National Modeling Tools

1.0 Introduction

There are several tools which have been used to model energy systems at the national level. These tools can be considered expansion planning tools but are distinct in that they generally account for (a) energy infrastructure beyond that of just the electric power system and (b) environmental impacts. We summarized these tools earlier in the course, and repeat our summary here, in Table 1. But we did not describe them; we will do so in these notes.

Table 1

		NEMS	MARKAL/TIMES	WASP-IV
Output		Alternative energy assessment	Optimal investment plan	Optimal investment plan
Optimization model	Objective function	Single objective	Single objective	Single objective
	Stochastic events	√	√	√
	Formulation	Modular	Generalized network	Generalized network, modular
Forecast horizon		20-25 years	Unconstrained	30 years
Sustainability	Greenhouse gases	√	√	√
	Other emissions	√	√	√
Resiliency				Loss of load
Energy represented	Primary energy sources	√	√	
	Electricity	√	√	√
	Liquid fuels	√		
Transportation	Freight	√ ?	Only fuel demand	
	Passenger	?	?	

2.0 WASP-IV

WASP-IV does not model energy infrastructure beyond that of the electric system, and so it is a more classical expansion planning software tool, similar to EGEAS. It does model emissions. I have placed an overview of its capabilities on the website. Note carefully its program structure, which is given at the end of the posted document. Reference [1] is an extensive documentation of planning methods in general, and it dedicates a lengthy chapter to describing the methods employed in WASP. Reference [2] also provides some treatment of some of the methods employed in WASP.

3.0 The National Energy Modeling System (NEMS)

Information about NEMS presented in this section was obtained from [3]. The first version of NEMS was completed in 1993, developed by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). Because of the complexity of NEMS, and the relatively high cost of the proprietary software, NEMS is not widely used outside of the Department of Energy. However, NEMS, or portions of it, is installed at the Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, the Electric Power Research Institute, the National Energy Technology Laboratory, the National Renewable Energy Laboratory, and several private consulting firms.

The National Energy Modeling System (NEMS) is a computer-based, energy-economy modeling system of U.S. energy markets for the midterm period through 2025. NEMS projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics.

Applications

NEMS is used to project the energy, economic, environmental, and security impacts on the United States of alternative energy policies and of different assumptions about energy markets. The forecast horizon is meant to be approximately 20 to 25 years into the future. This time period is one in which technology, demographics, and economic conditions are sufficiently understood in order to represent energy markets with a reasonable degree of confidence.

NEMS can be used to analyze

- the effects of existing and proposed government laws and regulations related to energy production and use;
- the potential impacts of new and advanced energy production, conversion, and consumption technologies;
- the impacts and costs of carbon emissions reductions;
- the impacts of increased use of renewable energy sources;
- the potential savings from increased efficiency of energy use; and
- the changes in emission levels that are likely to result from such policies as the Clean Air Act Amendments of 1990, regulations on the use of alternative or reformulated fuels, and climate change policy.

Regional Aggregation Level

NEMS models the entire US at a regional level. For example, the demand modules (e.g., residential, commercial, industrial and transportation) use the nine Census divisions (illustrated in Fig. 1), the Electricity Market Module uses 15 supply regions based on the North American Electric Reliability Council (NERC) regions, the Oil and Gas Supply Module uses 7 onshore and 3 offshore supply regions based on geologic breakdowns, and the Petroleum Market Module uses 3 regions based on combinations of the five Petroleum Administration for Defense Districts. Table 2 on the next page summarizes the different aggregation levels implemented in NEMS.

