Argonne NATIONAL LABORATORY

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Energy and Power Evaluation Program (ENPEP-BALANCE)

Software Manual - Version 2.25

Decision and Information Sciences Division
Center for Energy, Environmental, and Economic Systems Analysis

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I Introduction and Background

1.1 Introduction

The ENPEP for Windows model has its origins in the DOS version of the Energy and Power Evaluation Program (ENPEP), which was developed by Argonne National Laboratory (ANL) under the auspices of the U.S. Department of Energy (DOE) and the International Atomic Energy Agency (IAEA). However, ENPEP for Windows model is significantly modified and rather different in structure and capabilities from the older DOS version of ENPEP. It fully utilizes the Windows operating environment and provides the user with a graphical interface for designing a comprehensive model of the energy system of a country or region.

A beta test version of the ENPEP for Windows model was used at the IAEA/ANL international training course focusing on the overall energy planning and GHG mitigation. The training course took place at ANL from September 13 to November 5, 1999. A total of 30 participants from 10 different countries utilized ENPEP for Windows software to develop their national case studies.

1.2 Objective of the BALANCE Model

The objective of the BALANCE model is to simulate energy market and determine energy supply and demand balance over a long-term period of up to 75 years. To achieve this goal, the BALANCE module of ENPEP for Windows processes a representative network of all energy production, conversion, transport, distribution, and utilization activities in a country (or region) as well as the flows of energy and fuels among those activities. The environmental aspect is also taken into account by calculating the emissions of various pollutants. In addition to energy costs, the model also calculates the environmental costs. These costs can be used to affect the solution found by the market equilibrium algorithm. The main purpose of the software is to provide analytical capability and tools for the various analyses of energy and environmental systems, as well as for the development of a long-term energy strategy of a country or region.

1.3 Method of Solution

The BALANCE model works with an energy sector network that consists of nodes and links. The nodes represent processes, such as a petroleum refinery, while the links represent energy flows between pairs of nodes. The energy network is developed by defining the energy flows among 10 types of nodes. Each node type corresponds to a different submodel in BALANCE and is associated with specific equations that relate the prices and energy flows on the input and output links of the node.

The algorithm within the BALANCE module processes a system of simultaneous nonlinear equations and inequalities. These relationships, defined by input parameters associated with each node in the energy network, specify the transformation of energy quantities and prices through the various stages of energy production, processing, and use. An equilibrium model, represented by the energy network, is solved by finding a set of energy prices and quantities that satisfy all relevant equations and inequalities.

To find the solution, the model requires initial estimates of values of fuel importation and production quantities at the bottom of the network. Then, the prices of fuel on each successive link going up the network are computed from the prices equations defined by the various nodes. Next, the solutions to all the quantity equations associated with the nodes are computed for successive links going down the network. If all equations in the network are satisfied by the initial estimated quantities, a solution to the model has been found. Otherwise, the quantities at the bottom of the network are automatically adjusted, and all equations are solved again. This iterative process continues until the proper values for the quantities at the bottom of the network are attained.

1.4 Model Design Characteristics

The new ENPEP for Windows version of the BALANCE model is a major improvement to previous DOS ENPEP versions. ENPEP for Windows now fully utilizes the functionality of the Windows environment by allowing the users to build their energy networks within a graphical user interface right on the screen. The networks can now be built by simply dragging and dropping different nodes onto the screen and linking them with links. This greatly improves and simplifies the work with large and complex energy system representations. Figure 1 illustrates a relatively simple network of energy flow in one energy sector. A complete energy network for a country or region may consist of a large number of sectoral energy networks.

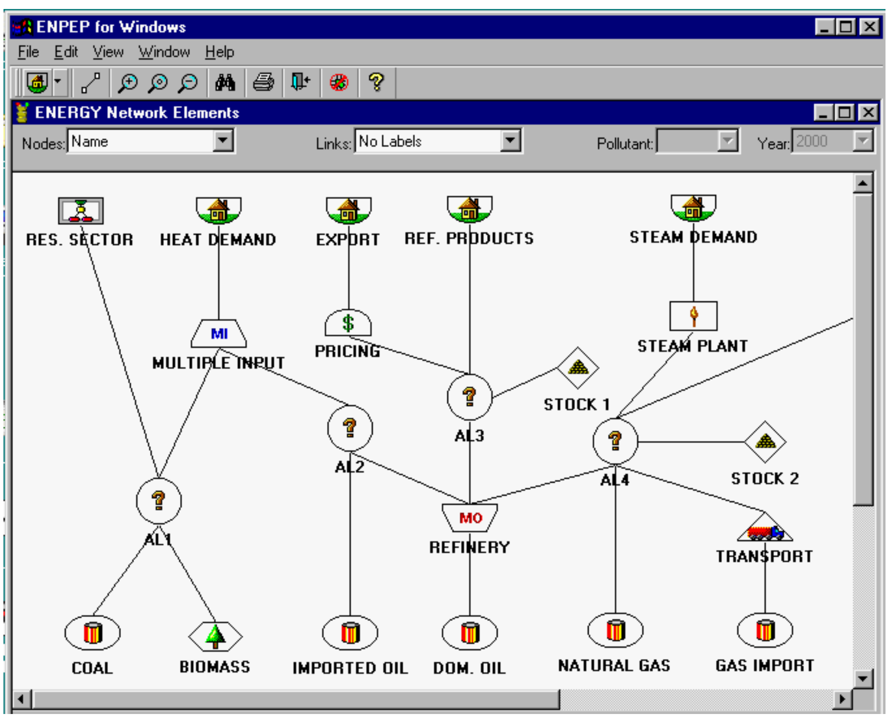


Figure 1: Simple Energy Network

The BALANCE module of ENPEP for Windows also allows editing the input data for each node through the Windows interface as well as viewing the results for each node as well as for the entire network. The user can access node and link input data simply by double-clicking the network objects. Right-clicking provides access to tabular and graphical presentations of node and link results. Within the interface, a variety of overlays are available in combination with the network displays. The user can add to the network displays result information on prices and energy flows by year as well as information on link capacities. Within the power sector a variety of detailed overlays can be used, including capacity factors, dispatch order, annual generation, annual fuel consumption, etc. An example of output results in a graphical form is presented in Figure 2.

