accessed through a utility program "**readda**" that will output a subset of convergence variables in text format.

[6] Generally, the highest setting used for this limit on iterations (MAXITR) is 6. With an additional iteration allowed for the final iteration and reporting loop, up to 7 iterations are performed. Since many convergence failures involve oscillations between two values, an even number of iterations ends on roughly the same trial solution values on each cycle. To more accurately reflect this type of convergence problem in the inter-cycle convergence tests, "MAXITR+1" should be an odd number, so MAXITR should be set by the user as an even number.

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.

Convergence metric

Often, it is difficult to judge how important the detailed, regional convergence failures are, as they are implemented on a pass-fail basis. That is, an all-or-nothing convergence test does not give one a sense of how poorly or how well the run is converged. A qualitative metric for convergence is presented in a NEMS output report (NEMS report writer output table 150) as an aid in evaluating the degree of convergence. The convergence metric, known as the Grade Point Average (GPA) scores the convergence tests on a 4-point, academic-style grading scale. With this idea, a run's convergence status is revealed with a single number associated with a sense of quality: a 4.0 GPA is a straight-A average, for example. A run with a convergence GPA of 2.0 (a C) is average, while a GPA of 1.0 (a D) is a poor grade. This heuristic grading scale is derived using a weighted average of the absolute value of percentage differences in convergence variables, aggregated across sectors and regions. The convergence GPA is calculated as follows:

1) Compute deviations for convergence variables for each fuel, region, and sector in year. Let:

$DEV_{f,r,s,y}$ = Absolute value of deviation in a convergence variable: fuel *f*, region *r*, sector *s*, year *y*, where a deviation is one of the following:

a) Quantity deviation: absolute value of (the current quantity minus the previous quantity)

b) Price deviation: absolute value of the current expenditure (i.e., price times quantity) minus the previous expenditure (the expenditures exclude any permit price adders)

c) Emission allowance price deviation: absolute value of the current allowance price minus the previous allowance price.

$PREV_{f,r,s,y}$ = Previous value for a convergence variable: fuel *f*, region *r*, sector *s*, year *y*

2) Group the convergence variables into five categories, *c*:

End-use sector energy consumption quantities
Electric power sector energy consumption quantities
End-use sector energy prices
Electric power sector energy prices
Environmental permits/Allowance prices: carbon dioxide, sulfur dioxide, and mercury

3) Aggregate the deviations (*DEV*) across regions, fuels, and sectors within each of the five categories, *c*, and express the deviations as percentage of the corresponding prior values (*PREV*). Let $AC_{c,y}$ = the aggregated change (or deviation) for category c and year y, expressed as a percentage. That is:

$$AC_{c,\,y} = \frac{\sum_{f}\sum_{r}\sum_{s} DEV_{c,f,r,s,y}}{\sum_{f}\sum_{r}\sum_{s} PREV_{c,f,r,s,y}} * 100.$$

for all fuels *f*, regions *r*, and sectors *s* that belong in category *c*.

4) Compute a composite score by averaging the aggregated changes (AC) of the 5 categories, using the following weights (the basis for the values is described further below):

Category	Weight
End-use sector energy consumption quantities	24.5
Electric power sector energy consumption quantities	24.5
End-Use sector energy prices	24.5
Electric power sector energy price	24.5
Environmental allowance fees	
Carbon dioxide (if applicable)	0
Sulfur dioxide	1
Mercury (if applicable)	1

5) Scale or grade the composite score into a grade point average (GPA), by interpolating the score from the following table:

Score (% basis)	Grade on 4-pt scale	Letter Grade
0.5 or less	4.0	A
2.0	3.0	B
5.0	2.0	C
10.0	1.0	D
15.0 or more	0.01	F

6) This process is also used to calculate the metric based on national-level data.

The weights and the grading scale tend to magnify the importance of common convergence problems. The carbon dioxide allowance price has been weighted as 0 (thus not entering into the convergence decision) because the sectoral prices include the carbon dioxide allowance price; thus any movement from cycle to cycle will be reflected in the end use prices. This allowance price also greatly influences capacity expansion decisions made in the electric power sector and macroeconomic feedbacks, so stability in this price is essential for inter-cycle convergence. Fuel demands and prices in the electric power sector are also given a relatively strong weight in the scoring. Flexibility in electric power sector fuel demands, the use of linear programs for plant dispatch and capacity build decisions, and complex interactions with the coal supply module with respect to environmental constraints all tend to foster

convergence difficulties in this sector. The capacity choices, influenced by fuel price expectations and any energy-related taxes or emission allowance fees, are a primary source of inter-cycle convergence problems, as reflected by the fuel consumption in the electric power sector.

The cycling of NEMS runs continues for a user-specified number of cycles (run-time option NRUNS) or until the inter-cycle convergence objective has been met. The objective is based on the average of the three lowest (worst) yearly GPAs. If this average GPA is lower than the user-specified minimum (run-time option MINSCORE), the cycling continues. Otherwise, the cycling stops. Additional user-specified options can be set to perform all of the requested cycles regardless of convergence (run-time option DOEMALL) or to perform at least a certain number of cycles (run-time option DOAMINOF).

