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A STRUCTURAL COMPARISON OF MODELS USED IN EMF 12 TO ANALYZE THE COSTS OF POLICIES FOR REDUCING ENERGY-SECTOR CO_2 EMISSIONS

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Abstract

As part of every Energy Modeling Forum (EMF) study, a comparison of model structures is conducted in order to better understand the (often disparate) results reported by the models. In EMF 12, this effort has been extensive due to the heterogeneity of the fourteen participating models.

This diversity has a number of advantages, chief among them being the greater number of insights that can be obtained by comparing the models' results in various scenarios which are relevant to the global-warming policy debate. To fully appreciate both individual model outputs and intermodel output differences, however, it is necessary to understand how each model's structure affects its results. The disadvantage of a diverse set of models is that it complicates the structural comparison, and hence the interpretation of results This paper develops a paradigm which facilitates this process.

The fundamental policy issue with which EMF 12 is concerned is the economic cost incurred when policies are enacted that reduce energy sector carbon emissions. Since the energy sector is the dominant carbon emissions source, and the demand for energy is closely tied to the demand for goods and services throughout the economy, the interpretative framework is based upon a simple identity relating domestic energy sector carbon emissions to gross domestic output (GDP) and domestic energy consumption. Each term in the identity is decomposed until the rate of change in carbon emissions is a function of price and quantity changes in each sector of the economy, including the secondary and primary fuel markets. Although this model cannot itself be used to generate emissions reduction scenarios, it helps focus the structural comparison on those aspects of the participating models which affect the results of interest.

These model characteristics fall into three general areas of comparison. The first is the general model type, e.g., recursive general equilibrium or dynamic optimal growth, which also includes the models' time horizons, data sources, and foresight assumptions. Here it is seen that, despite the many differences among the fourteen models, there are five broad classes within which models actually have striking similarity. Moreover, the class in which a model fits indicates the types of policy questions the model is fit to answer.

Understanding the distinctions between these five classes also simplifies the analysis in the remaining two areas of comparison: demand modeling and supply modeling. These last two sections are forthcoming.

INTRODUCTION: COMPARING A DIVERSE SET OF MODELS

As part of every Energy Modeling Forum (EMF) study, a comparison of model structures is conducted in order to better understand the (often disparate) results reported by the models. In EMF 12, this effort has been extensive due to the heterogeneity of the fourteen participating models. The following examples of structural differences manifest this diversity.

- One model has 672 household types for the U.S. alone; another has one representative consumer for the entire planet.
- Some models have agents with perfect foresight about future prices; others have agents who only consider current prices when making current decisions.
- One contains approximately 100 distinct energy supply technologies available in the U.S.; another has five supply technologies, none of which are explicitly non-carbon.
- One model contains explicit representation of thirty non-energy sectors in the U.S. economy which interact to determine prices and output; others implement energy sector effects on the rest of the economy with several aggregate "feedback equations."
- Some have detailed modeling of international trade in non-energy goods; others allow no international trade or trade only in crude oil.
- Some are relatively short-term (2010) models based on econometric estimation of fuel demands; others are very long-term (2100) models containing parameters judiciously chosen by the modeler (albeit with reference to the econometric estimates).
- Some models allow the stock of capital -- e.g., buildings, vehicles, equipment -- to be perfectly malleable and costlessly mobile among economic sectors, with the level adjusting to the long-run optimum in every time period; others include explicit or implicit rigidities encountered or costs incurred when changing the level of capital.

This diversity has a number of advantages, chief among them being the greater number of insights that can be obtained by comparing the models' results in various scenarios which are relevant to the global-warming debate. To fully appreciate both individual model output and intermodel differences, however, it is necessary to understand how a model's structure affects its results. The major disadvantage of a diverse set of models is that it complicates this structural comparison, and hence the interpretation of results. The aim of this paper is, therefore, to develop a paradigm which facilitates structural comparison of the models participating in EMF 12.

MODEL STRUCTURE COMPARISON: WHAT TO LOOK FOR IN EMF 12

In EMF 12, the fundamental issue is the economic cost -- measured as decreased GDP relative to the unconstrained case -- incurred by achieving a given reduction in energy sector carbon emissions. Any costs or benefits due to the environmental impacts of the emissions themselves are not included in the study.[1]

The implicit assumption is that these impacts do not affect any of the mechanisms which determine energy sector carbon emissions levels. For example, suppose that enhanced global warming caused the oceans to rise enough so that significant capital must be invested in dikes to protect low-lying coastal areas. This would undoubtedly displace investment in productive capital like machines or vehicles. This could lead, in turn, to some decrease in the growth of the economy and, since carbon emissions are roughly proportional to economic output, in the growth of carbon emissions as well. The weakest assumptions that can justify this exclusion would be if environmental impacts cause only reduced "enjoyment" of the environment; and/or any costs incurred as a result of the impact, e.g., in constructing the dikes, reduce consumption but not investment; and/or the marginal affect on GDP of the lost investment is negligible.

The focus of EMF 12 is further restricted to only energy sector carbon emissions for several reasons. First, it is the most significant single anthropogenic greenhouse gas and, equally as important, its main source -- fossil fuel combustion -- is relatively easy to trace. In fact, since the energy sector is responsible for over 95% of anthropogenic carbon emissions, only carbon released due to the combustion of fossil fuels in the supply of energy is considered.

Second, despite the putative attractiveness of a "comprehensive greenhouse gas budget,"[2] the sources of the other greenhouse gasses such as methane, CFCs, etc., are multifarious and thus their control requires more extensive policy measures. (Imagine, for example, trying to enact policies which limit the amount of methane emitted by cows.) Moreover, these gasses' roles as greenhouse gasses and precursor chemicals are not as well understood, as evinced by the recent "new science" about CFCs. The focus of the EMF 12 model structure comparison, therefore, is on the mechanisms by which reduction of energy-sector carbon emissions can be accomplished.

<u>The Aggregate Model</u>

The paradigm used for the structural comparison is based upon the following simple identity,[3]

$$C(t) \equiv Y(t)\frac{E(t)}{Y(t)}\frac{C(t)}{E(t)}.$$

$C(t)$ is domestic energy-sector carbon emissions at time t in billions of tons, $Y(t)$ is gross domestic

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[1] The CETA model by Peck and Teisberg discussed later can include this feature, but this capability is not used when running EMF scenarios.

[2] This approach holds that the measure that is significant is the total radiative forcing potential that is being added to the atmosphere. Thus all non-carbon greenhouse gasses are converted to "carbon-equivalents," based on their radiative forcing potential. Then, if it is cheaper to reduce, say, CFCs than it is carbon, the cost of reducing the overall radiative impact a given amount is reduced.

[3] This paradigm is due to Kaya (1990) He did not, however, further decompose each term.

economic output (GDP) in trillions of dollars, and $E(t)$ is domestic primary energy consumption in exajoules (1 XJ $\equiv 10^{18}$J) by the energy sector. The two fractions represent the aggregate energy intensity of production, I_E, and the carbon intensity of energy supply, I_C, respectively. Thus the equation can be simplified to

$$C(t) \equiv Y(t)\, I_E(t)\, I_C(t).$$

Approximate numbers for the U.S. in 1990 are, for example:

$$\begin{aligned}
Y(t) &= 4.5 \text{ trillion \$} \\
I_E(t) &= \frac{80 \text{ XJ}}{4.5 \text{ trillion \$}} = 17.8 \text{ XJ / trillion \$} \\
I_C(t) &= \frac{1.4 \text{ billion tons}}{80 \text{ XJ}} = 17.5 \text{ million tons / XJ} \\
C(t) &= 1.4 \text{ billion tons.}
\end{aligned}$$

As will be seen, this is not a model which can independently generate emissions reduction scenarios. It does, however, focus the structural comparison on those aspects of the participating models which affect the results of interest.

Differentiating and converting to percentage terms yields

$$\frac{C'(t)}{C(t)} = \frac{Y'(t)}{Y(t)} + \frac{I_E'(t)}{I_E(t)} + \frac{I_C'(t)}{I_C(t)}$$

where the prime denotes the derivative with respect to time. Thus on the most aggregate level,

$$\begin{pmatrix}\text{\% change in}\\ \text{carbon}\\ \text{emissions}\end{pmatrix} = \begin{pmatrix}\text{\% change in}\\ \text{gross}\\ \text{domestic}\\ \text{product}\end{pmatrix} + \begin{pmatrix}\text{\% change in}\\ \text{aggregate}\\ \text{energy}\\ \text{intensity}\end{pmatrix} + \begin{pmatrix}\text{\% change in}\\ \text{aggregate}\\ \text{carbon}\\ \text{intensity}\end{pmatrix}$$

$$\begin{pmatrix}\text{\% change in}\\ \text{carbon}\\ \text{emissions}\end{pmatrix} = \begin{pmatrix}\text{"GDP}\\ \text{(Growth)}\\ \text{Effect"}\end{pmatrix} + \begin{pmatrix}\text{"Energy}\\ \text{Intensity}\\ \text{Effect"}\end{pmatrix} + \begin{pmatrix}\text{"Carbon}\\ \text{Intensity}\\ \text{Effect"}\end{pmatrix}.$$

Converting approximate percentage changes in these quantities for the U.S. base-case scenario between 1990 and 2020 to average instantaneous growth rates over that time period yields:[4]

4 For detailed numerical data for specific models and scenarios, see Sit (1992).

$$\frac{C'(t)}{C(t)} = +0.35\ \%,\ \frac{Y'(t)}{Y(t)} = +0.70\ \%,\quad \frac{I_E'(t)}{I_E(t)} = -0.30\ \%,\ \frac{I_C'(t)}{I_C(t)} = -0.05\ \%.$$

While this is already a convenient decomposition, additional disaggregation is possible and yields yet more insights. Consider the economy diagrammed in Figure 1. In this economy, say, the U.S., there are single capital (K) and labor (L), markets, as well as two resource markets for primary fossil energy and primary nonfossil solids (PF and PN, respectively), the latter of which may be, for example, biomass or uranium. Consumers (CONS) can divide their expenditures between a gas utility service (GU), an electric utility service (EU), a refined liquid fuel (R), other services (S), and final consumption goods (G). Electric conversion technologies are fossil-based (EU-PF), nonfossil solids-based (EU-PN), and solar (EU-SO), while for gas utilities and refineries only the fossil and the nonfossil solid conversion technologies are available (GU-PF, GU-PN, R-PF, R-PN, respectively). There is also an intermediate goods and materials industry (M).