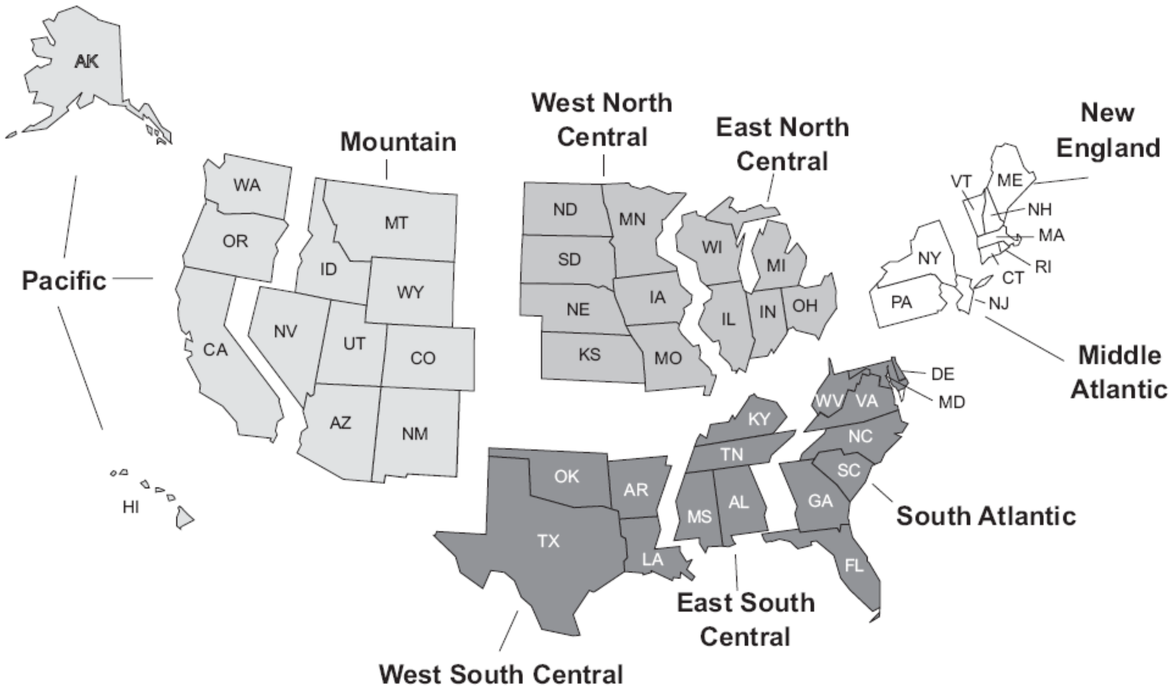
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Fig. 1

Table 2

Energ Acti it	Categories	Regions
Residential demand	Sixteen end-use services Three housing types Thirty–four 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 industries Eight non–energy–intensive industries Cogeneration	Four Census regions, shared to nine Census divisions
Transportation demand	Six car sizes Six light truck sizes Sixty–three conventional fuel-saving technologies for light–duty vehicles Gasoline, diesel, and thirteen alternative–fuel vehicle technologies for light-duty vehicles Twenty vintages for light-duty vehicles Narrow and wide–body aircraft Six advanced aircraft technologies Medium and heavy freight trucks Thirty–seven advanced freight truck technologie	Nine Census divisions
Electricity	Eleven fossil generation technologies Two distributed generation technologies Seven renewable generation technologies Conventional and advanced nuclear Marginal and average cost pricing Generation capacity expansion Seven environmental control technologies	Fifteen electricity supply regions (including Alaska and Hawaii) based on the North American Electric Reliability Council regions and subregions Nine Census divisions for demand
Renewables	Wind, geothermal, solar thermal, solar photovoltaic, landfill gas, biomass, conventional hydropower	Fifteen electricity supply regions
Oil supply	Onshore Deep and shallow offshore	Six lower 48 onshore regions Three lower 48 offshore regions Three Alaska regions
Natural gas supply	Conventional lower–48 onshore Lower–48 deep and shallow offshore Coalbed methane Gas shales Tight sands Canadian, Mexican, and liquefied natural gas Alaskan Gas	Six lower 48 onshore regions Three lower 48 offshore regions Three Alaska regions Eight liquefied natural gas import regions
Natural gas transmission and distribution	Core vs. noncore Peak vs. offpeak Pipeline capacity expansion	Twelve lower 48 regions Ten pipeline border points
Refining	Five crude oil categories Fourteen product categories More than 40 distinct technologies Refinery capacity expansion	Three refinery regions aggregated from Petroleum Administration for Defense Districts
Coal supply	Three sulfur categories Four thermal categories Underground and surface mining types Imports and Exports	Eleven supply regions Sixteen demand regions Sixteen export regions Twenty import regions

Domestic Energy System/Economy Interactions

The general level of economic activity, represented by gross domestic product, has traditionally been used as a key explanatory variable or driver for projections of energy consumption at the sectoral and regional levels. In turn, energy prices and other energy system activities influence economic growth and activity. NEMS captures this feedback between the domestic economy and the energy system. Thus, changes in energy prices affect the key macroeconomic variables—such as gross domestic product, disposable personal income, industrial output, housing starts, employment, and interest rates—that drive energy consumption and capacity expansion decisions.