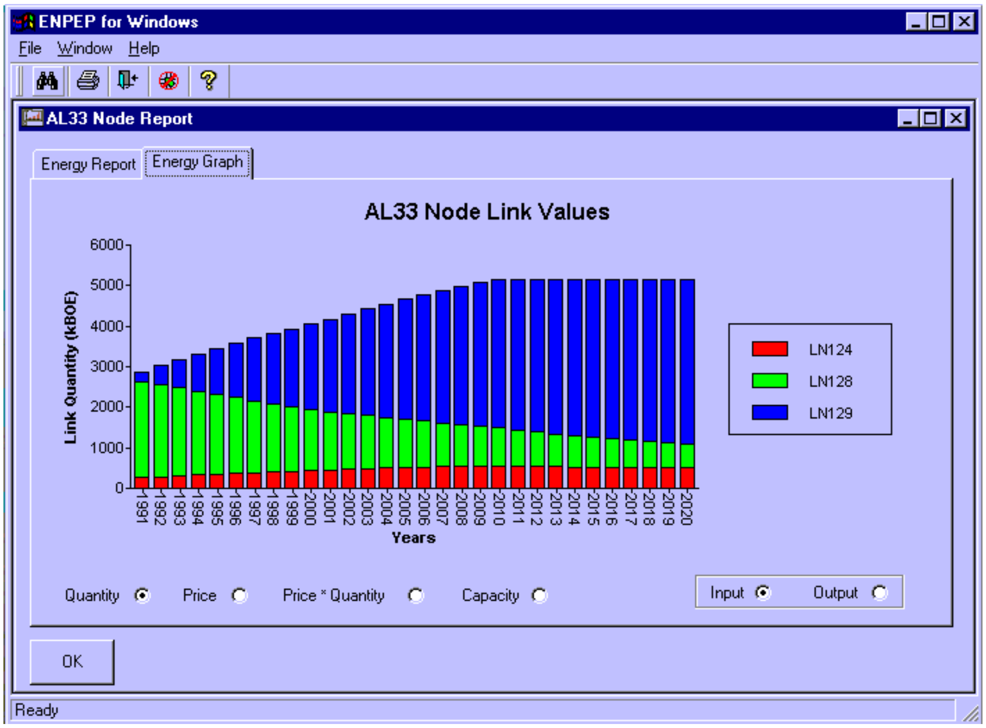
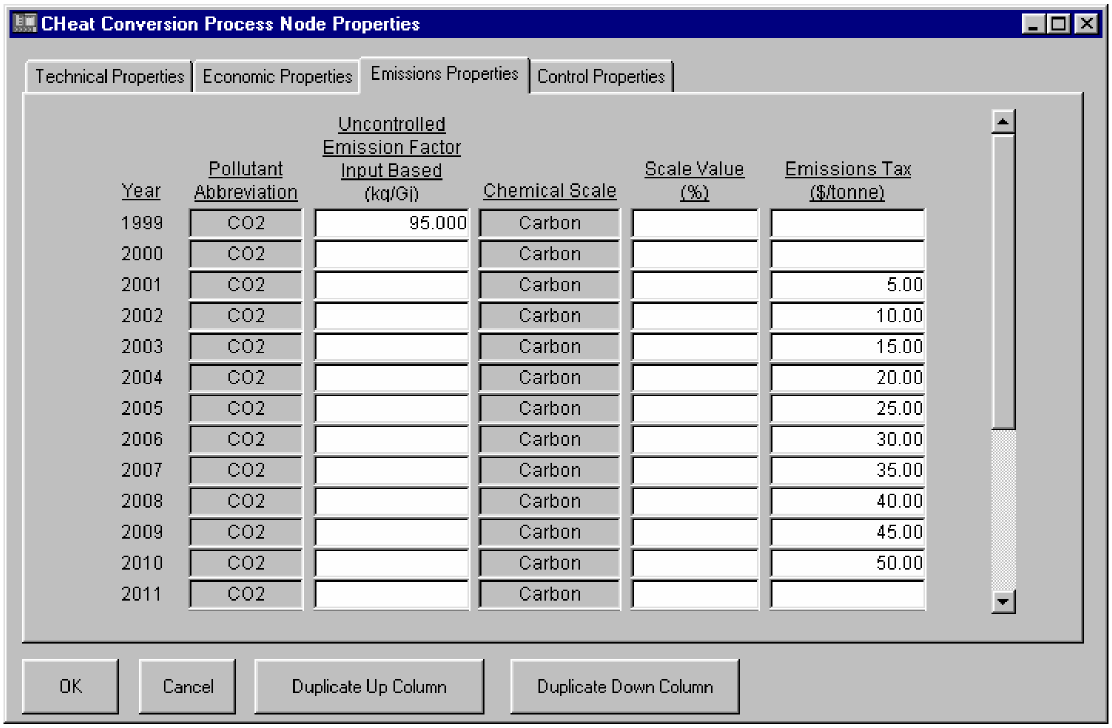


Figure 2: Graphical Representation of Results for Decision Node

The BALANCE module of ENPEP for Windows now also combines energy with environmental calculations in one integrated framework, as opposed to performing environmental computations in a separate module as in the previous ENPEP versions. Environmental node input data can be accessed together with the energy-related information. The environmental routines also now include an emissions tax feature that was previously not available. Figure 3 provides an illustration of environmental input data for a conversion process node.

All output results (e.g., energy flows, prices, etc.) can be graphically displayed on the nodes and links of the energy network or, for viewing more detailed results for a single component (node or link) of the network, by double-clicking on that component and selecting the option to view the results.



Year	Pollutant Abbreviation	Uncontrolled Emission Factor Input Based (kg/GJ)	Chemical Scale	Scale Value (%)	Emissions Tax ($/tonne)
1999	CO2	95.000	Carbon		
2000	CO2		Carbon		
2001	CO2		Carbon		5.00
2002	CO2		Carbon		10.00
2003	CO2		Carbon		15.00
2004	CO2		Carbon		20.00
2005	CO2		Carbon		25.00
2006	CO2		Carbon		30.00
2007	CO2		Carbon		35.00
2008	CO2		Carbon		40.00
2009	CO2		Carbon		45.00
2010	CO2		Carbon		50.00
2011	CO2		Carbon		

Figure 3: Environmental Data for a Conversion Process

1.5 Programming Environment

The ENPEP for Windows software package was developed using the PowerSoft's PowerBuilder 7.0 programming environment. PowerBuilder is an excellent package for the construction of large-scale applications. It has a proven track record and impressive market support. PowerBuilder comes with its own internal database (SYBASE) and has very good connectivity with other (external) databases. ENPEP for Windows development fully utilized this database-supported environment so that all input data and output results are stored in the database which provides a convenient interface between different ENPEP for Windows modules.

II Description and BALANCE Methodology

2.1 Overview

The central requirement of a comprehensive energy analysis is the evaluation of alternative configurations of the energy system that will balance energy supply and demand. The BALANCE module of ENPEP for Windows is designed to provide the planner with this capability. BALANCE uses a non-linear, equilibrium approach to determine the energy supply and demand balance. For its simulation, the Model uses an energy network that is designed to trace the flow of energy from primary resource (e.g., crude oil, coal) through to final energy demand (i.e., diesel, fuel oil) and/or useful energy demand (i.e., residential hot water, industrial process steam). Demand is sensitive to the prices of alternatives. Supply price is sensitive to the quantity demanded. BALANCE seeks to find the intersection of the supply and demand curves as illustrated by Figure 4. In its operation, BALANCE simultaneously tries to find the intersection for all energy supply forms and all energy uses that are included in the energy network. The equilibrium is reached when the model finds a set of prices and quantities that satisfy all relevant equations and inequalities. The simulation time step is one year for up to 75 years. However, the Model is typically used to analyze a 20 to 30-year forecast period.

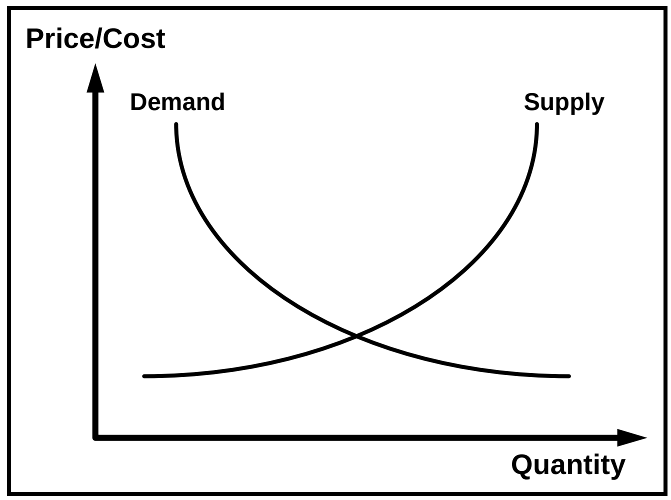


Figure 4: BALANCE Supply and Demand Curves

2.2 Energy Network and Equilibrium Solution

The energy network represents all energy production, conversion, transport, distribution, and utilization activities in a country or region, as well as the flows of energy and fuels among those activities. The energy network is constructed with a set of submodels or building blocks, called *nodes* (see Figure 5 for available node types and their symbols). The nodes of the network represent energy activities or processes, such as petroleum refining. The user connects the nodes with a set of *links*. The links represent energy and fuel flows and associated costs among the specific energy activities. Links convey this information (i.e., price and quantity) from one node to another. The energy network is developed by defining the energy flows among the different types of nodes for a given base year. All sectors of the energy supply and demand system are included in a typical BALANCE analysis. As an example, Figure 6 illustrates a typical sectoral energy network depicting the total energy system of a country or region. Each energy sector contains a more detailed energy network that consists of nodes and links representing the flow of energy within the sector, as well as the connections with other sectors.

