Energy Policy 35 (2007) 5267–5286

ENERGY POLICY

www.elsevier.com/locate/enpol

The implications of the historical decline in US energy intensity for long-run CO_2 emission projections

Ian Sue Wing[a,*], Richard S. Eckaus[b]

[a]*Center for Energy and Environmental Studies and Department of Geography and Environment, Boston University and Joint Program on the Science and Policy of Global Change, MIT, Room 141, 675 Commonwealth Avenue, Boston, MA 02215, USA*

[b]*Economics Department and Joint Program on the Science and Policy of Global Change, MIT, MA, USA*

Received 15 September 2005; received in revised form 31 December 2005; accepted 1 January 2006
Available online 17 July 2007

Abstract

This paper analyzes the influence of the long-run decline in US energy intensity on projections of energy use and carbon emissions to the year 2050. We build on our own recent work which decomposes changes in the aggregate US 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 US economy to analyze the implications of these findings for future energy use and carbon emissions. Comparison of the simulation results against projections of 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. Even so, our results suggest that US emissions may well grow faster in the future than in the recent past.

Keywords: Autonomous energy efficiency improvement; CGE models; Climate change policy

1. Introduction

This paper projects the energy use and greenhouse gas emissions of the US 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 US 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 raises unusual and uncomfortable problems that do not exist in conventional, shorter-term economic forecasts. Perhaps the thorniest problem is the issue of how to model the effect of technological progress, which, some have 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.

*Corresponding author. Tel.: +1 617 353 5741; fax: +1 617 353 5986.
E-mail address: isw@bu.edu (I. Sue Wing).

0301-4215/$ - see front matter
doi:10.1016/j.enpol.2006.01.035

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 economies, especially those which are industrialized. 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; Paltsev et al., 2005).

The need for the AEEI arises because, without drastic changes in prices and economic quantities, the production and utility functions in the economic simulations used to project energy use and GHG emissions 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 distribution 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 in the absence of exogenous shocks simulation models 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 twenty-first 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, 2000).

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, 2000), 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 US economy by Jorgenson and Fraumeni (1981) and Jorgenson (1984) find an energy-*using* bias of technical progress in the majority of US 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.

The present paper takes a first step toward using these empirical results to constrain the values of the AEEI parameter in CGE models for climate policy analysis. Section 2 develops a theoretical framework for attributing changes in aggregate energy intensity to the influences of prices and technology on changes in the mix of industries and changes in the efficiency of energy use within industries. We demonstrate the sensitivity of the results of this procedure to the level of sectoral aggregation, and show that the measure of efficiency's influence on the energy intensity of broad sectors may be substantially contaminated by the effects of sub-sectoral changes in industrial composition. Consequently, the influences of structural and efficiency changes on energy intensity vary widely, not only among industrial sectors but also between industries and final consumption, and may sometimes have an energy-using effect rather than an energy-saving effect. The general implication is that it may be more appropriate to model the AEEI 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 US 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. Changes in energy intensity: the influences of substitution and technical progress on the contributions of structural shifts and energy efficiency

2.1. Theoretical framework and decomposition analysis

We begin by outlining the mechanisms through which technical progress and shifts in relative prices precipitate changes in aggregate output, energy use and CO_2 emissions. Considering first the effect of a change in the relative price of energy commodities, firms will substitute non-energy inputs for energy and cheaper fuels for more expensive ones. The result will be adjustments in firms' unit costs of production, the quantities of inputs they consume and the output they produce, and changes in their contributions to the output and energy use of the industry sectors to which they belong. In turn, the outputs and energy demands of these more aggregate sectors will change as well, precipitating changes in the shares of the latter in GDP and aggregate energy use. Moreover, holding prices constant, similar effects will arise as a result of inter-firm differences in the rate and energy-saving or -using bias of technical progress.

This description suggests that shifts in the aggregate energy–output ratio can be decomposed into the effects of changes in the distribution of firms and industries on energy use and output (i.e., structural change), and those of changes in the intensity with which energy is used per unit of product (i.e., efficiency change). A further implication is that each of these influences embodies price-based and non-price components.