Also, when evaluating the just-completed NEMS cycle, one of several event occurrences will cause NEMS to proceed to the next cycle, even if the convergence criteria are met. These events are "true/false" tests as to the successful completion of the IHS Global Insight macroeconomic model and the Liquid Fuels Market Module linear program. Ideally, a fully acceptable NEMS run will not include any of these computational irregularities.

Discontinuities and convergence problems in NEMS

The characterization of NEMS as a set of supply and demand curves provides a useful framework for discussing convergence properties. Though supply and demand curves are generally treated as continuous functions, various NEMS modules contain linear programs or their analogues that result in discontinuities. Such discontinuities cause significant problems in the solution process.

Several modules incorporate algorithms that yield these discontinuous results. For example, the international module outputs a set of crude oil supply curves and petroleum product import supply curves which the Liquid Fuels Market Module translates to step curves for input to a linear program, representing refinery operations and solving for fuel prices and refinery fuel demands to minimize costs. This type of approach yields discontinuous petroleum pricing and fuel demands. The Electricity Fuel Dispatch submodule is also implemented as a linear program and contains discontinuities due to the nature of the merit-order plant dispatch. The coal distribution submodule is also 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. Figure 4 and Figure 5 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.

Figure 4. The supply curve cuts across the horizontal portion of the demand curve

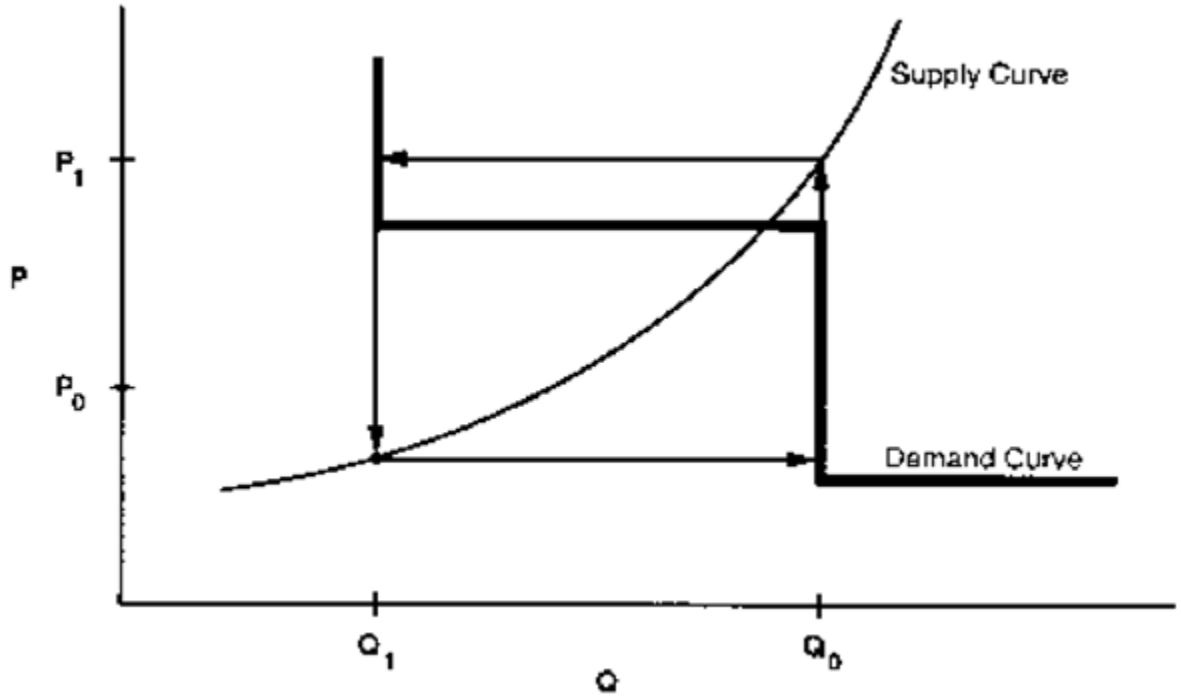
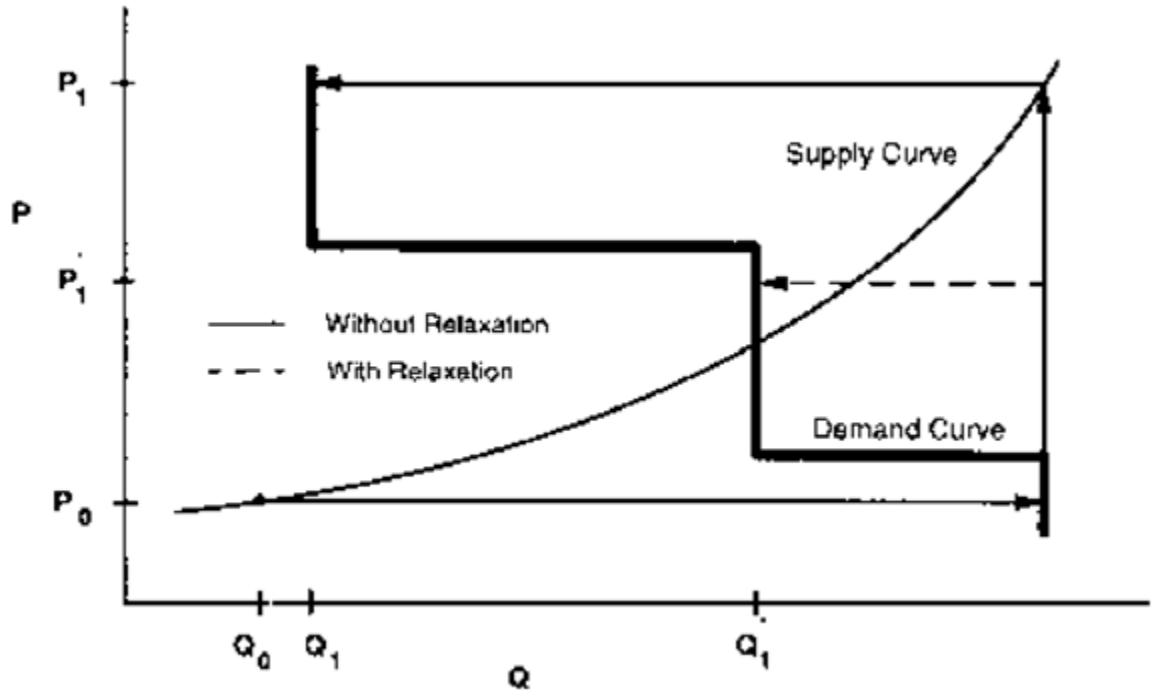


