The Decline in U.S. Energy Intensity:

Its Origins and Implications for Long-Run CO_2 Emission Projections

Ian Sue Wing*

Boston University Center for Energy & Environmental Studies and Geography Department

and MIT Joint Program on the Science & Policy of Global Change

Richard S. Eckaus

MIT Economics Department and Joint Program on the Science & Policy of Global Change

Abstract

This paper analyzes the influence of the long-run decline in energy intensity on projections of U.S. energy use and carbon emissions to the year 2050. We build on our own recent work which decomposes changes in the aggregate U.S. energy-GDP ratio into shifts in sectoral composition (structural change) and adjustments in the energy demand of individual industries (intensity change), and identifies the impact on the latter of price-induced substitution of variable inputs, shifts in the composition of capital and embodied and disembodied technical progress. We employ a recursive-dynamic computable general equilibrium (CGE) model of the U.S. economy to analyze the implications of these findings for future energy use and carbon emissions. Comparison of the simulation results against the historical trends in GDP, energy use and emissions reveals that the range of values for the rate of autonomous energy efficiency improvement (AEEI) conventionally used in CGE models is consistent with the effects of structural changes at the sub-sector level, rather than disembodied technological change. Our results suggest that we may well experience faster growth of emissions than have been observed historically, even when the energy-saving effects of sub-sectoral changes are accounted for.

JEL Classification: Q3, Q4, C68

Keywords: autonomous energy efficiency improvement, energy intensity, CGE models, climate change policy

---

* Corresponding author. Address: Rm. 141, 675 Commonwealth Ave., Boston MA 02215. Email: isw@bu.edu. Phone: (617) 353-5741. Fax: (617) 353-5986.

ISW was supported by U.S. Department of Energy Office of Science (BER) Grant No. DE-FG02-02ER63484. This paper has benefited from helpful comments by Jake Jacoby. Errors and omissions remain the sole responsibility of the authors.

The Decline in U.S. Energy Intensity:

Its Origins and Implications for Long-Run CO_2 Emission Projections

Abstract

This paper analyzes the influence of the long-run decline in energy intensity on projections of U.S. energy use and carbon emissions to the year 2050. We build on our own recent work which decomposes changes in the aggregate U.S. energy-GDP ratio into shifts in sectoral composition (structural change) and adjustments in the energy demand of individual industries (intensity change), and identifies the impact on the latter of price-induced substitution of variable inputs, shifts in the composition of capital and embodied and disembodied technical progress. We employ a recursive-dynamic computable general equilibrium (CGE) model of the U.S. economy to analyze the implications of these findings for future energy use and carbon emissions. Comparison of the simulation results against the historical trends in GDP, energy use and emissions reveals that the range of values for the rate of autonomous energy efficiency improvement (AEEI) conventionally used in CGE models is consistent with the effects of structural changes at the sub-sector level, rather than disembodied technological change. Our results suggest that we may well experience faster growth of emissions than have been observed historically, even when the energy-saving effects of sub-sectoral changes are accounted for.

JEL Classification: Q3, Q4, C68

Keywords: autonomous energy efficiency improvement, energy intensity, CGE models, climate change policy

1. Introduction

This paper projects the energy use and greenhouse gas emissions of the U.S. economy to the year 2050, embodying the results of recent work by the authors which indicates that there is substantial variability across industries in the drivers of changes in their energy intensities. Our projections employ a recursive-dynamic computable general equilibrium model of the U.S. economy in which the rates of change in the coefficients on energy use are constrained to match the empirically-determined values of various drivers of energy-intensity change. We find that the effects of structural changes at the sub-sector level, rather than disembodied technological change, are most consistent with the historical growth rates of aggregate energy use and carbon dioxide (CO_2) emissions. Moreover, our results suggest that we may well experience faster growth of emissions than have been observed historically, even when the energy-saving effects of such sub-sectoral changes are accounted for.

To analyze potential climate change it is necessary to forecast the evolution of the stock of atmospheric greenhouse gases (GHGs) into the far future. These predictions in turn require long-run forecasts of the emission of GHGs, which are based on the projected expansion of the world's economies and their demand for energy from fossil fuels. Making such economic projections raise unusual and uncomfortable problems that do not exist in conventional, shorter-term economic forecasts. Perhaps the most thorny problem is the issue of how to model the effect of technological progress, which is often argued has been the major influence on the intensity of fossil-fuel use. But the projection of technological change is, in turn, one of the most difficult tasks that economists have undertaken, and the literature is strewn with efforts that are at best only partially successful.

The conventional technique for taking technological change into account in making long term projections of fossil fuel use and their emissions is to assume some continuing "autonomous energy efficiency improvement" (AEEI). The basic idea is to specify a declining trend in the coefficients on energy use in the production functions of the simulated economy, with the AEEI parameter being the rate of decline. Use of this device has been justified by the evident reduction in the ratio of energy use to GDP over the last 40 years in many, especially in the industrialized countries. The AEEI's first recorded use appears to be Edmonds and Reilly (1985), who constructed an energy-economic simulation model in which the coefficients on energy use in the economy's sectoral production functions were made to decline according to the inverse of an index of energy-saving technological progress. This trick is still used in state-of-the-art intertemporal computable general equilibrium (CGE) models for climate policy analysis (e.g. Bernstein et al. 1999).

The need for the AEEI arises because otherwise production and utility functions used in the economic simulations, on which projections of energy use and GHG emissions are based, retain the characteristics of their initial conditions when run forward into the future. This problem occurs because there are a range of processes that are imperfectly represented within these models. The main contributor is the use of homogenous production and utility functions such as the multi-level Cobb-Douglas or constant-elasticity of substitution (CES) functions with fixed share and elasticity parameters, whose homothetic, input-share preserving character tends to maintain both the ratio of energy use to economic output and the structural composition of the economy that prevails in the initial period. The result is that economic simulations generally lack the ability to endogenously generate important trends in the inter-sectoral evolution of the economy that one might expect over a long time-horizon.

The upshot of these difficulties is that model projections of the future growth of energy use and emissions may have significantly different characteristics from the corresponding historical time series. In particular, without some adjustment that reduces the coefficient on fossil fuel inputs in the models' production functions, energy use and GHG emissions over the 21st century rise to levels that are deemed implausibly high by modelers and policy makers alike. Thus, as a practical matter the AEEI is a "fudge factor" which allows the results of climate-economy simulations to be tuned according to the analyst's sense of plausibility. Nevertheless, it has long been recognized that the AEEI is also a short-hand approximation for several, more fundamental processes. Energy-saving technological progress, which is implied by its namesake, is only one of these. Others are the shift in the composition of the economy toward activities that demand smaller quantities of fossil fuels (i.e., structural change), environmental policies restricting the use of fossil fuels, and the removal of "market barriers" to the diffusion of more energy-efficient technologies, in a sense that has not as yet been precisely defined (Williams 1987,1990; Williams et al 1987; Weyant 1999).

Without the means to attribute the observed changes in energy intensity to the processes outlined above, the origins of the AEEI remain unknown. Values of this parameter employed in modeling studies have tended to cluster around one percent (Weyant 1999), but, as Manne and Richels (1990) acknowledge, there is no well established empirical basis for such a secular decline in the coefficient on energy. Indeed, studies of the U.S. economy by Jorgenson and Fraumeni (1981) and Jorgenson (1984) find an energy-using bias of technical progress in the majority of U.S. industries over the period 1958-1979, which is inconsistent with the assumption of energy-saving technical change, so much so that Hogan and Jorgenson (1991) argue that the AEEI may actually be negative.

Still, the last 50 years have seen a marked decline in aggregate energy intensity, which has coincided with substantial shifts in the composition of output. In a previous paper (Sue Wing and Eckaus 2004) we decomposed the trend in the energy-GDP ratio into the contributions of structural change and shifts in the intensity of energy use within individual sectors in order to highlight the importance of the latter effect. Our econometric estimations in that paper also indicated that while these intra-sectoral reductions in intensity were driven by the substitution of variable inputs and the embodied energy-saving technology within accumulating stocks of capital (particularly equipment and information technology), the overall influence of disembodied technological progress was small and, moreover, energy-using in its overall character.

Our objective in the present paper is to illustrate how such empirical results can be used to constrain the values of the AEEI parameter in CGE models for climate policy analysis. To this end, in section 2 we take the first step of repeating our decomposition analysis at the higher level of sectoral aggregation commonly found in CGE models. The results show that the influences of structural and technological changes on energy intensity vary widely, not only among industrial sectors, but also between industries and final consumption, sometimes having an energy-using rather than an energy-saving effect. We conclude that the AEEI is more appropriately modeled as a vector of values applied to different industries, whose elements vary both in magnitude and sign.

In section 3 we take our analysis a step further by imposing our empirically-determined, sectorally heterogeneous rates of change in the components of energy intensity as trends in the coefficients on energy use in a CGE model of the U.S. economy. Section 4 presents and analyzes the model's projections of GDP, energy use and emissions to 2050. Our results highlight the importance of specifying an AEEI parameter for the household sector's consumption of energy. We also find that the trajectories of energy use and emissions generated by simulations with the "consensus" value of one percent for the AEEI differ markedly from those in which we impose the effect of disembodied technological progress on energy intensity within the detailed industries that make up the broad sectors in our model. However, they are consistent with simulations in which the AEEI values reflect the changes in energy intensity at the sub-sector level, and the AEEI for the household sector reflects the historical declines in energy's share of consumption expenditures. Nevertheless, even in these cases the emission trajectories generated by the model are substantially higher than projections based on historical growth rates would suggest, due to a variety of factors that influence inter-fuel substitution. Section 5 concludes.

2. Non-Price Induced Changes in Energy Intensity: Structural Shifts vs. Substitution vs. Technology?

We begin by summarizing the key elements of our previous work on this topic. In Sue Wing and Eckaus (2004) we isolate the impact of technical change on aggregate energy intensity using a simple decomposition technique that partitions the observed change in aggregate intensity into the effects of change in energy intensity within industries and change in the mix of industries in the economy. We divide the economy into *k* detailed industry groups ($k = 1, ..., |k|$) and model the ratio of aggregate energy E^* to GDP Y^* at time *t* as the weighted average of the industry sectors' intensities of energy use in that period:

(1) $$\frac{E_t^*}{Y_t^*} = \frac{1}{|k|} \sum_k \phi_{k,t} \left(\frac{E_{k,t}}{Y_{k,t}} \right).$$

Here, industry k's weight (ϕ_k) is the ratio of its share of GDP to its share of total energy use. The logarithmic time-derivative of this expression is:

(2) $$\frac{\partial}{\partial t}\ln\left(\frac{E_t^*}{Y_t^*}\right) = \underbrace{\frac{1}{|k|}\sum_k \frac{\partial}{\partial t}\ln\phi_{k,t}}_{\Phi^*} + \underbrace{\frac{1}{|k|}\sum_k \frac{\partial}{\partial t}\ln\left(\frac{E_{k,t}}{Y_{k,t}}\right)}_{\Psi^*}.$$

The observed fractional change in aggregate energy intensity, $\partial\ln(E^*/Y^*) / \partial t$, is then the result of two effects, given by the terms on the right hand side of this expression. These are, respectively, the average of changes in industries' contributions to aggregate energy intensity—an aggregate "structural change effect", which we denote Φ*, and the average of changes in energy intensity within industries—an aggregate "intensity change effect", which we denote Ψ*.

