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Dynamic Simulation Model of the National Security Consequences from Energy Supply Distruptions

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Abstract

Recent terrorist attacks in the United States have increased concerns about potential national security consequences from energy supply disruptions. The purpose of this Laboratory Directed Research & Development (LDRD) is to develop a high-level dynamic simulation model that would allow policy makers to explore the national security consequences of major U.S. energy supply disruptions, and to do so in a way that would integrate energy, economic and environmental components.

The model allows exploration of potential combinations of demand-driven energy supplies that meet chosen policy objectives, including:

- Mitigating economic losses, measured in national economic output and employment levels, due to terrorist activity or forced outages of the type seen in California
- Control of greenhouse gas levels and growth rates
- Moderating U.S. energy import requirements

This work has built upon the Sandia U.S. Energy and greenhouse Gas Model (USEGM) by integrating a macroeconomic input-output framework into the model, adding the capability to assess the potential economic impact of energy supply disruptions and the associated national security issues. The economic impacts of disruptions are measured in terms of lost U.S. output (e.g., GDP, sectoral output) and lost employment, and are assessed either at a broad sectoral level (3 sectors) or at a disaggregated level (52 sectors). In this version of the model, physical energy disruptions result in quantitative energy shortfalls, and energy prices are not permitted to rise to clear the markets.

The USEGM code was rewritten in Powersim Studio, a newer upgraded software capable of handling the required macroeconomic/input-output interfaces of the new model. IMPLAN software was used to develop the macroeconomic input-output components of the model.

Acknowledgements

Arnold Baker served as the project Principal Investigator. Len Malczynski served as the Project Manager and Thomas Drennen participated on the study team.

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Introduction

The main objective of this LDRD project was to develop a high-level economic model that would allow policy makers and their staffs to explore the national security consequences of major U.S. energy supply disruptions, and to do so in a way that would integrate energy, economic and environmental components. This model provides rapid “what if” analyses of different energy security scenarios, rather than forecasts of U.S. energy demand and supply conditions. This model is integrated with and builds upon the Sandia U.S. Energy and Greenhouse Gas Model (USEGM) SAND2000-2637. The model adds the capability to assess the potential economic impacts of energy disruptions and associated national security issues by linking an input-output model framework with the dynamic simulation structure of the USEGM.

This document describes the structure of the U.S. Energy Security Model (USES M) that is designed for use as a learning tool in considering alternative U.S. energy policy options in response to energy disruptions in the U.S. economy. Energy disruptions using the USESM will impact gross national product (GDP) and employment under different scenarios. USESM is designed to complement rather than substitute for or duplicate existing complex models, allowing users to explore “what-if” type energy, economic, and environmental questions in real time. In addition to energy disruption impacts, the model allows analysis of policy options that affect overall energy demand, choice of fuel mix, electric power supply portfolios, and resulting U.S. carbon emissions. Detailed, complex models, such as the National Energy Modeling System (NEMS) used by the Energy Information Administration (EIA) of the Department of Energy, provide a framework for such analyses. However, the complexity of existing models makes it difficult to quickly interpret the model results or to perform rapid evaluations of policy options.

The first section of this paper includes a general description of the modeling approach used to develop the earlier U.S. Energy and Greenhouse Gases Model (USEGM). This dynamic simulation model provides the basic model structure for the USESM. The second section contains descriptions of the overall modeling approach selected, measures of energy disruption, the modules developed for addition to the basic USEGM, and the links between dynamic simulation and an input-output structure used in the USESM. The third through sixth sections explain in detail the four different modules of the USESM that provide different approaches to defining energy disruption impacts on the economy, and different economic measures of the effects of such disruptions – demand-side and supply-side – for modeling energy disruptions that can be applied with the USESM input-output components. The seventh section examines USESM results in terms of GDP and employment impacts because of energy disruptions. Examples of policy options are included in this section. The final section contains a summary of the model development results, and suggestions for further work to expand USESM capabilities.

Overview and Overall Model Approach

Since the goal of the new model is to facilitate real-time analysis of U.S. energy security issues, a definition of the appropriate measures of energy security is required. Energy security, as suggested by Ahearne [2] and others [3], [11], [12], [16], [17] has three elements:

1. The U.S. has adequate energy supplies to support a healthy economy.
2. Our allies also have adequate supplies.
3. We and our allies in concert have the capability to protect our vital energy supplies if they are threatened.

The focus of the new model is on the first element, and puts aside the international and potentially military policy aspects of the second and third elements of energy security. Given this narrower definition of energy security, indicators of national economic well being become the important measures of economic security related to energy demand and supply scenarios. Gross domestic product (GDP) and employment are the indicators used in the USESM. The original USEGM does contain GDP, but does not include sectoral detail. The USEGM also does not contain employment measures and impacts. Employment measures and impacts of energy disruptions are not included in the USEGM. The purpose for development of the USESM was to attempt to expand the USEGM model framework to allow for disaggregation of GDP, as well as disaggregated employment information. Computable general equilibrium and input-output models can provide such disaggregation. Computable general equilibrium models offer the most complete characterization of an economy, and can provide simultaneous consideration of demand-side and supply-side energy and economic conditions, but at the cost of large data requirements and difficulty in running real-time policy considerations of different energy scenarios. As a result, an input-output model framework was selected as the approach to expand the original USEGM.

Thus, the new USESM utilizes two distinct model frameworks: a dynamic simulation structure similar to the structure in the original USEGM energy and green house gas model; and an input-output framework which provides the capability to analyze disaggregated information on the impacts of different energy policies or energy disruption on different parts of the U.S. economy. Each model approach is briefly discussed below.

The U.S. Energy and Greenhouse Gas Model (USEGM)

The USEGM is a dynamic simulation model. Since their introduction by Prof. J. W. Forrester in the early 1950s, analysts have used dynamic simulation models for gaining insights into the behavior of complex, dynamic systems: systems with dynamics that are too complex to comprehend by analysts using only mental or linear models. A dynamic simulation model is a formal description of the system's flows (the transfers of entities between system components) and the levels (the accumulations of entities within the system). The formal description consists of the relationships between the flows and levels and the mathematical definition of how variables change dynamically with each time step. Executing the model simulates the development of the variables in a system, over time, to depict the current state of the system at each time step. Specifically, this dynamic system model is a functional mapping of a system into itself where each iteration of the mapping corresponds to a discrete time step. Complex system behavior including feedback loops, nonlinearities, and delayed and transient responses can be observed as the model executes.

Within the USEGM the principal flows represent the demand for and the supply of energy to the major economic sectors, and the levels represent the accumulations of the demand and supply. The model provides an opportunity to simulate the response of the system to specific internal or external influences and to measure their impact on the state of the system, thus providing the analyst with the capability to experiment and explore the system's behavior. A systems dynamics approach using Powersim Constructor software was chosen to develop the model, which is based on historic data for 1990 through 2000 from the EIA's Annual Energy Review (AER). USEGM estimates energy demand and associated carbon emissions to 2020 for four economic sectors (industrial, commercial, transportation, and residential) plus electric power generation. Seven energy sources (coal, oil, natural gas, nuclear, hydroelectric, wind, and solar) are specified in the model in the electric generation sector. Coal, oil, natural gas, electric power, and renewable energy comprise the energy sources in the model for the economic sectors. The basic model structure of USEGM is illustrated in Figure 1.

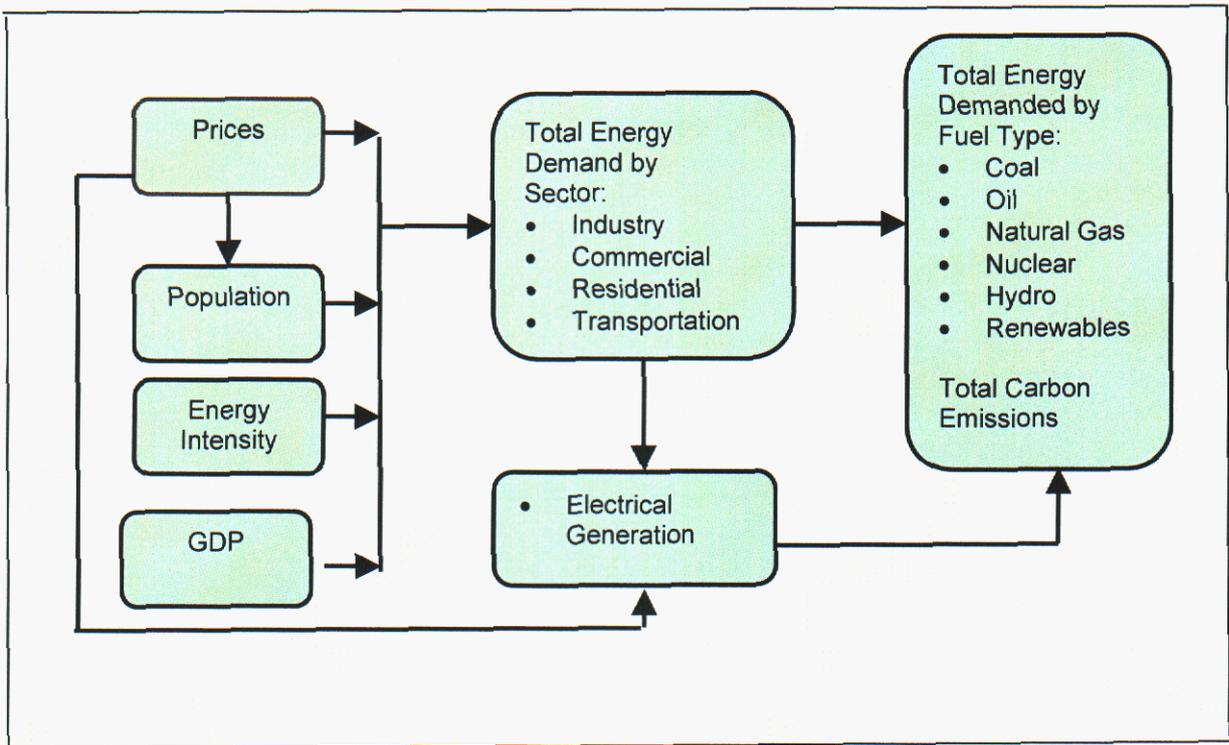


Figure 1. Basic Model Structure

In order to provide a frame of reference for policy discussions, the model is benchmarked to five EIA Annual Energy Outlook 2002 (AEO2002) scenarios:

- Reference case
- High economic growth case
- Low economic growth case
- High oil price case
- Low oil price case

The five scenarios provide different projections for GDP, energy intensities, and energy prices. These are integrated into the USEGM framework, but are not determined by the operation of the model.¹ The USEGM provides the capability of assessing such policy questions as impacts of different fuel mixes driven by price changes or policy constraints, and the effects of changes in energy intensity on carbon emissions and oil imports. These capabilities are retained in the expanded USESM.