The flow of goods are indicated along the arrows connecting each of the sectors. Nonsubscripted variables denote quantity, while the subscripts denote the sector in which the quantity is consumed. For example, PF_{EU} is the quantity of primary fossil energy (PF) demanded by the electric utility sector (EU), and EU_{CONS} is the quantity of electric energy (EU) demanded by consumers (CONS). Similarly, the quantity of electric output generated by the solar electric conversion technology, for example, is denoted *EU-SO*. Although this model is conceptually simple, there is the unfortunate problem of some messy notation. Appendix A contains a short "notational glossary" for the interested reader.

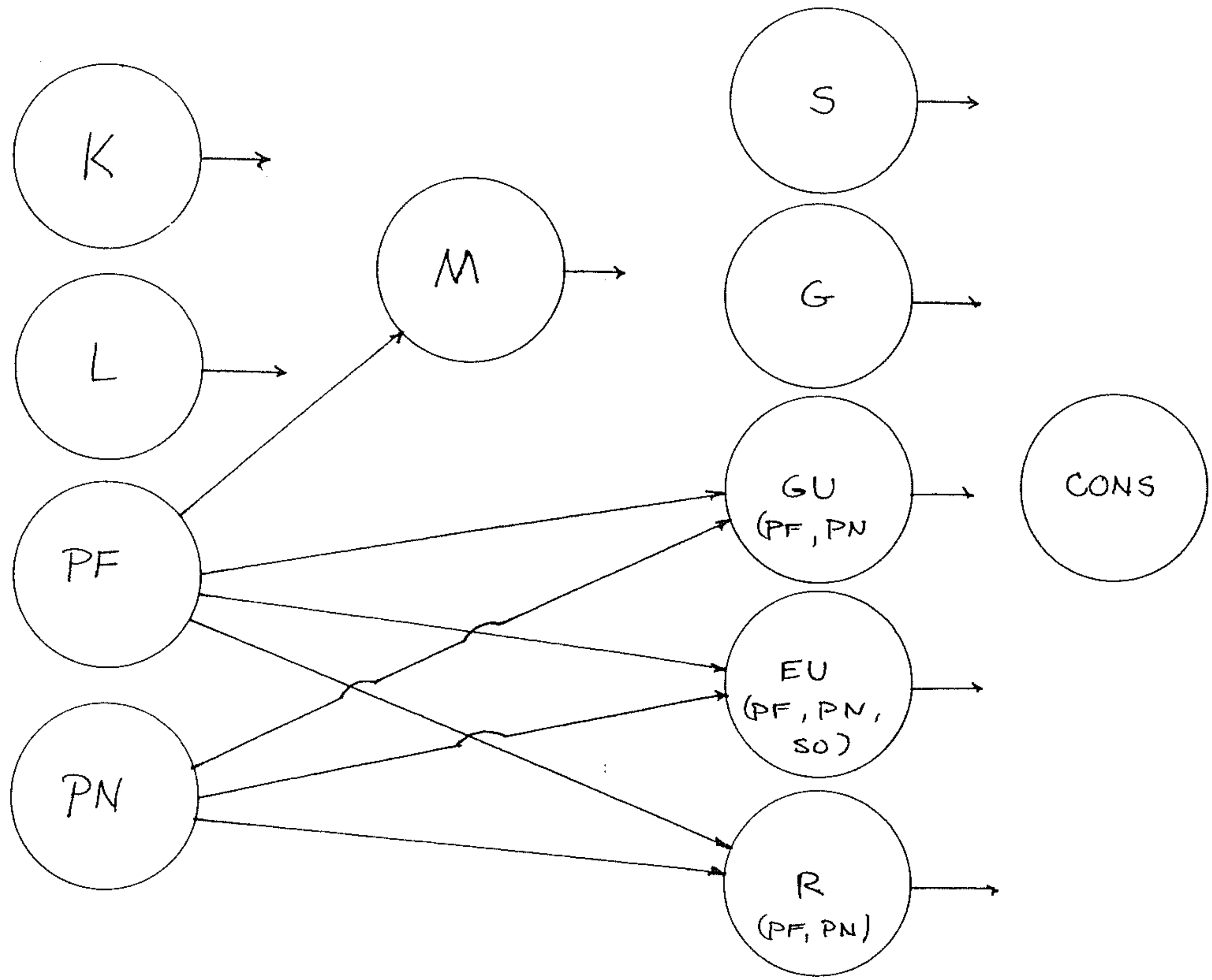
The U.S. trades with the rest-of-world economy (ROW) which has the same basic structure. Moreover, it is assumed that GDP equals GNP, which is a weak assumption since in the U.S., for example, the payments to U.S. capital and labor overseas are only 1% of GNP.

For notational convenience, the following sets are used.

• Intermediate and Final Non-energy Goods and Services:	*IFGS*	≡	{S, G, M}
• Primary Energy:	*PEN*	≡	{PF, PN}
• Secondary Energy:	*SEN*	≡	{R, GU, EU}
• Industrial Secondary Energy Demands:	*INDSEND*	≡	$PEN \cup IFGS$ [5]
• Total Secondary Energy Demands:	*SEND*	≡	$INDSEND \cup$ {CONS}
• Economic Sectors:	*SECT*	≡	$PEN \cup SEN \cup IFGS$

[5] The symbol "∪" means roughly "all the members which are in both sets."

FLOW OF GOODS



The GDP Effect

Since the demand for energy is derived from the demand for other goods and services, including energy services such as space heating and transport, it is most natural to view GDP from the production side, i.e., through sectoral value-added. GDP is simply the sum of the value-added in each sector of the economy, and is denoted V_i for sector i. Dropping the time argument,

$$Y \equiv \sum_{i \in SECT} V_i .$$

The sectoral shares in aggregate output at time t are

$$v_i(t) \equiv \frac{V_i(t)}{Y(t)},$$

so the GDP effect in terms of percentage changes in sectoral value-added is

$$\frac{Y'}{Y} = \sum_{i \in SECT} v_i \frac{V_i'}{V_i}$$

$$\left(\begin{array}{c} \text{"GDP} \\ \text{(Growth)} \\ \text{Effect"} \end{array} \right) = \left(\begin{array}{c} \text{weighted sum of} \\ \text{each sector's} \\ \text{percentage growth} \end{array} \right).$$

The change in each sector's value-added can, in turn, be thought of as the sum of four components. Although it may in practice be impossible to measure each, the conceptual distinction is crucial. The first is due to the workings of the marketplace which would occur independent of foreign competition; the second is due to the change in aggregate income; the third is an "autonomous" effect due to, say, consumption preference shifts or the nature of the economy as it matures which are independent of income changes; and the fourth is due to the net "export" of production to ROW.

Given the previous assumption that GNP = GDP, this last effect can occur when a ROW industry has a competitive advantage over its U.S. counterpart, but not when a U.S. industry partially relocates overseas. This can not happen in this model by assumption. There will be more said on this topic later.

Summary: The GDP Effect -- What to Look for in the Structural Comparison

- *How is aggregate economic growth modeled?*

- *If there is sectoral aggregation, what are the mechanisms by which sectoral value-added can change?*

The Energy Intensity Effect

Energy intensity in sector i is $I_{E_i} \equiv \frac{E_i}{V_i}$, where E_i is the net energy consumption in exajoules. Aggregate energy demand is found by summing across all sectors,

$$E \equiv \sum_{i \in SECT} I_{E_i} V_i \, .$$

The percentage change in aggregate energy consumption, therefore, is

$$\frac{E'}{E} = \frac{1}{I_E} \sum_{i \in SECT} v_i \left(I_{E_i}' + I_{E_i} \frac{V_i'}{V_i} \right).$$

After some algebra, the aggregate energy intensity effect is found to be

$$\frac{I_E'}{I_E} = \sum_{i \in SECT} v_i \left[\frac{I_{E_i}'}{I_{E_i}} + \left(\frac{I_{E_i} - I_E}{I_E} \right) \frac{V_i'}{V_i} \right]$$

$$\begin{pmatrix} \text{"Energy} \\ \text{Intensity} \\ \text{Effect"} \end{pmatrix} = \begin{pmatrix} \text{weighted sum of} \\ \text{sectoral energy-} \\ \text{intensity effects} \end{pmatrix} + \begin{pmatrix} \text{"Sector} \\ \text{Shift} \\ \text{Effect"} \end{pmatrix}.$$

Here it is important to consider the four components of the percentage change in value-added. If one is concerned with *global* reductions in carbon emissions, for example, then simply "exporting" the more energy-intensive ($I_{E_i} - I_E > 0$) industries' output will decrease domestic emissions, all else equal, but may not decrease global carbon emissions. This might occur when there is a unilateral carbon tax imposed in the U.S., for example, which confers a competitive advantage on energy-intensive industries in untaxed regions.