Figure 1 presents chained indices of Φ* and Ψ*, which are computed using data on the quantities of output and energy input for the 35 industries in the KLEM dataset developed by Jorgenson and associates.[1] The figure also shows an index of the joint impact of the structural change effect and the intensity change effect (Φ* + Ψ*), as well as an index of the aggregate energy-GDP ratio, $\partial\ln(E^*/Y^*) / \partial t$, which constructed using using real GDP from the NIPAs and aggregate energy consumption from DOE (2002).[2] The fact that these two series closely track one another is evidence of the excellent agreement between the data at the sectoral and the aggregate levels.

The results in Figure 1 indicate that the marked reduction in aggregate energy- U.S. intensity was primarily due to changes in the sectoral composition of the economy prior to 1973. This change is responsible for a 14 percent decline in aggregate energy intensity from its 1958 level, but this is largely balanced by increases in energy intensity within industries. After the first

[1] The dataset is described more fully in Sue Wing and Eckaus (2004). The industries indexed by k are shown in Table 1.

[2] In this calculation we are concerned with energy intensity change that is solely due to domestic production. We therefore use GDP net of imports as the denominator in aggregate E / Y.

OPEC oil shock the effects of the two sources of change are virtually reversed, however. Subsequently, throughout the 1980s and 1990s changes in the sectoral composition of output have little persistent impacts on aggregate energy intensity, while energy intensity within industries declines rapidly until the end of the sample period, at which point it is 25 percent below its 1958 level.

These aggregate-level results are the starting point for our inquiry into the origins of the AEEI. We build on them by elaborating their underpinnings at the typical level of sectoral disaggregation employed in economic simulations of climate change mitigation policies. To this end we reproduce the above decomposition at a higher degree of disaggregation, and examine the sources of changes in the intensity of energy use across the ten broad sectoral groupings shown in Table 1, which we denoted using the index j ($j = 1, ..., |j|$). It is apparent from the table that these broad sectors are a coarser aggregation of the economy than tabulated in the Jorgenson dataset, so that $|j| < |k|$.

For each aggregate sector, j, we denote energy use by E'_j and output by Y'_j. We model the energy intensity at time t in sector j in a manner analogous to eq. (1) at the aggregate level, namely, as the weighted average of the intensities of energy use of its constituent sub-sectors in that period:

$$(3) \qquad \frac{E'_{j,t}}{Y'_{j,t}} = \frac{1}{|k \subset j|} \sum_{k \subset j} \phi'_{k,j,t} \left(\frac{E_{k,t}}{Y_{k,t}} \right).$$

Similar to eq. (1), sub-sector k's weight in sector j ($\phi'_{k,j}$) is the ratio of its share of j's output to its share of j's energy use, and the logarithmic time-derivative of (3) has the same form as eq. (2):

$$(4) \qquad \frac{\partial}{\partial t} \ln\left(\frac{E'_{j,t}}{Y'_{j,t}} \right) = \underbrace{\frac{1}{|k \subset j|} \sum_{k \subset j} \frac{\partial}{\partial t} \ln \phi'_{k,j,t}}_{\Phi'_j} + \underbrace{\frac{1}{|k \subset j|} \sum_{k \subset j} \frac{\partial}{\partial t} \ln\left(\frac{E_{k,t}}{Y_{k,t}} \right)}_{\Psi'_j}.$$

As in the case of the aggregate-level decomposition, the observed fractional change in sector *j*'s energy intensity, $\partial \ln(E'_j/Y'_j) / \partial t$, can be partitioned into the effects of structural change (Φ'_j) and changes in unit energy demand within industries (Ψ'_j) at the sub-sector level.

This decomposition is merely the first step in disentangling the myriad influences which the AEEI is purported to represent. In particular, it should be stressed that both the structural shifts and the changes in energy-intensity among the detailed industries at the sub-sector level will be influenced by price and non-price factors. Therefore, true value of the AEEI, which should properly reflect the non-price induced trend in intensity in each broad sector, can be thought of as the sum of the non-price components of Φ' and Ψ'.

In our previous econometric work we investigated the extent to which changes in industries' unit energy demand were attributable to technical change. Here, we build on our earlier approach to develop an approximation of the technological component of Ψ'_j. Our analysis regressed industries' unit energy demands on indices of variable input prices and the input quantities of five different types of capital to partition observed changes in energy intensity into the effects of input-price based substitution and capital accumulation. The regression equations also included a time trend, the estimated coefficient on which we denote $\hat{\alpha}_{Etk}$. This parameter indicates the average effect of non-price induced changes in energy intensity, which has come to be associated with the partial effect of disembodied technological progress, $[\partial \ln(E_{k,t} / Y_{k,t}) / \partial t\,]_{TECH}$. This interpretation allows us to develop an expression similar to the second term of eq. (4) to denote the technological component of structural change in the aggregated sectors of the economy, $\Psi'_{TECH,j}$:

(5) $$\Psi'_{TECH,j} = \frac{1}{|k \subset j|} \sum_{k \subset j} \frac{\hat{\alpha}_{Etk}}{(E_{k,t} / Y_{k,t})}\,.$$

An important limitation of our previous work is its inability to be used to develop an analogous measure for the non-price component of sub-sectoral change in industrial composition, Φ'_{TECH}. This would have required us to have to statistically estimated the contributions of variable input price changes and the accumulation of different types of capital to the changes in industries weights, ϕ', in the energy intensity of the broader sectors, which is something we have left to future research. Consequently, we currently lack the ability to estimate the true index of non-price induced components, $\Phi'_{TECH} + \Psi'_{TECH}$.

Our imperfect solution to this dilemma is to compute indices of Φ', Ψ', $\partial \ln(E'/Y') / \partial t$ and Ψ'_{TECH} to attribute the growth of each of these variables in turn to the AEEI within a computational economic model. All of these measures will biased indicators of the true value of the AEEI. The first three embody price-based components to unknown degrees, while the last omits the influence of the secular trend in sub-sectoral structural change. Nevertheless, our approach allows us to use what empirical estimates we do have to at least partially constrain the range of values for the AEEI within various industries, and to assess their impacts in a simulated economy.

We compute indices of Φ', Ψ', Ψ'_{TECH} and $\partial \ln(E'/Y') / \partial t$ using the Jorgenson dataset and our previous econometric estimates for $\hat{\alpha}_{Etk}$. We present results for the years 1980-1996, a period in which the U.S. economy experienced a sustained reduction in energy intensity, which gives rise to the recent trend most likely to be incorporated for the existence of a secular increase in energy efficiency. For j we choose the ten aggregate sectors in Table 1. We focus our attention on the non-energy sectors of the economy, because it is within these industries that policy models usually apply the AEEI to generate a reduction in energy use per unit output.

The detailed results of our calculations are shown in Figure 2. Panel A indicates that changes in the mix of industries within the large sectors gave rise to modest reductions in aggregate energy intensity, and that their influence on individual sectors varied substantially. For example, the energy intensity of services declined rapidly in the early 1980s but stagnated thereafter, while in the rest-of-economy aggregate of mining and construction industries intensity fluctuated before increasing substantially after the late 1980s.[3]

The influence of the changes in the intensity of energy use in the industries within each aggregate sector is shown in panel B. In line with Figure 1, the economy-wide effect of these changes has been to substantially reduce energy intensity, with the reductions in the rest-of-economy sector being the largest, and the transportation and electricity sectors being the smallest.

Panel C traces the joint effects of the two prior influences. Together, they are responsible for large reductions in energy intensity at both the sectoral and the aggregate levels. The energy-intensive, manufacturing and service sectors all exhibit greater-than-average reductions in energy intensity, while the reverse is the case for the rest-of-economy aggregate.

Panel D shows what are perhaps the most surprising results, which are the estimated effects on changes in energy intensity due only to technological progress at the sub-sector level. Overall, the effects of technological change are energy using. Indeed, the effect is energy-saving only for the transportation sector. While there are only very modest increases in technologically

[3] We are unable to resolve the effects of structural changes at the sub-sector level for those aggregate sectors with which there is a one-to-one concordance with Jorgenson's industry groupings in Table 1.

induced energy intensity in manufacturing, the energy intensive sectors and the residual sectors, the effect in the service sector is substantial.[4]

These time series described above are summarized in Table 2 as annual average rates of change. The influence on aggregate sectors' energy intensity of the intensity changes within detailed industries in panel A (Φ') are larger in magnitude the influence of the structural changes at the sub-sector level tabulated in panel B (Ψ'). However, while the latter structural change effect has uniformly reduced the energy intensity of the aggregate sectors, the former intensity change effect is equivocal in its influence, increasing the energy intensity of energy-supply industries. The joint effect of Φ' and Ψ' shown in panel C generally follows the pattern of signs in panel B. All of these results differ markedly from the effects of disembodied technological change in panel D, which are an order of magnitude smaller in size and show a mostly positive influence on the energy intensity of non-energy-supply sectors.

All of the results developed thus far pertain to industries, in other words, the supply side of the economy. But we wish to emphasize that in terms of the drivers of the decline in the energy-GDP ratio this is only half the story. Several studies have pointed to the decline in energy's share of total consumption expenditure in conjunction with falling energy prices as additional evidence for a secular trend in the coefficient on energy.[5] The implication is that the AEEI exists not only within industries, but at the level of final energy use as well.

To account for this possibility, we use data from the NIPAs to estimate the average annual rate of change in the consumption shares of our aggregate fuel sectors from 198-2000. These rates of change are shown in Figure 3. The shifts in the trends in consumption shares of

[4] This result reflects our previous finding that disembodied technical change had a statistically significant impact in 18 of the 35 industries we considered, in ten of which its effect was energy using. This provides some support for Jorgenson's argument that the predominant influence of technological change is energy using.
[5] e.g., Williams (1990), who argues that the non-price-induced rate of improvement in the efficiency of final energy use is on the order of one percent.

motor gasoline, fuel oil and coal and natural gas follow similar patterns, over the decade of the 1980s falling from growth into steep decline, contracting slowly throughout the 1990s, and finally exhibiting a small expansion by the end of the decade. By contrast, electricity's share of consumption shrank much less dramatically over the early part of this period, and has shown a slow and steady contraction.