¹ There are links between GDP, energy demand, and energy prices in the USEGM, where price changes are treated as revenue-neutral tax changes for different energy sources. This GDP/price approach tends to "net out" any impacts of energy prices on GDP. The Sandia National Laboratories report SAND2000-2637, *Technical Description of the U.S. Energy and Greenhouse Gas Model* provides a detailed description of the USEGM.

Input-output Model Overview

Input-output models and analysis refers to a framework initially developed by Wassily Leontief in the late 1930s [7]. A basic input-output model is constructed as a system of linear equations that describe the distribution of each industry's production throughout the overall economy. A basic Leontief input-output model is constructed from the historical data for a specific geographic region (e.g., states, nation). The focus here is on the national input-output models of the U.S. that include energy use in the economy, and measures of GDP and employment. Work by Giarranti [4], Hawdon and Pearson [5], and the Office of Technology Assessment [11] are examples of input-output models with energy components.

The fundamental information in an input-output analysis concerns the flows of products from each industrial sector considered as a producer to each sector that is a product consumer. This information is displayed in an inter-industry transactions table, where the rows of the table describe the distribution of producers' outputs through the national economy, and the columns depict the combination of production inputs required for each industry to produce its output.

For illustration, if there are 3 sectors in the national economy, where the total output of sector 1 is given as X_1 and total final demand for sector 1 output is Y_1 then

$$(1) \quad X_1 = z_{11} + z_{12} + z_{13} + Y_1$$

where the z terms represent the inter-industry sales by sector 1 to the other sectors in the economy, including itself (z_{11}).² The transactions table will contain an equation of this form reflecting the sales of the output of each of the sectors of the national economy, where it has been disaggregated into 3 sectors:

$$(2) \quad \begin{aligned} X_1 &= z_{11} + z_{12} + z_{13} + Y_1 \\ X_2 &= z_{21} + z_{22} + z_{23} + Y_2 \\ X_3 &= z_{31} + z_{32} + z_{33} + Y_3 \end{aligned}$$

While the rows of z values are sales by a sector to other sectors (and itself) in the economy, the columns of z values list the purchases of the products of each sector (including itself) for use in a given sector. For example, the z values z_{11} , z_{21} , and z_{31} are the sector 1 purchases or inputs from other sectors of the economy, including itself (z_{11}). As a result, the set of linear equations describe the sales (output) and purchase (input) transactions of all the producing sectors of the economy. These z values are combined in a transactions or input-output table in the form shown in Table 1.

² The notation and formatting used to describe the input-output models in this paper follow the procedures used by Miller and Blair [9].

Table 1. Input-Output Table of Inter-industry Flows

Selling Sectors	Processing Sectors			
		1	2	3
	1	Z_{11}	Z_{12}	Z_{13}
	2	Z_{21}	Z_{22}	Z_{23}
3	Z_{31}	Z_{32}	Z_{33}	

This input-output table is incomplete in describing the full national economy, since final demand by consumers and the government sector for the products and services is not included.³ Further, Table 1 does not include payments for the value added by input factors to the output processes. These additional elements are included in Table 2, where Y comprises final consumption and government expenditures.

Table 2. Expanded Input-Output Table of an Economy

	Processing Sectors			Final Demand	Total Output	
	1	2	3			
Selling Sectors	1	Z_{11}	Z_{12}	Z_{13}	Y_1	X_1
	2	Z_{21}	Z_{22}	Z_{23}	Y_2	X_2
	3	Z_{31}	Z_{32}	Z_{33}	Y_3	X_3
Payments Sector	Labor	L_1	L_2	L_3	L_c	L
	Other	N_1	N_2	N_3	N_c	N
Total Outlays		X_1	X_2	X_3	Y	X

This input-output framework contains the two macroeconomic measures of gross national output or X, with total national expenditures (outlays) in the bottom row and total national production (output) in the right column:

- Outlays: $X = \sum_{i=1}^3 X_i + Y$
- Output: $X = \sum_{i=1}^3 X_i + L + N$

Total final demand, or gross domestic product, is Y.

³ Government purchases are combined with household consumption in order to link the input-output framework to the USEGM dynamic simulation structure. U.S. exports and imports are not included in final demand in USESM.

Production Functions in the Input-Output Model

The linear structure of input-output models implies that the relationship between production inputs and outputs are constant, exhibiting a production function with constant returns to scale. An increase or decrease in input outlays will increase or decrease output in the same proportion a_{ij} , where a is the fixed ratio between input z_{ij} and output X_j so

$$(3) \quad a_{ij} = z_{ij}/X_j, \text{ or } z_{ij} = a_{ij} X_j$$

This ratio a_{ij} is termed the fixed technical (or input) coefficient of input z_{ij} in the production of output j . Note that within the input-output production constraints, inputs z can be expressed as the product of fixed technical coefficients and outputs. This relationship allows the inter-industry and final demand equations (listed in equation set 2) to be rewritten as

$$(4) \quad \begin{aligned} X_1 &= a_{11}X_1 + a_{12}X_2 + a_{13}X_3 + Y_1 \\ X_2 &= a_{21}X_1 + a_{22}X_2 + a_{23}X_3 + Y_2 \\ X_3 &= a_{31}X_1 + a_{32}X_2 + a_{33}X_3 + Y_3 \end{aligned}$$

Rearranging,

$$(5) \quad \begin{aligned} X_1 - a_{11}X_1 - a_{12}X_2 - a_{13}X_3 &= Y_1 \\ X_2 - a_{21}X_1 - a_{22}X_2 - a_{23}X_3 &= Y_2 \\ X_3 - a_{31}X_1 - a_{32}X_2 - a_{33}X_3 &= Y_3 \end{aligned}$$

This set of equations can in turn be written in matrix equation form as

$$(6) \quad (I - A)X = Y$$

$$\text{where } I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \quad \text{and } Y = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix}$$

I is an identity matrix, A is a technical coefficients matrix, X is a total output vector, and Y is a final demand vector making up GDP.

Finally, the matrix equation can be rewritten as

$$(7) \quad X = (I - A)^{-1} Y$$

where $(I - A)^{-1}$ represents the Leontief inverse. This framework is the basic structure of an input-output model where total outputs X are determined by final demand Y .

In the traditional Leontief model, demand is viewed as the limiting factor and the source of any impacts on the economy. Given fixed technical coefficients (A), a change in final demand (ΔY) is post-multiplied across the Leontief inverse $((I-A)^{-1})$ resulting in a change in total output (ΔX):

$$(8) \quad \Delta X = (I-A)^{-1} \Delta Y$$

Industry-specific output multipliers are then the column sums of $(I-A)^{-1}$. Change in output is then linked to value-added resources (W) in the economy through ratios to output, for instance, wage income per unit output or employees per unit output. Total value-added resources in dollars (wage income, profits, rents, and net taxes) must equal total final demand (consumption, business investment, government expenditures, and net exports) in the typical double-accounting system for gross domestic product (GDP):

$$(9) \quad Y = W = GDP$$

In Figure 2, this demand-side direction of causality follows the arrows labeled D , starting in Y , flowing through the economic structure of the economy represented by $(I-A)^{-1}$, and ending at W , the value-added (or factor) inputs used to meet final demand. The matrix A captures all of the economic sectors considered to be the endogenous portion of the model, where both Y and W are considered exogenous as the source and sink, respectively, of economic change.

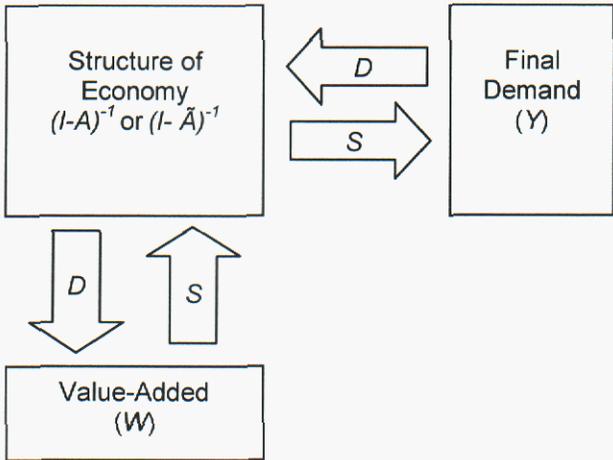


Figure 2. Direction of Causality in Input-Output Models

An input-output model comes with two major constraints. First, as noted above, the structure of the model is based on fixed technical coefficients (i.e., fixed input ratios) and constant returns to scale in production of all goods and services in an economy. A large body of economic research on real-world production conditions indicate production conditions tend to exhibit at least some variation in input ratios and returns to scale, especially over longer time periods. Since the USEGM model, which is the basis for the USESM, utilizes 20-year projections the fixed nature of production conditions in the input-output model are important to note.