Energy resources are either imported or produced domestically. Fuel conversion occurs, for example, in the oil refinery in the oil and gas supply sector (crude oil is converted to refined products) and in the electricity generation sector (coal, oil, or gas are converted to electricity). The transmission/ distribution sector routes the fuels to the various demand sectors (industry, residential, commercial, transport, and agriculture/fishing). A specific country may include more or fewer sectors and fuels than shown in Figure 6. Its modular structure makes BALANCE a very flexible tool and the user is free to define the sectors and the nodes and links that are in each sector according to specific analysis needs and/or available data.

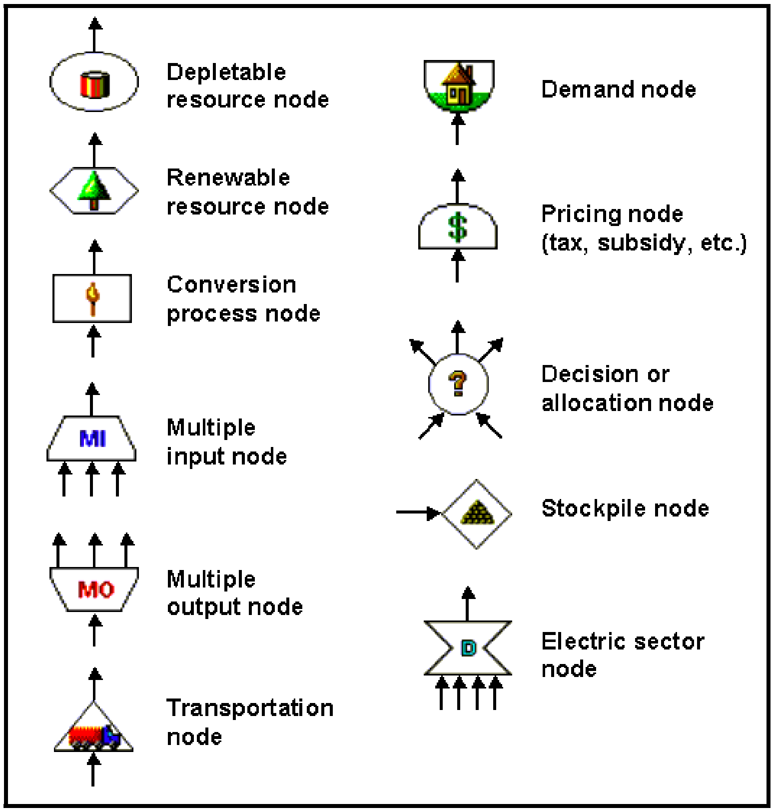


Figure 5: BALANCE Nodes

Appendix 1 presents a summary of BALANCE equations that determine energy flows and energy prices within each sector. Detailed explanations of BALANCE calculations for each node type are provided in the following sections.

By convention the energy network is constructed such that demand nodes are located at the top of the network and energy supply resources are at the bottom of the network. Conversion process nodes are located in the middle. Once the network is constructed and historical energy flows are simulated, the module forecasts future energy demands and prices. Demands are simulated by computing energy flows from demand nodes through conversion processes down to the supply resource nodes. This process is referred to as the down pass node sequence. Energy prices are computed by estimating costs for energy extraction and conversion processes through to the demand nodes. This process is referred to as the up-pass sequence. In the down pass sequence, when the Model computes energy flows, price estimates from the previous up pass sequence are used to determine the market shares of competing energy alternatives (i.e., input links). The market share is estimated by a logit function where the market share of a commodity is a function of the commodity's price relative to the price of alternative commodities.

As market shares of energy are dependent on energy prices and energy prices are dependent on the quantity of fuel demands, the BALANCE Model uses an iterative process to bring network prices and quantities into equilibrium. The up pass and down pass sequences are repeated until the difference in energy flows (i.e., quantities) on network links change very little from one iteration (i.e., down pass) to the next and the processes converge to within a user specified tolerance level.

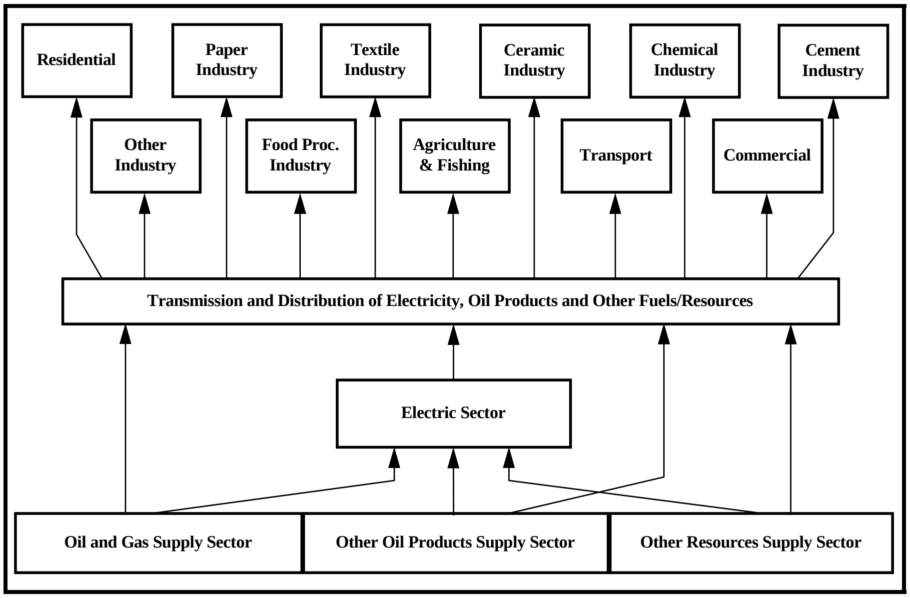


Figure 6: Sectoral Energy Supply and Demand Network

Since energy purchase decisions are not always solely based on price, premium multipliers are used in BALANCE to simulate the preference that consumers have for some commodities over others. Premium multipliers are used to simulate the market behavior when competing resources have different levels of quality or convenience. It can also be used to simulate the market behavior when high capital costs discourage the use of a specific technology or process. In addition, the Model uses a lag parameter to simulate the time that is required for prices and demands to reach an equilibrium or balance. In general, capital intensive industries have longer lag times than those which require relatively small capital investments.

The equilibrium modeling approach used in the BALANCE Module is based on the concept that the energy sector consists of autonomous energy producers and consumers that carry out production and consumption activities, each optimizing individual objectives. In contrast, optimization models of the entire energy sector, such as linear programming formulations, can take on the interpretation of a central planning authority that has control over all energy flows and prices in the entire energy sector.

The solution of an equilibrium model, such as the BALANCE program, should be interpreted as what is likely to happen, given that the assumptions about the relationships and data in the model are correct. In some circumstances, the output can also be interpreted as prescriptive, indicating what should happen or what will happen. For example, the model solution may prescribe what value energy prices should be set at in order to recover all costs of production and processing, if all government price controls are removed in a run of the model and prices are allowed to reflect only costs.