We formalize this intuition using a variant of the simple model developed in Sue Wing and Eckaus (2004). We consider an economy which is divided into k detailed industry groups, each of which uses energy E and produces output Y. Let E^* denote the economy's aggregate energy use and Y^* denote its GDP. We assume that at time t aggregate energy intensity is given by the weighted average of the industry sectors' intensities of energy use in that period, where industry k's weight (ϕ_k) is the ratio of its share of GDP to its share of total energy use, and $\varepsilon_{k,t} = E_{k,t}/Y_{k,t}$ represents the energy intensity of an individual industry at the finest level of detail available:

$$\frac{E_t^*}{Y_t^*} = \frac{1}{|k|}\sum_k \phi_{k,t}\varepsilon_{k,t}. \tag{1}$$

The effects of prices and technology are easily incorporated in Eq. (1) by assuming that ϕ and ε both depend on the economy's price vector, $\mathbf{P}$, as well as its vector of firm- or industry-specific technology levels $\mathbf{T}$:

$$\frac{E_t^*}{Y_t^*}(\mathbf{P},\mathbf{T}) = \frac{1}{|k|}\sum_k \phi_{k,t}(\mathbf{P},\mathbf{T})\varepsilon_{k,t}(\mathbf{P},\mathbf{T}).$$

The logarithmic time-derivative of this expression is

$$\frac{\partial}{\partial t}\ln\frac{E_t^*}{Y_t^*} = \underbrace{\frac{1}{|k|}\sum_k \frac{\partial}{\partial t}\ln\,\phi_{k,t}(\mathbf{P},\mathbf{T})}_{\Phi^*} + \underbrace{\frac{1}{|k|}\sum_k \frac{\partial}{\partial t}\ln\,\varepsilon_{k,t}(\mathbf{P},\mathbf{T})}_{\Psi^*}, \tag{2}$$

which says that the observed fractional change in aggregate energy intensity, $\partial\ln(E^*/Y^*)/\partial t$, is the result of two effects: Φ^*, the change in industries' contributions to aggregate energy intensity, which is a measure of structural change, and Ψ^*, the change in energy intensity within industries, which is a measure of efficiency change. We note that this decomposition has the attractive property of being exact in the sense that there is no residual.[1]

Eq. (2) may be further decomposed into the influences of substitution and innovation on the economic structure's contribution to intensity change (Φ_P^* and Φ_T^*, respectively), and on the efficiency's contribution (Ψ_P^* and Ψ_T^*, respectively):

$$\frac{\partial}{\partial t}\ln\frac{E_t^*}{Y_t^*} = \underbrace{\frac{1}{|k|}\sum_k \phi_{k,t}^{-1}\frac{\partial\phi_{k,t}}{\partial\mathbf{P}}\cdot\dot{\mathbf{P}}}_{\Phi_P^*} + \underbrace{\frac{1}{|k|}\sum_k \phi_{k,t}^{-1}\frac{\partial\phi_{k,t}}{\partial\mathbf{T}}\cdot\dot{\mathbf{T}}}_{\Phi_T^*} + \underbrace{\frac{1}{|k|}\sum_k \varepsilon_{k,t}^{-1}\frac{\partial\varepsilon_{k,t}}{\partial\mathbf{P}}\cdot\dot{\mathbf{P}}}_{\Psi_P^*} + \underbrace{\frac{1}{|k|}\sum_k \varepsilon_{k,t}^{-1}\frac{\partial\varepsilon_{k,t}}{\partial\mathbf{T}}\cdot\dot{\mathbf{T}}}_{\Psi_T^*}. \tag{3}$$

Here, a dot over a variable indicates its time derivative, so that price shocks are represented by $\dot{\mathbf{P}}$ and technological change by $\dot{\mathbf{T}}$. While the effect of the latter on efficiency (Ψ_T^*) is what the AEEI purports to measure, its justification as the driver of aggregate energy intensity decline betrays an attribution to the technological component of structural change (Φ_T^*) as well. Thus, our empirical investigation should not only estimate the effects of structure and

[1] See, e.g., Boyd and Roop (2004).

efficiency on intensity, but also disentangle their price- and non-price components.

In our previous work, we employed data at the approximate 2-digit SIC level of industry aggregation to first decompose the evolution of aggregate energy intensity into the impacts of structural change and efficiency change, and then estimate the contributions of substitution and technological progress to Ψ^*. 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 the CGE models used to simulate the economic effects of climate change mitigation policies.