Domestic/World Energy Market Interactions

World oil prices play a key role in domestic energy supply and demand decision–making and oil price assumptions are a typical starting point for energy system projections. The level of oil production and consumption in the U.S. energy system also has a significant influence on world oil markets and prices. In NEMS, an international energy module represents world oil production and demand, as well as the interactions between the domestic and world oil markets, and this module calculates the average world crude oil price and the supply of specific crude oils and petroleum products. As a result, domestic and world oil market projections are internally consistent. Imports and exports of natural gas, electricity, and coal—which are less influenced by volatile world conditions—are represented in the individual fuel supply modules.

Economic Decision-Making Over Time

The production and consumption of energy products today are influenced by past investment decisions to develop energy resources and acquire energy-using capital stock. Similarly, the production and consumption of energy in a future time period will be influenced by decisions made today and in the past.

Current investment decisions depend on expectations about future markets. For example, expectations of rising energy prices in the future increase the likelihood of current decisions to invest in more energy-efficient technologies or alternative energy sources.

A variety of assumptions about planning horizons, the formation of expectations about the future, and the role of those expectations in economic decision making are applied within the individual NEMS modules.

Technology Representation

A key feature of NEMS is the representation of technology and technology improvement over time. Five of the sectors—residential, commercial, transportation, electricity generation, and refining–include extensive treatment of individual technologies and their characteristics, such as the initial capital cost, operating cost, date of availability, efficiency, and other characteristics specific to the sector. Technological progress results in a gradual reduction in cost and is modeled as a function of time in these end–use sectors. In addition, the electricity sector accounts for technological optimism in the capital costs of first-of-a-kind generating technologies and for a decline in cost as experience with the technologies is gained both domestically and internationally.
In the other sectors—industrial, oil and gas supply, and coal supply—the treatment of technologies is more limited due to a lack of data on individual technologies.

In the industrial sector, only the combined heat and power and motor technologies are explicitly considered and characterized. Cost reductions resulting from technological progress in combined heat and power technologies is represented as a function of time as experience with the technologies grows.

Technological progress is not explicity modeled for the industrial motor technologies. Other technologies in the energy-intensive industries are represented by technology bundles, with technology possibility curves representing efficiency improvement over time.

In the oil and gas supply sector, technological progress is represented by econometrically estimated improvements in finding rates, success rates, and costs. Productivity improvements over time represent technological progress in coal production.

<u>Modularity</u>

NEMS is designed in a modular way which enables each sector to be represented with the methodology and the level of detail, including regional detail, appropriate for that sector, and it facilitates the analysis, maintenance, and testing of the NEMS component modules in the multi-user environment.

The NEMS modules consists of

- four supply modules (oil and gas, natural gas transmission and distribution, coal, and renewable fuels) - the modules interact to solve for the economic supply and demand balance for each fuel;
- two conversion modules (electricity and petroleum refineries);
- four end-use demand modules (residential, commercial, transportation, and industrial);
- one module to simulate energy/economy interactions (macroeconomic activity);
- one module to simulate world oil markets (international energy activity); and
- one module that provides the mechanism to achieve a general market equilibrium among all the other modules (integrating module).

Figure 2 depicts the high-level structure of NEMS.