The dashed horizontal lines plotted in Figure 3 indicate the average annual rates of change of the shares of the different fuels over the entire period in question. These values are summarized in panel E of Table 2. Although their negative values confirm the decline in energy's share of consumption identified by other authors, we are quick to point out that these averages reflect additional influences besides the effect of energy-saving technology. The industry focus of our earlier analysis makes it of limited utility in generating empirical estimates of the AEEI suitable for use in the household sector. Furthermore, it is not possible to disentangle how much of the observed declines may be attributable to technological progress alone without an additional, dedicated econometric analysis. Thus, similar to our estimates in panels A-C, the rates of change tabulated in panel E do not isolate the effects of substitution responses to changing energy supply and demand conditions from the secular trend in energy intensity. Consequently, they quite likely to overestimate the true secular trends in the coefficients on energy in consumption.

We now turn to the question of what these results imply for the projection of carbon emissions into the long-term future.

3. Model Description and Experimental Setup

To investigate the effect of the foregoing factors on future CO_2 emissions we incorporate the results of the previous section into a recursive-dynamic CGE model of the U.S. The model treats households as a single representative agent, aggregates the firms in the economy into 11 industry sectors, and solves for a sequence of static equilibria over the policy horizon 2000-2050 on a five-year time-step. Industries are treated as representative firms and are modeled using nested constant elasticity of substitution (CES) production functions according to Bovenberg and Goulder's (1996) KLEM structure and parameterization. The representative agent divides her income from factor rentals to the firms between consumption and saving/investment, which is determined by a balanced growth path condition. The path of the economy through time is driven by expansion of the aggregate labor supply at the rate of population growth, growth of the aggregate capital endowment through accumulation, growth of labor and capital in efficiency units due to augmentation at the rate of total factor productivity increase. The details of the model's structure and parameterization are given in the appendix.

Most relevant to our purposes here, we scale the coefficients on the inputs of energy commodities to non-energy industries and the consumption of the representative agent according to assumed rates of autonomous change in energy-intensity.[6] We conduct a number of numerical experiments, whose characteristics are described to the cases in Table 3. Focusing first on the industries in the economy, we first simulate a control run with no AEEI, before setting the AEEI to the commonly-used 1 percent value in non-energy sectors. In runs III, IV, V and VI we set the AEEI in non-energy sectors to match the rates of change of the components of energy intensity

[6] We do not apply the AEEI. to the energy-producing sectors in our model, because of the problems that this creates for the ability to account for flows of energy in the simulated economy. Imposing a declining trend on the coefficient on energy resource inputs to the energy supply sectors progressively increases the quantities of energy outputs which can be produced from given quantities of resources, which quickly raises the simulated efficiency of energy conversion to the point where it violates the laws of thermodynamics. McFarland et al (2004) discuss this issue as it pertains to the representation of electric power generation in a CGE model.

given in panels A, B, C and D of Table 2, respectively. We repeat these six runs for three settings of the AEEI specifically for household energy consumption.

The AEEI causes energy use to be progressively decoupled from economic output, with the result that the simulated economy's energy-GDP ratio exhibits a declining trend. The numerical experiments identify which of the sources of change in energy intensity, when attributed to the AEEI, gives the best fit between the model's projections and historical trends. We assess the reasonableness of the model's projections by comparing the simulated future growth rates of GDP, energy use, intensity and CO_2 emissions against the relevant rates of change over the past 50 years, which are shown in Figure 4. The historical average annual rates are 3.5 percent for GDP, 2.2 percent for energy use, -1.3 percent for energy intensity and 1.6 percent for emissions. By using these figures as a yardstick against which to judge the performance of our model, we are assuming that the future projections ought to be consistent with past trends. This hypothesis is not without controversy, as the next section illustrates.

4. Results and Discussion

The major features of solutions to 2050 of the CGE model with alternative specifications of the AEEI parameter are presented in Table 4. We begin our discussion with an examination of the cases which correspond to a zero value for the AEEI of in the household sector.

Panel A of the table summarizes the effect on GDP. With an AEEI of zero in industries (Case I(a)), the annual rate of GDP growth falls from approximately 3.6 percent in 2010 to 3.3 percent in 2050. The slowdown is due to the decline in the rate of growth of the labor force, diminishing returns to new investment, and the increasing cost of extracting resources in the energy supply sectors. To the extent that the AEEI diminishes sectors' demand for scarce and relatively costly energy inputs, it will boost the growth of aggregate output. The upshot is that GDP growth rates in cases II(a)-V(a) with larger AEEI values are very slightly higher than if there were no change in the coefficient on energy. Case VI(a) is the exception, as the AEEI attributed to the estimated effect of technical progress on energy use actually increases energy intensity in the energy-intensive, manufacturing and service sectors. Because these sectors' shares of aggregate output rise over time, the increased intensity of use of costly energy inputs slows the growth of the entire economy. Notwithstanding all these effects, the overall influence of the AEEI on GDP is largely inconsequential.

By contrast, panel B shows that the specification of the AEEI has important consequences for the growth rate of aggregate energy use. Again, with the exception of Case VI(a), the effect of the specified alternative values of this parameter is to slow the growth of energy use relative to its rate in the absence of an AEEI in Case I(a). In the early years growth of energy use slows by only a small amount, but by the end of the simulation its value is more than ten percent smaller than in Case I(a). The effects of structural change and change in energy intensity within sectors have the strongest effects in this regard, while technical progress alone increases in the growth of energy use relative to Case I(a), for the reasons cited above.

As indicated in Panel C, these changes in energy use translate into a decline in the aggregate energy-GDP ratio. Interestingly, aggregate energy intensity declines over the simulation horizon even without the AEEI, as constraints on the supply of energy resources raise the cost of using energy relative to non-energy inputs, which induces substitution toward the latter. As with total energy, the largest reductions in intensity occur in the beginning of the simulation before onset of the GDP growth slowdown. By the end of the period, an AEEI of 1 percent (Case II(a)) exhibits the largest decline. If the AEEI is set at the rate attributed to technical progress alone (Case VI(a)), the energy intensity reductions are the smallest, as technical change alone would result in significant increases in energy intensity in some sectors. AEEI values at the rates of sub-sectoral within-industry and overall energy intensity change (Cases IV(a) and V(a)) generate fastest decline in intensity as they coincide with slowest overall growth in energy use.

The effects of the AEEI on the growth of CO_2 emissions, shown in Panel D, are similar to the influences on energy. Like the changes in energy use, the growth rate of emissions declines over time across all specifications. Emissions grow fastest in where the AEEI is zero or is set equal to the rate of intensity change attributed to technological progress. The next highest growth of emissions occurs with an AEEI which is set to 1 percent or is attributed to sub-sector structural changes. Attributing within-sector and overall changes in energy intensity to the AEEI generates the lowest rates of growth of emissions.

In comparison with the trends shown in Figure 4, we note that the model results are more consistent with historical average growth rates in their projections of GDP than energy use or emissions. Such over-estimation of energy and emissions relative to historical trends is precisely the problem which motivates the need for the AEEI, and is an issue which we return to in the subsequent discussion.

We now turn to the simulation results in which the value of the AEEI for the final consumption of energy goods was set at 1 percent (Case (b)). Within this suite of model runs the overall characteristics of the solutions for the different values of the AEEI within industries are similar to those in Cases I(a)-VI(a). In the (b) cases, however, GDP growth rates are slightly higher, reflecting the additional influence of the consumption AEEI in alleviating the costs of energy in generating output, while energy use and emissions experience substantially slower growth, and energy intensity exhibits a much faster decline.

While the relative importance of the differing specifications of the industry AEEI in cases I-VI remain unchanged, the magnitudes of the changes wrought by variations in the values of this parameter diverge markedly. Where the AEEI within industries is zero or set at the rate attributed to technological change (Cases I(b) and VI(b)), the growth of energy use and emissions slows by a 7-8 percent and the rate of decline in energy intensity more than doubles relative to the corresponding scenarios with a household sector AEEI of zero. Industry AEEI values of 1 percent or at the rates attributable to sub-sector structural change (Cases II(b) and III(b)) result in 10 percent slower growth in energy and emissions than the corresponding cases with no AEEI in the household sector, while setting the AEEI at the rates attributable to sub-sector intensity change (Cases IV(b) and V(b)) slows the increase of energy and emissions by 13-17 percent relative to the corresponding earlier cases.

The foregoing energy and emission projections are much closer to the historical average rates of growth than those in Case (a), which indicates the importance of changes in the structure of consumption toward lower energy intensity. The simulated growth rates of energy use are within a few tenths of a percent of the historical long-run average, especially in Cases IV(b) and V(b). However, simulated trajectories of emissions still increase at rates 50-90 percent faster than the historical average.

The last six rows of Table 4 summarize the results of setting the household sector AEEI at the historical rate of change in the expenditure shares of the different energy commodities (Case (c)). While the general pattern of results mirrors that just discussed for Case (b), GDP growth rates remain essentially unchanged while the growth rates of aggregate energy use and emissions slow by a further 30-65 percent. As before, the results of Cases IV(c) and V(c), in which the AEEI is attributed to the effects of sub-sectoral within-industry change in energy intensity, match the historical growth of energy use most closely. But even in these cases the simulated growth rates of emissions remain some 40 percent higher than in recent history.

Despite the fact that the trends in model's aggregate variables in Case (c) are closer to their corresponding historical averages, one might expect the rapid rates of decline in coal and natural gas consumption due to the AEEI to have a more dramatic effect on energy use and emissions. However, as indicated in the social accounting matrix (Figure A-2), final consumption accounts for half of total electricity, one third of total petroleum and natural gas use and only a negligible fraction of coal. The large values for the AEEI in the household sector therefore reduce only a fraction of aggregate energy demand, and their strongest influence on carbon emissions is indirect, by reducing the demand for electricity generated from coal.

Table 5 summarizes our assessments of the goodness of fit of trajectories in the aggregate variables generated by the model under the various parameter assumptions. Our statistic of choice is the coefficient of variation (CV), which measures the average of the absolute deviations of the simulated trajectories of the variables from the relevant baseline historical growth rates.

The growth rate of TFP, which is the key exogenous parameter that controls the model's dynamic behavior, is calibrated to achieve reasonably good compliance with historical GDP growth. Yet despite this, the projected rates of growth of output steadily diverge from the long-run historical trend, on average deviating from the benchmark by approximately 10 percent, as indicated by panel A of the table. Nonetheless, we consider our results to be a reasonable approximation, considering the limitations of our empirical estimates and model.

By comparison, panel B indicates much less agreement between the simulated trajectory of energy use and the historical trend. Across cases I-VI the main features of the pattern of errors are as follows. We have seen that the simulations tend to exhibit higher growth rates of energy use than has been the case historically. This phenomenon is most prevalent in the cases where the AEEI is zero or is attributed to the effect of technical change within industries. Within industries, the AEEI is consistently associated with the smallest deviation from the historical trend in energy when it is set at the 1 percent consensus value, or where it is attributed to sub-sectoral changes in the energy intensity within industries. This is a key finding, which casts doubt on the popular attribution of the AEEI to energy-saving changes in technology.