2.3 Description of BALANCE Node Calculations

Each network node type corresponds to a different submodel in BALANCE and is associated with specific equations that relate the prices and energy flows on the input and output links of the node. The following node types are available in BALANCE (see also Figure 5):

- *Depletable Resource Node*: Models the production of a depletable resource that is either imported or domestically produced, such as crude oil, coal, or natural gas.
- *Renewable Resource Node*: Models the production of a renewable resource (e.g., biomass or solar energy).
- *Decision/Allocation Node*: Models the selection of fuels or energy forms from alternative sources of supply.
- *Conversion or Processing Node*: Models the conversion or processing of a resource, fuel, or product to another form. Examples include a boiler that converts fuel oil to steam, an automobile that converts gasoline to miles traveled, and a distillation process that converts biomass to ethanol.
- *Multiple-Input Node*: Models special conversion processes that have more than a single form of input fuel, such as a solar heater that uses LPG as a backup fuel.
- *Demand Node*: Models the final demand for a fuel or a form of useful energy such as process steam, and direct heat
- *Multiple Output (Refining) Node*: Also called a multiple-output-link node, this node is typically used to model the petroleum refining process in an aggregate form. More generally it can be used to model any process with two or more products.
- *Stockpile Node*: Models stockpiling of resources for use at some future time.
- *Pricing Node*: Models government price regulations and pricing policies, such as taxes, subsidies, and tariff structures.
- *Electricity Dispatch Node*: Models the loading and output of electricity generating units.

The following sections describe the BALANCE calculations in more detail for each of the node types.

2.4 Depletable Resource Node

By convention, a depletable resource node has a single output link and no input links as this represents the starting point of the energy supply system. Depletable resource nodes are used to model the domestic production and/or importation of depletable resources such as crude oil, coal, and petroleum products. A single equation is associated with a depletable resource node. The equation relates the cost (or price, depending upon the use of the resource node) of producing or importing the resource to the total, cumulative (over all periods) amount of the resource produced or imported. Effectively, the equation represents a long-run supply curve for the resource. The price of a depletable resource can be computed from the following simple quadratic equation:

$$\boxed{P_t = A(Q) \, x \, (1 + R_t) + B \, x \, Q_t + C \, x \, Q_t^2}$$

where:

P_t	=	production cost (price) of the resource in period t,
Q_t	=	quantity of the resource produced or imported in period t,
A(Q)	=	intercept of the supply curve for the resource after having extracted a cumulative amount Q of the resource previous to time t. This value is adjusted at the end of each year in the simulation period based on the amount of the resource produced or imported during the year (the initial value of A(Q) in the base year can be taken as the price of the resource in the base year),
R_t	=	growth rate in real terms of the cost (price) of the resource,
B	=	slope of the supply curve for the resource, and
C	=	a quadratic coefficient for the supply curve.

The base-year value of A(Q) and the values of B and C are user-defined, vary by resource, and are based on an evaluation of the historical performance of the specific resource production. To model the price projection of an imported fuel, the equation above can be used in the following way: (1) set A(Q) equal to the price of the imported fuel in the base year; (2) set B = 0 and C = 0 to nullify the effect of the amount of imported fuel on its price; and (3) provide the annual growth rates for the imported fuel price projections as data entered in the model. Supply curves can be defined at an aggregate level (e.g., one supply curve for all domestic crude oil production) or may be at a detailed level (e.g., a separate supply curve for each oil field).

2.5 Renewable Resource Node

By convention, a renewable resource node has a single output link and no input links, just as a depletable resource node. Renewable resource nodes are used to model the production of renewable energy resources such as solar energy and biomass residues. Examples of renewable resource nodes include solar energy in the household sector, sugar cane production in the sugar sector, wood produced for fuel in the biomass sector, and agricultural residues (such as coconut shells) in the biomass sector.

A step function is associated with a renewable resource node. The step function relates the cost (or price, depending upon the use of the resource node) of producing the resource to the annual production of that resource. Effectively, the step function represents an annual supply curve. A resource node also models any physical limits on the annual production of the resource. For example, the amount of solar insolation determines an upper limit on the annual amount of solar energy that can be used, or the amount of land devoted to wood production for energy needs allows the user to estimate an upper limit on annual wood production.

The form of the step function for a renewable resource node is:

$$
\begin{aligned}
P_t \quad &= C_1 \text{ if } Q_t \leq L_1 \\
&= C_2 \text{ if } Q_t \leq L_2 \\
&= C_3 \text{ if } Q_t \leq L_3 \\
&= C_4 \text{ if } Q_t \leq L_4 \\
&= C_5 \text{ if } Q_t \leq L_5
\end{aligned}
$$

where:

P_t = cost (price) of the resource in period t.
Q_t = quantity of the resource produced in period t.
C_i = cost of producing each unit of the resource from step I. (the maximum number of steps is 5.)
L_i = amount of the resource for step i.

Generally, each step represents a different source of production for the resource, and sources are ordered in terms of increasing costs. The following example illustrates the use of a renewable resource node. Suppose that land is to be devoted to growing trees to produce firewood. Each step of the step function could represent a different section of land. The sections vary by soil type, growing conditions, accessibility, and other factors that cause the cost of producing wood to vary. The cost variance among sections can be captured by the step function; the amount of the resource for each step would be the annual production capacity of wood for the section to which the step corresponds.

Some resources, such as solar energy, are more appropriately modeled as having only one step because the cost of using more solar energy (on a BOE output basis) does not necessarily increase as more is used.

In some cases, the renewable resource model provides a better means of modeling a depletable resource. Peat is such a case. This is because it is more appropriate to represent the cost of peat production as a function of the amount available as a step function (i.e., as renewable resource) rather than as a linear function (i.e., as a depletable resource). A special modification has been made to the renewable resource node to model peat. You may specify that the cost of production tracks the cumulative amount of the resource produced from the base year (as in the case of a depletable resource node) as the model progresses through the simulation period.

2.6 Decision/Allocation Node

This node is one of the most important in defining the role that competing energy technologies will play in a future energy system. They represent the market forces at play when choices are made to use a particular type of energy. The approach used in simulating the market decision process is to assume that the market share of an energy source is inversely proportional to its price relative to its competitors.

By convention, a decision node has one or more input links and one or more output links. Decision nodes select the amounts of fuel to be supplied from alternative sources (the input links of the node) at various points in the energy network, and route the energy to satisfy energy flow requirements of the output links of the node. Price and quantity equations are associated with a decision node. The quantity equation equates the total energy flow on the output links of the node to the total energy flow on the input links to the node; energy flow is conserved at a decision node. The price equation relates the prices of the fuels on the input links of the node to the price of fuel on the output links of the node. In addition, several other equations indicate the shares of fuel selected from the input links to the node. Shares are based on the relative prices of fuel from the alternative sources, capacity limits on the supply sources, and government policies. It should be noted that one of the features of the decision node algorithm is that energy requirements may be met by selecting fuels from several supply sources simultaneously rather than from a single source, as would be the case if fuel choices were based strictly on least cost. However, the decision node parameters can also be specified so the node selects fuel only from the least-cost source.

Decision nodes are positioned in the energy network to indicate the points at which fuel choices are made from alternative supply sources. Examples of decision nodes include (1) petroleum products from refineries and foreign sources in the oil sector; (2) charcoal produced from wood and agricultural residues in the distribution sector; (3) auto-travel demand met by gasoline and diesel autos in the transport sector; (4) cooking heat requirements satisfied by charcoal, kerosene, natural gas, wood, electricity, and LPG in the household sector; and (5) on-site generation and grid-produced electricity in the industry sector.