Figure 5. The supply curve cuts across the vertical portion of the demand curve



When the supply curve intersects the horizontal portion of the demand curve, there is an oscillation in the solution between quantities Q0 and Q1 and prices P0 and P1 (Figure 4). 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 5). In Figure 4 there is no relaxation fraction, r, for which convergence will occur. However, a value for r can be found so that the oscillation occurs around no more than two steps. Provided the steps are small enough to fall within the convergence tolerance, relaxation can prevent oscillations between steps from being a convergence problem.

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 and the three supply modules providing it with fuel prices: the Natural Gas Transmission and Distribution Module, the Liquid Fuels Market Module, and the Coal Market Module.

For a given time period, the Electricity Fuel Dispatch submodule of the EMM determines how generating capacity should be used 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 Fuel Dispatch submodule based on a linear program that effectively simulates a merit-order plant dispatch. The Fuel Dispatch submodule also simulates the capability of dual-fired plants to switch between natural gas and oil and coal plants to co-fire with biomass based on relative fuel prices and other operating costs. These modeling characteristics may result in discrete changes in the quantity of fuels required as relative prices change, often leading to convergence oscillations in the natural gas market model as depicted in Figure 4 and Figure 5.

Merit order switching in the electricity market commonly occurred between natural gas and other fuels, between types of coal (graded by sulfur content), and sometimes between class of natural gas customer (those receiving guaranteed service versus those under a less certain and/or continuous basis). Several techniques were used to reduce this effect, depending on the specific cause of the switch. These included incorporating demand curves in the Liquid Fuels Market Module and Natural Gas Transmission and Distribution Module, implementing price relaxation in the Integrating Module, and transferring the calculations of sulfur allowance pricing and coal choices by sulfur content from the Electricity Market Module to the Coal Market Module.

With the exception of a generic price relaxation algorithm in the Integrating Module, these convergence problems were addressed through changes in the individual supply and conversion modules of NEMS. The documentation of each module should be consulted for current modeling details (see Appendix A for references).

Additional convergence issues have been encountered with the introduction of the multi-cycle convergence process and energy-related emissions policy constraints. When NEMS is run to meet an overall annual carbon dioxide emission constraint, a trial carbon dioxide permit value is added to fuel

prices in proportion to each fuel's carbon content. The trial permit price is varied until the emission constraint is realized within a given tolerance. Electricity capacity expansion decisions are sensitive to expected permit prices. To reflect such expectations a solution process was configured to solve for the entire emissions permit price path. This involves execution of multiple cycles of NEMS and an approach to setting emission permit prices at the start of each cycle based on a weighted average of the realized and expected permit prices from the prior run. The cycling is repeated until realized and expected permit prices converge.[7]

Expected value foresight

Energy projections involve 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, the planning of electricity generating capacity additions, and the planning of infrastructure expansion, such as natural gas pipeline additions or E-85 fueling stations. 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 by 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 calculate 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 recommended that several options for modeling foresight be developed.[8] 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 was to be constructed so that an on-off switch was examined to determine whether the module would use centrally generated expectations.

[7] Most of these cases were resolved by increasing the dampening (the weight of the prior solution's expectation guess via the model option "WGTGUESS"), but at the expense of longer run times and more cycles.
[8] National Research Council, The National Energy Modeling System, Washington D.C.: National Academy Press, 1992.

When this central-control switch is turned on, the module uses these expectations; otherwise, the module uses self-generated expectations.

There are three options to generating expectations:

- The *myopic expectations* option is one in which expected prices for any projection period are assumed to be constant in real dollar terms relative to the current period in which decisions are being made. This case generally applies to expected prices and not expected quantities because an assumption of constant energy quantity demanded is rarely 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 representing 2021 for use in model year 2020 would be determined from the growth over the last few model years (e.g., 2018 to 2020), with the number of years being a model option. For expectations generated within individual modules, more elaborate behavioral models, or adaptive expectations, can be used.
- *The perfect foresight* approach is based on the theory of rational expectations. This 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 solution values. A variation in the integrating algorithm was required to implement perfect foresight. This option involves the iterative cycling of NEMS runs, with each cycle being a complete pass over the entire projection period. The objective is to have expected values and realized values converge between cycles, a state referred to as inter-cycle convergence, in addition to having convergence within the cycle for individual projection years, or intra-cycle convergence. As a result, it has become necessary to evaluate NEMS runs with respect to both inter-cycle convergence and intra-cycle convergence.