The results also highlight the importance of including a declining trend in energy's share of consumption expenditure in the model. A household sector AEEI value of zero gives rise to CVs on the order of 20-50 percent. Increasing the value of this parameter to 1 percent lowers the range of average deviations to 3-38 percent, while specifying the AEEI as the historical rates of change of energy expenditure shares gives rise to deviations of 6-32 percent. As the results in panel C illustrate, the implication is that these AEEI values in the household enable the model's projections to be more consistent with historical trends in energy intensity, especially in conjunction with industry AEEI values that reflect sub-sectoral intensity change.

However, we must once again qualify our results by noting that the AEEI which we specify in the household sector reflects the joint impacts of substitution, technological progress, or other non-price phenomena such as changes in tastes or the introduction of new goods. Given that substitution by the representative agent in the model also influences aggregate energy use, it remains unclear how robust these results may be to specifying the household sector AEEI as only the non-price component of the decline in energy's share of consumption. Given the large impact on emissions exerted by this parameter, an empirical investigation to isolate the secular component of this decline is a priority for future research.

Lastly, the fact that the average deviations of simulated emissions from historical trends shown in panel D are larger than the corresponding figures for energy use and intensity in panels B and C suggests that the model's projections of inter-fuel substitution are either not as large as occurred historically, or embody progressive shift toward more carbon and emission-intensive fuels such as coal. Such influences reflect the changes in the vectors of energy prices and quantities which are solved for by the general equilibrium sub-model at each time step. Therefore, in order to elucidate the origins of the divergence between panels B and D we must inquire into the details of the model's solutions.

To this end, we summarize the average rates of growth of the prices and quantities of energy commodities across our suite of model runs in Table 6. The prices of energy commodities tabulated in panel A change very little over time. In all cases electricity prices declines and coal prices increase monotonically throughout the simulation. While the rate of increase of the electricity price is insensitive to the different specifications of the AEEI in the household sector, it responds much more to the specification of the AEEI across industries. The two specifications for the AEEI have similarly-sized effects on coal prices. The prices of natural gas and petroleum behave similarly to one another, and to the aggregate index of energy prices. In the absence of an AEEI in the household sector these prices increase where the AEEI for industries is energy-using (Cases I and VI) and declining where it is energy-saving (Cases II-V), but even in the former cases, oil and gas prices show net declines as the value of the household sector AEEI increases. In general, the larger the values in both specifications of the AEEI, the faster the shift inward of the demand curve for energy, and the slower the growth or the faster the decline exhibited by energy prices, as one might expect.

The growth rates of energy commodities tabulated in Panel B clearly identify the origins of the progressive increase in CO_2 emissions relative to energy use. Despite the rapid rise in the price of coal, it still sees substantial increases in the majority of simulations. What accounts for this behavior is the high value of the resource supply elasticity parameter in the coal mining sector.[7] Additionally, the low value of this elasticity in the carbon-free electric sub-sector explains why electricity from nuclear and renewables is the slowest-growing form of energy in almost all runs of the model.

As with their prices, the growth rates of the quantities of coal and primary electricity are insensitive to the value of the household sector AEEI. By contrast, the quantities of natural gas and petroleum used by the economy are generally more responsive to the AEEI, especially in Cases IV and V where the growth in the use of these fuels is significantly attenuated by the combined effects of the industry and household specifications of the AEEI. When the value of the household sector AEEI is zero the growth rates of petroleum and natural gas use are similar, but an increase in the value of this parameter causes petroleum use to increase more rapidly. The overall effect of these substitution patterns is to make the economy progressively more coal- and oil-intensive, raising the carbon intensity of aggregate energy use.

Further sensitivity analyses can be undertaken to establish the influence of the nested structure of production and the values of the elasticities of substitution on the emissions-intensity of energy use. However, in the interest of conserving space we do not conduct such experiments here.

---

[7] Table A-1 gives the values of this parameter (η_R), which determines the responsiveness of the size of the endowment of natural resource inputs to a given industry to the price of that sector's output. The values used here are based on econometric estimates by Dahl and Duggan (1996) and assumptions discussed in Sue Wing (2001).

We end by examining the implications of the foregoing analysis for projections of energy use and emissions, which are presented in Figure 5. The shaded areas show the ranges of the trajectories of energy use and emissions (respectively) spanned by the suite of simulations, which in 2050 extend from 293-532 exajoules (EJ) of energy and from 17.5-31.6 GT of CO_2. The dashed lines identify the trajectories with the slowest increases of energy and emissions, which correspond to values of the AEEI within industries of 1 percent, or at the rates of sub-sectoral changes in the energy intensity within detailed industries (Cases II, IV and V). These trajectories illustrate the relative importance of the AEEI in the household sector as compared to that within industries.

By way of comparison, the triangles on each chart illustrate the five-year data points of the reference case energy and emissions forecasts from the 2005 Annual Energy Outlook (DOE/EIA 2005), while the heavy solid lines are the projections of energy and emissions from their base-year levels using the corresponding historical rates of growth. The range of projections from our simulations is uniformly higher than EIA's forecasts, which, notably, lie below the historical trends. By 2050 the latter predict energy use of 310 EJ and CO_2 emissions of 12.8 GT for the U.S. economy. In that year the gap between the projection of history and the trajectories for Cases II(c), IV(c) and V(c) for energy is 20 exajoules, or 6 percent of the historical benchmark, while for emissions the inter-fuel substitution accounts for a minimum deviation of 4.4 GT of emissions, or 35 percent of the historical benchmark.

Of course, there are numerous reasons why one might expect the future to differ significantly from the past. For example, if technological change in resource extraction does not keep pace with the depletion of fossil fuel resources then the long-run marginal costs of these commodities will rise above their historical levels, as will world energy prices. It is also reasonable to expect less vigorous substitution of lower-carbon energy commodities for coal than in the past, on one hand due to its lower extraction cost compared to relatively less abundant gaseous and liquid fossil fuels, and on the other hand due to the low probability of additional environmental restrictions on coal use at the scale of those in the past 50 years.[8] While the ability of our model to represent these phenomena is limited at best, its projections nonetheless suggest that we may well experience faster growth of emissions than have been observed historically, even when the energy-saving impacts of sub-sectoral changes in the economy are accounted for.

5. Conclusions

The main results of this study may be summarized as follows. First and foremost, in multi-sectoral top-down emission projection models the procedure of specifying the AEEI as a "one-size-fits-all" parameter is likely neither to be accurate nor to generate trajectories of energy use and CO_2 emissions which are consistent with historical trends. We find that the changes in both the price- and non-price components of movements in energy intensity within detailed industry groupings exhibit substantial inter-sectoral variability, which implies that the AEEI is more appropriately modeled as a vector of values applied to different industries, whose elements vary both in magnitude and sign.

Second, our empirical findings cast doubt on the popular attribution of the AEEI to energy-saving changes in technology. It might perhaps be more accurate to re-name the AEEI the "autonomous energy-intensity decline" (AEID) parameter, in recognition of the fact that the aforementioned structural changes played a much more important role in reducing aggregate energy intensity than disembodied technological progress, whose effect at the aggregate level is energy-using in character. When we incorporate our empirical results into a CGE model of the

[8] e.g., outright bans on the use of coal in the household sector.

U.S. economy, the influence of disembodied technological change on aggregate trends in energy use and CO_2 emissions is the opposite of the conventional 1 percent per year value of the AEEI. In contrast, attributing sub-sectoral changes in intra-industry energy intensity to the AEEI generates faster reductions in aggregate energy and emissions than does its conventional counterpart.

Third, projections of energy use and emissions are quite sensitive to the specification of the AEEI within the household sector. Our inclusion of the historical rates of decline of energy's share of consumption expenditure in the household sector of the model causes a widening of the gap between the results generated using the conventional AEEI and those arising from its specification as the rate of sub-sectoral energy intensity change. Across the range the computational experiments conducted, the latter simulations produce trends of energy use are the most consistent with historical rates of growth.

Fourth, even in the cases where the values of the AEEI in industries and the household sector generate trajectories of energy use that are consistent with historical trends, emissions may still increase significantly faster than the average rates of growth of CO_2 over the last 50 years. This result depends on the structural characteristics of the model and the elasticities of substitution and supply used in its numerical parameterization, but a variety of factors make it reasonable to expect that the share of coal in aggregate energy use will increase over the next half century. The consequences will be an increase in the carbon-intensity of energy use and more rapid growth of emissions than has historically been the norm.

There are a general cautions for modelers from this exercise. Relatively aggregated models which employ the conventional specification for the AEEI, but have limited opportunities to reflect changes in the sub-sectoral composition of industries and structural shifts in energy consumption, may well be producing biased estimates of the future decline in aggregate energy intensity. The implications for their projections of CO_2 emissions are equivocal, because they depend on the interaction between the AEEI and the model's structure and elasticity parameters, as noted above. The corollary is that in relatively disaggregated models where the AEEI parameter does permit the changes in the energy intensity of detailed sectors to be represented, the conventional 1 percent AEEI value may drastically overstate potential reductions in energy intensity, biasing emission projections downward.

Appendix

The simulations in the paper are constructed using a simple recursive-dynamic CGE simulation of the U.S. economy. The model treats households as a representative agent, aggregates the firms in the economy into 11 industry sectors, and solves for a sequence of static equilibria over the policy horizon 2000-2050 on a five-year time-step.

A-1. The Static Equilibrium Sub-Model: A CGE Model in a Small Open Economy Format

The static equilibrium sub-model is cast in a small open economy format and is structurally similar to Harrison et al (1997). Imports and exports are linked by a balance-of-payments constraint, commodity inputs to production or final uses are modeled as Armington (1969) constant elasticity of substitution (CES) composites of imported and domestically-produced varieties, and industries' production for export and the domestic market are modeled according to constant elasticity of transformation (CET) functions of their output.

Commodities, which are indexed by i, are of two types, energy goods (coal, oil, natural gas and electricity, denoted $e \subset i$) and non-energy goods (denoted $m \subset i$). Each good is produced by a single industry (indexed by j), which is modeled as a representative firm that generates output (Y') from inputs of primary factors (v) and intermediate uses of Armington commodities (x).

Households are modeled as a representative agent who is endowed with three factors of production, labor (L), capital (K) and industry-specific natural resources (R), indexed by $f = \{L, K, R\}$. The supply of capital is assumed to be perfectly inelastic. The endowment of labor is assumed to increase with the wage according to an aggregate labor supply elasticity, η_L, and the endowments of the different natural resources increase with the prices of domestic output in the industries to which these resources correspond, according to sector-specific supply elasticities, η_R. Income from the agent's rental of these factors to the firms finances her consumption of commodities, consumption of a government good, and savings.