Given the quantity of energy required on each output link of a decision node, the quantity equation equates the total energy flow into the node to the total energy flow out of the node:

$$\boxed{\sum_{i}^{n} Q_i = \sum_{o}^{p} Q_o}$$

where:

Q_i	=	quantity on input link i of the decision node,
Q_o	=	quantity on output link o of the decision node, and
n, p	=	total number of input and output links of the decision node.

If a decision node has a stockpile node associated with it, as large a quantity as possible is taken from the stockpile to supply the quantity demanded on the output links of the decision node. The remaining quantity, the quantity not satisfied by the stockpile reserves, is referred to as the net output quantity and is met by sources that are input links to the decision node. The quantity on any input link i of a decision node is the product of the net output quantity and the share allocated to source i, as the following equation indicates:

$$\boxed{Q_i = NQ \, x \, S_i}$$

where:

Q_i	=	quantity on input link i,
NQ	=	net output quantity of the decision node; the value of NQ is the sum of the quantities on all output links minus the amount in the stockpile, if this value is greater than zero; otherwise, NQ is assigned a value of 0, and
S_i	=	fraction (share) of input quantity allocated to input link i ($0 \leq S_i \leq 1$).

The share S_i is in general a function of the relative prices on the input links of the decision node. A higher price on an input link results in a smaller share of the quantity allocated to the input link. The share for an input link is given by the formula:

$$S_i = \frac{\left(\dfrac{1}{P_i \ x \ Pm_i}\right)^{\gamma}}{\sum_i^n \left(\dfrac{1}{P_i \ x \ Pm_i}\right)^{\gamma}}$$

where:

S_i	=	market share on input link i,
P_i	=	price on input link i,
γ	=	price sensitivity coefficient for the decision node,
n	=	number of input links to the decision node, and
Pm	=	premium multiplier on input link i.

Note that the above equation ensures that all shares are between 0 and 1, and that shares on all input links sum up to 1.

The price allocation formula is motivated by the empirical observation that all demand is not necessarily allocated to the least-cost source of supply. Rather, the allocation formula models the more general case in which shares depend on relative prices, with the more costly sources receiving relatively smaller shares. Non-price factors often enter into consumption decisions, resulting in a skewed distribution of consumption based on prices. A theoretical justification for the price allocation formula can be found in the energy modeling literature.

The price sensitivity parameter, γ, in the above equation, determines the degree to which differences in relative prices result in differences in market share. In some instances, there is a great deal of sensitivity to price differences. Small changes in relative price will produce fairly large changes in market share. A refinery purchasing crude oil is an example of price sensitive markets. Consumers buying automobiles is an example of relatively price-insensitive markets as other factors influence the decision. The sensitivity parameter γ is used to simulate these different conditions. A value of 0 for γ is an extreme case and indicates the least degree of share sensitivity to prices. A large value for γ, such as 15, indicates a high degree of share sensitivity to relative prices and approximates a situation in which 100% of the quantity is allocated to the single source having the lowest price. Thus, by varying the value of γ, the complete range of share-sensitivity cases can be modeled, including the case in which 100% of the quantity is allocated to the least-cost source. In general, the user should analyze recent historical values of market shares and relative prices to determine a reasonable value for the price sensitivity parameter at each of the decision nodes located throughout the energy network.

The decision node has several other features that are used to model situations where a particular market cannot readily respond to price changes, even of relatively large magnitude. A lagged adjustment parameter is included in the decision node sub-model to represent the lag that often occurs between a change in relative prices and an observed change in the shares of the sources of supply. Existing capital equipment or difficulty in getting access to the cheaper fuel are examples of circumstances that prevent market response. The lag function determines what portion of the market is able to adjust to a change in prices. The value of the lag parameter, λ can be related to the life expectancy of the energy equipment and therefore, to its turnover rate.

$$\boxed{S_{i,T} = S_{i,T-1} + (S_{i,T*} - S_{i,T-1})\ x\ \lambda}$$

where:

$S_{i,T}$	=	market share on input link i at time t with lag considerations included,
T	=	current year,
$S_{i,T-1}$	=	previous year's market share on input link i,
$S_{i,T*}$	=	intermediate value of market share on input link i without lag considerations as determined by the market share equation above,
λ	=	lag parameter.

The lag parameter value ranges from 0 to 1. A value of 1 indicates there is no lag, and shares respond immediately to current prices. A value of 0 indicates no response to prices; base-year shares will be maintained throughout the study period. In general, capital intensive industries have longer lag times than those which require relatively small capital investments.

In some cases, the quantity computed by the market share equation for an input link to a decision node may exceed the supply capacity of that source. In such a case, the quantity allocated to the source is set equal to its capacity, and the excess supply is reallocated to the remaining input links of the decision node. If several supply sources have capacity constraints, this procedure is repeated until the entire net output quantity has been allocated to the sources.

Government policies may exist that override allocation decisions based strictly on relative fuel prices. For example, a government may have a policy in place to use domestically refined petroleum products rather than imported products (usually made to protect local jobs). To model this situation, the decision node submodel can allocate a demand quantity to sources (input links) in a specified order. This priority allocation scheme is done without regard to the relative prices on the input links. A quantity is allocated to an input link up to the capacity of the source, if a capacity exists. This procedure is repeated until the entire net output quantity has been allocated to all input links.

An additional option for a decision node is to use it as a source of electricity to the electrical grid if an excess supply of electricity exists at a decentralized source of electric power generation. If a decision node has at least two input links, one link being central station electric power generation and the other being a decentralized source of electricity generation (such as an on-site diesel electric generator in the other-industry sector), this option may be used. If this option is specified, electricity demand will first be allocated to the sources based on either relative prices or priority allocation (whichever option you have specified). If the capacity specified for the decentralized source has not been exceeded, but the price of electricity from the decentralized source is less than the price of electricity from the grid, the decentralized source is assumed to produce at its full capacity. The excess power is routed through the decision node as a negative quantity and assigned to the grid link. This effectively reduces the demand for central station electricity in other parts of the energy network.

The price assigned to the output links of a decision node is equal to the average price of the inputs to the node, excluding the inputs from stockpiles. The output price is computed from the following:

$$\boxed{P_o = \sum_{i=1}^{n} (P_i \ x \ S_i)}$$

where:

P_o	=	price assigned to all output links of decision node,
P_i	=	price on input link i, and
S_i	=	share of net output quantity allocated to input link i.

2.7 Conversion or Processing Node

By convention, a conversion node has a single input link and a single output link. Two equations are associated with a conversion node: a quantity equation and a price equation. The quantity equation represents the transformation of the input (usually an energy form) to the output product (also usually an energy form). The price equation represents the value added to the price of the input due to the process. Examples of conversion nodes include (1) fuel oil oven in the cement sector (input = fuel oil, output = direct heat), (2) gasoline automobile in the transport sector (input = gasoline, output = vehicle-miles traveled), (3) fuel oil boilers in the ceramics sector (input = fuel oil, output = process steam), and (4) gas-fired gas turbine units in the electric sector (input = gas, output = electricity).

The following example illustrates the quantity and price equations for a generator that transforms fuel oil into electricity. The quantity of electricity is related to the quantity of fuel oil input by the following equation:

$$\boxed{Q_{elec} = Q_{fo} \ x \ \eta}$$

where:

Q_{elec}	=	quantity of electricity output,
Q_{fo}	=	quantity of fuel oil input, and
η	=	process efficiency.