The Electricity Market Module is heavily dependent on expectations techniques, requiring 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. In the past, algorithms to generate these expectations were implemented in the NEMS integrating model. In recent years, new approaches for electricity demand and coal price expectations have been implemented directly in the Electricity Market Module. At present, some aspects of the oil and natural gas price expectations for the Electricity Market Module are still implemented in the integrating module. The approaches are described below:

- Oil product price expectations are calculated from an external projection of world oil prices, assuming a constant markup between the regional product price and the world oil price. In each projection year, the assumed markup is derived from the prior projection year:

  $P_{c+y} = (P_c - W_c) + W_{c+y}$ for y=1,...,30 years (planning horizon for power plants)

  where P_c and W_c are the product price and the exogenous world oil price from the previous

projection year, and P_{c+y} and W_{c+y} are the prices in the expectation years.

- The wellhead price expectations through 2040 are generated by a perfect foresight method (by default). The wellhead price expectations are taken as a weighted average of the prior run's realized prices and its expected prices. The weight is specified by the user. 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 for the post-2040 period are based on a nonlinear function that relates the expected wellhead gas price to cumulative domestic gas production. The basis for this adaptive expectation approach is the notion that increases in cumulative production would be associated with the depletion of domestic resources and, in turn, general expectations of increases in price in the long run. An equation that tries to capture this general idea is of the following form:

$$P_y = A * Q_y^e + B \quad ,$$

where P is the wellhead price, Q is the cumulative production from 1991 to future year "y" in the planning horizon, "e" is a user-specified parameter, 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, as prices could be expected to rise as existing resources are depleted.

- The rate of change in wellhead prices is a function of the economical reserves that remain to be discovered and produced. The value of the parameter e determines the shape of the function.

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 value PF is an assumed input to the approach, while QF is assigned as the resource base in the Oil and Gas Supply Module for a specified year (2008 in *AEO2014*). In the *Annual Energy Outlook 2014,* the assumed value of PF was $9.00/mcf (in real 1998 dollars), corresponding to a cumulative production (QF) of 2,552 tcf. The annual production is assumed to grow at the rate observed over the prior three years within the projection. 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

$$A = (PF - PS) / (QF^e - QS^e)$$

$$B = PF - A*QF^e$$

The following assignment statement extrapolates cumulative production for future years, y = 1, ... , 30 years (with 30 years being the maximum planning horizon for power plants):

$$Q_y = Q_{y-1} + D$$

This generates the expected wellhead prices:

$$P_y = A * Q_y^e + B$$

$$= PF + \left(Q_y^e - QF^e\right) * \left(\frac{PF - PS}{QF^e - QS^e}\right).$$

The value for "e" is assumed to be .70 until the price reaches a point at which the unconventional recovery of natural gas becomes economic ($3.50 in real 1998 dollars), and 1.3 afterward, creating an inflection point in the curve which generally occurs prior to model execution year 2040 (in the *AEO2014* Reference case, this point occurred in 2025).

Carbon dioxide emission calculations

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

For fuel uses of energy, the combustion fractions are assumed to be 1.00 for solid, liquid and gaseous fuels. The potential emissions of carbon dioxide from nonfuel uses 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 dioxide coefficients, combustion fractions, and emission factors. The adjusted emission factors are input into the Emissions Policy Submodule through a file ("epmdata.txt"). Factors for the last available year, 2012, apply for all projection years.

Table 6. Carbon dioxide emissions factors

million metric tons per quadrillion Btu

Fuel Type	Carbon Dioxide Coefficient at Full Combustion	Combustion Fraction	Adjusted Emission Factor
Petroleum			
Propane			
Used as fuel	63.07	1.000	63.07
Used as feedstock	61.07	0.200	12.61
Ethane used as feedstock	59.58	0.200	11.92
Butane used as feedstock	64.94	0.200	12.98
Isobutane used as feedstock	65.08	0.200	13.02
Natural gasoline used as feedstock	66.88	0.300	21.12
Motor gasoline (net of ethanol)	71.26	1.000	71.26
Jet fuel	70.88	1.000	70.88
Distillate fuel (net of biodiesel)	73.15	1.000	73.15
Residual fuel	78.80	1.000	78.80
Asphalt and road oil	75.61	0.000	0.00
Lubricants	74.21	0.500	37.11
Petrochemical feedstocks	71.02	0.410	29.11
Kerosene	72.31	1.000	72.31
Petroleum coke	102.12	0.956	97.60
Petroleum still gas	64.20	1.000	64.20
Other industrial petroleum	74.54	1.000	74.54
Coal			
Residential and commercial	95.35	1.000	95.35
Metallurgical	93.71	1.000	93.71
Net coal coke imports	117.81	1.000	117.81
Other industrial	93.98	1.000	93.98
Electric power	95.52	1.000	95.52
Natural gas			
Used as fuel	53.06	1.000	53.06
Used as feedstock	53.06	0.437	23.21

Source: U.S. Energy Information Administration (EIA), *Monthly Energy Review, August 2013*, DOE/EIA-0035(2013/08) (Washington, D.C., August 2013), available on the web at http://www.eia.gov/totalenergy/data/monthly/archive/00351308.pdf .