The representative agent's preferences are modeled according to a CES utility function. The level of savings is endogenously determined by the aggregate return to capital through an investment demand function that maintains the economy on a balanced growth path in the short run. The government sector is modeled as a passive entity which demands commodities and transforms them into a government good, which in turn serves as an input to both consumption and investment. Aggregate investment and government output are produced according to Cobb-Douglas transformation functions of the goods produced by the industries in the economy. The demand for investment goods is specified according to a balanced growth path rule:

Industries are modeled according to the multi-level CES production function shown schematically in Figure A-1, which are adaptations of Bovenberg and Goulder's (1996) KLEM production structure. Each node of the tree in the diagram represents the output of an individual CES function, and the branches denote its inputs. Thus, in the non-resource based production sectors shown in panel A, output (Y'_j) is a CES function of a composite of labor and capital inputs (KL_j) and a composite of energy and material inputs (EM_j). KL_j represents the value added by primary factors' contribution to production, and is a CES function of inputs of labor, v_{Lj}, and capital, v_{Kj}. EM_j represents the value of intermediate inputs' contribution to production, and is a CES function of two further composites: E_j, which is itself a CES function of energy inputs, x_{ej}, and M_j, which is a CES function of non-energy material inputs, x_{mj}.

The production structure of resource-based industries is shown in panel B. In line with its importance to production in these industries, the natural resource is modeled as a sector-specific fixed factor whose input enters at the top level of the hierarchical production function. Output is thus a CES function of the resource input, v_{Rj}, and the composite of the inputs of capital, labor, energy and materials ($KLEM_j$) to that sector. In both resource-based and non-resource-based industries, the fungibility among inputs at the various levels of the nesting structure is controlled by the values of the corresponding elasticities of substitution: σ_{KLEM}, σ_{KL}, σ_{EM}, σ_E, σ_M and σ_R.

The production function for electric power embodies characteristics of both primary and non-primary sectors described above. The top-down model therefore represents the electricity sector as an amlgam of the production functions in panels A and B. Conventional fossil electricity production combines labor, capital and materials with inputs of coal, oil and natural gas according to the production structure in panel A. Nuclear and renewable electricity are generated by combining labor, capital and intermediate materials with a composite of non-fossil fixed-factor energy resources such as uranium deposits, wind energy and hydrostatic head using a production function similar to that in panel B, but without the fossil fuel composite, *E*. The resulting production structure is shown in panel C, where total output is a CES function of the outputs of the fossil (*F*) and non-fossil (*NF*) electricity production sub-sectors. The elasticity of substitution between y_F and y_{NF} is $\sigma_{F\text{-}NF} >> 1$, reflecting the fact that they are near-perfect substitutes.

A-2. Static Calibration: Data and Parameters

We formulate the general equilibrium of the simulated economy in a complementarity format (Scarf 1973; Mathiesen 1985a, b). Profit maximization by industries and utility maximization by the representative agent give rise to vectors of demands for commodities and factors. These demands are functions of goods and factor prices, industries' activity levels and the income level of the representative agent. Combining the demands with the general equilibrium conditions of market clearance, zero-profit and income balance yields a square system of nonlinear inequalities that forms the aggregate excess demand correspondence of the economy (Sue Wing 2004). The CGE model solves this system of equations as a mixed complementarity problem (MCP) using numerical techniques.

The equilibrium system described above is numerically calibrated on a social accounting matrix (SAM) for U.S. economy in the year 2000, using values for the elasticities of substitution (based on Bovenberg and Goulder 1996) and factor supply summarized in Table A-1. The basic SAM is constructed using data from BEA for 1999 on input-output transactions and the components of GDP by industry. The resulting benchmark table was then scaled to approximate the U.S. economy in the year 2000 using the growth rate of real GDP, deflated to year 2000 prices, and aggregated according to the industry groupings in Table 1.

The economic accounts do not record the contributions to the various sectors of the economy of key natural resources that are germane to the climate problem. Sue Wing (2001) employs information from a range of additional sources to approximate these values as shares of the input of capital to the agriculture, oil and gas, mining, coal, and electric power, and rest-of-economy industries. Applying these shares allows the value of natural resource inputs to be disaggregated from the factor supply matrix, with the value of capital being decremented accordingly.

The electric power sector in the SAM is disaggregated into fossil and non-fossil electricity production (y_F and y_{NF}, respectively) using the share of primary electricity (i.e., nuclear and renewables) in total net generation for the year 2000, given in DOE/EIA (2004). The corresponding share of the electric sector's labor, capital and non-fuel intermediate inputs is allocated to the between non-fossil sub-sector, as is the entire endowment of the electric sector's natural resource. The remainder of the labor, capital and intermediate materials, along with all of the fuel inputs to electricity, are allocated to the fossil sub-sector.

The final SAM, shown in Figure A-2, along with the parameters in Table A-1, specify the numerical calibration point for the static sub-model. The latter is formulated as an MCP and numerically calibrated using the MPSGE subsystem (Rutherford 1999) for GAMS (Brooke et al 1998) before being solved using the PATH solver (Dirkse and Ferris 1995).

A-3. Dynamic Calibration: Projecting Energy Use and CO_2 Emissions

Projections of future energy use and emissions of CO_2 are constructed by simulating the growth of the economy to 2050. The static equilibrium sub-model is embedded within a dynamic process which is responsible for updating the economy's endowments of labor and capital, as well as the supply of imports and demand for exports, and the growth of energy-saving and factor-augmenting technical progress.

Growth of the aggregate labor endowment is determined by the increase of labor supply, which is assumed to occur at the rate of growth of population as specified by the middle series of Hollmann et al (2000). The value of the aggregate endowment of capital, V_K, is scaled according to the growth of the capital stock, *KS*, assuming a constant rate of return:[9]

(A-1) $V_K(t) = (r+\delta)KS(t)$,

where $r = 0.089$ is the calibrated benchmark interest rate and $\delta = 0.05$ is the rate of depreciation. The capital stock accumulates according to the standard perpetual inventory equation:

(A-2) $KS(t+1) = I(t) + (1-\delta)KS(t)$

[9] The constancy of the rate of return is a well-known limitation of the recursive-dynamic modeling approach.

in which I denotes the value of the supply of investment. The demand for investment in each period is specified within the static equilibrium sub-problem according to an ad-hoc rule that attempts to maintain the economy on a balanced growth path:[10]

$$\text{(A-3)} \quad I(t) = V_K(t)\frac{\gamma + \delta}{r + \delta}.$$

In this expression $\gamma = 0.035$ is the balanced rate of growth, approximated by the long-run historical growth rate of GDP in Figure 4.

The model's endowments of labor, capital and sector-specific natural resources in natural units are assumed to be augmented by exogenous technical progress. This is achieved by means of a total factor productivity (TFP) augmentation coefficient whose value is specified to increase from unity in the base year at the average annual rate of TFP growth. The TFP growth rate is calibrated to be 1.5 percent per annum, which results in a long-run average annual GDP growth rate of just under 3.5 percent, comparable to the value in Figure 4.[11]

Single-region open-economy simulations require the modeler to make assumptions about the characteristics of international trade and the current account over the simulation horizon. Since trade is not our primary focus, we simply reduce the economy's base-year current account deficit from the benchmark level at the constant rate of one percent per year.

We project energy use and emissions by scaling the exajoules of energy used and megatons of CO_2 emitted in the base year according to the growth in the corresponding quantity indices of Armington energy demand. We do this by constructing energy-output factors (ε) and emissions-output factors (χ), each of which assumes a fixed relationship between the benchmark values of the coal, refined oil and natural gas use in the SAM and the delivered energy and the

[10] If the balanced growth rate is γ, then along the balanced path eq. (A-2) collapses to $I(t) = (\gamma + \delta)\, KS(t)$. Substituting this expression into eq. (A-1) and eliminating KS gives the relation between I and V_K in the text.

[11] Other forecasts such as the Annual Energy Outlook (DOE/EIA 2005) typically embody slower rates of GDP growth, on the order of 2.5-3 percent per annum.

carbon emission content of these goods in the benchmark year.[12] The resulting coefficients, whose values are shown in Table A-1, are applied to the quantities of the corresponding Armington energy goods solved for by the model at each time-step.

[12] Fossil-fuel energy supply and carbon emissions in the base year were divided by commodity use in the SAM, which we calculated as gross output – net exports. In the year 2000, U.S. primary energy demands for coal, petroleum and natural gas and electricity were 23.9, 40.5, 25.2, and 14.8 exajoules, respectively (DOE/EIA 2004). The corresponding benchmark emissions of CO_2 from the first three fossil fuels were 2112, 2439 and 1244 MT, respectively (DOE/EIA 2003). Aggregate uses of these energy commodities in the SAM are 21.8, 185.6, 107.1 and 6.21 billion dollars.

References

1. Brooke, A., D. Kendrick, A. Meeraus, and R. Raman (1998). GAMS: A User's Guide, Washington DC: GAMS Development Corp.
2. Dahl, C.A. and T.E. Duggan (1996). U.S. Energy Product Supply Elasticities: A Survey and Application to the U.S. Oil Market, Resource and Energy Economics 18(3): 243-263.
3. Dirkse, S.P. and M.C. Ferris (1995). The PATH Solver: A Non-Monotone Stabilization Scheme for Mixed Complementarity Problems, Optimization Methods and Software 5: 123-156.
4. DOE/EIA (2003). Emissions of Greenhouse Gases in the United States 2002, DOE/EIA-0573(2002), Washington DC.
5. DOE/EIA(2004). Annual Energy Review 2003, DOE/EIA-0384(2003), Washington DC.
6. DOE/EIA(2005). Annual Energy Outlook 2005, DOE/EIA-0383(2004), Washington DC.
7. Edmonds, J. and J.M. Reilly (1985). Global Energy: Assessing the Future, New York: Oxford University Press.
8. Hogan, W.W. and D.W. Jorgenson (1991). Productivity Trends and the Cost of Reducing Carbon Dioxide Emissions, Energy Journal 12(1): 67-85.
9. Hollmann, F.W., T.J. Mulder and J.E. Kallan (2000). Methodology and Assumptions for the Population Projections of the United States: 1999 to 2100, U.S. Census Bureau, Population Division Working Paper No. 38.
10. Jorgenson, D.W. and B.M. Fraumeni (1981). Relative Prices and Technical Change, in E. Berndt and B. Field (eds.), Modeling and Measuring Natural Resource Substitution, Cambridge: MIT Press, 17-47.

11. Jorgenson, D.W. (1984). The Role of Energy in Productivity Growth, in J.W. Kendrick (ed.), International Comparisons of Productivity and Causes of the Slowdown, Cambridge MA: Ballinger, 279-323.

12. Marland, G., T.A. Boden and R. J. Andres (2003). Global, Regional, and National Fossil Fuel CO_2 Emissions, in Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge TN: Oak Ridge National Laboratory.