On the other hand, as an economy matures there is typically a switch to less energy-intensive ($I_{E_i} - I_E < 0$) industries like banking and consulting and away from more intensive industries like steel production. The total effect depends upon the rates of decline, the value weights, and the percentage differences between the sectors' energy intensities and the aggregate intensity.

Energy Demand Effect Each sector's energy intensity effect is

$$\frac{I_{E_i}'}{I_{E_i}} = \left(\frac{E_i'}{E_i} - \frac{V_i'}{V_i}\right).$$

Then

$$\frac{I_E'}{I_E} = \left[\sum_{i \in SECT} v_i \left(\frac{E_i'}{E_i}\right)\right] - \frac{Y'}{Y} + \left[\sum_{i \in SECT} v_i \left(\frac{I_{E_i} - I_E}{I_E}\right)\frac{V_i'}{V_i}\right],$$

$$\begin{pmatrix}\text{"Energy}\\ \text{Intensity}\\ \text{Effect"}\end{pmatrix} = \begin{pmatrix}\text{"Energy}\\ \text{Demand}\\ \text{Effect"}\end{pmatrix} - \begin{pmatrix}\text{"GDP}\\ \text{(Growth)}\\ \text{Effect"}\end{pmatrix} + \begin{pmatrix}\text{"Sector}\\ \text{Shift}\\ \text{Effect"}\end{pmatrix}.$$

Sector i's net energy consumption is determined as follows. Industries G, S and M consume gas and electric utility services and refined fuels, and M also consumes primary fossil energy. Thus in general,[6]

$$E_i = EU_i + GU_i + R_i + PF_i \qquad \text{for } i \in IFGS.$$

Industries PF and PN, as well as consumers, demand only utility services and refined fuels, so

$$E_i = EU_i + GU_i + R_i \qquad \text{for } i \in PEN,$$

and

$$E_{CONS} = EU_{CONS} + GU_{CONS} + R_{CONS}.$$

Since the secondary energy sectors (EU, GU, R) convert one form of energy to another, one must subtract the total output of each from its total primary energy input (including solar) to avoid "double counting." Consequently, with the total demand for secondary energy industry i's output denoted i_{TOT},

$$i_{TOT} \equiv \sum_{d \in SEND} i_d \qquad \text{for } i \in SEN.$$

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[6] The notation "for $i \in A$" means roughly "for each member i of the set A."

Then net energy demand in each secondary energy sector is the sum of primary fossil energy, primary nonfossil energy, and "primary solar" (defined soon), less total secondary energy output. Because there is considerable interest in conversion efficiency in these industries, the summation takes a slightly different form.

The XJ-weighted market share of secondary fuel industry *i*'s output generated with primary energy form *f* is defined as technology *i-f*'s output divided by total industry output, or

$$\mu_{i\text{-}f} = \frac{i\text{-}f}{i_{\mathrm{TOT}}}.$$

For example, the share of electric energy generated by primary fossil energy is

$$\mu_{\mathrm{EU\text{-}PF}} = \frac{EU\text{-}PF}{EU_{\mathrm{TOT}}}.$$

Next, the conversion efficiency is defined as output of technology *i-f* divided by the energy input level, f_i, or

$$\gamma_{i\text{-}f} = \frac{i\text{-}f}{f_i}.$$

In the example, the conversion efficiency for primary fossil electric would be

$$\gamma_{\mathrm{PF\text{-}EU}} = \frac{EU\text{-}PF}{PF_{\mathrm{EU}}}.$$

Rearranging terms, the amount of primary energy form *f* demanded in secondary energy sector *i* is

$$f_i = \left(\frac{\mu_{i\text{-}f}}{\gamma_{i\text{-}f}}\right) i_{\mathrm{TOT}}.$$

In the example,

$$PF_{\mathrm{EU}} = \left(\frac{\mu_{EU\text{-}PF}}{\gamma_{EU\text{-}PF}}\right) EU_{\mathrm{TOT}}.$$

Thus in general,

$$E_i = \left(\frac{\mu_{i\text{-SO}}}{\gamma_{i\text{-SO}}} + \sum_{f \in PEN} \frac{\mu_{i\text{-}f}}{\gamma_{i\text{-}f}} - 1 \right) i_{\text{TOT}} \qquad \text{for } i \in SEN.$$

Of course, $\mu_{R\text{-}SO} = \mu_{GU\text{-}SO} = 0$. Also, all transmission and distribution losses are ignored.

Since solar displaces primary fossil and nonfossil energy forms, the convention for defining the conversion efficiency of solar technology is as a weighted average of the conversion efficiencies of the electric fossil and nonfossil technologies, i.e.,

$$\frac{1}{\gamma_{\text{EU-SO}}} \equiv \frac{\dfrac{\mu_{\text{EU-PF}}}{\gamma_{\text{EU-PF}}} - \dfrac{\mu_{\text{EU-PN}}}{\gamma_{\text{EU-PN}}}}{\mu_{\text{EU-PF}} + \mu_{\text{EU-PN}}}.$$

However, since most models do not change the solar efficiency as the other values change, it will be assumed here that the solar efficiency is fixed.

Now the percentage changes in each sector's total energy consumption can be determined. Let ϕ_{f_i} be the XJ-weighted fraction of industry i's total energy consumption satisfied by energy form f, so

$$\phi_{f_i} \equiv \frac{f_i}{E_i}.$$

Again, $\phi_{SO_R} = \phi_{SO_{GU}} = 0$ since they use no solar. Then [7]

$$\frac{E_i'}{E_i} = \sum_{f \in SEN} \phi_{f_i} \frac{f_i'}{f_i} \qquad \text{for } i \in INDSEND \backslash \{\text{M}\}$$

$$\frac{E_{\text{M}}'}{E_{\text{M}}} = \sum_{f \in SEN \cup \{\text{PF}\}} \phi_{f_{\text{M}}} \frac{f_{\text{M}}'}{f_{\text{M}}}$$

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[7] The notation "$A \backslash B$" means "all the elements in the set A except those in the set B."

$$\frac{E'_{\text{CONS}}}{E_{\text{CONS}}} = \sum_{f \in SEN} \phi_{f_{\text{CONS}}} \frac{f_{\text{CONS}}'}{f_{\text{CONS}}}$$

$$\frac{E_i'}{E_i} = \phi_{\text{SO}_i} \frac{\mu_{i\text{-SO}}'}{\mu_{i\text{-SO}}} + \left[\sum_{f \in PEN} \phi_{f_i} \left(\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} - \frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} \right) \right] + \frac{i_{\text{TOT}}'}{i_{\text{TOT}}} \qquad \text{for } i \in SEN .$$

Substituting the equations for the percentage changes in energy consumption in each sector i allows decomposing the energy demand effect,

$$\sum_{i \in SECT} v_i \left(\frac{E_i'}{E_i} \right) = \left[\sum_{\substack{f \in SEN \\ i \in INDSEND}} v_i \ \phi_{f_i} \frac{f_i'}{f_i} \right] + v_{\text{M}} \phi_{\text{PF}_\text{M}} \frac{PF_{\text{M}}'}{PF_{\text{M}}}$$

$$+ \left[\sum_{\substack{i \in SEN \\ f \in PEN \cup \{\text{SO}\}}} v_i \phi_{f_i} \left(\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} - \frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} \right) \right] + \left[\sum_{i \in SEN} v_i \frac{i_{\text{TOT}}'}{i_{\text{TOT}}} \right] ,$$

("Energy Demand Effect") = (weighted sum of % changes in indutrial secondary energy demands) + (weighted % change in direct-use of primary fossil energy)

+ (weighted sum of % changes in converted primary energy demand due to changing technology market shares and conversion efficiencies)

+ (weighted sum of % changes in converted primary energy demand due to % changes in secondary energy demands with composition constant) ,

("Energy Demand Effect") = ("Industrial Secondary Energy Demand Effect") + ("Primary Fossil Direct-Use Effect") + ("Converted Primary Energy Composition Effect") + ("Converted Primary Energy Derived-demand Effect").

Now it is necessary to decompose the percentage changes in energy demands, f_i, and, in the secondary fuel sectors, in the market shares, $\mu_{i\text{-}f}$, and conversion efficiencies, $\gamma_{i\text{-}f}$.

Towards this end, define $\mathbf{w}_{NEN}$ as the vector containing the natural logs of all the non-energy (NEN) prices in the economy,

$$\mathbf{w}_{NEN} \equiv [\ln w_K \ \ln w_L \ \ln w_M \ \ln w_G \ \ln w_S]^T.$$

Thus $\mathbf{w}_{NEN}'$ contains the percentage changes in prices,

$$\mathbf{w}_{NEN}' = \left[\frac{w_K'}{w_K} \ \frac{w_L'}{w_L} \ \frac{w_M'}{w_M} \ \frac{w_G'}{w_G} \ \frac{w_S'}{w_S}\right]^T.$$

Similarly, the energy log-price vectors are denoted

$$\mathbf{w}_{PEN} \equiv [\ln w_{PF} \ \ln w_{PN}]^T$$

for primary energy (sunshine, of course, is free) and

$$\mathbf{w}_{SEN} \equiv [\ln w_{EU} \ \ln w_{GU} \ \ln w_R]^T$$

for secondary energy forms.