Second, the input and output relationships in an input-output model are based on data for the U.S. economy in a single year; the transactions tables shown in Tables 1 and 2 are a “snapshot” of economic activity for one year, with associated supply and demand conditions. Both supply and demand will change over time, making the snapshot become less relevant to the real economy over time.

Linking the Dynamic Simulation and Input-Output Models

In order to explore the impact of energy shocks on the U.S. economy, both a Leontief and Ghoshian model (see Supply Side Module discussion below) were estimated from the 1999 IMPLAN database. The Leontief model is assumed to hold in non-shock years, where economic output and sectoral employment are generated by changes in final demand. The Ghoshian model is assumed to hold during energy-shock years, where a reduction in oil, natural gas, coal, and/or electricity restrains economic output and thus creates sectoral job loss. In both models, sectoral employment is calculated with output per employee ratios that change according to economy-wide employment productivity trends. Energy sectors are included in the exogenous value-added (W) and final demand (Y) accounts in order to serve as a source of shock to the Ghoshian system, following the S path in Figure 2.

Figure 3 is a schematic of the system of accounts that serve as the basis for scenario analysis, where:

Z	= interindustry transactions (55 x 55)
E	= exogeneous energy sector inputs to industry (4 x 55)
W	= other factor (value-added) inputs to industry (6 x 55)
E^Y	= energy sector demands on industry (55x4)
Y	= other final demand (55x4)
C	= transactions between energy sectors (e.g. coal inputs to electricity) (4x4)
Y^E	= final energy demand (e.g. residential energy demand)
W^E	= factor inputs to energy sectors (e.g. labor income generated in electricity sector)
X	= total output = $Z + E + W = Z + E_Y + Y$

	Industries	Energy	Final Demand	Total Output
Industries	Z	E^Y	Y	X
Energy	E	C	Y^E	
Value-Added	W	W^E		
Total Output	X			

Figure 3. Input-Output Accounts with Exogeneous Energy Sectors

To follow an energy shock from energy type to employment impact, consider an economy-wide energy shock ΔE_z , on fuel type z ($z = 1, 2, 3, \text{ or } 4$). Assume that the shock is distributed across all sectors ($i = 1$ to 55) according to current sectoral fuel shares:

$$(10) \quad \eta_{zi} = \frac{E_{zi}}{E_z + C_z + Y_z^E}$$

that sum to 1 for energy type z across energy consumption by industry (E_z), by energy producers (C_z), and by final demand (Y_z^E). Let N equal a ($z \times i$) matrix of sectoral fuel shares, then the impact vector becomes:

$$(11) \quad \Delta E = \Delta E_z N$$

and the impact on total output is captured by the Ghoshian system as:

$$(12) \quad \Delta X = \Delta E (I - \tilde{A})^{-1}.$$

Impact to sectoral employment (ΔL) is then captured by pre-multiplying a time dependent productivity scalar (α_t) to a vector of output per employee ratios (M), with the product multiplied on the sectoral output changes (ΔX):

$$(13) \quad \Delta L = \alpha_t M \Delta X$$

This example is simplified by allowing the original energy shock to occur in dollars, however, can be easily accommodated to handle shocks in energy units such as quads. This requires the adoption of sector and fuel specific energy intensities. Let Ω represent a 4×55 matrix of energy intensities in dollars of total value-added (W) per unit of energy in quads. Now a type- z energy shock of ΔE_z measured in quads can be converted into the impact vector ΔE from above as:

$$(14) \quad \Delta E = \Delta E_z \Omega$$

Four components were integrated into the USEGM to link the dynamic simulation and the input-output models: demand side, supply side, employment, and fuel constraint modules, as illustrated in Figure 4. Each module is discussed below.

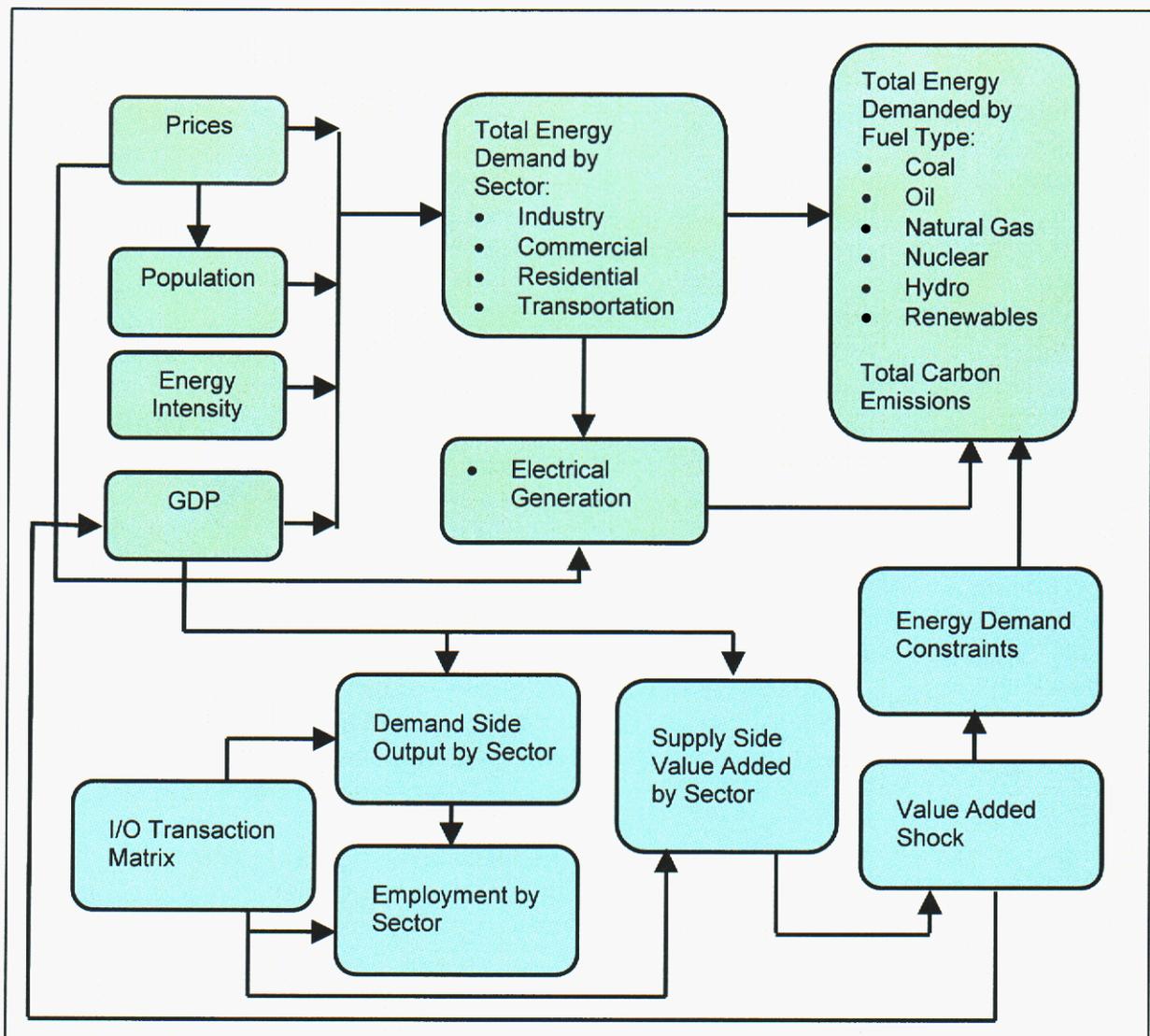


Figure 4. USEGM with Added Modules to Create USESM

The dynamic simulation software package used for the model is Powersim Studio. This is an upgraded version of Powersim Constructor 2.51, which was used to build the earlier USEGM system. The USEGM was rewritten in Powersim Studio 2001 to improve model functionality and to take advantage of the new features in Studio 2001, specifically:

- Measurement units: The forced assignment of measurement units can greatly improve the quality of models, as illegal use of units will be prevented by the system automatically. Additional key benefit of units: values are display with unit; values can be entered with unit, automatic unit conversion.
- Presentation mode: Presentation mode builds on a web browser metaphor. It has a simple toolbar with back and forward buttons (in addition to the necessary simulation control commands), and diagram pages act as the equivalent of web pages. The new hyperlink object (and the accompanying bookmark object acting as target) makes it easy to create links to diagram pages (as well as to files, applications, and web pages).
- Arrays: Explicitly identified array functions, new array functions, better, and more standard array notation.
- Simulation persistence: The history (time series) and state of variables can be saved along with the simulation. This means that a simulation that was stopped and then saved to file can be resumed when the project is opened. Furthermore, there is now a command for taking a snapshot of the simulation at a particular point in time, also referred to as adding a cue point. At a later stage the simulation can be restored to a given cue point and for example re-simulated from this point on. An arbitrary number of cue points can be added, and a dropdown command lets the user choose which cue point to revert to.
- Reference Data: Reference data can be shown alongside the results of the active simulation results. Reference data allows comparison of various scenarios in a very illustrative way.

The Impact Analysis for PLANning (IMPLAN) software and database were selected for the input-output model. The IMPLAN input-output database originally was developed in 1979 by the U.S. Forest Service, the Federal Emergency Management Agency (FEMA), and the U.S. Bureau of Land Management (BLM) to assist in land and resource management planning. Further development and maintenance of the IMPLAN software and database was taken over by the University of Minnesota in 1987, and was transferred to the Minnesota IMPLAN Group, Inc. in 1993. The system software and the databases are the two components of the IMPLAN framework. The software performs the input-output model calculations, and provides the flexibility to develop demand side and supply side model structures. The databases provide the information needed to create the national input-output model used here to link with the dynamic simulation model. A short description of the IMPLAN database components is given in Appendix A-1.