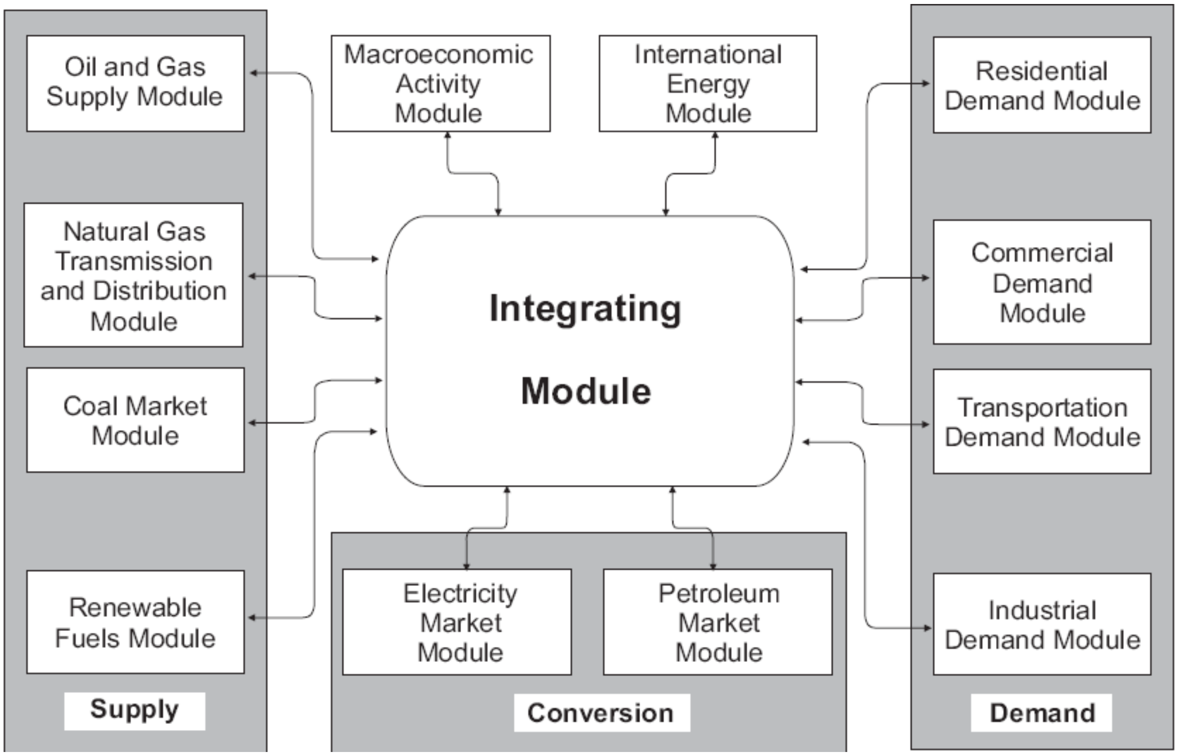

Fig. 2

Supply modules include:

- Renewable Fuels Module
- Oil and Gas Supply Module
- Natural Gas Transmission and Distribution Module
- Coal Market Module

Conversion modules include:

- Electricity Market Module
- Petroleum Market Module

Demand modules include:

- Residential Demand Module
- Commercial Demand Module
- Industrial Demand Module
- Transportation Demand Module

Three other modules include:

- Integrating module: this includes the Carbon Dioxide and Methane Emissions Submodule
- Macroeconomic Activity Module
- International Energy Module

These modules are described in overview fashion in [3]. We will only make a few comments about the integrating module and the transportation demand module. Students working in closely related areas should read the referenced document closely.

Integrating module and convergence

The NEMS integrating module controls the entire NEMS solution process as it iterates to determine a general market equilibrium across all the NEMS modules. It has the following functions:

- Manages the NEMS global data structure
- Executes all or any of the user-selected modules in an iterative convergence algorithm
- Checks for convergence and reports out-of-tolerance variables
- Implements convergence relaxation on selected variables between iterations to accelerate convergence
- Updates expected values of the key NEMS variables.

The integrating module executes demand, conversion, and supply modules iteratively until it achieves an economic equilibrium of supply and demand in all the consuming and producing sectors. Each module is called in sequence and solved, assuming all other variables in the energy markets are fixed. The modules are called iteratively until end-use prices and quantities remain constant within a specified tolerance.

In addition, the macroeconomic and international modules are executed iteratively to incorporate the feedback on the economy and international markets from changes in the domestic energy markets.

Convergence tests check the stability of a set of key macroeconomic and international trade variables in response to interactions with the domestic energy system.

The NEMS algorithm executes the system of modules until convergence is reached.