Industrial Secondary Energy Demand Effect and Primary Fossil Direct-Use Effect For industries $i \in INDSEND \backslash \{M\}$, it is assumed that consumption of each secondary energy form is a function of input factor prices, industry output quantity, and time. Thus for each energy demand f_i,[8]

$$\frac{f_i'}{f_i} = \mathbf{e}_{NENf_i}^T \mathbf{w}_{NEN}' + \mathbf{e}_{SENf_i}^T \mathbf{w}_{SEN}' + \theta_{f_i} \frac{i_{TOT}'}{i_{TOT}} + \alpha_{f_i} .$$

Here $\mathbf{e}_{NENf_i}$ and $\mathbf{e}_{SENf_i}$ are energy form f- and industry i-specific price elasticities for nonenergy and secondary energy prices, respectively. They measure the percentage change in energy form f demand which occurs from each percentage change in the corresponding prices. If a price is

[8] If $\mathbf{x}$ and $\mathbf{y}$ are two vectors of the same dimension, i.e., with the same number of components, say n, then vector multiplication is defined as

$$\mathbf{x}^T\mathbf{y} \equiv \sum_{i=1}^{n} x_i y_i .$$

irrelevant to an industry, of course, then the elasticity is identically zero.

θ_{f_i} is a scale and homotheticity[9] elasticity which measures the percentage change in fuel demand induced by each percentage change in output level, i_{TOT}. It describes a purely technical relationship between output and inputs for a given technology assuming that input levels are optimal given their prices (and it may be dependent upon prices and time as well). This parameter is important to include because nonhomothetic or nonlinearly-homogeneous technologies can give the false impression of technical change if output changes are not accounted for. For example, if the industry's technology is linearly homogeneous (constant returns to scale), then it is also homothetic and $\theta_{f_i} = 1$. More generally, the function could be homothetic and homogeneous of degree δ, then $\theta_{f_i} = 1/\delta$. If the function is nonhomothetic, it is difficult to say anything in general. θ_{f_i} may even be negative, in which case the good is an "inferior good."

α_{f_i} is the percentage change in energy demand f_i with prices and output held constant, and thus is closely related to the "AEEI" parameter used in several of the EMF models. If negative (positive), it is commonly thought of as energy-saving (-using) technical change. However, capital or other factor adjustment lags, changes in perceived uncertainty or price expectations, or other phenomena may enter here. Despite this muddled interpretation, this parameter will be called the "autonomous" effect for lack of a better word.

Secondary energy and primary fossil energy demands in the intermediate goods and materials industry (M) take exactly the same form as the above equation, except the term

$$+ \ \varepsilon_{PFf_M} \frac{w_{PF}'}{w_{PF}}$$

is added to account for the fact that primary fossil energy is consumed in industry M, and changes in its price can alter all energy demands f_M through the primary fossil cross-price elasticity, ε_{PFf_M}.

The entire effect can now be summarized and simplified with the introduction of some additional notation. Let ϕ_{SEN_i} be the vector of industry i's secondary energy shares,

$$\phi_{SEN_i}^T \equiv [\phi_{EU_i} \ \phi_{GU_i} \ \ \phi_{R_i}] \qquad \text{for } i \in \mathit{INDSEND} \setminus \{M\},$$

and let f_{SEN_i} be the vector of the natural logs of the industries' or consumer's secondary energy demands. Then the vector of percentage changes is

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[9] A production technology is homothetic if it is of the form $f(\mathbf{x}) = g(h(\mathbf{x}))$, where h is linearly homogeneous, and g is a strictly monotone transformation. These functions have many attractive properties but a thorough discussion is beyond the scope of this paper.

$$f_{SEN_i}' = \left[\frac{EU_i'}{EU_i} \;\; \frac{GU_i'}{GU_i} \;\; \frac{R_i'}{R_i}\right]^T \qquad \text{for } i \in INDSEND \setminus \{M\}.$$

The matrices of industry i's nonenergy and secondary price elasticities are defined as

$$\Lambda_{NEN_i} \equiv \begin{bmatrix} e_{NEN\,EU_i}^T \\ e_{NEN\,GU_i}^T \\ e_{NEN\,R_i}^T \end{bmatrix} \qquad \Lambda_{SEN_i} \equiv \begin{bmatrix} e_{SEN\,EU_i}^T \\ e_{SEN\,GU_i}^T \\ e_{SEN\,R_i}^T \end{bmatrix},$$

while the vector of M's primary fossil price elasticities is denoted

$$e_{PF_M} = [e_{PF\,EU_M}\, e_{PF\,GU_M}\, e_{PF\,R_M}]^T .$$

The vector of industry i's scale and homotheticity elasticities is

$$\theta_{SEN_i}^T \equiv [\theta_{EU_i}\; \theta_{GU_i}\; \theta_{R_i}],$$

and the vector of industry i's autonomous effects is

$$\alpha_{SEN_i}^T \equiv [\alpha_{EU_i}\; \alpha_{GU_i}\; \alpha_{R_i}].$$

Then the percentage changes in secondary energy and direct-use fossil demands are

$$f_{SEN_i}' = \Lambda_{NEN_i}\, w_{NEN}' + \Lambda_{SEN_i}\, w_{SEN}' + \theta_{SEN_i} \frac{i_{TOT}'}{i_{TOT}} + \alpha_{SEN_i} \qquad \text{for } i \in INDSEND \setminus \{M\},$$

$$f_{SEN_M}' = \Lambda_{NEN_M}\, w_{NEN}' + \Lambda_{SEN_M}\, w_{SEN}' + e_{PF_M} \frac{w_{PF}'}{w_{PF}} + \theta_{SEN_M} \frac{M_{TOT}'}{M_{TOT}} + \alpha_{SEN_M},$$

$$\frac{PF_M'}{PF_M} = e_{NEN\,PF_M}^T\, w_{NEN}' + e_{SEN\,PF_M}^T\, w_{SEN}' + \varepsilon_{PF\,PF_M} \frac{w_{PF}'}{w_{PF}} + \theta_{PF_M} \frac{M_{TOT}'}{M_{TOT}} + \alpha_{PF_M} .$$

Then by definition, the total percentage changes in energy consumption in these sectors are

$$\frac{E_i'}{E_i} = \phi_{SEN_i}^T\, f_{SEN_i}' \qquad \text{for } i \in INDSEND \setminus \{M\},$$

$$\frac{E_M{}'}{E_M} = \phi_{SEN_M}{}^T f_{SEN_M}{}' + \phi_{PF_M} \frac{PF_i{}'}{PF_i} .$$

So now the secondary energy demand effect and the primary fossil demand effect can be decomposed. Recall that the industrial secondary energy demand effect is

$$\sum_{\substack{f \in SEN \\ i \in INDSEND}} v_i \; \phi_{f_i} \frac{f_i{}'}{f_i} = \sum_{i \in INDSEND} v_i \; \phi_{SEN_i}{}^T f_{SEN_i}{}'$$

$$= \sum_{i \in INDSEND} v_i \; \phi_{SEN_i}{}^T \left[\Lambda_{NEN_i} w_{NEN}{}' + \Lambda_{SEN_i} w_{SEN}{}' + \theta_{SEN_i} \frac{i_{TOT}{}'}{i_{TOT}} + \alpha_{SEN_i} \right]$$

$$+ v_M \phi_{SEN_M}{}^T e_{PF\,M} \frac{w_{PF}{}'}{w_{PF}} ,$$

$$\begin{pmatrix} \text{"Industrial} \\ \text{Secondary} \\ \text{Energy Demand} \\ \text{Effect"} \end{pmatrix} = \begin{pmatrix} \text{weighted sum} \\ \text{of nonenergy} \\ \text{price effects on} \\ \text{industrial} \\ \text{secondary} \\ \text{energy demands} \end{pmatrix} + \begin{pmatrix} \text{weighted sum of} \\ \text{secondary energy} \\ \text{price effects} \\ \text{on industrial} \\ \text{secondary} \\ \text{energy demands} \end{pmatrix}$$

$$+ \begin{pmatrix} \text{weighted sum of} \\ \text{scale and} \\ \text{homotheticity} \\ \text{effects on} \\ \text{industrial} \\ \text{secondary} \\ \text{energy demands} \end{pmatrix} + \begin{pmatrix} \text{weighted sum} \\ \text{of autonomous} \\ \text{effects on} \\ \text{industrial} \\ \text{secondary} \\ \text{energy demands} \end{pmatrix} + \begin{pmatrix} \text{weighted primary} \\ \text{fossil price} \\ \text{effect on} \\ \text{M's secondary} \\ \text{energy demands} \end{pmatrix} ,$$

$$\begin{pmatrix} \text{"Industrial} \\ \text{Secondary} \\ \text{Energy Demand} \\ \text{Effect"} \end{pmatrix} = \begin{pmatrix} \text{"Nonenergy} \\ \text{Price Effect} \\ \text{on Industrial} \\ \text{Secondary} \\ \text{Energy Demand"} \end{pmatrix} + \begin{pmatrix} \text{"Secondary Energy} \\ \text{Price Effect} \\ \text{on Industrial} \\ \text{Secondary} \\ \text{Energy Demand"} \end{pmatrix}$$

$$+ \begin{pmatrix} \text{"Industrial Output} \\ \text{Effect on} \\ \text{Industrial} \\ \text{Secondary} \\ \text{Energy Demand"} \end{pmatrix} + \begin{pmatrix} \text{"Autonomous} \\ \text{Effect on} \\ \text{Industrial} \\ \text{Secondary} \\ \text{Energy Demand"} \end{pmatrix} + \begin{pmatrix} \text{"Primary Fossil} \\ \text{Price Effect on} \\ \text{M's Secondary} \\ \text{Energy Demand"} \end{pmatrix} .$$