A key issue which must be dealt with in moving between empirical and computational analyses is the bias induced by aggregation. Suppose that the economy above is represented in a CGE model which only resolves j broad sectoral groupings, with $|j|<|k|$. Letting $\xi_{j,t}=E_{j,t}/Y_{j,t}$ represent the energy intensity of these aggregated sectors, the aggregate intensity can be specified in the same way as Eq. (1), i.e., as a weighted average of sectoral intensities,

$$\frac{E_t^*}{Y_t^*}=\frac{1}{|j|}\sum_j \omega_{j,t}\xi_{j,t}, \tag{4}$$

where sector j's weight (ω_j) is the ratio of its share of GDP to its share of total energy use, as before. In like manner, the logarithmic derivative of Eq. (4) decomposes changes in energy intensity into measures of structural change, $\tilde{\Phi}^*$, and efficiency change, $\tilde{\Psi}^*$, which are analogous to the components of Eq. (3), but at a higher degree of aggregation

$$\frac{\partial}{\partial t}\ln\frac{E_t^*}{Y_t^*}=\underbrace{\frac{1}{|j|}\sum_j\frac{\partial}{\partial t}\ln\,\omega_{j,t}}_{\tilde{\Phi}^*}+\underbrace{\frac{1}{|j|}\sum_j\frac{\partial}{\partial t}\ln\,\xi_{j,t}}_{\tilde{\Psi}^*}. \tag{5}$$

It is important to note that $\tilde{\Phi}^*\neq\Phi^*$ and $\tilde{\Psi}^*\neq\Psi^*$. This is easy to see if we model the energy intensity of each broad sector in the same way as that of the entire economy, i.e., as the weighted sum of the detailed industries that it encompasses:

$$\xi_{j,t}=\frac{1}{|k\in j|}\sum_{k\in j}\lambda_{k,j,t}\varepsilon_{k,t}. \tag{6}$$

In this expression, industry k's weight ($\lambda_{k,j}$) is the ratio of its share of the output of sector j to its share of j's energy use. Expressing the weights ω and λ as functions of prices and the state of technology, substituting Eq. (6) into Eq. (5), and simplifying allow us to further decompose the broad structural and efficiency effects as follows:

$$\tilde{\Phi}^*=\underbrace{\frac{1}{|j|}\sum_j\omega_{j,t}^{-1}\frac{\partial\omega_{j,t}}{\partial\mathbf{P}}\cdot\dot{\mathbf{P}}}_{\tilde{\Phi}_P^*}+\underbrace{\frac{1}{|j|}\sum_j\omega_{j,t}^{-1}\frac{\partial\omega_{j,t}}{\partial\mathbf{T}}\cdot\dot{\mathbf{T}}}_{\tilde{\Phi}_T^*}, \tag{7a}$$

$$\tilde{\Psi}^*=\frac{1}{|j|}\sum_j\left[\begin{array}{l}\underbrace{\frac{1}{|k\in j|}\sum_{k\in j}\lambda_{k,j,t}^{-1}\frac{\partial\eta_{k,j,t}}{\partial P}\cdot\dot{\mathbf{P}}}_{\Phi'_{j,P}}+\underbrace{\frac{1}{|k\in j|}\sum_{k\in j}\lambda_{k,j,t}^{-1}\frac{\partial\eta_{k,j,t}}{\partial\mathbf{T}}\cdot\dot{\mathbf{T}}}_{\Phi'_{j,T}}\\ +\underbrace{\frac{1}{|k\in j|}\sum_{k\in j}\varepsilon_{k,t}^{-1}\frac{\partial\varepsilon_{k,t}}{\partial\mathbf{P}}\cdot\dot{\mathbf{P}}}_{\Psi'_{j,P}}+\underbrace{\frac{1}{|k\in j|}\sum_{k\in j}\varepsilon_{k,t}^{-1}\frac{\partial\varepsilon_{k,t}}{\partial\mathbf{T}}\cdot\dot{\mathbf{T}}}_{\Psi'_{j,T}}\end{array}\right]. \tag{7b}$$

These expressions make clear that changes in aggregate energy intensity are made up of:

- the effects of structural changes at the level of the broad sectors: $\tilde{\Phi}_P^*$ and $\tilde{\Phi}_T^*$;
- in each broad sector, the effects of sub-sectoral changes in the structure of output in detailed industries: $\Phi'_{j,P}$ and $\Phi'_{j,T}$; and
- in each broad sector, the effects of sub-sectoral changes in the efficiency of energy use in detailed industries: $\Psi'_{j,P}$ and $\Psi'_{j,T}$.