13. Mathiesen, L. (1985a). Computational Experience in Solving Equilibrium Models by a Sequence of Linear Complementarity Problems, Operations Research 33: 1225-1250.

14. Mathiesen, L. (1985b). Computation of Economic Equilibria by a Sequence of Linear Complementarity Problems, Mathematical Programming Study 23: 144-162.

15. McFarland, J., J.M. Reilly and H.J. Herzog (2004). Representing Energy Technologies in Top-down Economic Models Using Bottom-up Information, Energy Economics 26(4): 685-707.

16. Rutherford, T.F. (1999). Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax, Computational Economics 14: 1-46.

17. Scarf, H., with T. Hansen (1973). The Computation of Economic Equilibria, Cowles Foundation Monograph No. 24, Yale University.

18. Sue Wing, I. (2001). Induced Technical Change in Computable General Equilibrium Models for Climate Policy Analysis, unpublished Ph.D. dissertation, Massachusetts Institute of Technology.

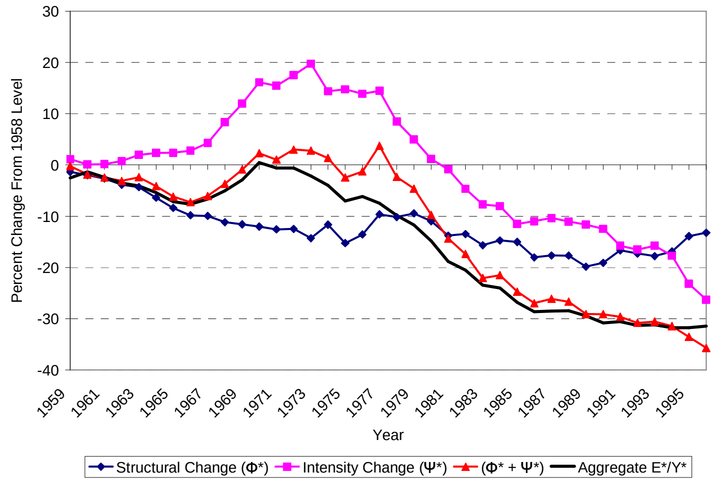
19. Sue Wing, I. (2004). Computable General Equilibrium Models and Their Use in Economy-Wide Policy Analysis: Everything You Ever Wanted to Know (But Were Afraid to Ask),

MIT Joint Program on the Science and Policy of Global Change Technical Note No. 6, Cambridge MA.

20. Sue Wing, I. and R.S. Eckaus (2004). Explaining Long-Run Changes in the Energy Intensity of the U.S. Economy, MIT Joint Program on the Science and Policy of Global Change Report No. 116, Cambridge MA.
21. Williams, R.H. (1987). A Low Energy Future for the United States, Energy 12: 939-944.
22. Williams, R.H. (1990). Low-Cost Strategies for Coping with CO_2 Emission Limits, Energy Journal 11: 35-59.
23. Williams, R.H., E. Larson and M. Ross (1987). Materials, Affluence, and Industrial Energy Use, Annual Review of Energy 12: 99-144.
24. Weyant, J.P. (2000). An Introduction to the Economics of Climate Change Policy, Pew Center on Global Climate Change Report.

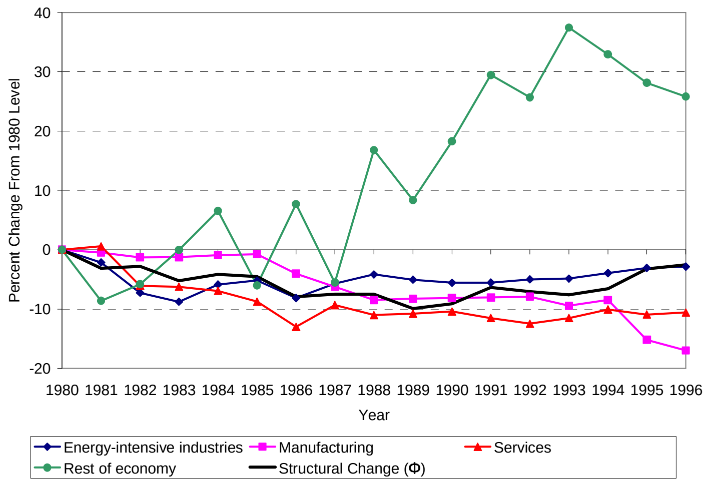
Figure 1. Contribution of Structural Change (Φ) and Intensity Change (Ψ)

to Change in Aggregate Energy Intensity ($d\ln(E^*/Y^*)$), 1958-1996

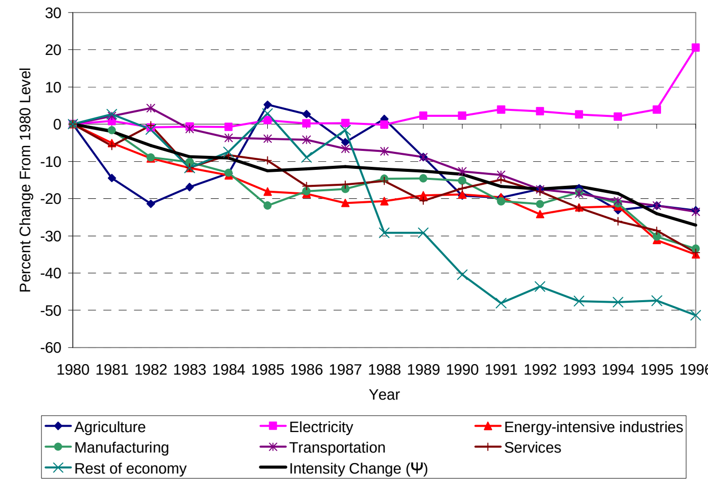


Source: Sue Wing and Eckaus (2004)

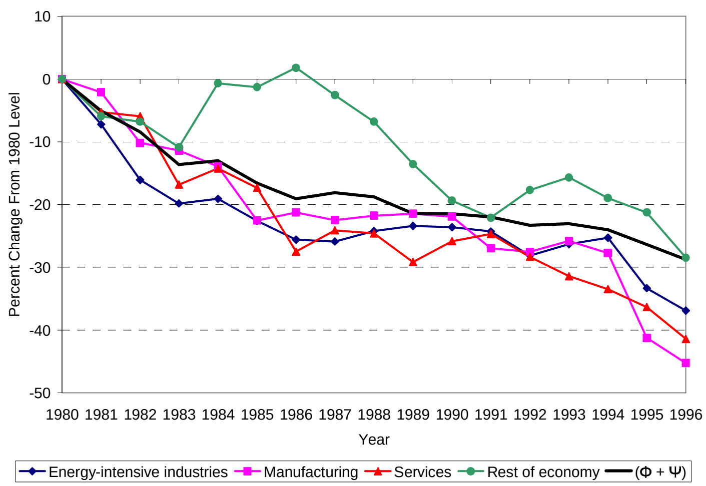
Figure 2. Contributions of Structural Change (Φ'_j) and Intensity Change (Ψ'_j) to Changes in Industries' Energy Intensity, 1980-1996



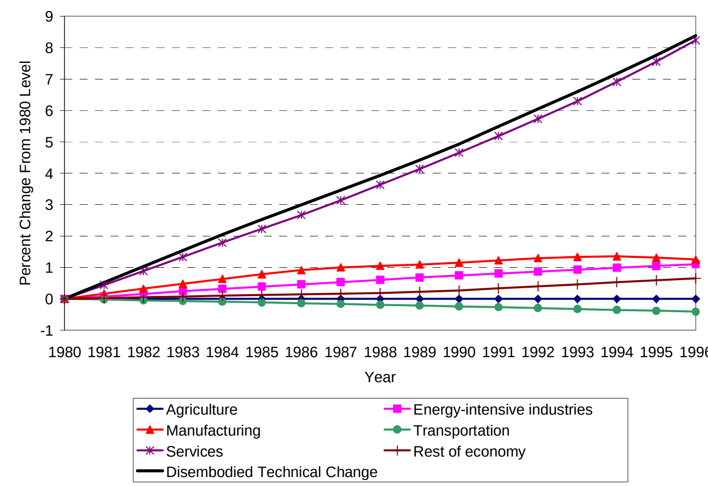
A. Effect of Changing Industrial Composition (Φ'_j)



B. Pure Within-Industry Energy Intensity Change (Ψ'_j)



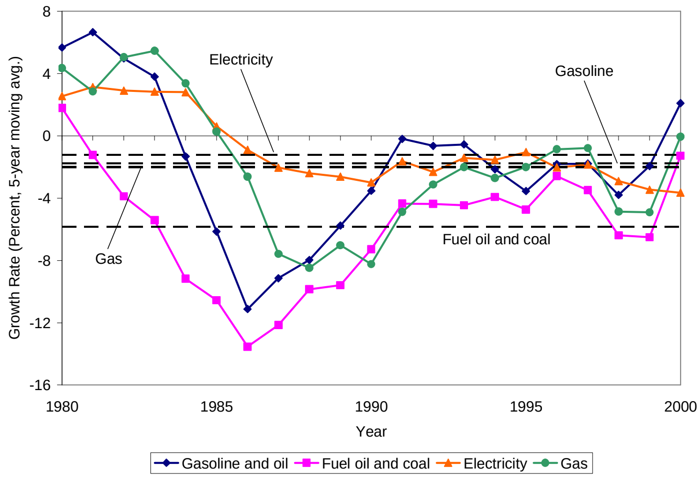
C. Overall Change in Energy Intensity ($\Phi'_j + \Psi'_j$)



D. Disembodied Technical Change Component of Ψ'_j

Figure 3. Historical Rates of Change in the Shares of Energy Commodities in Final Consumption

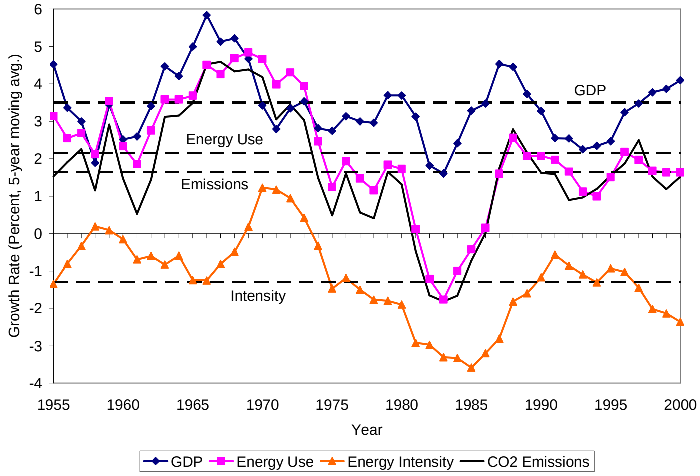
(5-year moving averages)



Source: Bureau of Economic Analysis and authors' calculations.