Next, recall that the primary fossil energy direct use effect is $v_M \, \phi_{PF_M} \frac{PF_M'}{PF_M}$, or

$$v_M \, \phi_{PF_M} \left[e_{NEN \, PF_M}^T \, w_{NEN}' + e_{SEN \, PF_M}^T \, w_{SEN}' + \varepsilon_{PF \, PF_M} \frac{w_{PF}'}{w_{PF}} + \theta_{PF_M} \frac{M_{TOT}'}{M_{TOT}} + \alpha_{PF_M} \right].$$

$$\begin{pmatrix}\text{"Primary}\\ \text{Fossil}\\ \text{Direct-use}\\ \text{Effect"}\end{pmatrix} = \begin{pmatrix}\text{"Nonenergy}\\ \text{Price Effect}\\ \text{on Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix} + \begin{pmatrix}\text{"Secondary}\\ \text{Energy Price}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix} + \begin{pmatrix}\text{"Own-price}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix} + \begin{pmatrix}\text{"M's Output}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix} + \begin{pmatrix}\text{"Autonomous}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix}.$$

Consumer's Secondary Energy Demand Effect For consumers (CONS), secondary energy demand is assumed to be a function of personal income, prices, and time. Thus for each secondary energy form f,

$$\frac{f_{CONS}'}{f_{CONS}} = e_{NEN f_{CONS}}^T \, w_{NEN}' + e_{SEN f_{CONS}}^T \, w_{SEN}' + \eta_{f_{CONS}} \frac{Y'}{Y} + \alpha_{f_{CONS}}.$$

The terms have the same interpretation as before, except $\eta_{f_{CONS}}$ is defined as the income elasticity of demand for energy form f. Since this model has no governmental sector and assumes GDP = GNP, percentage income change is identically equal to the percentage GDP change ("GDP Effect"). If the elasticity is equal to unity, for instance, a one-percent change in income will result in a one-percent change in fuel demand. If negative, the energy form is called "inferior."

The term $\alpha_{f_{CONS}}$ here measures consumption preference (not technology) changes with prices and income (not output) constant; otherwise, all the additional phenomena listed earlier for the industries, e.g., changes in price expectations, may be included here as well.

In a similar manner to that in the previous section, the percentage change in total energy consumption is

$$\frac{E_{CONS}'}{E_{CONS}} = \phi_{SEN_{CONS}}^T \, f_{SEN_{CONS}}',$$

where

$$f_{SEN_{CONS}}' = \Lambda_{NEN_{CONS}} \, w_{NEN}' + \Lambda_{SEN_{CONS}} \, w_{SEN}' + \eta_{SEN_M} \frac{Y'}{Y} + \alpha_{SEN_{CONS}} \, .$$

This expression will be used later. The only difference from above is that the vector of income elasticities, and the interpretation of a is different.

$$\eta_{SEN_M} \equiv [\eta_{EU_{CONS}} \; \eta_{GU_{CONS}} \; \eta_{R_{CONS}} \,]^T ,$$

replaces the vector of scale and homotheticity elasticities.

<u>Converted Primary Energy Composition Effect</u> For the secondary energy sectors, the decomposition takes a slightly different form, since both technology market share and conversion efficiency are explicitly modeled.

For each secondary energy industry i and primary energy form $f \in PEN \cup \{SO\}$,

$$\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} = \frac{i\text{-}f'}{i\text{-}f} - \frac{i_{TOT}'}{i_{TOT}} .$$

The level of output from each technology i-f is assumed to be determined by nonenergy prices, the cost of each primary energy per unit output (price divided by conversion efficiency), total industry secondary energy output, and time. Hence,

$$\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} = \mathbf{e}_{NEN\mu_{i\text{-}f}}{}^T \mathbf{w}_{NEN}' + \mathbf{e}_{PEN\mu_{i\text{-}f}}{}^T \left(\mathbf{w}_{PEN}' - \begin{bmatrix} \frac{\gamma_{i\text{-}PF}'}{\gamma_{i\text{-}PF}} \\ \frac{\gamma_{i\text{-}PN}'}{\gamma_{i\text{-}PN}} \end{bmatrix} \right) + (\theta_{\mu_{i\text{-}f}} - 1) \frac{i_{TOT}'}{i_{TOT}} + \alpha_{\mu_{i\text{-}f}} \; .$$

Here $\mathbf{e}_{NEN_{f_i}}$ and $\mathbf{e}_{PEN_{f_i}}$ are energy form f- and industry i-specific price elasticity vector for nonenergy prices and the two primary energy *costs*, respectively. The conversion efficiency is included since an increase (decrease) in its value makes a fuel cheaper (more expensive), even with constant primary energy prices.

$\theta_{\mu_{i\text{-}f}}$ measures the percentage change in technology i-f output as total output increases. For example, if all technology utilization increased at the same rate as output increased, $\theta_{\mu_{i\text{-}f}}$ would be unity for all technologies, and output changes would not affect market share. On the other hand, suppose solar electric output was constrained. As total electric output increases, then, solar's market share would decrease since it could produce none of the additional electric energy.

$\alpha_{\mu_{i\text{-}f}}$ measures the shift to or from technology i-f independent of price or output changes. For example, there may be a shift towards more PN (say, biomass) used to produce electricity as more small power generators are built over time.

The change in conversion efficiency takes a similar form. Here it is assumed that fuel input f_i is determined by the prices of nonenergy goods, its own price, and time. It is further assumed that the conversion technology exhibits constant returns to scale, thus the output level is irrelevant. Since

$$\frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} = \frac{i\text{-}f'}{i\text{-}f} - \frac{f_i'}{f_i'},$$

$$\frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} = -\,\mathbf{e}_{\mathrm{NEN}\gamma_{i\text{-}f}}{}^{\mathrm{T}}\,\mathbf{w}_{\mathrm{NEN}}' - e_{f\,\gamma_{i\text{-}f}}\frac{w_f'}{w_f} - \alpha_{\gamma_{i\text{-}f}}\,.$$

Here $\mathbf{e}_{\mathrm{NEN}\gamma_{i\text{-}f}}$ measures how much the energy demand f_i changes with one-percent changes in nonenergy prices, and $e_{f\,\gamma_{i\text{-}f}}$ is the own-price elasticity for energy form f. Other energy prices do not enter here since they do not affect technology i-f's conversion efficiency. $\alpha_{\gamma_{i\text{-}f}}$ measures the change in primary energy consumed with technology output and prices constant. It is preceded by a negative sign, since if negative (input energy use is declining), the efficiency increases. Finally, recall that the efficiency of solar electric is fixed.

Combining the two expressions yields

$$\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} - \frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} = (\mathbf{e}_{\mathrm{NEN}\mu_{i\text{-}f}} + \mathbf{e}_{\mathrm{NEN}\gamma_{i\text{-}f}})^{\mathrm{T}}\,\mathbf{w}_{\mathrm{NEN}}' + (\mathbf{e}_{\mathrm{PEN}\mu_{i\text{-}f}}{}^{\mathrm{T}}\,\mathbf{w}_{\mathrm{PEN}}' + e_{f\,\gamma_{i\text{-}f}}\frac{w_f'}{w_f})$$

$$- \,\mathbf{e}_{\mathrm{PEN}\mu_{i\text{-}f}}{}^{\mathrm{T}}\begin{bmatrix}\dfrac{\gamma_{i\text{-}PF}'}{\gamma_{i\text{-}PF}}\\[2ex] \dfrac{\gamma_{i\text{-}PN}'}{\gamma_{i\text{-}PN}}\end{bmatrix} + (\theta_{\mu_{i\text{-}f}} - 1)\frac{i_{\mathrm{TOT}}'}{i_{\mathrm{TOT}}} + (\alpha_{\mu_{i\text{-}f}} + \alpha_{\gamma_{i\text{-}f}})\,.$$

To summarize, let the vectors of market share and conversion efficiency percentage changes in secondary energy industry i be, respectively,

$$\gamma_i' \equiv \begin{bmatrix}\dfrac{\gamma_{i\text{-}PF}'}{\gamma_{i\text{-}PF}} & \dfrac{\gamma_{i\text{-}PN}'}{\gamma_{i\text{-}PN}} & \dfrac{\gamma_{i\text{-}SO}'}{\gamma_{i\text{-}SO}}\end{bmatrix}^{\mathrm{T}}, \qquad \mu_i' \equiv \begin{bmatrix}\dfrac{\mu_{i\text{-}PF}'}{\mu_{i\text{-}PF}} & \dfrac{\mu_{i\text{-}PN}'}{\mu_{i\text{-}PN}} & 0\end{bmatrix}^{\mathrm{T}}.$$