Two key implications follow from Eq. (7). First, the aggregate index of efficiency change may be thought of as the sum of the contributions of the price and technology effects in each broad sector, $\tilde{\Psi}_j^*=\Phi'_{j,P}+\Phi'_{j,T}+\Psi'_{j,P}+\Psi'_{j,T}$. These quantities will generally differ among sectors, a fact which calls into question the custom of simultaneously applying a uniform AEEI coefficient in the production functions of different industries. Second, a comparison with Eq. (3) reveals that when the characteristics of detailed industries are observed, the "true" disaggregate measures of the effects of structure and efficiency are $\Phi^*=\tilde{\Phi}_P^*+\tilde{\Phi}_T^*+\sum_j(\Psi'_{j,P}+\Psi'_{j,T})$ and $\Psi^*=\sum_j(\Psi'_{j,P}+\Psi'_{j,T})$. The implication is that the more highly aggregated the sectors j, the larger the bias in estimates of both aggregate structural change and sectoral efficiency change, as a result of misattribution of sub-sectoral shifts in the mix of industries to the latter. These are important results, which will figure prominently in our subsequent empirical and numerical analyses.

Although the CGE models' strength is their ability to capture the substitution effects associated with relative price movements, they have only limited ability to endogenously represent the impacts of technical advance. The substitution possibilities represented in a model's sectoral production functions therefore tend to capture the effect $(\Phi'_{j,P}+\Psi'_{j,P})$ but omit $\Phi'_{j,T}$ and $\Psi'_{j,T}$, while its intersectoral supply–demand linkages reflect $\tilde{\Phi}_P^*$ but not $\tilde{\Phi}_T^*$. The challenge for empirical analysis is to separately identify the components $\Phi'_{j,T}$, $\Psi'_{j,T}$ and $\tilde{\Phi}_T^*$. The missing effect of technological progress can then be captured by using these indices to adjust the coefficients of the model's production and demand functions over time.

In this regard, our previous results suffer from several limitations. First, they cannot be used to develop measures of the non-price components of either sub-sectoral changes in industrial composition, $\Phi'_{j,T}$, or broad structural change,

$\tilde{\Phi}_T^*$. We have not separately estimated the influences of variable input price changes, capital accumulation and technological progress on the impacts of changes in the weights $\lambda_{k,j}$ or ω_j. Consequently, we lack accurate estimates of the composite impact of non-price influences at the sub-sectoral level, $(\Phi'_{j,T} + \Psi'_{j,T})$.

We are able, however, to approximate the effect $\Psi'_{j,T}$. Our earlier econometric analysis, which regressed industries' energy–output ratios on variable input prices and the input quantities of five different types of capital, attributed observed changes in ε_k to the influences of substitution and capital accumulation. The regression equations also included a time trend, whose estimated coefficient, $\hat{\alpha}_{Etk}$, indicates the average secular trend in energy intensity which is customarily attributed to the effect of disembodied technological change. We therefore approximate the technological component of efficiency change in each broad sector as

$$\Psi'_{j,T} = \frac{1}{|k \in j|} \sum_{k \in j} \hat{\alpha}_{Etk} / \varepsilon_{k,t}. \tag{8}$$

We are careful to emphasize that Eq. (8) only captures the effect of disembodied technology, not innovation, which has been capitalized into industries' stocks of quasi-fixed inputs.

Our admittedly imperfect remedy to the lack of appropriate estimates is to compute indices of the combined price and non-price effects of structure and efficiency at the sub-sectoral level: $\Phi'_j = \Phi'_{j,P} + \Phi'_{j,T}$, $\Psi'_j = \Psi'_{j,P} + \Psi'_{j,T}$, $\partial \ln \xi_j/\partial t = \Phi'_j + \Psi'_j$ and $\Psi'_{j,T}$. We employ the latter two variables to bound the range of the AEEI in the sectoral production functions of a CGE model. In particular, $(\Phi' + \psi')$ assumes that the relevant sub-sectoral impacts are omitted entirely in the model's solution, while Ψ'_T assumes that they are fully incorporated. All of these measures are biased indicators of the true value of the AEEI. The first three will be contaminated by the influence of prices to an unknown degree, while the last omits the effects of non-price influences on sub-sectoral structural change. Nevertheless, this approach allows us to use the empirical estimates we have to at least partially constrain the range of values for the AEEI within various industries.