The basic assumption in developing the price equation for the conversion node is that the annual revenue obtained from the output of the process equals the annual costs of the fuel oil and the processing operations. The equation relating annual revenue and cost is:

$$\boxed{Q_{elec} \ x \ P_{elec} = Q_{fo} \ x \ P_{fo} + OM \ x \ Q_{elec} + TCI \ x \ CRF(i,n)}$$

(Revenue) = Cost)

where:

P_{elec}	=	price of electricity,
P_{fo}	=	price of fuel oil,
OM	=	operating and maintenance cost of distillation process. (This cost excludes the costs of the fuel oil; the fuel oil cost is accounted for in the term Q_{fo} x P_{fo}.),
TCI	=	total capital cost of a representative generator process or plant, and
CRF(i,n)	=	capital recovery factor that amortizes the capital cost over the life of the process, n, at the annual interest rate i.

$$\boxed{CRF(i,n) = \frac{i\,x(1+i)^n}{(1+i)^n - 1}}$$

If both sides of the above equation are divided by Q_{elec}, η is substituted for Q_{elec}/Q_{fo}, and the process is assumed to operate near its annual rated output capacity, then the following equation is obtained relating the required electricity price to the fuel oil price and processing costs:

$$\boxed{P_{elec} = \frac{P_{fo}}{\eta} + OM + \left[\frac{TCI}{CAP\ x\ CF}\right] x\ CRF(i,n)}$$

where:

CAP	=	annual maximum rated output capacity of a representative plant, and
CF	=	capacity factor for a representative plant (indicating the fraction of the time the plant operates over a one-year period).

Both equations are used to compute the output quantity and price, respectively, for a conversion node.

The capital recovery factor, CRF(i, n), for amortizing the capital cost of a process over a fixed number of discrete time intervals is computed from the following standard equation:

2.8 Multiple Input Node

By convention, a multiple-input-link conversion node has a single output link and two or more input links. Several equations are associated with a multiple input conversion node -- a number of quantity equations equal to the number of input links and a price equation. The quantity equations represent the transformation of the inputs to the node (generally forms of fuel) to the output (generally a form of energy). The price equation represents the value added to the prices of the input fuels by processing. Examples of multiple-input-link nodes include (1) a solar heater in the household sector that has LPG as a backup fuel; (2) a node that blends gasoline and ethanol to produce gasohol in the transport sector; and (3) a preprocessor in which heavy crude is spiked with lighter fractions in the oil sector.

The following example illustrates the price and quantity equations for a node with two inputs: a solar heater that transforms solar energy into heat and a backup heater fueled by LPG. The quantity of solar energy input (on an energy-content basis) required to produce a quantity of heat output is given by the following equation:

$$\boxed{Q_s = Q_h \ x \ IO_s}$$

where:

Q_s	=	quantity of solar energy input,
Q_h	=	quantity of heat output, and
IO_s	=	quantity of solar energy input required per unit of heat output.

Similarly, the quantity of LPG required to produce a quantity of heat is given by the equation:

$$\boxed{Q_1 = Q_h \ x \ IO_1}$$

where:

Q_1	=	quantity of LPG input, and
IO_1	=	quantity of LPG input required per unit of heat output.

The input/output ratio, IO_s, can be thought of as the ratio of the total solar energy converted to heat during the course of a typical year in a typical application for such a process, divided by the total heat produced by the process over a typical year. The total heat produced by the process over a typical year includes the heat produced by both the solar energy and the LPG.

The basic assumption used in developing the price equation for the multiple-input-link conversion node is that the value of the output of the process equals the costs of the process and input fuels on an annual basis. The following equation relates the annual value (revenue) and cost:

$$\boxed{Q_h \ x \ P_h = Q_s \ x \ P_s + Q_1 \ x \ P_1 + OM \ x \ Q_h + TCI \ x \ CRF(i,n)}$$

(Value) = (Cost)

where:

P_h	=	price of heat output (on an equivalent heat content basis),
P_s	=	price (if any) of solar energy,
P_1	=	price of LPG,

OM	=	operating and maintenance cost of the heater for converting solar energy and LPG to heat (this cost includes labor and material costs for operating the process, but excludes the costs of the LPG and solar energy inputs),
TCI	=	total capital cost of a representative heater, and
CRF(i,n)	=	capital recovery factor that amortizes the capital cost of the heater over its life n, at annual interest rate i.

If both sides of the equation above are divided by Q_h, IO_s is substituted for Q_s/Q_h, IO_1 is substituted for (Q_1/Q_h), and the process is assumed to operate near its annual assumed output capacity, then the following equation is obtained relating the price of heat output to the prices of the LPG, solar energy, and the heater costs:

$$\boxed{P_h = P_s \times IO_s + P_1 \times IO_1 + OM + \frac{TCI \times CRF(i,n)}{CAP \times CF}}$$

where:

CAP	=	annual maximum rated output capacity of a representative heater, and
CF	=	capacity factor for a representative heater (indicating the fraction of time over the course of a year the heater is expected to be in operation).

The equations above are used to model a multiple-input-link conversion node having two input links. This logic can be readily extended to model conversion nodes with any number of input links.

2.9 Demand Node

By convention, a demand node has a single input link and no output links. No equations are associated with a demand node. Demand nodes must be positioned in the energy network to indicate the points of final demand, that is, points that terminate energy flows throughout the network. Examples of demand nodes include (1) cement demand in the cement sector; (2) electricity demand in the commercial sector; and (3) space heating demand in the household sector.

The BALANCE Model associates a set of user-specified demand projections over the simulation period with each demand node. The demand node assigns the computed demand quantity in each year to the demand node input link; this quantity is then used as the required output quantity of the node at the input end of the link.

2.10 Multiple Output (Refinery) Node

By convention, a multiple-output-link (typically a refinery) node has a single input link and two or more output links. Several price and quantity equations are associated with a refinery node. The quantity equations represent the transformation of the input (such as crude oil) to the outputs (such as petroleum products). The price equations represent the value added by the processing to the input, and allocate the processing costs to the outputs. A refinery node can be used to model any process that has a single input and multiple output products. For example, besides a crude oil refinery, a refinery node can be used to model an industrial cogeneration process that produces steam and electricity. Examples of refinery nodes in the BALANCE model include (1) a refinery in the oil sector (input = crude oil, outputs = LPG, distillate, gasoline, residual oil, etc.); (2) cogeneration in the food sector (input = wood/bagasse, outputs = steam and electricity); and (3) sugar juice production in the renewables sector (input = sugar cane, outputs = sugar juice and bagasse).

The following example of a refinery node with two output products illustrates the price and quantity equations. The quantity of product 1 is related to the quantity of crude input by the following equation:

$$\boxed{Q_1 = Q_c \ x \ s_1}$$

where:

Q_1	=	quantity of product 1 output,
Q_c	=	quantity of crude input, and
s_1	=	slate or ratio of product 1 output per unit of input crude.

An equation similar to the equation above relates the quantity of product 2 produced for each unit of crude input. In the equation, Q_2 and s_2 would be defined similarly to Q_1 and s_1, respectively, for the second product. The parameters s_1 and s_2 constitute the refinery *slate*.

The basic assumption in developing the price equations for the refinery node is that the annual total revenue obtained from the outputs of the refinery is equal to the annual cost of the crude input plus the associated processing costs. The equation relating annual revenue and cost is:

$$\boxed{Q_1 \ x \ P_1 + Q_2 \ x \ P_2 = [Q_c \ x \ P_c + OM \ x \ Q_c + TCI \ x \ CRF(i,n)] \ x \ (1 + PFF)}$$

(Revenue) = (Cost + Profit)

where:

Q_1, Q_2	=	quantities of product 1 and 2, respectively,
P_1, P_2	=	prices of product 1 and 2, respectively,
P_c	=	price of crude,
OM	=	operating and maintenance cost of the refinery (this cost includes the costs of labor and materials for operating the refinery but excludes the cost of the input crude),
TCI	=	total capital cost of the refinery (if the refinery already exists, this value is the present value of the remaining debt),
CRF(i,n)	=	capital recovery factor that amortizes the capital cost of the refinery over its life n, at annual interest rate i, and
PFF	=	profit factor.