- The solution procedure for one iteration involves the execution of all the component modules, as well as the updating of expectation variables (related to foresight assumptions) for use in the next iteration.
- The system is executed sequentially for each year in the forecast period.
- During each iteration within a year, each of the modules is executed in turn, with intervening convergence checks that isolate specific modules that are not converging. A convergence check is made for each price and quantity variable to see whether the percentage change in the variable is within the assumed tolerance.
- To avoid unnecessary iterations for changes in insignificant values, the quantity convergence check is omitted for quantities less than a user-specified minimum level.
- The order of execution of the modules may affect the rate of convergence but will generally not prevent convergence to an equilibrium solution or significantly alter the results.
- An optional relaxation routine can be executed to dampen swings in solution values between iterations. With this option, the current iteration values are reset partway between solution values from the current and previous iterations.

Transportation demand module

The transportation demand module (TRAN) forecasts the consumption of transportation sector fuels by transportation mode, including the use of renewables and alternative fuels, subject to delivered prices of energy fuels and macroeconomic variables, including disposable personal income, gross domestic product, level of imports and exports, industrial output, new car and light truck sales, and population. Table 3 identifies inputs and outputs for this module. The structure of the module is shown in Figure 3.

Table 3

TRAN Outputs	Inputs from NEMS	Exogenous Inputs
Fuel demand by mode Sales, stocks and characteristics of vehicle types by size class Vehicle-miles traveled Fuel efficiencies by technology type Alternative-fuel vehicle sales 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	Current and projected demographics Existing vehicle stocks by vintage and fuel efficiency Vehicle survival rates New vehicle technology characteristics Fuel availability Commercial availability Vehicle safety and emissions regulations Vehicle miles-per-gallon degradation rates