An additional problem is the lack of estimates of the technology component of the effects of structural changes at broad sectoral scales, $\tilde{\Phi}_T^*$. Historically, a powerful driver of the sectoral succession represented by this index has been changes in the final demands for industries' outputs associated with the introduction of new goods or improvements in the characteristics of existing commodities. In particular, the decline in energy's share of households' expenditure in conjunction with falling energy prices has been cited as evidence of energy-saving progress in the technology of consumption.[2] The implication is that the AEEI exists not only within industries, but at the level of final energy use as well. Indeed, the foregoing process has been parameterized using a secular decline in the coefficient on energy in models' end-use demand functions.[3]

We too adopt this strategy in an attempt to proxy for the effect of $\tilde{\Phi}_T^*$. The industry focus of our earlier analysis cannot be used to derive the necessary estimates of the AEEI for the household sector. Furthermore, it is not possible to disentangle how much of the decline in energy's share of consumption is due to technological progress alone without an additional, dedicated econometric analysis. Our partial solution is therefore to attribute the historically observed average change in energy's share of final expenditure to technical progress. As with our sectoral estimates above, this measure is contaminated by the influence of prices to an unknown degree. We attempt to mitigate this shortcoming by performing a sensitivity analysis which illustrates the effect of different values of the final-use AEEI on the emission projections of a CGE model.

2.2. Sectoral contributions to energy intensity change

We begin by accounting for the influence of technological progress on the contributions of broad sectors to changes in aggregate intensity. First, however, it is useful to review the results of our previous analysis, which computed chained indices of Φ^* and Ψ^* using data on the quantities of output and energy input for the 35 detailed industries in Table 1. These data are taken from the KLEM dataset developed by Jorgenson and associates.[4] We also constructed chained indices of the joint impact of changes in structure and efficiency $(\Phi^* + \Psi^*)$, and of the change in the aggregate energy–GDP ratio, $\partial \ln(E^*/Y^*)/\partial t$, which we compute using real GDP from the NIPAs and aggregate energy consumption from DOE/EIA (2004).

The results are shown in Fig. 1, which indicates that the marked reduction in aggregate energy 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 is largely offset by a decline in energy efficiency within industries. After the first 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 industries' energy efficiency rises rapidly until the end of the sample period, by which point their energy–output ratio is 25 percent below its 1958 level.

Moving to the level of broad sectors, we construct chained indices of the effects Φ', Ψ', $\partial \ln \xi_j/\partial t$ and $\Psi'_{j,T}$,

[2] In the US, a key aspect of this decline is the reduction in energy demand per unit of households' own-supplied transportation associated with long-run increases in the fuel efficiency of the passenger vehicle fleet. Schafer and Jacoby (2005) discuss the implications for the AEEI.

[3] E.g., Williams (1990) argues that the non-price-induced rate of improvement in the efficiency of final energy use is on the order of one percent.

[4] The dataset is described more fully in Sue Wing and Eckaus (2004).

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 and gas	Crude oil and gas
Natural gas	Natural gas
Petroleum	Petroleum
Electricity	Electricity
Energy-intensive mfg.	Paper and allied; chemicals; rubber and plastics; stone, clay and glass; primary metals
Manufacturing	Food and allied; tobacco; textile mill products; apparel; lumber and wood; furniture and fixtures; printing, publishing and allied; leather; fabricated metal; non-electrical machinery; electrical machinery; motor vehicles; transportation equipment and ordnance; instruments; misc. manufacturing
Transportation	Transportation
Services	Communications; trade; finance, insurance and real estate; government enterprises
Rest of economy	Metal mining; non-metal mining; construction

using the Jorgenson dataset and our previous econometric estimates of $\hat{\alpha}_{Etk}$. We present the results for the years 1980–1996, the period that is most recent (and therefore relevant) and coincides with a sustained reduction in aggregate energy intensity of the kind used to casually justify the existence of the AEEI. The set *j* is given by the 10 broad sectors in Table 1; however, 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.[5]

The results of our calculations are shown in Fig. 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.[6]

The influence of the changes in energy efficiency of the industries within each aggregate sector is shown in panel B. In line with Fig. 1, the economy-wide effect of these changes has been to substantially reduce the overall energy intensity, with the reductions in the rest-of-economy sector being the largest and those in 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 the estimated effects on changes in energy intensity due only to disembodied technological progress at the sub-sector level, which are perhaps the most surprising results. Overall, the effects of technological change are energy using. Indeed, the effect is energy saving only for the transportation sector. While technologically induced increases in energy intensity are modest in the manufacturing, energy-intensive and residual sectors, the effect in the service sector is substantial.[7]

The time series described above are summarized in Table 2 as annual average rates of change. The effects on energy intensity of the structural changes at the sub-sector level in panel A (Φ') are generally smaller in magnitude than those of the efficiency changes in Panel B (Ψ'). However, while the former effect has uniformly reduced the energy intensity of the aggregate sectors, the latter 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 have a mostly positive influence on the energy intensity of non-energy-supply sectors.