Any carbon dioxide emitted by renewable sources is considered balanced by the carbon dioxide sequestration that occurred in its creation. Therefore, following convention, net emissions of carbon dioxide 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.

Several adjustments to the carbon dioxide 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 the potential emissions of carbon dioxide to be sequestered in the product. The amount of carbon dioxide sequestered depends on product characteristics that are not defined explicitly in NEMS. Following EIA's practice, an average sequestration fraction is used for each nonfuel use. In the Industrial Module, consumption of propane and natural gas are divided into feedstock and combustion categories. For the feedstock uses, an appropriate sequestration rate is applied to account for the average proportion of carbon dioxide sequestered among products in this category. "Other" petroleum products used in the industrial sector include lubricants, waxes, 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 dioxide emissions, the total consumption of motor gasoline is reduced by the amount of ethanol used in its production before multiplication by the emission coefficient. This modification represents about 75 million metric tons of carbon dioxide in 2040 for the *AEO2014* Reference case. A similar adjustment reduces transportation distillate by the amount of biodiesel used, representing about 10 million metric tons of carbon dioxide in 2040.

Electricity Generation Market: Carbon dioxide emissions from coal are computed for each of seven categories of coal, as determined in the Electricity Market Module and the Coal Market Module. The carbon dioxide emission factor for each coal category is 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 implements four carbon dioxide policy evaluation options. These options can be used to simulate proposed market-based approaches to meet national carbon dioxide emission objectives. The four policy options are as follows:

1) **Carbon dioxide 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 dioxide emission factor.[9] 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 dioxide emissions reductions.

[9] A single tax rate applies to all categories of carbon dioxide. A switch in the control file allows the tax rate to be treated as either a carbon dioxide tax (dollar per kilogram carbon) or as a Btu tax (dollar per million Btu). This flexibility allows the emissions policy module to be used to analyze simple energy tax policies as well.

Revenue from the tax is passed to the macroeconomic module where treatment of such revenue (e.g., reducing the deficit or reducing other taxes through a lump sum redistribution to consumers) depends on a user-specified option setting. 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 dioxide 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 dioxide goal by clearing the auction market. The permit fee is treated as a carbon dioxide emissions tax and used as an adjustment to the fossil fuel prices. A new auction price is set at the end of each NEMS iteration (where one iteration in the solution algorithm refers to a single execution pass through all NEMS modules for a single projection year) 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 Dioxide 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 dioxide emission permits is simulated assuming that an initial distribution of marketable permits to emission sources takes place. The permits are transferable. Depending on a user-specified model option, the permits may be treated as bankable across years. As with the carbon dioxide tax and auction options, the full market price of the permits is added to 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.

In an open, competitive permit market, the permit will tend to be priced at the marginal cost of reducing carbon dioxide 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 dioxide emissions 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 in the Liquid Fuels Market 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 at the end of each NEMS iteration (where one iteration in the solution algorithm refers to a single execution pass through all NEMS modules for a single projection year). The fee is adjusted up or down in response to the total carbon dioxide emissions obtained. The price of an allowance is adjusted until the total carbon dioxide 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 tradable emissions permits to increase through a user-specified supply of offsets, expressed as marginal abatement cost tables for other (non-carbon dioxide) gases. This option can be used to analyze a greenhouse gas emission reduction policy that credits reductions in emissions from non-covered sources, reforestation, or purchases of emission reductions credits from abroad. Purchases of offsets, in millions of metric tons available at the given allowance price, are added to the carbon dioxide goal. While some test values for offsets are available, any formal use of this option would require additional research to arrive at appropriate assumptions. The specification of offset supply curves, or marginal abatement cost tables, along with exogenous projections of greenhouse gases other than energy-related carbon dioxide, are made through an input file "ghgoff.xml."

5. Emissions Policy Submodule Implementation and Mathematical Specification

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

The fee on carbon dioxide 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 dioxide fee added, and an adjusted set of prices that includes the carbon dioxide fee. The unadjusted prices are those determined by the NEMS supply and conversion modules. The adjusted prices, with the carbon dioxide fee included, are the price 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 dioxide fee.

Input-output linkages

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

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

The total carbon dioxide emissions from both combustion and non-combustion sources are calculated in the Emissions Policy Submodule from information in the common blocks QBLK, INDOUT, PMMRPT, EMMOUT, and COALEMM. The common block QBLK contains the quantities of end-use fuels consumed. In QBLK, feedstock uses of propane and natural gas are not broken out separately from total industrial liquefied petroleum gases and natural gas, respectively. The feedstock portion of these fuels is obtained from two variables, QPRINPF and INQNGPF, in the common blocks QMORE and INDOUT, respectively. Consumption of biodiesel and ethanol, stored in common block PMMRPT, are removed prior to calculating the emissions from petroleum in the transportation sector. The EMMOUT common block has natural gas consumption reported by Electricity Market Module region for firm, interruptible, and competitive categories. The COALEMM block contains coal consumption by sulfur dioxide classification category and emissions factors for coal aggregated to those same categories. Several policy options result in revenue from the carbon dioxide penalty flowing to the government. This revenue is furnished to the Macroeconomic Activity Module through the EMISSION common block.