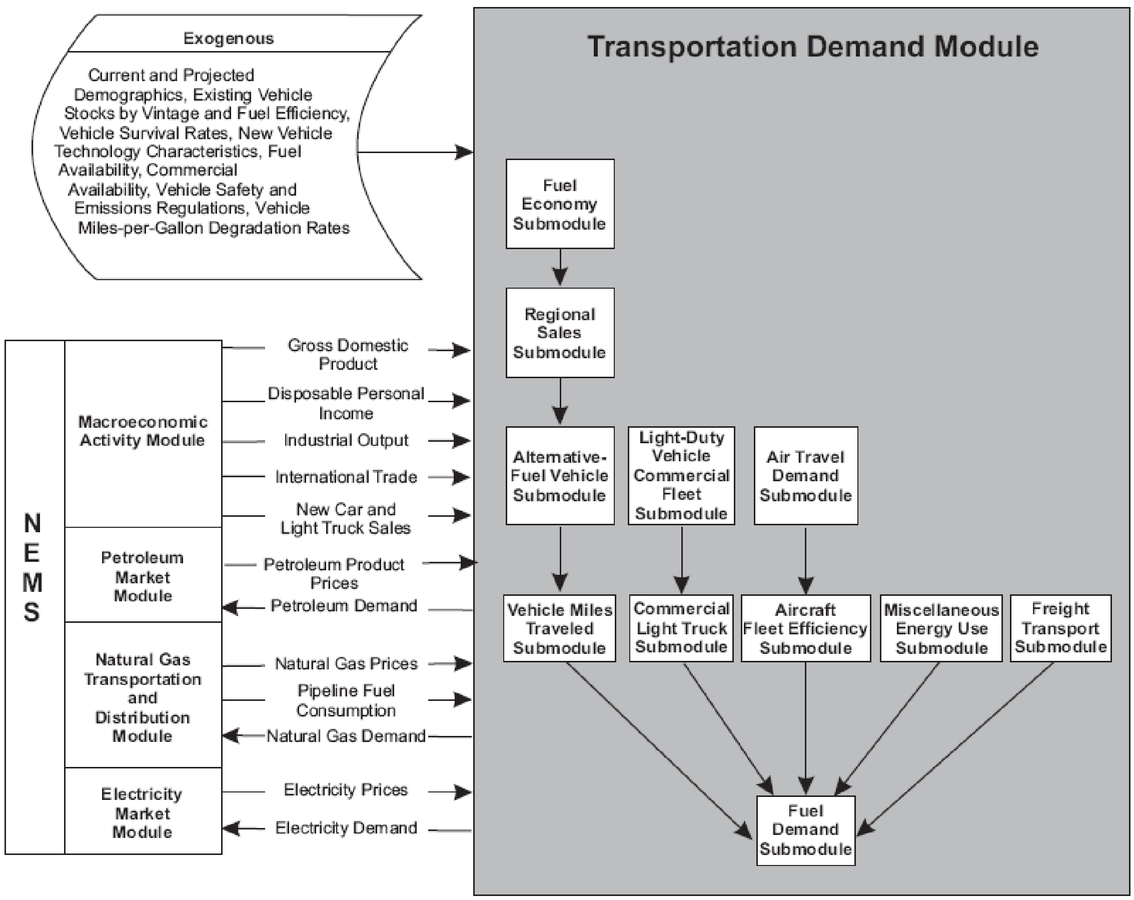

Fig. 3

4.0 Markal

Much of the information in this section was adapted from [4]. MARKAL (MARKet Allocation) is a bottom-up, dynamic linear programming model of a country's energy system. The model, first developed in the late 1970s for energy planning, continues to undergo development. Energy Technology Systems Analysis Programme (ETSAP) (www.etsap.org/index.asp) coordinates these activities, sponsored by the International Energy Agency (IEA).

MARKAL is a family of models that represent energy systems by the set of technologies used to extract, transport or transmit, convert, and use energy to meet projected future energy service demands.

MARKAL provides policy makers and planners in the public and private sector with detail on energy producing and consuming technologies, and it can provide an understanding of the interplay between the macroeconomy and energy use. As a result, this modeling framework has helped national and local energy planning, and the development of carbon mitigation strategies.

MARKAL can be used

- to identify least-cost energy systems
- to identify cost-effective responses to restrictions on emissions
- to perform prospective analysis of long-term energy balances under different scenarios
- to evaluate new technologies and priorities for R&D
- to evaluate the effects of regulations, taxes, and subsidies
- to project inventories of greenhouse gas emissions
- to estimate the value of regional cooperation

By using the MARKAL family of models, users can evaluate the effects of various technology programs on both the average and shadow costs of carbon. Current versions of the model can be used to model interregional, international, and intracountry carbon permit trading schemes.

The various versions of MARKAL have generally been developed by individual participants in ETSAP to meet their specific needs. However, with the exceptions noted below by an asterisk, they are now incorporated in a common model. The user activates these features by providing the appropriate data and/or switches. Most of the MARKAL versions can be coupled to combine desired features.

- MARKAL-ED: MARKAL with elastic demands. In this "partial equilibrium" approach, the projected energy demands, rather than being fixed for future years, are modified as part of the solution of the program in response to the changing cost of energy. The energy demands are represented with a stepwise linear approximation, where the user provides own-price elasticities for each "flexible" demand sector. There is also an extension to MARKAL-ED that permits income elasticities (MEDI) also to be provided by sector.
- MARKAL-ETL: A nonlinear version of MARKAL in which the unit costs of technologies may decline with increasing total capacity as a result of endogenous technological learning, that is, down the learning curve.
- MARKAL-EV: A version that includes for a combination of pollutants the calculation of environmental damage, or nonlinear optimization of an objective function that includes the damage calculation.
- MARKAL-GP*: A variant of MARKAL used for goal programming. Rather than "hard" constraints, such as maximum allowable emissions of pollutants, target values are specified. With different weights given to their importance, a set of Pareto-efficient solutions can be found to enable decisionmakers to examine a range of solutions representing different goals.
- MARKAL-MACRO: A nonlinear, dynamic optimization model that links MARKAL with MACRO, a top-down macroeconomic growth model. Multiple MARKAL-MACRO models may be

linked to represent trade among countries in energy and emission permits.