If both sides of the equation above are divided by Q_c, s_1 is substituted for (Q_1/Q_c) and s_2 for (Q_2/Q_c), and the refinery is assumed to operate near its expected capacity, then the following equation relates the price of product 1 to the crude input price, the price of product 2, and the processing costs:

$$\boxed{P_1 = \left[\frac{P_c}{s_1} + \frac{OM}{s_1} + \frac{TCI \;\; x \;\; CFR}{CAP \;\; x \;\; CF \;\; x \;\; s_1} \right] x \; (1 + PFF) - P_2 \;\; x \; \frac{s_2}{s_1}}$$

where:

CAP	=	crude input capacity of the refinery, and
CF	=	capacity factor (indicating the fraction of time the refinery is expected to operate).

To determine the product prices P_1 and P_2, an additional equation is required that indicates how the costs of crude and processing are to be allocated among the two products. This equation is assumed to be linear and of the form:

$$\boxed{P_2 = w_2 \;\; x \;\; P_1}$$

where:

w_2	=	a user-specified parameter.

The product prices P_1 and P_2 can be determined from the two equations above given the price of crude, P_c, the product slate, s_1 and s_2, and the processing costs.

The procedure described above can be used to model a refinery node with any number of outputs. Similar equations must be specified for each additional product, such as LPG, gasoline, distillate oil, and residual fuel oil. Several forms of equations are possible. For example, if a refinery node has four output links, the price for the fourth output product can be related to the price of the input (crude) rather than to the price of the first product, as in the above example. The price of the fourth product is related to the price of the input crude to model the condition that, in general, residual oil prices are more closely tied to the price of crude oil than to the price of the other petroleum products.

An additional aspect of the refinery node submodel deserves mention. A refinery node may produce too much or too little product to meet the demand requirements on the refinery for a particular type of product. This occurs when the mix of product demand does not exactly match the refinery product slate, which is assumed to be inflexible. The logic of the refinery node model is such that the crude input requirement is based on the demand requirement of one of the products. This particular product, referred to as the *sizing* product, is specified by the model user. The demand on the refinery for the sizing product is met exactly. The demands for the other products may be exceeded or may not be met by the refinery's production. If the refinery produces an excess of a particular product, you have the option of specifying that this excess amount be placed in a stockpile (stockpile node) for possible consumption in future periods. If the refinery demand for a product cannot be met, you must specify an alternative link of the network from which the needed amount will be obtained to make up the shortage. This link is called the excess demand link (e.g., imports).

2.11 Stockpile Node

By convention, a stockpile node has a single link that functions as both an input link for filling the stockpile and an output link for reducing the stockpile. A stockpile node is used in conjunction with a multiple-output-link node (such as a refinery) and a decision node. The purpose of a stockpile node is to store the quantity of a particular type of a multiple-output-link product that exceeds the demand for that product. An example is a stockpile for residual oil from a specific refinery in the oil sector of the network.

Any excess production of each output product of a multiple-output-link node is added to the existing amount in a corresponding stockpile each year in the simulation period. The logic for computing the amount of the product to be extracted from the stockpile node is explained below.

A convention adopted in the BALANCE program is that the link of a stockpile must be an input link to some decision node of the network. The decision node inspects the amount in the stockpile each year and removes as much of the product as possible to meet the demand requirement on the multiple-output-link process. Any remaining demand requirement is considered the net demand requirement that the process then attempts to meet.

2.12 Pricing Node

By convention, a pricing node has a single input link and a single output link. A pricing node changes the price on the input link of the node to simulate a government tax, subsidy, price ceiling, price floor, or other government pricing policy. The resulting price is assigned to the output link of the node. Examples of pricing nodes typically include (1) tax nodes to represent taxes on petroleum products from a refinery; and (2) a subsidy node in the transport sector that equates the price of ethanol to the price of gasoline.

The output price of a pricing node is determined from the following equation:

$$\boxed{P_o \;=\; a \;x\; P_i \;+\; b}$$

where:

P_o	=	price on output link of pricing node,
P_i	=	price on input link of pricing node,
a	=	price multiplier, and
b	=	price increment (or decrement).

A percentage subsidy is modeled using the above equation by specifying a < 1 and b = 0. For example, to model a 10% subsidy, set a = 0.90 and b = 0. A percentage tax is modeled by specifying a > 1 and b = 0. A fixed subsidy is modeled by specifying a = 1 and b < 0. For example, a $0.05/gallon gasoline subsidy is specified by setting a = 1 and b = -0.05 (assuming the input price is in the units of $U.S./gallon). A fixed tax can be modeled in a similar way. Combinations of percentage and fixed taxes and subsidies can also be modeled by specifying the appropriate values for a and b.

If a price ceiling or price floor is specified for a pricing node, the computed output price P_o is compared with the price ceiling or floor. If P_o is outside of the allowable price range, P_o is reset to either the price ceiling (if the price ceiling is exceeded) or the price floor (if the price is less than the price floor). That is,

P_o = Price Ceiling if P_o > Price Ceiling
P_o = Price Floor if P_o < Price Floor

Another option for a pricing node is to specify that the price on the output link of the pricing node is to be set equal to a multiple of the price on another user-specified link somewhere else in the network. For example, this option would be used if the price of ethanol is to be subsidized so it matches the price of gasoline. If this pricing option is selected, the output price is computed from the following equation:

$$\boxed{P_o = c \ x \ P(L) + d}$$

where:

L = user-specified link number,
P(L) = price on the user-specified link,
c = user-specified multiplier, and
d = user-specified price increment or decrement.

The quantity on the output link of a pricing node is set equal to the quantity on the input link of the node - the node does not change the quantity on the input link of the node. The quantity equation is very simple:

$$\boxed{Q_o = Q_i}$$

where:

Q_i = quantity on input link of pricing node, and
Q_o = quantity on output link of pricing node.

2.13 Electricity Dispatch Node

This node handles the special requirements for the electric sector. The manner in which electrical generation plants are used is based on the development of the load. This can be expressed in form of load duration curves. The load duration curve specifies the portion of time the load exceeds a given level. In dispatching generators to meet the load, electric utilities will use their lowest operating cost units (usually large hydropower, coal, or nuclear units) to meet the continuous or base load. Units with higher operating costs are brought on line as the load increases but are reduced in output or shut down as the daily load decreases. Special units (usually gas turbines, pumped storage facilities, smaller hydro units) are used to meet the peak portion of the load. These units are characterized by being able to be switched on and off rapidly but often have higher operating costs than the base load units.

Within the Electricity Dispatch Node, a load duration curve is approximated with a fifth-order polynomial. Also, the current and planned electric generation units are identified. The node proceeds to select the units to be used to satisfy the load duration curve by picking the ones with lowest operating cost first and running them as base load. Higher cost units are added later with a resulting lower overall utilization rate. The specialized peaking units are reserved to meet the peak portions of the curve.

The node has special features to account for units that are needed to meet an electric utility's reserve margin but are not used for generation, for units that have been planned but are not needed to meet lower demand levels, and for units that are retrofitted to change fuel.

The node will calculate the quantity of electricity generated by each of the available generators, the total cost of electricity, and the average cost of electricity generated per kilowatt-hour. The node will not determine an optimum build schedule for generation facilities. Rather, it uses the input build schedule and utilizes the available plants as needed. The build schedule can be determined, for example, by the ELECTRIC (WASP) Module of ENPEP.

2.14 Special Events

Special events allow the user to change the input data for any process in the network in each year of the forecast period. The user must identify the node and the type of data that will be modified. The user also needs to specify the new input data.