Next, let the matrices of technology and primary energy demand elasticities with respect to nonenergy prices be, respectively,

$$T_{NEN_i} \equiv \begin{bmatrix} e_{NEN\mu_{i\text{-}PF}}^T \\ e_{NEN\mu_{i\text{-}PN}}^T \\ e_{NEN\mu_{i\text{-}SO}}^T \end{bmatrix} \qquad \Pi_{NEN_i} \equiv \begin{bmatrix} e_{NEN\gamma_{i\text{-}PF}}^T \\ e_{NEN\gamma_{i\text{-}PN}}^T \\ e_{NEN\gamma_{i\text{-}SO}}^T \end{bmatrix}.$$

Next let the matrix of technology demand elasticities with respect to primary energy prices be

$$T_{PEN_i} \equiv \begin{bmatrix} e_{PEN\mu_{i\text{-}PF}}^T \\ e_{PEN\mu_{i\text{-}PN}}^T \\ e_{PEN\mu_{i\text{-}SO}}^T \end{bmatrix}.$$

Finally, the technology output elasticity vectors and autonomous effect vectors are

$$\theta_{\mu_i} \equiv [\theta_{\mu_{i\text{-}PF}} \quad \theta_{\mu_{i\text{-}PN}} \quad \theta_{\mu_{i\text{-}SO}}]^T,$$

$$\alpha_{\mu_i} \equiv [\alpha_{\mu_{i\text{-}PF}} \quad \alpha_{\mu_{i\text{-}PN}} \quad \alpha_{\mu_{i\text{-}SO}}]^T,$$

$$\alpha_{\mu_i} \equiv [\alpha_{\gamma_{i\text{-}PF}} \quad \alpha_{\gamma_{i\text{-}PN}} \quad \alpha_{\gamma_{i\text{-}SO}}]^T.$$

These expressions can then be combined. For each secondary energy industry i,[10]

$$\mu_i - \gamma_i = (T_{NEN_i} + \Pi_{NEN_i} - T_{PEN_i}\Pi_{NEN_i})\, \mathbf{w}_{NEN}'$$

$$+ T_{PEN_i}\mathbf{W}_{PEN}' + (\mathbf{I} - T_{PEN_i}) \begin{bmatrix} e_{PF}\, \gamma_{i\text{-}f}\, \dfrac{w_{PF}'}{w_{PF}} \\ e_{PN}\, \gamma_{i\text{-}f}\, \dfrac{w_{PN}'}{w_{PN}} \\ 0 \end{bmatrix}$$

$$+ (\theta_{\mu_i} - \mathbf{1})\frac{i_{TOT}'}{i_{TOT}} + (\mathbf{I} - T_{PEN_i})\, \alpha_{\gamma_i} + \alpha_{\mu_i}.$$

The interpretation is (surprise!) straightforward. Nonenergy price changes, $\mathbf{w}_{NEN}'$, change

[10] The matrix $\mathbf{I}$ is the identity matrix; for a vector $\mathbf{x}$, $\mathbf{Ix} \equiv \mathbf{x}$. The unity vector $\mathbf{1} \equiv [1 \ 1 \ \ldots 1]$.

composition by affecting both technology choices and primary fuel demand for any given technology through the elasticity matrices T_{NEN_i} and Π_{NEN_i}. Moreover, the indirect effect of these price changes is on the conversion efficiency (primary fuel demand per unit output) through Π_{NEN_i}, which in turn changes the cost of per unit output of the various primary fuels, thus altering primary energy composition through T_{PEN_i}.

Primary energy price changes, $\mathbf{w}_{PEN}'$, affect technology choice through T_{PEN_i}. Moreover, primary energy price changes affect conversion efficiency, which also affects technology costs; thus the conversion efficiency change is multiplied by $(\mathbf{I} - T_{PEN_i})$ to capture both direct and indirect affects on composition.

The output effect is relatively simple. The autonomous conversion efficiency change has both direct and, as before, indirect effects through T_{PEN_i}. Finally, autonomous technology market share directly affects primary energy composition.

Now let ϕ_{PEN_i} be secondary energy industry i's vector of primary energy shares,

$$\phi_{PEN_i} \equiv [\phi_{PF_i} \;\; \phi_{PN_i} \;\; \phi_{SO_i}]^T \qquad \text{for } i \in SEN .$$

Thus the converted primary energy composition effect is

$$\sum_{\substack{i \in SEN \\ f \in PEN \cup \{SO\}}} v_i \, \phi_{f_i} \left(\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} - \frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} \right) = \sum_{i \in SEN} v_i \, \phi_{PEN_i}{}^{T} (\mu_i - \gamma_i) \; ,$$

$$\left(\begin{array}{c}\text{"Converted}\\ \text{Primary Energy}\\ \text{Composition}\\ \text{Effect"}\end{array}\right) = \left(\begin{array}{c}\text{"Direct and}\\ \text{Indirect}\\ \text{Nonenergy}\\ \text{Price Effects}\\ \text{on Composition"}\end{array}\right) + \left(\begin{array}{c}\text{"Primary}\\ \text{Energy Price}\\ \text{Effect on}\\ \text{Conversion}\\ \text{Technology}\\ \text{Market Share"}\end{array}\right)$$

$$+ \left(\begin{array}{c}\text{"Direct and}\\ \text{Indirect}\\ \text{Primary}\\ \text{Energy Own-}\\ \text{price Efficiency}\\ \text{Effects on}\\ \text{Composition"}\end{array}\right) + \left(\begin{array}{c}\text{"Output}\\ \text{Effect on}\\ \text{Conversion}\\ \text{Technology}\\ \text{Market}\\ \text{Share"}\end{array}\right) + \left(\begin{array}{c}\text{"Direct and}\\ \text{Indirect}\\ \text{Autonomous}\\ \text{Conversion}\\ \text{Efficiency}\\ \text{Effects on}\\ \text{Composition"}\end{array}\right) + \left(\begin{array}{c}\text{"Autonomous}\\ \text{Market}\\ \text{Share}\\ \text{Effect"}\end{array}\right)$$

<u>Converted Primary Derived-demand Effect</u> For each secondary energy sector i, let ω_i be the vector containing the fractions of output consumed by each of the secondary energy demand sectors (each

sector in the set *SEND*),

$$\omega_i^{\mathrm{T}} \equiv [\omega_{i\mathrm{CONS}}\ \omega_{i\mathrm{G}}\ \omega_{i\mathrm{S}}\ \omega_{i\mathrm{M}}\ \omega_{i\mathrm{PF}}\ \omega_{i\mathrm{PN}}].$$

Then with

$$\Omega_i \equiv [\ln i_{\mathrm{CONS}} \ldots \ln i_{\mathrm{PN}}],$$

$$\frac{i_{\mathrm{TOT}}'}{i_{\mathrm{TOT}}} = \omega_i^{\mathrm{T}}\ \Omega_i', \qquad \text{for } i \in SEN.$$

Thus Ω_i' contains the percentage changes in secondary energy consumption in each of the various demand markets. Expressions for these have already been found, so as before there will be price, output, and autonomous effects.

The converted primary derived-demand effect was found to be

$$\sum_{i \in SEN} v_i \frac{i_{\mathrm{TOT}}'}{i_{\mathrm{TOT}}} = \sum_{i \in SEN} v_i\ \omega_i^{\mathrm{T}}\ \Omega_i',$$

$$\begin{pmatrix}\text{"Converted Primary}\\ \text{Derived-demand}\\ \text{Effect"}\end{pmatrix} = \begin{pmatrix}\text{"Total Secondary}\\ \text{Energy Demand}\\ \text{Effect"}\end{pmatrix}.$$

Summary: Energy Intensity Effect -- What to Look for in the Structural Comparison The main results of this (brief) section are reiterated.

- Aggregate Energy Intensity Effect

$$\frac{I_E'}{I_E} = \sum_{i \in SECT} v_i \left[\frac{I_{E_i}'}{I_{E_i}} + \left(\frac{I_{E_i} - I_E}{I_E}\right)\frac{V_i'}{V_i}\right] = \left[\sum_{i \in SECT} v_i \left(\frac{E_i'}{E_i}\right)\right] - \frac{Y'}{Y} + \left[\sum_{i \in SECT} v_i \left(\frac{I_{E_i} - I_E}{I_E}\right)\frac{V_i'}{V_i}\right]$$

$$\begin{pmatrix}\text{"Energy}\\ \text{Intensity}\\ \text{Effect"}\end{pmatrix} = \begin{pmatrix}\text{"Energy}\\ \text{Demand}\\ \text{Effect"}\end{pmatrix} - \begin{pmatrix}\text{"GDP}\\ \text{(Growth)}\\ \text{Effect"}\end{pmatrix} + \begin{pmatrix}\text{"Sector}\\ \text{Shift}\\ \text{Effect"}\end{pmatrix}$$

- *If sectoral aggregation is included in the model, can sectoral value-added shift between sectors with different energy intensities?*

- Energy Demand Effect

$$\sum_{i \in SECT} v_i \left(\frac{E_i'}{E_i}\right) = \left[\sum_{\substack{f \in SEN \\ i \in INDSEND}} v_i \ \phi_{f_i} \frac{f_i'}{f_i} \right] + v_M \phi_{PF_M} \frac{PF_M'}{PF_M}$$

$$+ \left[\sum_{\substack{i \in SEN \\ f \in PEN \cup \{SO\}}} v_i \ \phi_{f_i} \left(\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} - \frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} \right) \right] + \left[\sum_{i \in SEN} v_i \frac{i_{TOT}'}{i_{TOT}} \right]$$