2.3. *Impacts of broad structural change on energy intensity*

Our final empirical task is to estimate how shifts in the structure of consumption might influence the effect of changes in the mix of broad industries on the energy–GDP ratio. To do this, we use data from the NIPAs to estimate the average annual rate of change in the consumption shares of our aggregate fuel sectors from 1980 to 2000. These rates of change are shown in Fig. 3. The shifts in the trends in consumption shares of 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.

[5] It is customary to omit the AEEI in the energy-supply sectors of a CGE model (see, e.g., Paltsev et al., 2005). Otherwise, its inclusion causes a reduction in the quantity of resource inputs necessary to produce energy commodities, which, along the solution trajectory, can create problems for energy and CO_2 accounting so much so that the models' economic solution may violate the laws of thermodynamics!

[6] Obviously, we cannot resolve structural changes within those sectors which correspond to detailed industry groupings in the Jorgenson dataset.

[7] 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.

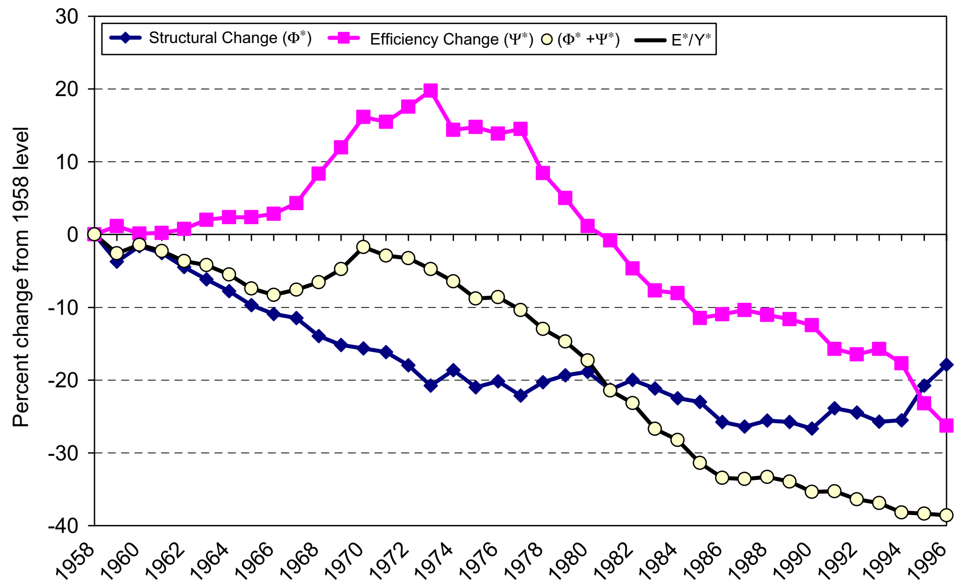

Fig. 1. Contribution of structural change (Φ^*) and efficiency change (Ψ^*) to the change in aggregate energy intensity (E^*/Y^*), 1958–1996. *Source*: Sue Wing and Eckaus (2004).