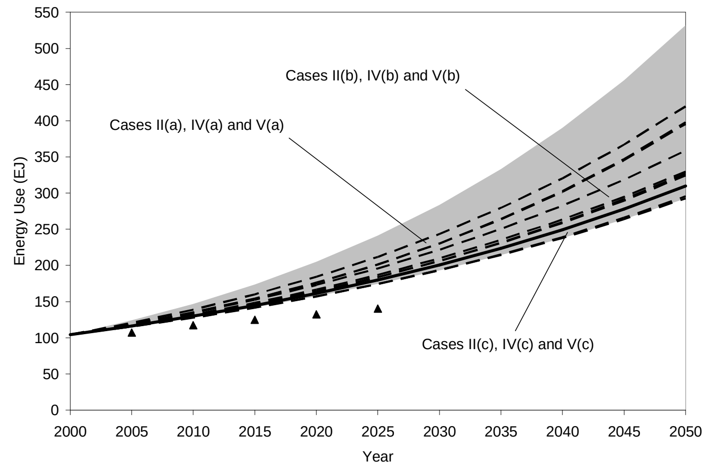
Figure 4. Historical Rates of Change of GDP, Energy Use, Energy Intensity and CO_2 Emissions

(5-year moving averages)

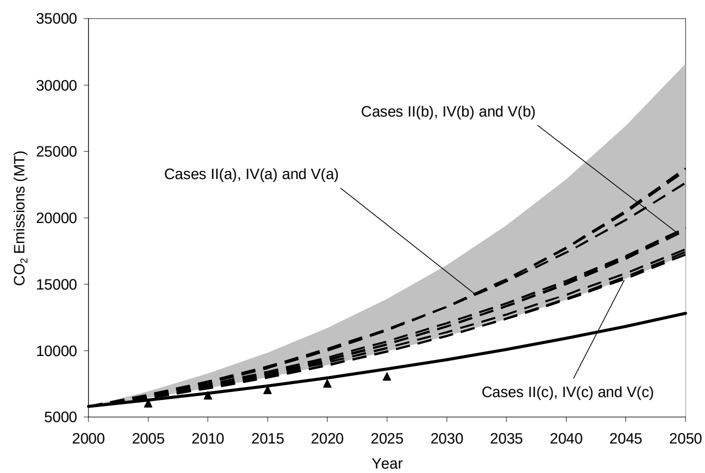


Sources: Real GDP - Bureau of Economic Analysis; Energy use - DOE/EIA (2004); Emissions - Marland et al (2003).

Figure 5. Range of Uncertainties in Model Projections



A. Energy Use



B. Emissions

Figure A-1. The Structure of Production in the CGE Model

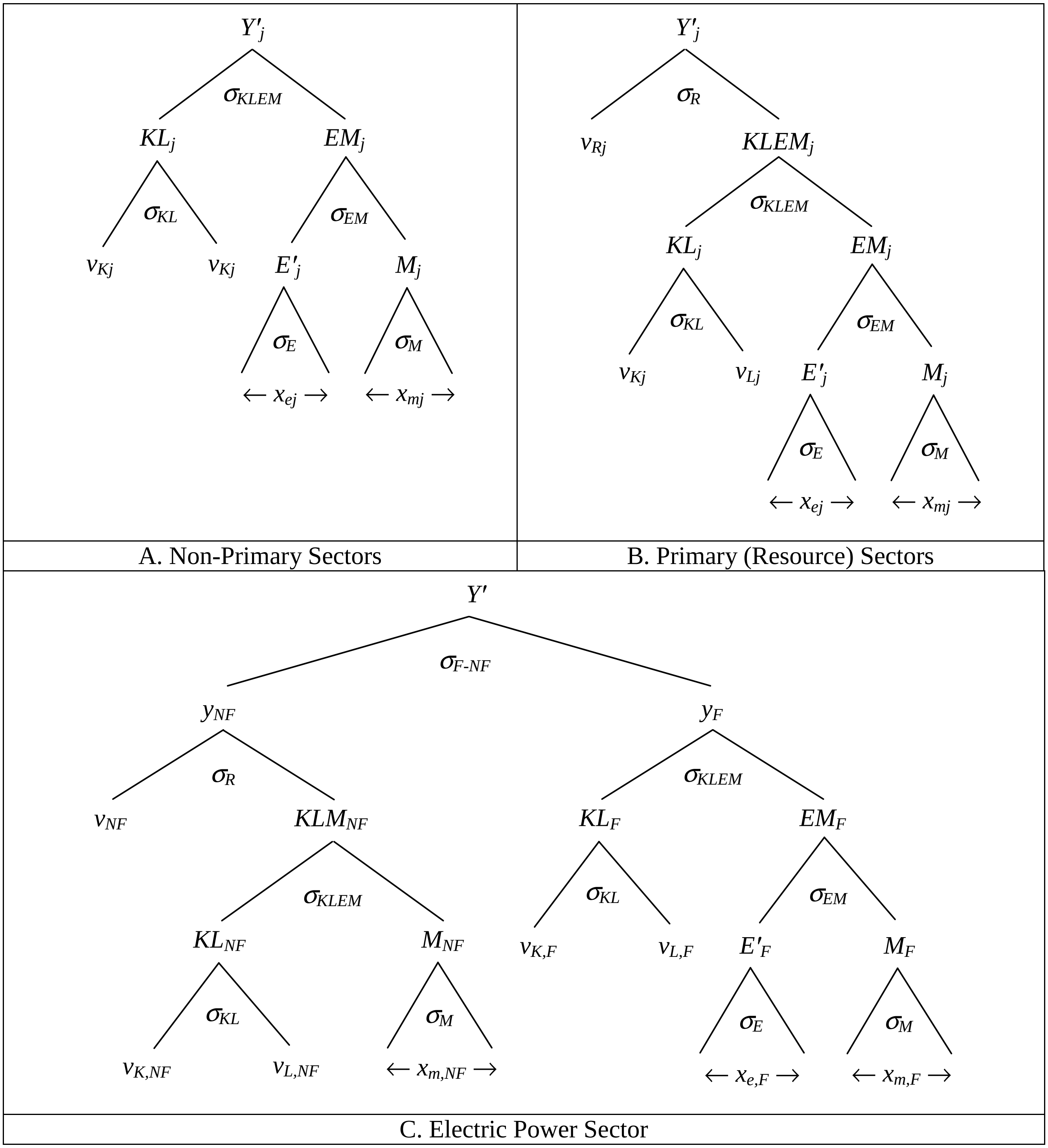


Figure A-2. Year 2000 Social Accounting Matrix for the U.S. (2000 Dollars $\times 10^{10}$)

	Coal	Electricity	Gas	Agriculture	Crude oil & gas	Refined petroleum	Energy intensive manufacturing	Manufacturing	Transportation	Services	Rest of the economy	Private consumption	Private investment	Government consumption	Government investment	Imports	Exports	Total
Coal	0.24	1.45	0.00	0.00	0.00	0.00	0.22	0.06	0.01	0.06	0.13	0.01	-0.01	0.01	0.00	-0.03	0.15	2.29
Electricity	0.05	0.08	0.03	0.28	0.12	0.17	1.38	2.35	0.28	6.45	0.46	10.21	0.00	2.70	0.00	-0.15	0.05	24.47
Gas	0.00	0.53	2.28	0.04	0.45	0.25	0.82	0.73	0.06	1.22	0.21	3.53	0.00	0.61	0.00	0.00	0.04	10.76
Agriculture	0.00	0.01	0.00	7.03	0.00	0.01	0.17	14.88	0.01	3.07	0.72	3.85	-0.09	0.31	0.00	-2.49	1.88	29.37
Crude oil & gas	0.00	0.02	4.80	0.00	2.68	8.38	0.94	0.02	0.03	0.06	0.04	0.00	0.07	0.01	0.00	-6.53	0.34	10.86
Refined petroleum	0.07	0.24	0.04	0.47	0.07	1.75	0.63	0.61	2.43	2.14	1.73	6.43	0.13	1.91	0.00	-1.54	1.00	18.10
Energy intensive mfg.	0.10	0.12	0.02	1.42	0.29	0.51	17.43	29.83	0.18	6.81	9.47	7.13	0.89	2.11	0.01	-11.47	7.96	72.82
Manu-facturing	0.34	0.35	0.05	3.16	0.18	0.19	5.51	91.16	2.28	43.48	24.57	108.95	71.89	10.67	7.44	-84.41	46.88	332.69
Transport.	0.16	0.95	0.13	0.88	0.12	0.78	3.55	7.68	9.80	8.30	2.98	14.70	1.38	2.62	0.12	-1.54	6.65	59.24
Services	0.39	2.27	0.74	4.78	3.99	2.26	10.78	49.31	11.17	240.36	25.59	500.94	40.24	5.28	5.70	0.73	20.57	925.08
Rest of the economy	0.02	2.51	1.11	0.40	0.52	0.35	3.51	4.97	2.60	24.81	2.69	5.95	58.87	115.31	19.01	-15.40	10.83	238.06
Labor	0.44	4.42	0.43	4.19	0.67	1.14	16.13	84.31	19.03	353.96	111.49							596.21
Capital	0.17	8.39	0.87	7.67	0.84	2.11	10.81	41.03	9.79	187.89	66.51							336.07
Resources	0.11	0.44	0.00	0.16	0.69	0.00	0.00	0.00	0.00	0.00	7.39							8.79
Taxes	0.20	2.69	0.26	0.63	0.26	0.20	0.94	5.77	1.71	47.31	1.26							61.23
Subsidies	0.00	0.00	0.00	-1.72	0.00	0.00	0.00	0.00	-0.13	-0.82	-17.19							-19.87
Total	2.29	24.47	10.76	29.37	10.86	18.10	72.82	332.69	59.24	925.08	238.06	661.69	173.37	141.55	32.28	-122.84	96.37	

Value added = GDP = 9.82 Trillion dollars
Gross Output = 17.24 Trillion dollars
Source: Bureau of Economic Analysis; author's calculations and assumptions

Table 1. Industry Concordance Between CGE Model and Jorgenson Dataset

Broad CGE model sectors (*j*)	Detailed sectors in Jorgenson dataset (*k*)
Agriculture	Agriculture
Coal	Coal mining
Crude oil & gas	Crude oil & gas
Natural gas	Natural gas
Petroleum	Petroleum
Electricity	Electricity
Energy-intensive industries	Paper and allied; Chemicals; Rubber & plastics; Stone, clay & Glass; Primary metals
Manufacturing	Food & allied; Tobacco; Textile mill products; Apparel; Lumber & wood; Furniture & fixtures; Printing, publishing & allied; Leather; Fabricated metal; Non-electrical machinery; Electrical machinery; Motor vehicles; Transportation equipment & ordnance; Instruments; Misc. manufacturing
Transportation	Transportation
Services	Communications; Trade; Finance, insurance & real estate; Government enterprises
Rest of economy	Metal mining; Non-metal mining; Construction

Table 2. Average Annual Change in Sub-Sectoral Components of Energy Intensity (Percent)

Sector	A. Sub-Sectoral Structural Change (Φ'_j) [a]	B. Sub-Sectoral Intensity Change (Ψ'_j) [a]	C. Observed Sectoral Energy Intensity ($\Phi'_j + \Psi'_j$) [a]	D. Disembodied Technical Progress Component ($\Psi'_{TECH,\,j}$) [a]	E. Energy share of aggregate consumption expenditure [b]
Agriculture	–	-1.1	-1.1	0.00	–
Coal	–	-1.4	-1.4	-0.08	-5.82 [c]
Crude oil & gas	–	2.9	2.9	0.12	–
Natural gas	–	5.2	5.2	-0.02	-1.99
Petroleum	–	-0.3	-0.3	0.00	-1.76
Electricity	–	0.6	0.6	0.02	-1.23
Energy-intensive industries	-0.2	-1.8	-1.9	0.07	–
Manufacturing	-1.5	-2.8	-1.8	0.08	–
Transportation	–	-1.9	-1.9	-0.03	–
Services	-1.7	-2.7	-2.1	0.49	–
Rest of economy	-1.2	-1.7	-5.3	0.04	–
Aggregate economy	-0.2	-1.2	-1.5	0.50	–

[a] 1980-1996; [b] 1980-2000; [c] In the absence of data to further disaggregate the fuel categories in the NIPAs we attribute the rate of change in the consumption share of fuel oil and coal to coal alone.