The IMPLAN software produces several tables showing income and expenditures in the economy. These tables correspond to elements of the general input-output framework described above. The tables are:

- Use Table – details the dollar value of goods and services purchased by each industry to use in their production processes. Table 1 shown above, which is based on equation set (2), is an example of a use table.
- Value Added Table – lists payments made by each industry to labor, taxes, interest, and other returns to factors of production. Table 2 above is an example of a value added table, with payments for production inputs listed in each processing sector column.
- Absorption Table – the coefficient form of the Use Table derived by dividing each element of the Use Table by the respective industry's dollar output. Each column is an industry's production function. Equation set (4) shows the equations that comprise the absorption table.
- Final Demand Table – lists the goods and services for final consumption. The Y vector in equations (5) and (6) are examples of the components of the final demand table.

These tables show the components of the input-output model, and, with the final demand table, the results or output of the model. Operation of the linked Powersim and IMPLAN systems requires information on:

- U.S. output and GDP initialized for a base year, typically 2000
- Energy demand by sector
- Energy prices
- Energy intensities by sector
- Definition of output and GDP sectoral shares
- Listing of employees per unit of sectoral output
- Value added per sector

Operation of the USESM is accomplished through a series of user interface screens that provide choices of demand side or supply side approaches, and allows selection of different energy security options to analyze the impacts of policy options. The demand and supply side modules do not have separate control screens, but are activated by control screens in the main USESM framework.

Demand Side Module

Overview and Module Description

The structure of the dynamic simulation model using the Powersim Studio software is the same for both the demand side and supply side approaches. The standard Leontief input-output structure described above and the format taken from IMPLAN are the input-output elements for the demand side module used in USESM. This input-output system is driven by final demand in the sectors of the economy and the technical coefficients matrix A . The model provides two levels of sector disaggregation. At the higher level, the U.S. economy is divided into three sectors: industrial, commercial, and transportation. The second, more detailed, level of disaggregation apportions the economy into the 55 2-digit Standard Industrial Classification (SIC) sectors. The SIC sectors and their associated IMPLAN listings are given in Appendix A-2. The Leontief demand side framework is linked to the USEGM GDP, energy demand, and energy intensity elements to provide the demand side projection module. The demand side USESM is driven by final demands for products and services in the economy as a whole. Production inputs, such as labor and energy, are assumed to be available to fulfill the required productive capacity needed to meet final demands. The demand side module interacts with the employment module (described below) to determine labor requirements and with the fuel elements in the dynamic simulation portion of the USESM to determine energy requirements.

The elements of the demand side module are shown in Figure 5. The IMPLAN input-output components are combined to determine the Leontief inverse, which allows calculation of the demand side total output. Disaggregation the 55 SIC sectors is done through use of final demand shares for each sector, which in turn establishes GDP by SIC sector. The demand side GDP in turn links to GDP and other variables of the USEGM model (not shown here). Note that the demand side module does not contain elements to disrupt or shock the economy. Shocks are initiated in the dynamic simulation portion of the model rather than the demand side input-output framework.

Demand Side I/O Model

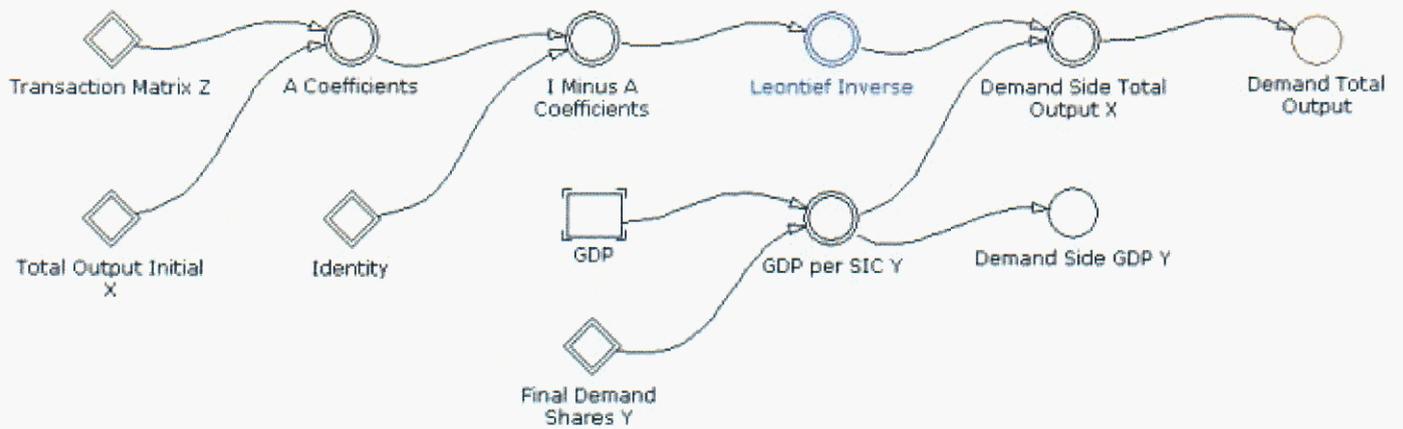


Figure 5. Demand Side I/O Module

Optional User Inputs

There are several user options that can be selected in the USESM that involve the demand side module, including energy prices by economic sector, energy shares by economic sector, and GDP growth paths. For example, Figure 6 shows the sector energy prices control screen. The values for carbon emissions, oil imports, and total energy are based upon the reference projection scenarios provided in the Energy Information Administration Annual Energy Outlook 2002. The “slider” bars allow the model user to increase or decrease energy prices in each sector. Changes in prices affect demand for energy types in the economic sectors, and in turn impact the demand side total output and GDP.

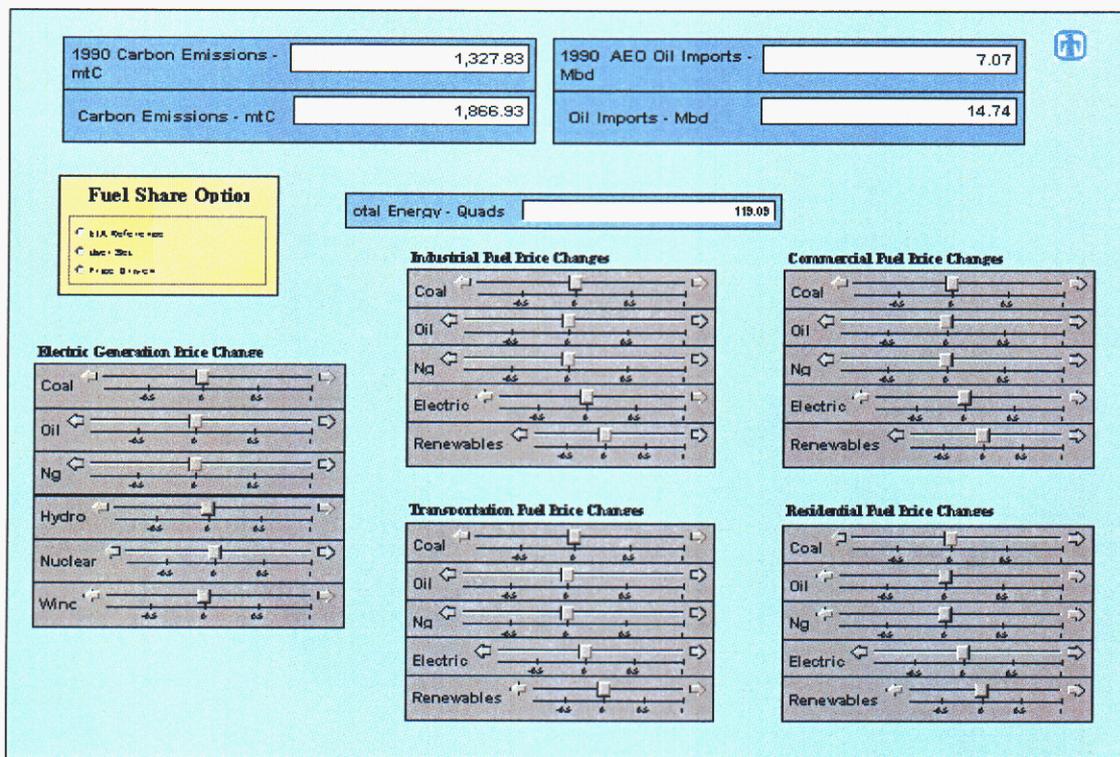


Figure 6. USESM Energy Price Control Screen

Supply Side Module

Overview and Module Description

A mirror image of this demand-driven process must also hold on the supply-side. Often called a Ghoshian model after Ghosh (1958), the source of economic change can also derive from W and follow the arrows labeled S in Figure 2, through a Ghoshian inverse $(I-\tilde{A})^{-1}$, and impact Y . Here W becomes the limiting factor and the source of economic change, and Y is now the sink. Technical coefficients are again fixed, but are derived by dividing output into rows of the transaction matrix, rather than down columns as in the Leontief system (denoted as \tilde{A}). In contrast to the fixed input requirements in the demand-driven Leontief system, the supply-driven Ghoshian system assumes fixed output coefficients and the following equality:

$$(15) \quad \Delta X = \Delta W(I - \tilde{A})^{-1}$$

The Leontief model is most useful when describing a short-run economic system with idle resources and thus very elastic factor-supply curves. However, the Ghoshian system is plausible under conditions of resource scarcity and very inelastic factor-supply curves, as in the case of energy shocks. For instance, Giarratani (1976) estimated a Ghoshian input-output model to investigate supply linkages associated with U.S. energy production and the impact of oil supply allocation schemes on the U.S. economy.