("Energy Demand Effect") = ("Industrial Secondary Energy Demand Effect") + ("Primary Fossil Direct-Use Effect") + ("Converted Primary Energy Composition Effect") + ("Converted Primary Energy Derived-demand Effect")

- *How do models represent industrial and consumer secondary energy demands, industrial fossil energy direct-use, and the composition of the secondary conversion technologies?*

- Industrial Secondary Energy Demand Effect

$$\sum_{\substack{f \in SEN \\ i \in INDSEND}} v_i \ \phi_{f_i} \frac{f_i'}{f_i} = \sum_{i \in INDSEND} v_i \ \phi_{SEN_i}^T \, f_{SEN_i}'$$

$$= \sum_{i \in INDSEND} v_i \ \phi_{SEN_i}^T \left[\Lambda_{NEN_i} w_{NEN}' + \Lambda_{SEN_i} \ w_{SEN}' + \ \theta_{SEN_i} \frac{i_{TOT}'}{i_{TOT}} + \alpha_{SEN_i} \right]$$

$$+ \ v_M \ \phi_{SEN_M}^T e_{PF\,M} \ \frac{w_{PF}'}{w_{PF}}$$

$$\begin{pmatrix}\text{"Industrial}\\ \text{Secondary}\\ \text{Energy Demand}\\ \text{Effect"}\end{pmatrix} = \begin{pmatrix}\text{"Nonenergy}\\ \text{Price Effect}\\ \text{on Industrial}\\ \text{Secondary}\\ \text{Energy Demand"}\end{pmatrix} + \begin{pmatrix}\text{"Secondary Energy}\\ \text{Price Effect}\\ \text{on Industrial}\\ \text{Secondary}\\ \text{Energy Demand"}\end{pmatrix}$$

$$+ \begin{pmatrix}\text{"Industrial Output}\\ \text{Effect on}\\ \text{Industrial}\\ \text{Secondary}\\ \text{Energy Demand"}\end{pmatrix} + \begin{pmatrix}\text{"Autonomous}\\ \text{Effect on}\\ \text{Industrial}\\ \text{Secondary}\\ \text{Energy Demand"}\end{pmatrix} + \begin{pmatrix}\text{"Primary Fossil}\\ \text{Price Effect on}\\ \text{M's Secondary}\\ \text{Energy Demand"}\end{pmatrix}$$

- *How do industrial secondary energy demands vary with nonenergy and energy prices?*
- *What is the nature of the production technologies? Are there (dis)economies to scale? Are there any nonhomotheticities?*
- *Are there any autonomous effects which change industrial secondary energy demands? Are there any other effects which might be hidden here?*

- Primary Fossil Direct-use Effect

$$v_M \, \phi_{PF_M} \left[e_{NEN\,PF_M}{}^T \, W_{NEN}{}' + e_{SEN\,PF_M}{}^T \, W_{SEN}{}' + \varepsilon_{PF\,PF_M} \frac{w_{PF}{}'}{w_{PF}} + \theta_{PF_M} \frac{M_{TOT}{}'}{M_{TOT}} + \alpha_{PF_M} \right].$$

$$\begin{pmatrix}\text{"Primary}\\ \text{Fossil}\\ \text{Direct-use}\\ \text{Effect"}\end{pmatrix} = \begin{pmatrix}\text{"Nonenergy}\\ \text{Price Effect}\\ \text{on Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix} + \begin{pmatrix}\text{"Secondary}\\ \text{Energy Price}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix} + \begin{pmatrix}\text{"Own-price}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix}$$

$$+ \begin{pmatrix}\text{"M's Output}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix} + \begin{pmatrix}\text{"Autonomous}\\ \text{Effect on}\\ \text{Primary}\\ \text{Fossil}\\ \text{Direct-use"}\end{pmatrix}.$$

- *Same as above, except substitute direct-use demands for secondary energy demands.*

- Consumer Secondary Energy Demand Effect

$$f_{SEN_{CONS}}{}' = \Lambda_{NEN_{CONS}} \, w_{NEN}{}' + \Lambda_{SEN_{CONS}} \, w_{SEN}{}' + \eta_{SEN_M} \frac{Y'}{Y} + \alpha_{SEN_{CONS}}.$$

- *How do consumers' demands of secondary fuels change with nonenergy and energy prices?*
- *How do consumers' demands of secondary fuels change with income? How are income changes*

modeled?

- *Are there any autonomous effects which change the demands of secondary fuels over time? Are there any "nonautonomous" effects which might be hidden here?*

- Converted Primary Energy Composition Effect

$$\sum_{\substack{i \in SEN \\ f \in PEN \cup \{SO\}}} v_i \, \phi_{f_i} \left(\frac{\mu_{i\text{-}f}'}{\mu_{i\text{-}f}} - \frac{\gamma_{i\text{-}f}'}{\gamma_{i\text{-}f}} \right) = \sum_{i \in SEN} v_i \; \phi_{PEN_i}{}^{T} (\mu_i - \gamma_i)$$

$$\mu_i - \gamma_i = (T_{NEN_i} + \Pi_{NEN_i} - T_{PEN_i} \Pi_{NEN_i}) \, w_{NEN}' + T_{PEN_i} \, w_{PEN}' +$$

$$(I - T_{PEN_i}) \begin{bmatrix} e_{PF} \, \gamma_{i\text{-}f} \dfrac{w_{PF}'}{w_{PF}} \\ e_{PN} \, \gamma_{i\text{-}f} \dfrac{w_{PN}'}{w_{PN}} \\ 0 \end{bmatrix} + (\theta_{\mu_i} - 1) \frac{i_{TOT}'}{i_{TOT}} + (I - T_{PEN_i}) \, \alpha_{\gamma_i} + \alpha_{\mu_i}$$

("Converted Primary Energy Composition Effect") = ("Direct and Indirect Nonenergy Price Effects on Composition") + ("Primary Energy Price Effect on Conversion Technology Market Share")

+ ("Direct and Indirect Primary Energy Own-price Efficiency Effects on Composition") + ("Output Effect on Conversion Technology Market Share") + ("Direct and Indirect Autonomous Conversion Efficiency Effects on Composition") + ("Autonomous Market Share Effect").

- *How do conversion technology and primary input energy demands vary with nonenergy and energy prices?*
- *What is the nature of the conversion technologies? Are there dis/economies to scale? Are there any nonhomotheticicities?*
- *Are there any constraints on the expansion or contraction of the use of given conversion technologies?*
- *Are there any autonomous effects which change industrial secondary energy demands? What*

"nonautonomous" effects might be hidden here?

• Converted Primary Derived-demand Effect

$$\sum_{i \in SEN} v_i \frac{i_{TOT}'}{i_{TOT}} = \sum_{i \in SEN} v_i \; \omega_i \; {}^{T}\Omega_i' \; ,$$

$$\begin{pmatrix}\text{"Converted Primary} \\ \text{Derived-demand} \\ \text{Effect"}\end{pmatrix} = \begin{pmatrix}\text{"Total Secondary} \\ \text{Energy Demand} \\ \text{Effect"}\end{pmatrix} .$$

- *Issues are addressed above.*

The Carbon Intensity Effect

The carbon intensity effect is defined to be

$$\frac{I_C'}{I_C} = \frac{C'}{C} - \frac{E'}{E}.$$

The amount of carbon emitted is directly proportional to the amount of fossil fuel consumed, since in this model there is only one form of fossil energy. (In subsequent versions, there will be two types of fossil fuels, one with high and one with low carbon content per XJ) Thus with χ denoting the amount of carbon per XJ,

$$C \equiv \chi \, PF_{TOT} , \qquad \frac{C'}{C} = \frac{PF_{TOT}'}{PF_{TOT}} .$$

There are four sectors which consume primary fossil energy: M, EU, GU, and R. Let π_{PF} be the vector containing the fractions of the total primary fossil demand each sector consumes,

$$\pi_{PF}^{T} \equiv [\pi_{PF_M} \; \pi_{PF_{EU}} \; \pi_{PF_{GU}} \; \pi_{PF_R}]$$

Then

$$\frac{PF'}{PF} = \pi_{PF}^{T} \begin{bmatrix} \frac{PF_M'}{PF_M} \\ \frac{PF_{EU}'}{PF_{EU}} \\ \frac{PF_{GU}'}{PF_{GU}} \\ \frac{PF_R}{PF_R} \end{bmatrix}.$$

Expressions for the percent changes were derived in the previous section.

Summary: Carbon-Intensity Effect -- What to Look for in the Structural Comparison

- *What sectors demand primary fossil energy, and what are the mechanisms of reducing its total consumption? (See previous section for details.)*

MODEL STRUCTURE COMPARISON

The foregoing interpretive framework helps focus the model structure comparison on the relevant model characteristics. These fall into three general areas: model type (e.g., dynamic general equilibrium), energy demand modeling, and energy supply modeling. The first, model type, includes the model's time horizon, data sources, and foresight assumptions as well.

Model Type

The fourteen models participating in the core set of EMF 12 scenarios are listed in Table 1, along with the principal modelers and/or project managers. The "Model of Warming Commitment" (MWC) is not included in this draft of the paper due to incomplete information.