Emissions policy submodule algorithm

The Emissions Policy Submodule is executed once per iteration to determine total carbon dioxide emissions produced, the revenue created by any tax or permit fees for carbon dioxide emissions, and, depending upon the scenario, the level of offsets produced. For carbon dioxide emission policy options, a heuristic algorithm (subroutine REGFALSI) sets a new carbon dioxide fee to bring the carbon dioxide emissions closer to the carbon dioxide 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, “epmcntl.txt,” 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 dioxide goal (EMISSIONS_GOAL), and maximum tax (MAX_TAX).
      2) 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”).
      3) Read exogenous emission baseline for other (non-CO_2) gases and offset assumptions (marginal abatement cost tables) from file ghgoff.xml.
      4) Read mercury emission classes and caps (for use in the Electricity and Coal Market Modules).
      5) Read emission allowance auction shares.

II. Calculate carbon dioxide emissions and sum to a national total (Call SUM_EMISSIONS). Under a market permit system with offsets, determine what level of emission offsets is available to raise the carbon dioxide cap, given the current carbon dioxide tax (Call OGHG).

III. Calculate revenues from carbon dioxide tax or carbon dioxide permit fees (Call ACCNTREV).

IV. Under a market permit system, allocate revenue to end-use sectors based on initial sector shares of carbon dioxide emissions (Call INITREV).

V. With a permit auction or market, assign a new carbon dioxide tax to reduce the absolute difference between the carbon dioxide emissions and the carbon dioxide goal (Call REGFALSI).

VI. Calculate the energy price adjustment for end-use fuels from the carbon dioxide tax by multiplying the carbon dioxide tax by the fuels' emission factor (Call PRICE_ADJUST).

VII. After each NEMS module is called, recalculate the prices to include a tax by adding the tax price to the prices determined by the supply modules (Call COPY_ADJUST).

Emissions policy submodule mathematical specification

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

SUBROUTINE: EPM

Description: This subroutine is the main controlling subroutine for the Emissions Policy Submodule. Initially, the subroutine reads flags to determine the scenario type: carbon dioxide 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 dioxide emissions are estimated (SUM_EMISSIONS), and the revenue from any carbon dioxide fee, regardless of whether it is from a carbon dioxide 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 dioxide 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 dioxide 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:
SUM_EMISSIONS
ACCNTREV
INITREV
REGFALSI
OFFSETS
PRICE_ADJUST

Arguments: None

Equations: None

SUBROUTINE: SUM_EMISSIONS

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

Called by: EPM

Calls: None

Arguments: None

Equations:

$$AMTPOL = \sum_{i} \sum_{j} \sum_{k} Em(ik) * Qf(ijk)$$

where

AMTPOL = Total carbon dioxide emissions from all fuels i (billion kilograms of carbon) from all regions j in year k,

Em(ik) = Carbon dioxide emission factor for fuel i (kilograms of carbon per 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

Arguments: None

Equations:

$$REV(l) = \sum_i \sum_j \sum_k EMTAX(k) Em(ik) Qf(ijk)$$

where

REV(l) = Total revenue collected in sector l from all fuels i from all regions j in year k (million 1987 dollars),

Em(ik) = Emission factor for fuel i (kilograms of carbon per million Btu) in year k,

EMTAX(k) = Carbon dioxide tax or permit fee (1987 dollars per kilogram of carbon) in year k,

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

The revenue from this calculation is subsequently converted to billion dollars by dividing by 1000. Revenue is then converted to nominal dollars.

SUBROUTINE: INITREV

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 dioxide permit fee.

Called by: EPM

Calls: None

Arguments: None

Equations: $CallocInit = Sallocinit * Palloc$

where,

CallocInit	=	Total value of initial allocation of permits (billion 1987 dollars),
SallocInit	=	Permits allocated initially (billion kilograms of carbon)
Palloc	=	Price of a permit (1987 dollars per kilogram of carbon)

SUBROUTINE: PRICE_ADJUST

Description: This subroutine assigns the price adjustment of each fuel to reflect the carbon dioxide emissions tax or 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 dioxide tax or permit fee.

Called by: EPM

Calls: None

Arguments: None

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

where,

Em(ik)	=	Emission factor for fuel i (kilograms of carbon per million Btu) in year k,
EMTAX(k)	=	Carbon dioxide tax (1987 dollars per kilogram of carbon) in year k,
Eadj(ik)	=	Price adjustment of fuel i (1987 dollars per million Btu) in year k

SUBROUTINE: REGFALSI

Description: This subroutine adjusts the carbon dioxide tax (or carbon dioxide permit fee) such that the carbon dioxide emission goal is met. In general, the routine will increase the tax if the carbon dioxide 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)* represent the difference between the carbon dioxide emissions and the carbon dioxide goal for a carbon dioxide 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 dioxide penalty, x_i and a_i, where $a_i < x_i$, $f(x_i) < 0$, 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

Argumets: Receives previous iteration values for tax, and for emission level minus goal minus applicable offsets

Equations:

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

where,

a_i = Carbon dioxide tax on some previous iteration i such that $f(a_i) > 0$,

x_i = Carbon dioxide tax on some previous iteration i such that $f(x_i) < 0$,

u = New carbon dioxide 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 $f(u) = 0$ within a specified tolerance.