Development of a supply side input-output framework for our model requires modification of the standard Leontief demand side structure. While the Leontief demand side approach assumes all the required inputs to meet production are available, the supply side view allows for disruptions or shortages of inputs, which will constrain total production and GDP. The supply side interpretation relates sectoral production to inputs rather than sectoral demands. This approach is achieved by transposing the basic input-output model by dividing each row of the interindustry Z matrix by sectoral gross output X_j instead of dividing each column of Z by X_j which is done in the standard model. Using the three-sector format used above to describe the basic input-output model, the demand side production conditions specified in equation (3) are expressed as

$$(16) \quad a_{ij} = z_{ij}/X_j, \text{ or } z_{ij} = a_{ij} X_j$$

The supply side reformulation becomes

$$(17) \quad \tilde{a}_{ij} = z_{ij}/X_i \text{ or } z_{ij} = \tilde{a}_{ij} X_i,$$

where \bar{a}_{ij} are the direct output coefficients for a new coefficients matrix \bar{A} . As a result, fixed output coefficients rather than fixed input coefficients are used in the supply side model. This formulation allows equation set (4) to be rewritten as

$$(18) \quad \begin{aligned} X_1 &= \bar{a}_{11} X_1 + \bar{a}_{12} X_2 + \bar{a}_{13} X_3 + W_1 \\ X_2 &= \bar{a}_{21} X_1 + \bar{a}_{22} X_2 + \bar{a}_{23} X_3 + W_2 \\ X_3 &= \bar{a}_{31} X_1 + \bar{a}_{32} X_2 + \bar{a}_{33} X_3 + W_3 \end{aligned}$$

where W_j are the payments by the j^{th} sector for production inputs. Equation set (5) becomes

$$(19) \quad \begin{aligned} X_1 - \bar{a}_{11} X_1 + \bar{a}_{12} X_2 + \bar{a}_{13} X_3 &= W_1 \\ X_2 - \bar{a}_{21} X_1 + \bar{a}_{22} X_2 + \bar{a}_{23} X_3 &= W_2 \\ X_3 - \bar{a}_{31} X_1 + \bar{a}_{32} X_2 + \bar{a}_{33} X_3 &= W_3 \end{aligned}$$

or, in matrix equation form,

$$(20) \quad X'(\mathbf{I} - \bar{\mathbf{A}}) = W$$

Equation (11) can finally be rearranged as

$$(21) \quad X' = W(\mathbf{I} - \bar{\mathbf{A}})^{-1}$$

Equation (12) is the supply side, or Ghosian, input-output framework referred to above. The supply side input-output system is driven by input factor payments to establish final output and GDP in the economy. Changes (declines) in factor payments W (or disruptions in the supply of production factors, resulting in lower payments) cause changes (declines) in output X' . As a result, final output depends on inputs such as labor and energy in the supply side module. The model assumes that final demand will be available to purchase the outputs of the economy.

The supply side module also provides either the 3-sector or 55-sector levels of input-output disaggregation, and is linked to the employment module to determine sectoral outputs given labor supply, as measured by payments to labor. The size, timing, and duration of input shocks or disruptions are included in the supply side module to model the impacts of shocks on total output and GDP.

The elements of the supply side module are depicted in Figure 7. The IMPLAN input-output components are located in the upper right of the figure, where the supply side

Ghoshian matrix is calculated and used to generate supply side total output. Disaggregated GDP, as measured by value added shares in the supply side framework, is calculated for the 55 SIC sectors.

The shock variables in this module represent a new aspect based on the input-output structure in the USESM. The shocks modeled in this module focus on shocks to the production or factor inputs, such as labor. As noted earlier, an important assumption of the supply side approach is that demand conditions in the economy take all sectoral output to satisfy demand. As a result, if an input to production is shocked or constrained, total demand in the economy will be constrained, and GDP and employment will decline. Supply side shocks are characterized in three ways: the value (size), starting year, and duration of the shock.

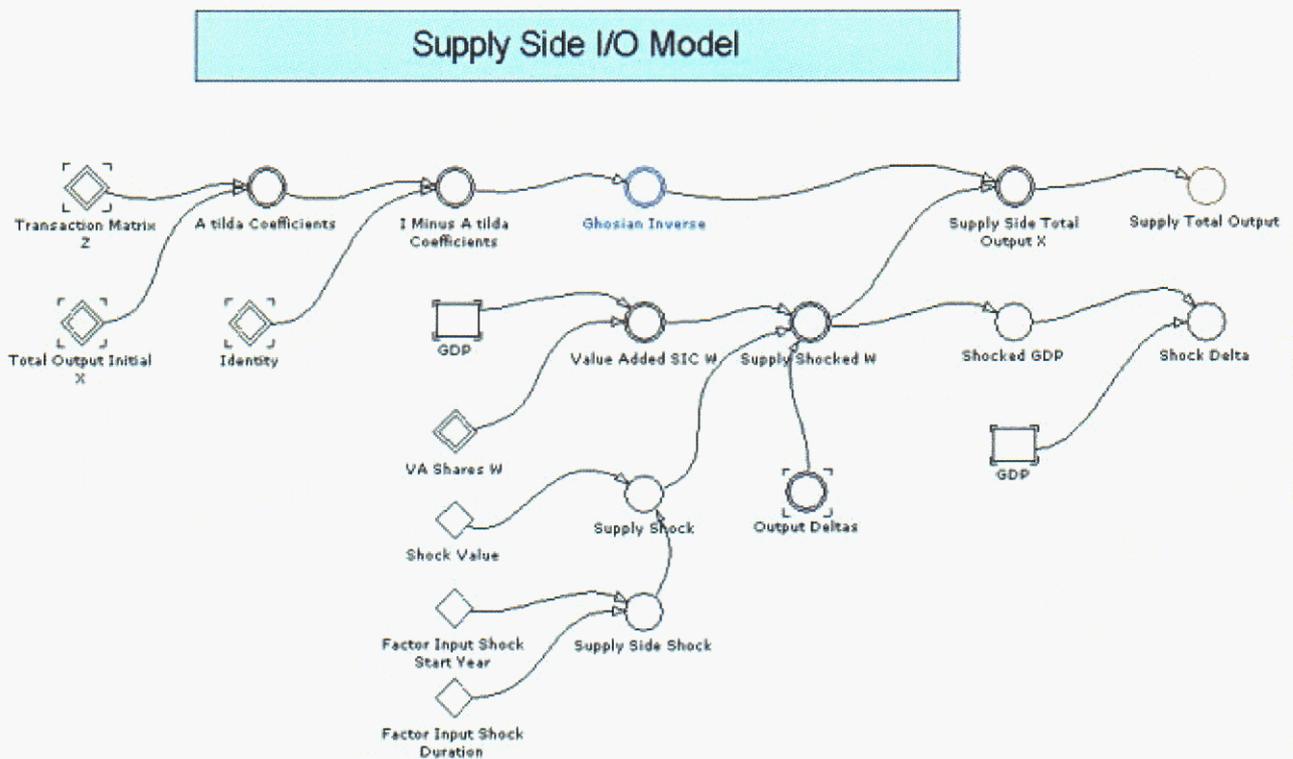


Figure 7. Supply Side I/O Module

Optional User Inputs

Optional user inputs with the supply side demand module include those measures that affect input availability and/or prices, which in turn will impact supply side GDP and employment. These include energy supply constraints, and energy prices. Energy supply constraints are contained in a separate module, described below. In addition to controls in the energy supply constraints module, the energy shares for different energy types can be controlled. For example, the control screen shown in Figure 8 illustrates the “sliders” used to change energy types in each economic sector. Using this control screen allows for permanent changes in energy mix in each sector, while the energy supply constraint control screen provides for shorter run (one year or more) shocks or disruptions in energy types for different economic sectors.

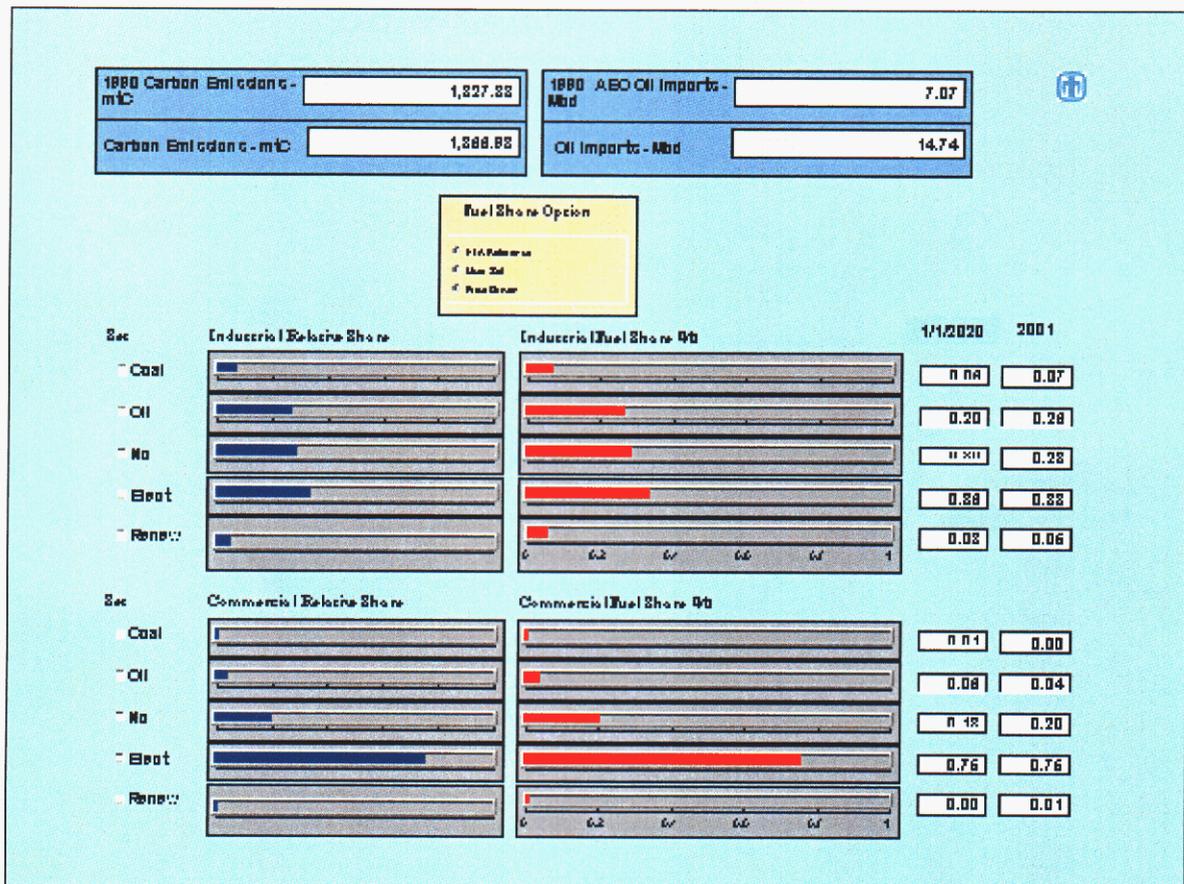


Figure 8. USESM Energy Share Control Screen

Employment Module

Overview and Module Description

The purpose of the employment module is to provide capability to specifically consider employment impacts of changes in final demand (demand side module) or changes in input payments (supply side module) by sectors of the economy. The employment module provides the choice of demand side or supply side modules when considering employment impacts. Labor is one of the input factors of production, and could be considered implicitly in the supply side shocks that are available in the supply side module. The employment module allows the user to focus on the employment impacts of a general supply side shock or an energy fuel supply shock. These shocks in turn impact on total output.