The broadest distinction that can be made about the remaining thirteen models is whether they are "energy models" or "energy-economy models." Although there is no strict rule placing a model in one group or the other, the energy models tend to focus more heavily on energy supply and demand technologies and less heavily on the rest of the economy. On the other hand, the energy-economy models tend to treat the energy sector in a more aggregated fashion, to have no explicit demand technologies but rather a homogeneous "capital good" which could be a tractor or a water heater, and to contain much more detail on the rest of the economy.

There are three types of models which, for this paper's purposes, will be called energy models: "optimization," "general*ized* equilibrium," and "regression models." Similarly, there are two types of energy-economy models: "optimal growth" and "general equilibrium models." Their salient characteristics are listed in Table 2, along with which of the thirteen models are included in each class.

CETA (Carbon Emissions Trajectory Assessment)	Stephen Peck, Thomas Teisberg
CRTM (Carbon Rights Trade Model)	Thomas Rutherford
Jorgensen-Wilcoxen (neo-DGEM) (Dynamic General Equilibrium Model)	Dale Jorgenson, Peter Wilcoxen
EDS (IEA Energy Demand System)	Lakis Vouyoukis, Niko Kouvaritakis (IEA)
ERM (Edmonds-Reilly Model)	Jae Edmonds, David Barns
FOSSIL2	Sharon Belanger, Roger Naill (AES)
GEMINI	Dave Cohan, Adriana Diener (DFI), Joel Scheraga (EPA)
GLOBAL 2100	Alan Manne, Rich Richels
GLOBAL MACRO-ENERGY	Bill Pepper (ICF)
GOULDER	Larry Goulder
GREEN (GeneRal Equilibrium ENvironmental)	John Martin, Jean-Marc Burniaux (OECD)
MARKAL (MARKet ALlocation model)	Samuel Morris (BNL)
MWC (Model of Warming Commitment)	Irving Mintzer
T-GAS (Trace Gas Accounting System)	Bob Kaufmann

Table 1: The Core Models of EMF 12

Model Name(s)	Model Type	Distinguishing Characteristics
MARKAL	optimization (linear program)	• model-wide objective function • minimizes total U.S. energy sector costs of meeting exogenously-set energy service demands • no economic effects outside energy sector • no effects of higher cost of energy except introduction of more energy-efficient technologies
EDS ERM FOSSIL2 GEMINI GLOBAL MACRO-ENERGY	generalized equilibrium	• equilibrium in energy sector's markets: primary, secondary, electric, etc. • either detailed technology (U.S.) or multiple global regions • no markets for capital, labor, or other nonenergy goods • reference GDP and/or energy service demand/price paths exogenously-set • price and/or GDP effects on demand though aggregate "feedback equations"
T-GAS	regression	• exogenous inputs of prices, GDP, population, etc. • energy intensity by sector determined from regression equation and given inputs • some user control over parameters in functions
CETA GLOBAL 2100	optimal growth	• maximizes discounted consumer satisfaction ("utility") subject to resource and technology constraints • consumer determines labor supply, consumption, and investment • GDP produced from aggregate production function • moderate detail in energy sector
CRTM DGEM GOULDER GREEN	general equilibrium	• market equilibria for all goods: capital, labor, materials, other goods • consumers choose savings/investment levels • GDP, energy intensity changes determined by interactions throughout the economy • some forms of international trade and governmental sectors • less detail in energy sector

Table 2: Model Types and Distinguishing Characteristics

APPENDIX A: NOTATIONAL GLOSSARY

Aggregate Model

Y	gross domestic output (GDP)
E	total domestic primary energy consumption
C	domestic energy-sector carbon emissions
I_E	ratio of total domestic primary energy consumption to GDP
I_C	ratio of domestic energy-sector carbon emissions to energy

Commodities/sectors

K	capital
L	labor
S	other services
G	final consumption goods
M	intermediate goods and materials
EU	electric utilities
GU	gas utilities
R	refineries
PF	primary fossil energy
PN	primary nonfossil energy (solid)
CONS	consumers (homogeneous)

Conversion Technologies

EU-PF	electric fossil conversion technology
EU-PN	electric nonfossil conversion technology
EU-SO	electric solar conversion technology
GU-PF	gas utility fossil conversion technology
GU-PN	gas utility nonfossil conversion technology
R-PF	refined fossil conversion technology
R-PN	refined nonfossil conversion technology

Sets

IFGS	intermediate and final goods and services	{S, G, M}
PEN	primary energy sectors	{PF, PN}
SEN	secondary energy sectors	{EU, GU, R}
INDSEND	industrial secondary energy demands	{PF, PN, S, G, M}
SEND	all secondary energy demands	{PF, PN, S, G, M, CONS}
SECT	economic sectors	{PF, PN, EU, GU, R, S, G, M}

The GDP Effect

V_i	value-added (in $) in sector i
v_i	industry i's value-added as fraction of GDP

The Energy Intensity Effect

$\mu_{i\text{-}f}$	XJ-weighted market share of technology *i-f* in secondary energy industry *i*
μ_i	vector of technology market shares in energy conversion sector *i*
$\gamma_{i\text{-}f}$	conversion efficiency of technology *i-f*
γ_i	vector of converison efficiencies for secondary energy sector *i*
ϕ_{f_i}	XJ-weighted fraction of industry *i*'s total energy consumption met by energy form *f*
ϕ_{SEN_i}	vector of secondary fuel shares (XJ-weighted) in industry *i*
ϕ_{PEN_i}	vector of primary fuel shares (XJ-weighted) in industry *i*
w_j	price of commodity *j*
w_{NEN}	vector of natural logs of nonenergy prices
w_{SEN}	vector of natural logs of secondary energy prices
w_{PEN}	vector of natural logs of primary energy prices
e_{jk_i}	price elasticity: percentage change in demand for commodity *k* from one-percent change in price of commodity *j* in industry *i*
e_{NENk_i}	vector of price elasticities: percentage changes in demand for commodity *k* from one percent changes in nonenergy prices in industry *i*
e_{SENk_i}	vector of price elasticities: percentage changes in demand for commodity *k* from one-percent secondary energy price changes in industry *i*
e_{PENk_i}	vector ofprice elasticities: percentage changes in demand for commodity *k* from one-percent primary energy prices changes in industry *i*
$e_{SEN\ PF_M}$	vector of secondary energy price elasticities for primary fossil demand in sector M
$e_{NEN\gamma_{i\text{-}f}}$	vector of nonenergy price elasticities for primary energy input in technology *i-f*
$e_{SEN\gamma_{i\text{-}f}}$	vector of secondary energy price elasticities for primary energy input in technology *i-f*
T_{NEN_i}	matrix of technology *i-f* nonenergy price elasticity vectors in secondary energy sector *i*
T_{PEN_i}	matrix of technology *i-f* primary energy price vectors in secondary energy sector *i*
Π_{NEN_i}	matrix of nonenergy price elasticities for primary energy demands in secondary sector *i*
$e_{f\gamma_{i\text{-}f}}$	own-price elasticity of primary fuel *f* for technology *i-f*
$e_{NEN\mu_{i\text{-}f}}$	vector on nonenergy price elasticities for demand for technology *i-f*
$e_{PEN\mu_{i\text{-}f}}$	vector on primary energy price elasticities for demand for technology *i-f*
$\eta_{f_{CONS}}$	income elasticity for commodity *f* for the consumer

η_{SECONS}	vector of income elasticities for secondary energy forms for the consumer
θ_{f_i}	output elasticity: percent increase in demand for commodity *f* from one-percent increase in industry *i*'s total output
θ_{SENi}	vector of output elasticities for secondary energy inputs in industry *i*
$\theta_{\mu_{i\text{-}f}}$	output elasticity: percent increase in demand for technology *i-f* from one-percent increase in industry *i*'s total output
$\theta_{\mu_{i\text{-}f}}$	vector of ouutput elasticities for secondary energy sector *i*'stechnologies
α_{f_i}	percentage change in demand for commodity *f* with output/income and prices constant
α_{SEN_i}	vector of percentage changes in secondary energy demands with prices and output/income constant
$\alpha_{\gamma_{i\text{-}f}}$	percentage change in primary energy demand for technology *i-f* with technology *i-f* output and prices constant
α_{γ_i}	vector of changes in primary energy demands for technology *i-f* with technology output and prices constant
$\alpha_{\mu_{i\text{-}f}}$	percentage change in technology *i-f*'s market share in secondary energy sector *i* with total output prices constant
α_{μ_i}	vector of percentage changes in technology market share in secondary energy sector *i* with prices and output constant
f_{SEN_i}	vector of natural logs of secondary fuel demands for industry *i*
Λ_{NEN_i}	matrix of nonenergy price elasticity vectors for secondary energy demands in industry *i*
Λ_{SEN_i}	matrix of secondary energy price elasticity vectors for secondary energy demands in industry *i*
ω_{i_j}	fraction of secondary energy sector *i*'s output consumed by sector *j*
ω_i	vector of secondary energy sector *i*'s output consumption fractions
Ω_i	vector of natural logs of actual sectoral cdemands for each secondary energy sector; includes consumers

<u>Carbon Intensity Effect</u>

π_{PF_i}	fraction of total primary fuel consumed in sector *i*
π_{PF}	vector of primary fuel consumption fractions