- MARKAL-MACRO-MERGE*: An integration of one MARKAL-MACRO region (e.g., USA) with MERGE regions that define a global trade model.
- MARKAL-MICRO: Like MARKAL-ED, a partial equilibrium approach. In this case, projected energy demands are represented as nonlinear functions, and the solution is obtained using nonlinear programming techniques.
- MARKAL-Stochastics: A version that allows for uncertainty in such input values as the permitted future level of carbon dioxide emissions, prices of energy and technologies, and levels of demand. Probabilities are assigned to alternative future scenarios. The model calculates the hedging strategy: the singular optimal mix of technologies for the near term until the uncertainty is resolved at an assumed future date.
- MATTER: An extension of MARKAL that includes the flow of materials as well as the flow of energy.
- RMARKAL: Regionalized MARKAL in which a set of MARKAL models may be linked by flows of energy, materials, and emission permits.
- Global RMM*: A global RMARKAL model with five world regions, trade, and endogenous learning that includes spillovers among regions.
- SAGE: System to Analyze Global Energy, a version of MARKAL that permits stepped (or “myopic”) solutions in successive time periods to the model horizon.
- TIMES: The Integrated MARKAL-EFOM System, which is the evolutionary replacement of MARKAL. It offers the analyst greater flexibility and additional features.

5.0 TIMES - Overview

The most recent addition to the MARKAL family, TIMES (The Integrated MARKAL-EFOM System), an optimization framework[1], significantly expands the number of policy and planning issues that MARKAL can address. For example, this version of the model should allow the evaluation of the effects of time-of-use electrical rates on load curves.

The vintaging (most recent version) aspect of this member of the MARKAL family should allow more complete evaluation of governmental policies designed to encourage the replacement of obsolete capital equipment. This version of the model also more rigorously evaluates industrial processes through the enhanced portrayal of these processes.

The following additional material on TIMES was adapted from [5].

TIMES is a ***model generator*** for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multiple period time horizon. ***It is usually applied to the analysis of the entire energy sector***, but may also applied to study in detail single sectors (e.g., the electricity and district heat sector).

[1] I do not think this means previous versions of MARKAL had no optimization, but rather, that previous versions did not have the very smooth interface with GAMS that TIMES has.

In TIMES, reference case projections of end-use energy service demands (e.g., car road travel, residential lighting, steel production and the like) are provided by the user for each region. In addition, the user provides estimates of the existing stock of energy related equipment in all sectors in the base year, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials. ***Using these as inputs, the model aims to supply energy services at minimum global cost (more accurately at minimum loss of total surplus) by simultaneously making decisions on equipment investment, equipment operation, primary energy supply, and energy trade. TIMES is thus a vertically integrated model of the entire extended energy system.*** One important attribute of TIMES is its ability to simulate very long periods of time, leading to the need to distinguish between scenario analysis and forecasted analysis.

Scenario vs. forecast

The TIMES model is particularly suited to the exploration of possible long term energy futures based on contrasted scenarios. Given the long horizons simulated with TIMES (up to 2100 in the current versions of the model), the scenario approach is really the only choice. Scenarios, unlike forecasts, do not pre-suppose advance knowledge of the main drivers of the energy system. Instead, a scenario consists of a set of coherent assumptions about the future trajectories of these drivers, leading to a coherent organization of the system under study. A scenario builder must therefore carefully test the assumptions made for internal coherence, via a credible storyline. In TIMES, a complete scenario consists of four types of input: energy service demands, primary resource potentials, a policy setting, and the descriptions of a set of technologies. These are described in the reference [5].

Some attributes of TIMES

From MARKAL, TIMES inherits the detailed description of technologies, the RES concept, and the equilibrium properties. From EFOM, TIMES inherits the detailed representation of energy flows at the technology level. In addition, TIMES has specific features that were not present in the ancestor models, as follows:

- Variable length periods;
- Vintaged technologies;
- Detailed representation of cash flows in the objective function;
- Technologies with flexible inputs and flexible outputs;
- Stochastic programming with risk aversion;
- Climate module;
- Endogenous energy trade between regions

Two of these are worth additional explanation.

Surplus-maximization

In TIMES, the quantities and prices of the various commodities are in equilibrium, i.e., their prices and quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers. This equilibrium has the property that the total surplus (consumers plus producers surpluses) is maximized.

Climate model

In addition, TIMES includes a climate module that calculates the impact of energy decisions on greenhouse gas emissions and concentration, as well as on the resulting changes in atmospheric forcing, and in global temperature. The Climate Module is especially useful in global incarnations of TIMES, such as TIAM.