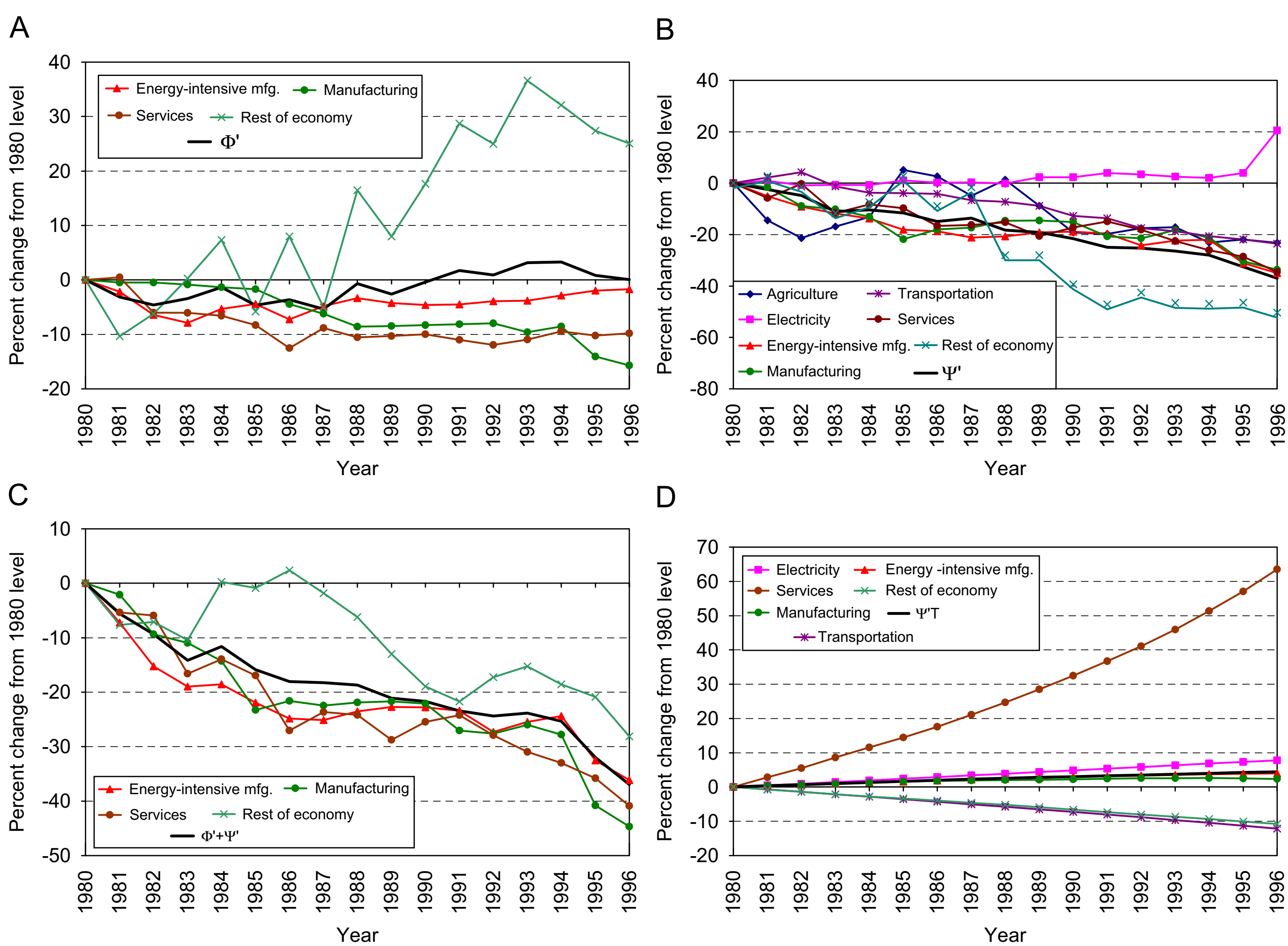

Fig. 2. Contributions of structural change (Φ_j') and intensity change (Ψ_j') to changes in industries' energy intensity, 1980–1996. (A) Effect of changing industrial composition (Φ_j'). (B) Pure within-industry energy intensity change (Ψ_j'). (C) Overall change in energy intensity ($\Phi_j' + \Psi_j'$). (D) Disembodied technical change component of Ψ_j'.

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 ($\Psi'_{j,T}$)[a]	E. Energy share of aggregate consumption expenditure[b]
Agriculture	—	−1.3	−1.3	—	—
Coal	—	−1.1	−1.1	−2.6	−5.82[c]
Crude oil and gas	—	3.3	3.3	3.6	—
Natural gas	—	4.4	4.4	−0.5	−1.99
Petroleum	—	0.3	0.3	—	−1.76
Electricity	—	1.2	1.2	0.5	−1.23
Energy-intensive industries	−0.1	−2.6	−2.7	0.2	—
Manufacturing	−1.0	−2.4	−3.5	0.1	—
Transportation	—	−1.6	−1.6	−0.8	—
Services	−0.6	−2.5	−3.1	3.1	—
Rest of economy	1.9	−3.8	−1.9	−0.7	—
Aggregate economy	0.0	−0.5	−0.5	0.3	—

[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.