The structure of the employment module is shown in Figure 9. Employment is measured by linking output for any sector with output per employee, and to changes in labor productivity. When the demand side approach to the USESM is used, total output in terms of final demand and GDP determine the employees for each sector of the economy, given a specified sectoral labor input productivity. Whether the supply side or the demand side framework is used, sectoral output per employee and changes in labor productivity help determine the total output of the economy.

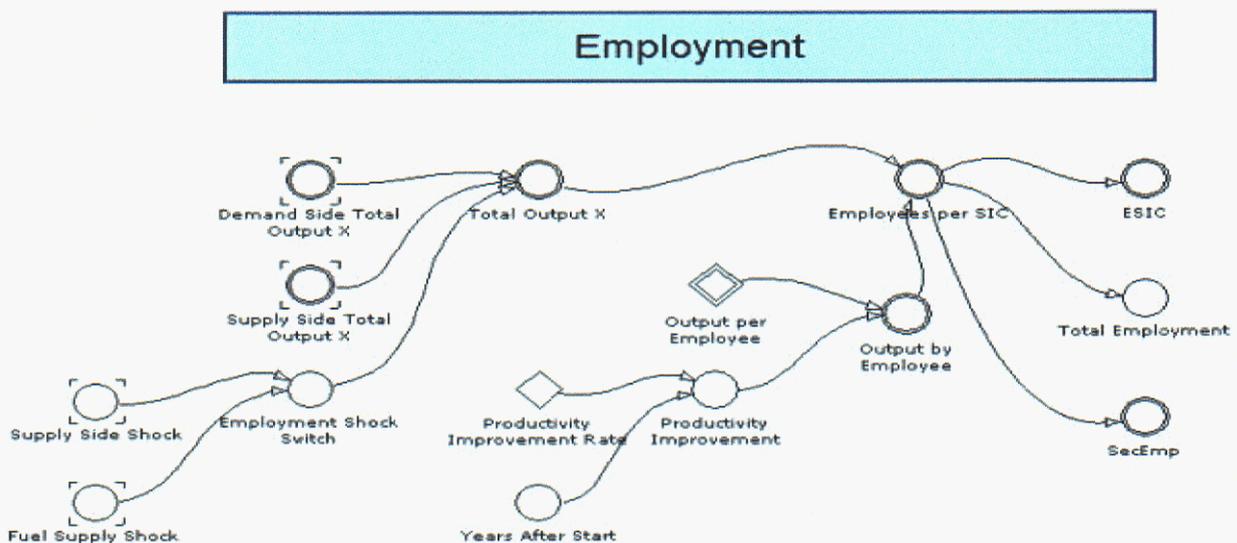


Figure 9. Employment Module

Optional User Inputs

Changing employee productivity is an option in this module, based on a productivity improvement rate and years after start that productivity improvements accrue. Figure 10 illustrates the Employment Control Screen associated with the Employment Effects Module. The productivity improvement rate of 1.85 percent per year listed in the illustrated screen is based on the AEO2002 reference case projection.

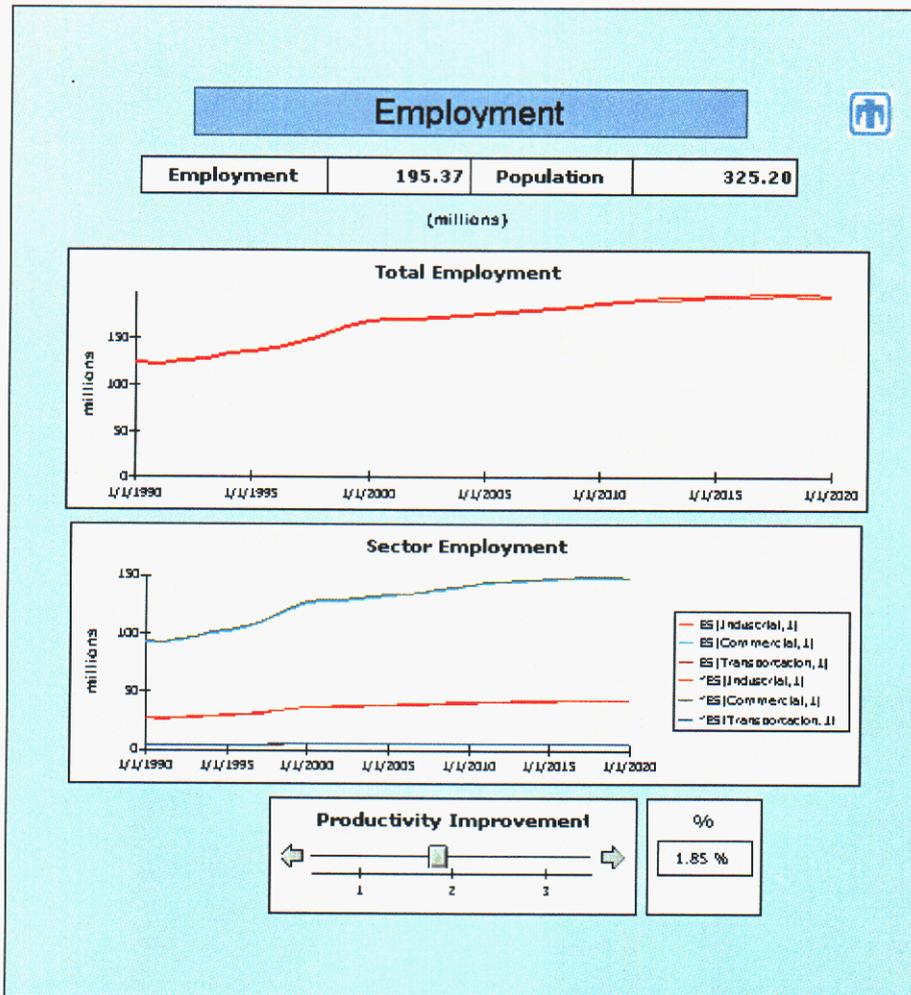


Figure 10. Employment Control Screen

Fuel Supply Constraints Module

Overview and Module Description

The fuel supply constraints module provides the capability to constrain any one or a combination of the six fuel types in the model. The structure of the module is shown in Figure 11. The fuel types are coal, oil, natural gas, renewables, and nuclear, and electricity. The electricity sector uses coal, oil, natural gas, and nuclear power as inputs to the production of electricity. In turn the fuel types are linked to economic sector fuel use as one of the factor inputs to production. The economic sectors are the industrial, commercial, transportation, and residential sectors. Placing a constraint on fuel supply results in a constraint on an input to production, which leads to constraints on supply side output, GDP, and employment.

The fuel constraint module starts with fuel stocks for the six fuel types, fuel shares for the four economic sectors, and demand by fuel type by the electric sector. These are linked to the dynamic USEGM structure. In turn the fuel shares of the four economic sectors are disaggregated into the 55-sector SIC structure used in the IMPLAN framework.

Fuel shocks can be placed on individual fuel types and on electricity production. A shock on electricity production has two impact paths. First, an electricity production constraint causes shocks on the demand for the other fuel types used in electricity production. Second, an electricity production constraint places a constraint on production of goods and services by constraining a factor input. Fuel shocks are characterized in three ways: the value (percent change), starting year, and duration of the shock.

Energy intensities also can be modified in the electric fuel options module control screen in the USESM.