SUBROUTINE: COPY_ADJUSTED

Description: This subroutine updates the adjusted price common blocks, adding a fuel-specific cost adjustment to reflect a carbon dioxide tax or permit fee on each fuel. All of the prices in the unadjusted price common blocks MPBLK, NGDTMOUT, COALPRC, PMORE, PCDR, EUSPRC, and PONROAD are copied to the corresponding adjusted price common blocks AMPBLK, ANGTDM, ACOALPRC, APMORE, APCDR, AEUSPRC, and APONROAD 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

Arguments: None

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

where,

Padj(ijk)	=	Adjusted price of fuel i in region j and year k (1987 dollars per million Btu),
Pbase(ijk)	=	Unadjusted price of fuel i (1987 dollars per million Btu) in region j and year k
Eadj(ik)	=	Price adjustment of fuel i (1987 dollars per million Btu) in year k

SUBROUTINE: EPM_READ

Description: This subroutine reads the initial carbon dioxide penalty, emission factors, and offset curves.

Called by: NSOLVE

Calls: None

Arguments: None

Equations: None

Appendix A. Bibliography

The National Energy Modeling System is documented in a series of model documentation reports, available on the Internet at http://www.eia.doe.gov/bookshelf/docs.html . Most of the references in the Bibliography refer to these documentation reports and their publication numbers. The model documentation reports listed below are those available or expected to be updated in 2014 to reflect modeling changes for the *AEO2014*.

The reports listed below, unless cited otherwise, were produced by the U.S. Energy Information Administration in Washington, DC.

Annual Energy Outlook 2014, DOE/EIA-0383(2014) (May 2014).

Coal Market Module of the National Energy Modeling System, Model Documentation 2014, DOE/EIA-M060(2014).

Commercial Demand Module of the National Energy Modeling System, Model Documentation 2014, DOE/EIA-M066(2014) .

Electricity Market Module of the National Energy Modeling System, Model Documentation Report 2014, DOE/EIA-M068(2014).

Monthly Energy Review, August 2013, DOE/EIA-0573(2013/08), (August 2013).

Industrial Demand Module of the National Energy Modeling System, Documentation Report 2014, DOE/EIA-M064(2014).

International Energy Module, Model Documentation 2014, DOE/EIA-M071(2014).

Macroeconomic Activity Module (MAM) of the National Energy Modeling System—Model Documentation 2014, DOE/EIA-M065(2014).

Liquid Fuels Market Model of the National Energy Modeling System, Model Documentation 2014, DOE/EIA-M059 (2014).

The National Energy Modeling System: An Overview 2009, DOE/EIA-0581(2009), (October 2009).

Natural Gas Transmission and Distribution Model of the National Energy Modeling System, Model Documentation 2014, DOE/EIA-M062(2014).

Oil and Gas Supply Module (OGSM), Model Documentation 2014, DOE/EIA-M063(2014).

Renewable Fuels Module of the National Energy Modeling System, Model Documentation 2014, DOE/EIA-M069(2014).

Residential Demand Module of the National Energy Model System, Model Documentation 2014, DOE/EIA-M067(2014).

Transportation Sector Model of the National Energy Modeling System, Model Documentation 2014, DOE/EIA-M070(2014).

Appendix B. NEMS Software Management and Implementation

This appendix describes some aspects of NEMS integration related to software management and NEMS implementation. The features described relate to how NEMS is organized and implemented for use in EIA's multi-user development environment. These features do not apply to the archival version of NEMS, which is designed for a single user and a particular version of NEMS.

Configuration management

A custom configuration management system employing the public domain Revision Control System (RCS) is implemented at the file level and integrated into various model management features. The MKS Toolkit, used for Korn shell emulation and scripting, is used to implement most of these RCS features in a command-oriented shell environment that runs under the Microsoft Windows operating system. These commands and scripts have been updated to also run in an alternate Korn shell emulation and scripting package, Cygwin.

Centralized file storage and user directories

Files are stored on shared servers that are backed up by EIA's Office of Information Technology (incremental backups nightly; full backups weekly). The read-access to a common, shared storage area for NEMS files (called "/default") is open to all members of a NEMS group, but write-access to this area is controlled through configuration management procedures (e.g., check-in and check-out). The primary subdirectories in the NEMS common storage area are:

/default/input	input files
/default/source	source code files (.f)
/default/includes	supplementary source code, known as include files, with variable and common block declarations
/default/objects	compiled code known as object files
/default/logs	log files
/default/scripts	programs, Korn shell scripts, and related files

Each of the above directories has an RCS subdirectory. The RCS software stores revision histories of each file in the RCS subdirectory (e.g., /default/input/RCS). Additional subdirectories in the common storage area that are not subject to revision control are:

/default/oml	libraries for the Optimization and Modeling Library (OML)
/default/doc	miscellaneous files with user-oriented documentation and guidelines
/default/installcdcopies	copies of software installation CDs for disaster recovery (administrative access only)
/default/rcs_programs	executables for the RCS software

User directories, stored independently of the "/default" directory on the servers, are organized in four directories by functional areas of the users:

/mid	macroeconomic, international, demand
/rec	renewables, electricity, and coal
/ogs	oil and gas supply
/main	integration and other

These four areas have user-specific subdirectories to store each user's work-in-progress files, trial versions, and so on. Incremental nightly backups and full weekly backups provide a recovery capability for file accidents and hardware failure.