Table 3. Experiments with the Numerical Model

Case	Growth Rate of AEEI
	Industries (all industries except fossil fuel supply sectors)
I	None
II	1 percent per year
II	Average annual rate of sub-sectoral structural change (Φ')
IV	Average annual rate of sub-sectoral intensity change (Ψ')
V	Average rate of sectoral energy intensity change ($\Phi' + \Psi'$)
VI	Disembodied technical progress component of intensity change (Ψ'_{TECH})
	Consumption
(a)	None
(b)	1 percent per year
(c)	Average annual rate of change in consumption expenditures by fuel

Table 4. Simulated Average Annual Growth Rates of GDP, Energy Use, Energy Intensity and Carbon Emissions (percent)

Case	A. GDP			B. Energy Use			C. Energy Intensity			D. CO_2 Emissions		
	2010	2030	2050	2010	2030	2050	2010	2030	2050	2010	2030	2050
I(a)	3.5	3.4	3.3	3.4	3.2	3.1	-0.2	-0.2	-0.2	3.5	3.4	3.2
II(a)	3.6	3.4	3.3	2.9	2.8	2.7	-0.7	-0.6	-0.5	2.8	2.8	2.7
III(a)	3.6	3.4	3.3	3.0	2.9	2.8	-0.6	-0.5	-0.4	3.1	3.0	2.9
IV(a)	3.6	3.4	3.3	2.6	2.7	2.8	-0.9	-0.7	-0.5	2.8	2.9	2.9
V(a)	3.6	3.4	3.3	2.6	2.8	2.8	-0.9	-0.7	-0.5	2.7	2.9	2.9
VI(a)	3.5	3.4	3.3	3.4	3.3	3.1	-0.1	-0.1	-0.1	3.6	3.4	3.3
I(b)	3.6	3.4	3.3	3.1	3.0	2.9	-0.5	-0.5	-0.4	3.2	3.1	3.0
II(b)	3.6	3.5	3.3	2.6	2.5	2.4	-1.0	-0.9	-0.9	2.5	2.4	2.3
III(b)	3.6	3.5	3.3	2.7	2.6	2.5	-0.9	-0.8	-0.7	2.7	2.7	2.6
IV(b)	3.6	3.5	3.3	2.3	2.3	2.3	-1.3	-1.1	-1.0	2.4	2.4	2.4
V(b)	3.6	3.5	3.3	2.3	2.3	2.3	-1.3	-1.1	-0.9	2.4	2.5	2.5
VI(b)	3.6	3.4	3.3	3.2	3.1	3.0	-0.4	-0.4	-0.3	3.3	3.2	3.1
I(c)	3.6	3.4	3.3	2.9	2.9	2.8	-0.7	-0.6	-0.5	3.0	3.0	2.9
II(c)	3.6	3.5	3.3	2.4	2.3	2.3	-1.2	-1.1	-1.0	2.3	2.3	2.2
III(c)	3.6	3.5	3.3	2.5	2.5	2.4	-1.1	-1.0	-0.9	2.5	2.5	2.5
IV(c)	3.6	3.5	3.3	2.1	2.1	2.1	-1.5	-1.3	-1.2	2.2	2.2	2.2
V(c)	3.6	3.5	3.3	2.0	2.1	2.1	-1.5	-1.3	-1.1	2.1	2.3	2.3
VI(c)	3.6	3.4	3.3	3.0	3.0	2.9	-0.6	-0.5	-0.4	3.1	3.1	3.0

Table 5. Coefficients of Variation of Model Deviations From Historical Growth Rates [a]

Case	A. GDP	B. Energy Use	C. Energy Intensity	D. CO_2 Emissions
I(a)	0.037	0.525	-0.900	1.100
II(a)	0.034	0.324	-0.560	0.715
III(a)	0.035	0.378	-0.650	0.883
IV(a)	0.036	0.264	-0.472	0.767
V(a)	0.036	0.271	-0.488	0.778
VI(a)	0.038	0.564	-0.968	1.158
I(b)	0.034	0.401	-0.683	0.929
II(b)	0.033	0.168	-0.290	0.501
III(b)	0.034	0.222	-0.383	0.667
IV(b)	0.035	0.064	-0.149	0.488
V(b)	0.035	0.074	-0.174	0.502
VI(b)	0.035	0.446	-0.763	0.996
I(c)	0.034	0.337	-0.580	0.848
II(c)	0.034	0.083	-0.158	0.387
III(c)	0.034	0.141	-0.255	0.563
IV(c)	0.036	0.039	-0.114	0.356
V(c)	0.036	0.034	-0.127	0.373
VI(c)	0.035	0.387	-0.666	0.922

[a] Coefficient of variation = $\frac{1}{\tilde{x}}\sqrt{\frac{(x-\tilde{x})^2}{N-1}}$, where *x* is the average annual rate of growth for the variable in question, $\tilde{x}$ is the corresponding historical average rate from Figure 4, and *N* is the number of data points projected by the model.

Table 6. Simulated Average Annual Growth Rates of Prices and Quantities

of Armington Energy Commodities (percent)

	A. Prices					B. Quantities			
	Coal	Electricity	Gas	Petroleum	Energy [a]	Coal	Electricity [b]	Gas	Petroleum
I(a)	0.36	-0.43	0.03	-0.02	0.06	3.4	2.3	3.3	3.3
II(a)	0.09	-0.62	-0.05	-0.13	-0.13	2.3	2.8	2.9	3.0
III(a)	0.24	-0.45	-0.03	-0.10	-0.03	2.9	2.2	3.0	3.1
IV(a)	0.23	-0.33	-0.10	-0.19	-0.06	2.9	1.6	2.8	2.8
V(a)	0.25	-0.32	-0.10	-0.19	-0.06	3.0	1.7	2.9	2.8
VI(a)	0.39	-0.43	0.04	-0.01	0.08	3.6	2.4	3.4	3.4
I(b)	0.30	-0.43	-0.02	-0.09	0.00	3.2	2.2	3.0	3.1
II(b)	0.03	-0.62	-0.13	-0.22	-0.20	2.0	2.6	2.5	2.7
III(b)	0.17	-0.45	-0.10	-0.18	-0.10	2.6	2.0	2.6	2.8
IV(b)	0.14	-0.34	-0.19	-0.30	-0.16	2.5	1.5	2.3	2.4
V(b)	0.15	-0.34	-0.19	-0.30	-0.15	2.5	1.5	2.4	2.4
VI(b)	0.34	-0.43	-0.01	-0.07	0.03	3.3	2.3	3.1	3.2
I(c)	0.29	-0.43	-0.06	-0.13	-0.03	3.1	2.2	2.7	3.0
II(c)	0.02	-0.62	-0.18	-0.28	-0.24	1.9	2.6	2.2	2.5
III(c)	0.16	-0.45	-0.15	-0.24	-0.14	2.5	2.0	2.2	2.7
IV(c)	0.12	-0.35	-0.24	-0.37	-0.20	2.4	1.5	1.9	2.2
V(c)	0.13	-0.34	-0.24	-0.38	-0.20	2.4	1.5	2.0	2.2
VI(c)	0.33	-0.42	-0.04	-0.11	0.00	3.3	2.2	2.8	3.0

[a] Quantity-weighted average of coal, electricity, natural gas and petroleum prices; [b] Primary electricity (nuclear and renewables) only.

Table A-1. Substitution and Supply Elasticities

Sector	σ_{KL} [a]	σ_E [b]	σ_A [c]	σ_R [d]	η_R [e]	ε [f]	χ [g]
Agriculture	0.68	1.45	2.31	0.4	0.5	–	–
Crude Oil & Gas	0.68	1.45	5.00	0.4	1.0	–	–
Coal	0.80	1.08	1.14	0.4	2.0	1.0956	0.0969
Refined Oil	0.74	1.04	2.21	–	–	0.2173	0.0131
Natural Gas	0.96	1.04	1.00	–	–	0.2355	0.0116
Electricity	0.81	0.97	1.00	0.4	0.5	0.2381	–
Energy Intensive Mfg.	0.94	1.08	2.74	–	–	–	–
Transportation	0.80	1.04	1.00	–	–	–	–
Manufacturing	0.94	1.08	2.74	–	–	–	–
Services	0.80	1.81	1.00	–	–	–	–
Rest of the Economy	0.98	1.07	1.00	0.4	1.0	–	–

All Sectors	
σ_{KLEM} [h]	0.7
σ_{EM} [i]	0.7
σ_M [j]	0.6
σ_T [k]	1.0
η_L [l]	0.3

Electricity	
$\sigma_{F\text{-}NF}$ [m]	10

[a] Elasticity of substitution between capital and labor; [b] Inter-fuel elasticity of substitution; [c] Armington elasticity of substitution; [d] Elasticity of substitution between KLEM composite and natural resources; [e] Elasticity of natural resource supply with respect to output price; [f] Energy-output factor (GJ/$); [g] CO_2 emission factor (Tons/$); [h] Elasticity of substitution between value added and energy-materials composite; [i] Elasticity of substitution between energy and material composites; [j] Elasticity of substitution among intermediate materials; [k] Elasticity of output transformation between domestic and exported commodity types; [l] Labor supply elasticity; [m] Elasticity of substitution between fossil and non-fossil electric output.