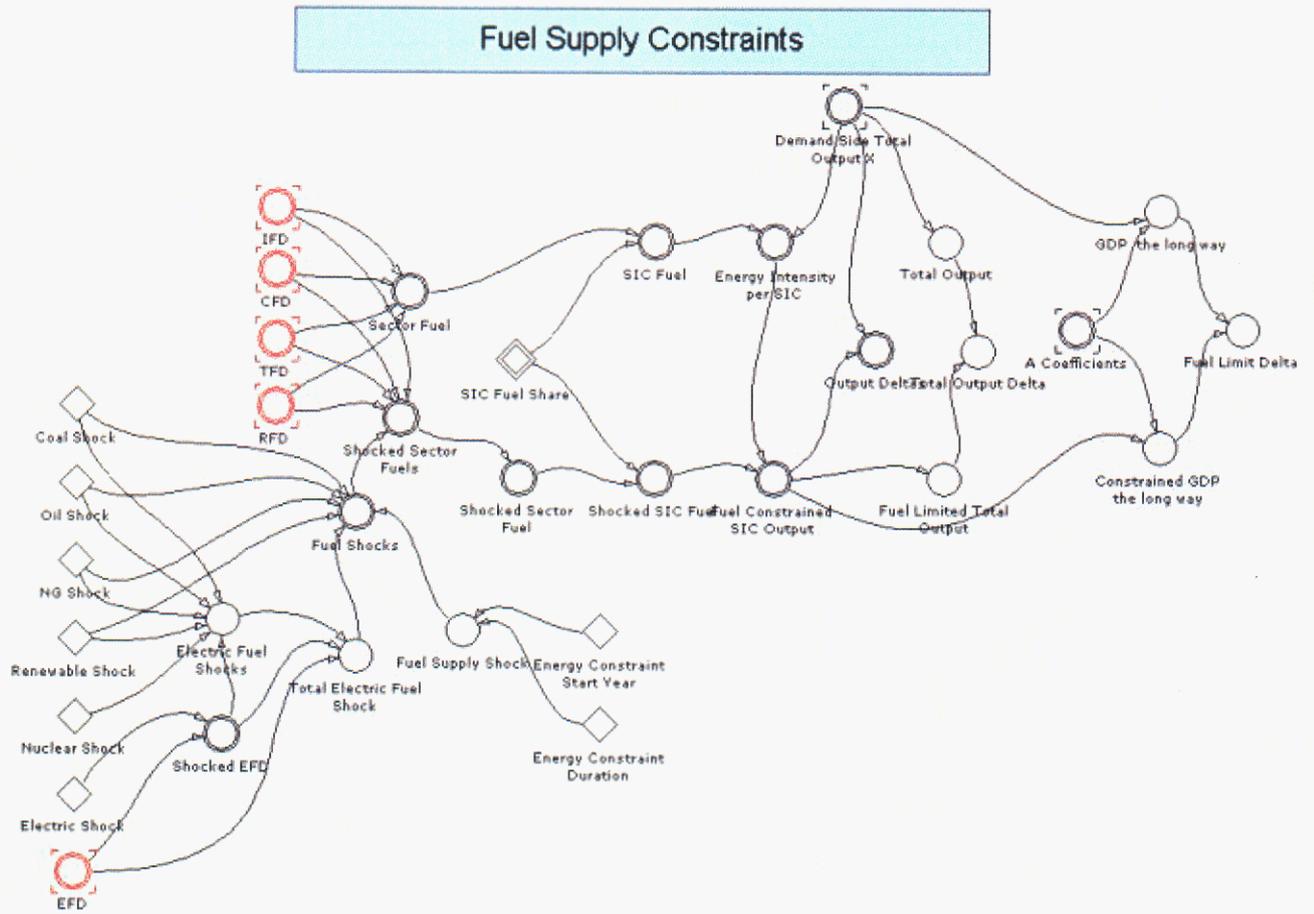


Figure 11. Fuel Supply Constraint Module

Optional User Inputs

USESME users can use the energy supply constraints control screen shown in Figure 12 to provide inputs on fuel shocks in the model. As noted above, the user has three characteristics of a fuel shock to specify. Values, or percent change in any fuel type, are controlled through use of “sliders.” The sliders provide ranges for percent changes in fuels. Start year and duration of fuel shocks are set in the respective boxes on the left of the control screen.

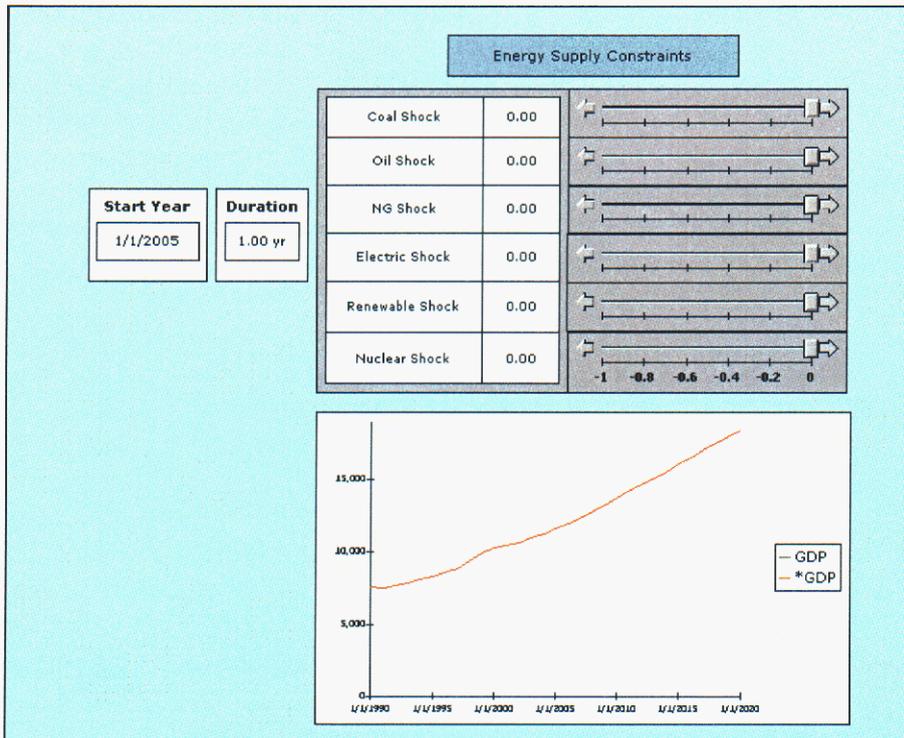


Figure 12. Energy Supply Constraints Control Screen

USESME Results

The USESM is intended as a high-level tool to help frame policy discussions on US energy, economic, environmental policy and US energy security. The purpose of this section is to give a brief example of the type of policy analysis this model allows. The first example depicts placing an energy supply constraint of a ten percent reduction in the supply of oil, starting in 2005 with a duration of one year. The appropriate settings on the energy supply constraints control screen are shown in Figure 13.

In addition to the control setting for energy constraints this screen also shows the impact on GDP from the oil constraint. The one-year duration of the oil supply constraint permanently lowers the GDP growth path through the model run, with the constrained GDP growing at the same rate as the original GDP growth path, but at a lower level. The effect of the oil supply constraint on GDP can also be viewed on the GDP screen of the USESM, as shown in Figure 14. Note that the current version of the model does not permit GDP to return to its pre-shock levels. We would anticipate that future model versions would permit such adjustment. This holds for the employment impacts as well.

The employment impacts of the ten percent oil constraint are shown at two levels, as depicted in Figures 15 and 16. Figure 15 shows the impact of the oil constraint on total U.S. employment, and employment in the economic sectors. The total employment impact follows a pattern similar to the impact on GDP, with an initial decline in 2005, and a parallel but lower growth path in later years. The same pattern can be seen for employment in the commercial sector in the lower chart in Figure 15. While an employment impact also can be expected in the transportation sector because of the sector's dependence on oil as a fuel source, the chart in Figure 15 does not clearly show this employment effect because of the relatively small share of total employment in the transportation sector.

An additional feature of the USESM allows the user to select any of the economic sector and disaggregate to the SIC level. Figure 16 focuses on the disaggregated transportation sector. Seven transportation sectors are included in the IMPLAN database at the 2-digit SIC level. The employment impacts of the oil constraint are shown for these seven sectors in Figure 16. The largest relative impact of the oil constraint is on the motor freight & warehousing SIC sector, although all of the transportation sectors experience employment declines because of the oil shock.