Outputs of runs may be stored locally on the user's PC or on the servers. Most runs are stored in an output directory on one of the servers. A run is stored in a scenario and date/version subdirectory (such as /output/aeo2014/ref2014/d102413a).

File change history

A text-formatted log recording a comment for changes to each file is maintained and the history of changes is retained. The change log is implemented at the file level, meaning there is one log and revision-history for each file. The command fdef {filename} is used to find and identify the default version of a given file and list its change history.

Input file naming convention

Each input file is named generically as well as with a unique version component. For example, the generic file, ghgoff.xml, has versions identified as ghgoff.v1.1.xml, ghgoff.v1.2.xml, etc. The generic version of the file name is used when it is copied to a run-specific input subdirectory and when it is checked-out for editing. In many cases, the name and version of the file are included in a file header, so that the version one is working with is evident, even if it is the generically-named file. (RCS can automatically maintain this internal version/file-name header for text files.)

NEMS input files are stored in the "/default/input" directory.

Defaults log

A text-formatted log ("/default/logs/defaults") is maintained with at least one line for each file in the modeling system. A log entry identifies the version (e.g., 1.2) of the file that is designated as the default. Other lines may identify the version(s) associated with a particular symbolic name (usually a run scenario such as "aeo2014co2"). Entries in the defaults log are maintained in sync with the file's RCS change history log. That is, symbolic names identifying a version (such as "default" or "aeo2014co2") are also added to the file's RCS change-history log whenever the defaults log is changed.

File check-out and locking

To change a file, a user "checks out" the file (using command "nemsco"). The user may lock the file, signifying an intention to change it and to prevent another user from changing it without coordination. A log ("/default/logs/ciolog") identifies the user and location of each locked file (a command "listlock" lists a user's locked files). Other users can therefore find out where files under development are located.

File check-in and version defaulting

Files may be returned to the common area using a check-in procedure ("nemsci"). A new version is assigned, a comment from the user is recorded, and, if requested, the new file version may be designated as the new default.

Model programming utility

Several features are available to support model development. A command-line procedure to compile a NEMS Fortran module is available ("nfort"). The default NEMS source code is stored in the "/default/source" and "/default/includes" directories. For model development, source code files (with extension ".f") and "include" files[10] are checked out for local modification and testing. The compiled code is stored in object files (extension ".obj"). Defaulted object files are stored in the "/default/objects" directory. A compilation log (*"*complog_*module"*) for each defaulted object file identifies the source code version and include file versions used to create it. Special procedures to check-out or check-in a source code version and its associated include files are implemented to support the linkages between specific source code and object file versions. These procedures are called "group check-out" and "group check-in."

Job setup keys for files and options

The "varkeys" file ("/default/scripts/varkeys") is a list of all the job setup keys that can be used to designate a run's input files and many other job submission options. This file is used by the NEMS run submitter to identify acceptable job options and convert job templates, or shells, into executable scripts.

Run submitter and job control

There are two versions of the NEMS job submitter: "runnems" (windows-oriented) and "jognems" (Korn shell command line script), as well as the "parnems" command described in the text for partitioned execution of NEMS. These programs initialize a run and either start it running immediately or submit it for batch execution. They read a user's run options from scenario-description files (scedes.*scenario*). A job log showing the status of currently executing jobs is available for status monitoring. The job log is displayed using the "jc" (job control) command with no arguments. A job control menu is displayed with the "jc menu" option and can be used to monitor, stop, or suspend individual jobs. Subroutines in the NEMS integrating module report status information during a run and respond to job control requests to stop, suspend execution, or change priority.

Distributed job processing

A mechanism to support group-wide, distributed batch job processing on individual workstations has been implemented to run NEMS jobs. The program that implements this on each workstation is called runit.exe. "Runit" monitors job submissions and can dispatch a NEMS run awaiting execution on its host workstation. The processing is controlled to limit the number of simultaneous jobs executing on any single workstation or server. Users can direct a job to run a particular workstation that has Runit executing (using *"*hostpc=*servername"* in the scedes file). The list of available Runit queues can be displayed using the "sq" (show queues) command. The status of job processing can be displayed using the "jc" (job control) command.

[10] Include files are files that are inserted into the primary source code by the compiler and are typically used to store declarations.

Run log

Runs are identified by a unique name using a scenario/datekey convention (e.g., ref2013/d102312a, where "ref2013" is the scenario and "a" is a version letter for that scenario run on October 23, 2013 (10/23/13). Version "a" was the first scenario named "ref2013" submitted on that day.). The run identifier also is used to name the location (folder) of the run's work-space and its output files. An entry for each run is made to central run log ("/default/logs/runlog"), identifying the output directory for the run and the user who submitted the run. In the output directory of a run, a text file named "launched.from" provides additional information on how the run was set up and the directory it was submitted from, as an aid in problem diagnosis/replication.

Record of run options and files used

All options and input files (and code files) for each run are recorded in a file in the output directory (called "scedes.all") and in the working directory from which the job was submitted (scedes.all.scenario.datekey).

Run replication and archival capability

Each run can be replicated by using its "scedes.all" to designate settings. A run can be initialized using the options/files from a prior run, then selectively updated with alternative options. A run archival script is available to collect all of the input files, object code, source code, and output files for a given run and save it in a package for model archival.