- Valid decision/allocation node (AL) data special events:

PRI	priority link

- Valid multiple-input-link node (MI) special events:

OM	operation and maintenance cost
IO	input-output coefficient
TCI	total capital investment
CAPM	capacity of a representative unit
CF	capacity factor
LIFE	process lifetime
IR	interest rate for amortizing capital
CAPL	capacity on output link

- Valid multiple-output-link node (RE) special events:

SIZE	sizing link number
SLAT	output slate parameter

PRAT	output pricing ratio
STOC	stockpile for production excess
EXCS	supply links for production shortage
CNTL	control link
REMU	multipliers for control link
OM	operation and maintenance cost
TCI	total capital investment
CAPM	capacity of a representative unit
CF	capacity factor
LIFE	process lifetime
IR	interest rate for amortizing capital
CAPL	total capacity of all such processes (only valid if the output link of the process is an input link to a decision/allocation node)

- Valid pricing node (PP) special events:

ALPH	price multiplier
DELT	price increment
PMAX	price ceiling
PMIN	price floor
LINP	specified price link

- Valid depletable resource/import node (RS) special events:

CAPL	capacity on output link (only valid if the output link of the process is an input link to a decision/allocation node)

- Valid renewable resource node (RN) special events:

CAPL	capacity on output link (only valid if the output link of the process is an input link to a decision/allocation node)

- Valid conversion process node (PR) special events:

OM	operation and maintenance cost
EFF	efficiency
TCI	total capital investment
CAPM	capacity of a representative unit
CF	capacity factor
LIFE	process lifetime
IR	interest rate for amortizing capital
CAPL	total capacity of all such processes (only valid if the output link of the process is an input link to a decision/allocation node)

- Valid capacitated link (CA) special events:

CAPL capacity on link

2.15 Up-Pass Node Call Sequence

The *up-pass node call sequence* designates the order in which submodels that process the various types of nodes in the energy network are called. These submodels perform price calculations on the up-pass of the iterative simulation process. All nodes other than the demand nodes must be included in this sequence. The order of the sequence is very important. All depletable and renewable resources nodes must be listed first; the order of these is not important. The remaining nodes must be sequenced such that a given node *N* is not called until all nodes whose output links are input links to node *N* have been called.

2.16 Down-Pass Node Call Sequence

The *down-pass node call sequence* designates the order in which submodels that process the various types of nodes in the energy network are called. These submodels perform quantity calculations on the down-pass of the iterative simulation process. The order in which nodes are processed during down-pass processing is very important. Nodes must be sequenced such that a given node *N* is not called until all nodes whose input links are output links from node *N* have been called.

APPENDIX 1

BALANCE EQUATIONS

BALANCE EQUATIONS

NODE	PRICE EQUATION	QUANTITY EQUATION
RS	$Pout_t = A(Qout_{t-1}) \times (1 + R_t) + B \times Qout_t + C \times Qout_t^2$	$Qout_0$ in the base year is user-specified.
RN	$Pout_t = C_i$ if $Qout_t <= L_i$, where i = 1 to 5	$Qout_0$ in the base year is user-specified.
PR	$Pout_t = Pin_t /f + OM + [TCI/(CAP \times CF)] \times CRF(i,n)$	$Qout_t = Qin_t \times f$
RE	Method 1: $Pout_{(t,o)} = Pin_t \times w_0$ Method 2: $Pout_{(t,k)} = [\ Pin_t /s_k + OM/s_k + [TCI/(CAP \times CF \times s_k)] \times$ $\times CRF(i,n)] \times (1+PFF) - \sum_{o\neq k} [(s_o/s_k) \times P_o]$ $Pout_{(t,o)} = Pin_{(t,k)} \times w_o$, for the remaining output links	$Qin_t = \sum_o [Qout_{(t,o)} \times s_o]$
ST	The price is 0 for stockpiled products.	ST nodes store the excess product produced by refinery nodes. The link of an ST node must be an input to some allocation node of the network. Each year, the allocation node removes as much of the product as possible to meet the required demand. Any remaining demand is met by the other supply alternatives of the allocation node.
MI	$Pout_t = \sum_l [Pin_{(t,l)} \times IO_l] + OM + [TCI / (CAP \times CF)] \times CRF(i,n)$	$Qin_{(t,l)} = Qout_t \times IO_l$
AL	$Pout_{(t,o)} = \sum_l [P_l \times S_l]$ In other words, the weighted average price over all supply alternatives is used as the price on all output links.	The AL node first meets the quantity demanded by available stocks, additional demand is met based on the user-specified priority up to the capacity limits of the supply alternatives remaining demand is then allocated based on relative market shares: $Qin_{(t,l)} = NQ \times [S_l \times LAG + OMS \times (1–LAG)]$ $S_l = [1/(P_l \times PM_l)^r]/ \sum_l [1/(P_l \times PM_l)^r]$
PP	$Pout_t = a \times P_l + b$, where Price Floor $<= Pout_t <=$ Price Ceiling	$Qin_t = Qout_t$
DE	Prices are not adjusted at the DE node	Qin_0 is calculated on the up pass in the base year, for the remaining years $Qin_{(t)} = Qin_{(t-1)} \times (1+D_t)$

NOTATION

l	-	Input link.
k	-	The refinery price link.
o	-	output link.
Pin_t	-	Price ($U.S./BOE) of the energy input to a node in period t.
$Pout_t$	-	Price ($U.S./BOE) of the energy output from a node in period t.
P_l	-	Price ($U.S./BOE) on any link (*l*) in the network.
Qin_t	-	Total quantity input (10^3 BOE) to a node in period t.
$Qout_t$	-	total quantity output (10^3 BOE) from a node in period t.
$A(Q_{t-1})$	-	intercept of the supply curve for the resource after having extracted a cumulative amount Q of the resource pervious to time t. The initial value of $A(Q_{t-l})$ in the base year can be taken as the price ($U.S./BOE) of the resource in the base year.
R_t	-	growth rate in real terms of the price of the resource (from Depletable Resource Price Projection Set.)
B	-	slope of the supply curve for the resource.
C	-	quadratic coefficient for the supply curve.
$C_1 – C_5$	-	price ($U.S./BOE) of resource production for each step of the renewable resource supply curve.
$L_1 – L_5$	-	resource quantity (10^3 BOE) for each step of the renewable resource supply curve.
OM	-	operating and maintenance cost ($U.S./BOE).
TCI	-	total capital cost of a representative plant (10^3 $U.S.).
CAP		annual maximum rated output capacity (10^3 BOE/year) of a representative plant.
CF	-	capacity factor for a representative plant (indicating the fraction of time the plant operates over a one-year period.)
CRF	-	the capital recovery factor for amortizing the capital cost of a process over its lifetime (n) at a given interest rate (i). $CRF(i,n) = i(1 + i)^n / [(1 + i)^n – 1]$.
PFF	-	profit factor
f	-	ratio of output to input. If both the input and output quantities are in energy units, this value represents the thermal efficiency of the process.
s_o	-	ratio of output per unit of input for output link o.
s_l	-	ratio of input per unit of output for input link *l*.
w_o	-	user-specified parameter relating one price to another.
IO_l	-	input/output ratio that indicates input quantity per unit of output for input link *l*.
NQ	-	net output quantity of the decision node at time t. NQ equals the sum of the quantities on the output links minus the amount in the stockpile.
OMS_i	-	share of previous years demand met by supply alternative i.

LAG - lag parameter. Value = 1.0 implies no lag; immediate response to price. Value = 0.0 implies no response to price; base year market shares are maintained throughout the study period.

PM_l - premium multiplies for input link *l*.

a - price multiplier.