Program output

For each scenario, TIMES produces two types of result. First, the primal solution of the Linear Program provides, at each time period and in each region:

- A set of investments in all technologies;
- The operating levels of all technologies;
- The imports and exports of each type of tradeable energy forms and materials;
- The extraction levels of each primary energy form and material;
- The flows of each commodity into and out of each technology;
- The emissions of each substance by each technology, sector, and total;
- The changes in concentration of the greenhouse gases;
- The radiative forcing induced by the atmospheric concentration of GHG in the atmosphere;
- The change in global temperature induced by the change in radiative forcing.

In addition, the dual solution of the Linear Program provides:
- The shadow price of each commodity present in the RES (energy form, demand, emission, material);
- The reduced cost of each technology in the RES, i.e., the required cost reduction to make that technology competitive.

6.0 TIMES – An optimization framework

The following description is adapted from www.etsap.org/Tools.asp.

The model

The model is a set of data files (spreadsheets, databases, simple ASCII files), which fully describes the underlying energy system (technologies, commodities, resources and demands for energy services) in a format compatible with the associated model generator (MARKAL or TIMES, see 2.); for example, instances of global models include the Energy Technology Perspectives (ETP) project MARKAL model of the IEA, the System for Analysis of Global Energy markets (SAGE) model of the US-EIA, the Global MARKAL-Macro of the Paul Scherrer Institute, and the European Fusion Development Agreement TIMES model; the national models of the ETSAP partner institutions; and various regional and municipal models developed by other institutions. Each set of files defines one model (perhaps consisting of a number of regional models) and is "owned" by the developer(s).

The model generator

The MARKAL and TIMES Model Generators are the source codes, which process each set of data files (the model) and generate a matrix with all the coefficients that specify the economic equilibrium model of the energy system as a mathematical programming problem. The Model Generators also post-process the optimization results. MARKAL and TIMES result from the contributions of the Contracting Parties and the ingenuity of the developers. The source code for either model generator is available free of charge, upon providing a signed copy of the ETSAP Letter of Agreement to the ETSAP Primary Software Coordinator (ETSAP PSC, currently DecisionWare, Inc.).

The General Algebraic Modeling System (GAMS) is the computer programming language in which the MARKAL and TIMES Model Generators are written. GAMS is the property of GAMS Development Corporation, Washington D.C. Information on GAMS may be found at www.gams.com.

The solver

The solver is a software package integrated with GAMS which solves the mathematical programming problem produced by the Model Generator for a particular instance of the MARKAL or TIMES model. Information on solvers may be found at www.gams.com.

User interface

A "shell" is a user interface which oversees all aspects of working with a model including management of the input data, running of the Model Generator, and examining the results. It thereby makes practical the use of robust models (theoretically simple models can be handled by means of ASCII file editors, if desired). "Shells" include MUSS, developed by DecisionWare Inc. for early MARKAL models; ANSWER originally developed by ABARE and subsequently the property of Noble-Soft Systems Pty Ltd for all MARKAL variants and partly for TIMES; and VEDA developed by KanORS Consulting Inc. for both TIMES and MARKAL. The "shells" were partly developed using ETSAP resources, and as such small group licenses (5 personal computers (PC)) for each are provided on request free of charge to ETSAP contracting parties and their designated representatives.

GAMS, appropriate solver(s) and a "shell", referred to as Third Party Software, have to be purchased by those looking to effectively use MARKAL or TIMES at the prices established by the developers (see recent indicative prices). Collectively the Model Generator(s) and Third Party Software are referred to as ETSAP Tools.

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[1] International Atomic Energy Agency, “Expansion planning for electrical generation systems,” Technical Reports Series No 241, 1984.

[2] X. Wang and J. McDonald, “Modern Power System Planning,” McGraw Hill, 1994.

[3] ‘The National Energy Modeling System: An Overview,” Energy Information Administration Office of Integrated Analysis and Forecasting, U.S. Department of Energy 2003, March 2003.

[4] “Energy Planning And The Development Of Carbon Mitigation Strategies Using The Markal Family Of Models,” International Resources Group, Wash DC, available at www.etsap.org/reports/markal-irg.pdf.

[5] R. Loulou and M. Labriet, “ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure,” CMS (2008) 5:7–40, DOI 10.1007/s10287-007-0046-z, Published online: 24 February 2007, Springer-Verlag.