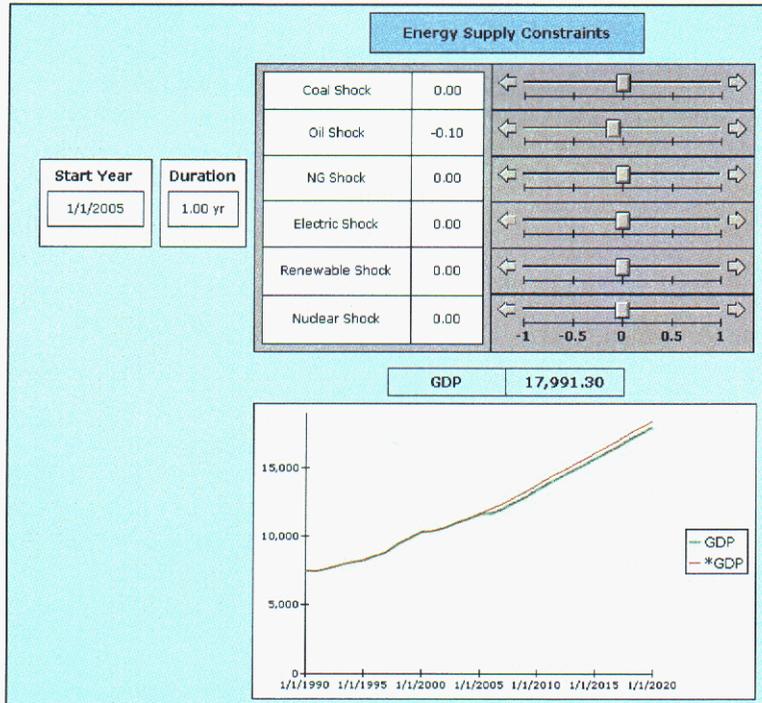


Figure 13. Example of a Ten Percent Constraint on Oil Supply

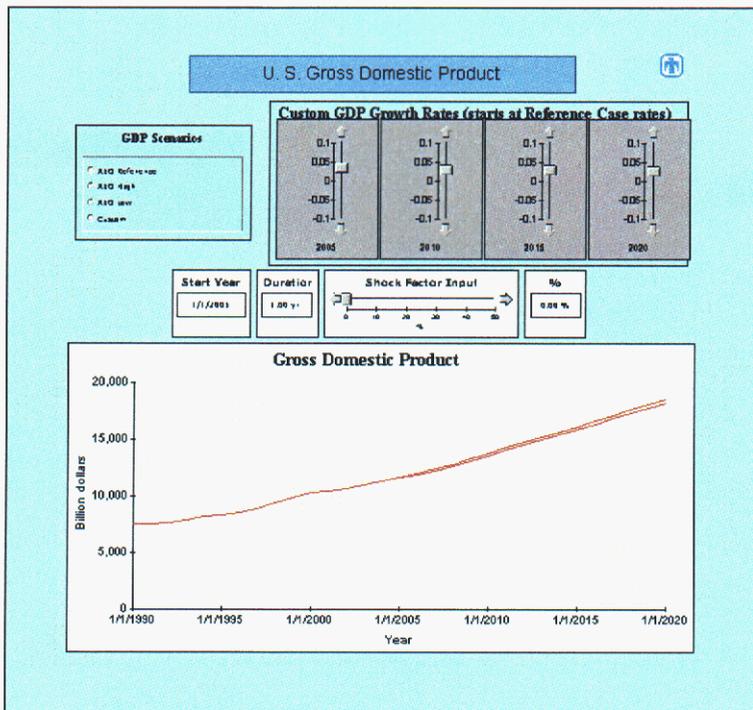


Figure 14. GDP Impact of Ten Percent Constraint on Oil Supply

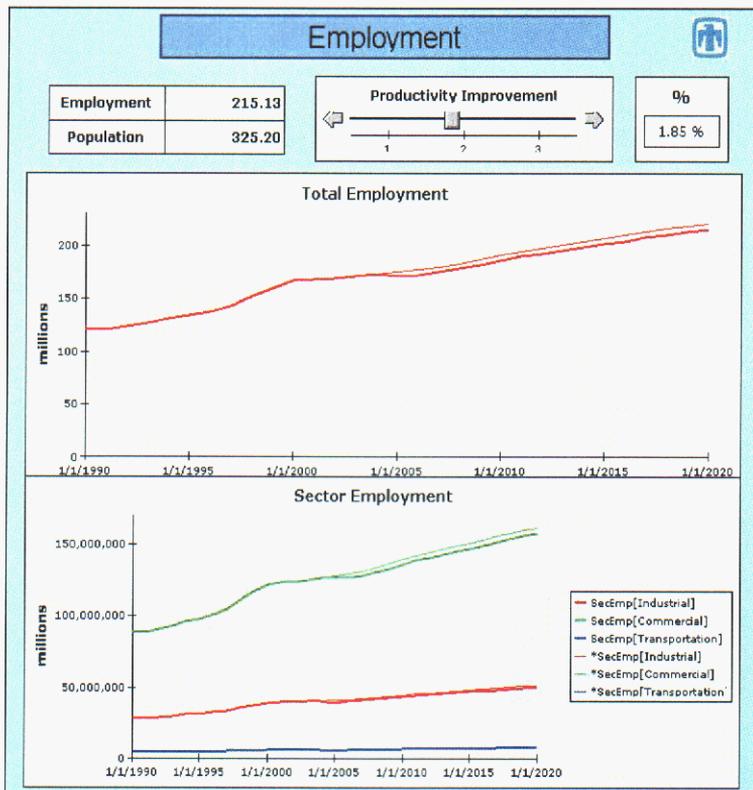


Figure 15. Impact of Oil Constraint on Economic Sector Employment

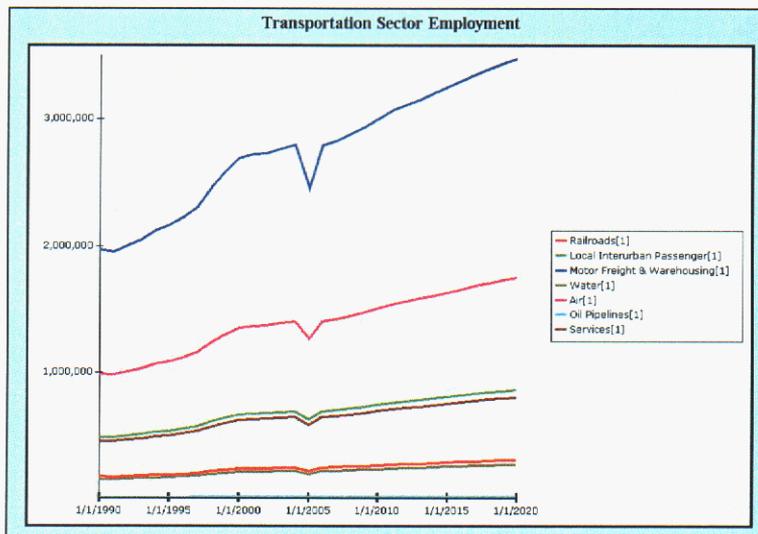


Figure 16. Impact of Oil Constraint on Transportation SIC Sector Employment

A policy exercise in this example would be to reconfigure the energy mix in one or more energy sectors and examine the impact on GDP and employment of that reconfiguration on this oil supply shock. Other types of questions for which the model could be used include:

- What is the impact on GDP and employment of a partial nuclear power capacity shut down? What are the impacts in different SIC sectors?
- What is the impact of substituting natural gas for coal in electricity both on reducing carbon emissions and with respect to a natural gas or electricity disruption? What different impacts on sectoral GDP and employment would such a substitution have?
- What is the role of energy efficiency improvements for different energy sectors in reducing the economic impact of energy market disruptions?

Summary and Suggestions for Further Work

The USESM is a high-level integrated dynamic simulation and input-output model that provides a framework for policy discussions on energy security issues on a real-time basis. The model includes interactions and impacts of U.S. GDP, energy prices, energy intensities, and energy constraints on energy demand, output, and employment in the economic and electric power sectors through 2020. In addition, use of the input-output framework allows the impacts to be disaggregated to 55 SIC sectors of the U.S. economy. The dynamic simulation approach used in the model allows the user to observe the time paths of changes in the demand or supply conditions for different energy fuel types in the economic and electric power sectors of the economy, which can suggest different policy approaches to energy use, energy security, and carbon emissions. In turn the relatively high-level results of USESM analyses can be complemented by more detailed study using more complex models, such as the NEMS.

The USESM should be viewed as a work in progress. Several aspects require additional work for this model to serve as a credible learning tool. First, as previously noted, the current USESM implicitly assumes that any energy shock will not alter the price of that energy type; i.e., no supply or demand response will occur. In the real world, an energy shortfall would be translated into a change in price that would affect both the demand and supply for that energy form, and would clear the market (unless the government intervenes). This is an important weakness of the current model.

Second, as also noted above, the current model version assumes that GDP and employment will not return to pre-shock levels after the shock occurs. This does not adequately represent the dynamics of post shock GDP, and thus overstates the economic consequences of a given energy shock. This weakness should be corrected.

A third weakness in the current model is the way it deal with the employment value added by sector in response to energy shocks. Currently the proportion of employment value added is constant within each of the four economic sectors. Employment impacts are calculated correctly if the USESM is used at the aggregated economic sector level. However, the employee share of value added is the same for all the SIC sectors within

each economic sector. The IMPLAN database contains information that would aid in the development of different input value added ratios at the SIC level, which would increase the capability of the USESM, particularly at the disaggregated level.

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Appendix A.

Appendix A-1. IMPLAN I/O Data System

Much of the IMPLAN data system focuses on regional information, since the IMPLAN system is designed to provide analysis of regional as well as national impacts. The components and subcomponents listed are available at the national or regional (usually by state) level.

Major Components

- Employment
- Value-Added
- Final Demand
- Output
- Inter-Institution Transfers
- National Structural Matrices

Subcomponents of Value added

- Employee Compensation
- Proprietary Income
- Other Property Type Income
- Indirect Business Taxes

Subcomponents of Final Demand

- Household Personal Consumption Expenditures
- Federal Government Military Purchases
- Federal Government Non-military Purchases
- Federal Government Non-military Investment
- State and Local Government Non-education Purchases
- State and Local Government Education Purchases
- State and Local Government Non-education Investment
- Inventory Purchases Capital
- Foreign Exports
- State and Local Government Sales
- Federal Government Sales
- Inventory Sales

Appendix A-2. SIC Categories

Table A-2.1. IMPLAN/SIC Code Matches

Sector	IMPLAN Code	SIC Group
Industrial	1	Farms
	24	Forestry Products
	25	Commercial Fishing
	26	Ag Services
	28	Metal mining
	40	Non-metal mining
	48	Construction
	57	Maintenance and Repair Oil and Gas Wells
	58	Food processing
	104	Tobacco mfg
	108	Textiles
	124	Apparel
	133	Wood products
	148	Furniture
	161	Pulp and paper
	174	Printing and publishing
	186	Chemicals and allied
	210	Petroleum products
	215	Rubber products
	221	Leather products
	230	Stone, glass and clay
	254	Primary metals
	273	Fabricated metal
	307	Industrial machinery
	355	Electrical equipment
	384	Transportation equipment
	400	Scientific instruments
	415	Miscellaneous mfg
Transportation	433	Railroads and Related Services
	434	Local, Interurban Passenger Transit
	435	Motor Freight Transport and Warehousing
	436	Water Transportation
	437	Air Transportation

IMPLAN		
Sector	Code	SIC Group
	438	Pipe Lines, Except Natural Gas
	439	Transportation Services
Commercial	441	Communications
	444	Utilities (w/o electric serv.)
	447	Wholesale Trade
	448	Retail Trade
	456	Finance, Insurance, Real Estate
	463	Hotels and Lodging Places
	464	Personal services
	469	Business services
	477	Automotive services
	480	Repair services
	483	Motion Pictures
	484	Recreation services
	490	Health services
	494	Legal Services
	495	Education services
	498	Social services
	502	Non-profit organizations
	506	Professional services
	510	State & local non-ed government
	513	Federal non-military
	516	Special sectors
	519	Federal Government - Military
	522	State & Local Government - Education
	525	Domestic Services

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