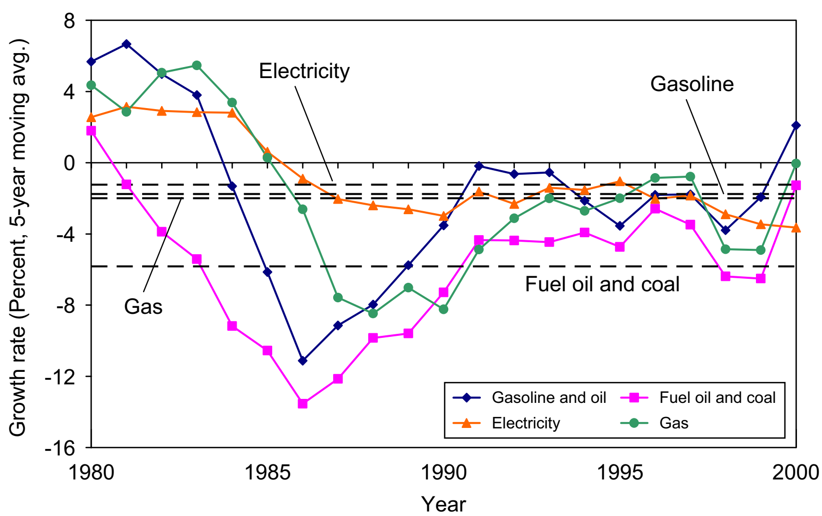

Fig. 3. Historical rates of change in the shares of energy commodities in final consumption (5-year moving averages). *Source*: Bureau of Economic Analysis and authors' calculations.

The dashed horizontal lines plotted in Fig. 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 re-emphasize that these averages reflect additional influences besides the effect of energy-saving technology. 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 are likely to overestimate the true impact of technology on the coefficients on energy goods in consumers' demand functions.

We now turn to the question of what these results imply for the projection of CO_2 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 US. 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 5-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 Appendix A.

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.[8] Using the empirical estimates developed in Section 2, we conduct a number of numerical experiments, whose characteristics are described in the cases outlined in Table 3. Focusing first on the industries in the economy, we first simulate a control run with no AEEI (I), before setting the AEEI to the commonly used value of one percent in non-energy sectors (II). Runs III and IV assess the implications of using our empirical results to bound the values of the AEEI. Here, the values of the AEEI in non-energy sectors equal the rates of change of the components of energy intensity given in panels C and D of Table 2, respectively. Lastly, in run V, we investigate the importance of differentiating the AEEI by sector. We perform a simulation with a uniform AEEI coefficient equal to the average rate of decline in aggregate energy intensity in run III.[9]

We repeat these five runs for three settings of the AEEI in the household sector: (a) no trend in energy's share of consumption, (b) a common one-percent decline in the consumption of all energy commodities and (c) reductions in the coefficients on energy in the household's expenditure function at the rates of historical decline given in Fig. 3.

Finally, in order to evaluate the reasonableness of the model results, we need a yardstick against which to judge their performance. As the model simulates the growth of GDP, energy use, intensity and CO_2 emissions over the coming half-century, a natural candidate for a counterfactual is the corresponding rates of change in these variables over the past 50 years, which are shown in Fig. 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. But assuming that the future projections ought to be consistent with these trends is not without controversy, as Section 4 illustrates.

Table 3
Experiments with the numerical model

Case	Growth rate of AEEI
Industries (all industries except fossil fuel supply sectors)	
I	None
II	Average rate of 1 percent per year, applied equally across sectors
III	Average rate of sectoral energy intensity change ($\Phi' + \Psi'$), differentiated by sector
IV	Disembodied technical progress component of sectoral intensity change (Ψ'_{TECH}), differentiated by sector
V	Average rate of aggregate energy intensity change in III, applied equally across sectors
Consumption	
(a)	None
(b)	1 percent per year
(c)	Average annual rate of change in consumption expenditures by fuel

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 in the household sector.

Panel A of the table summarizes the feedback effect of the assumed improvements in energy intensity on GDP. In the base case where the AEEI is zero within industries (Case I(a)), the annual rate of GDP growth falls from 3.5 percent in 2010 to 3.1 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. Likewise, GDP growth rates in cases II(a) and III(a) with larger AEEI values are slightly higher. Case IV(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 sector, manufacturing industries and, especially, services. 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 very slight.

[8]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.

[9]We thank a referee for suggesting this test to us.

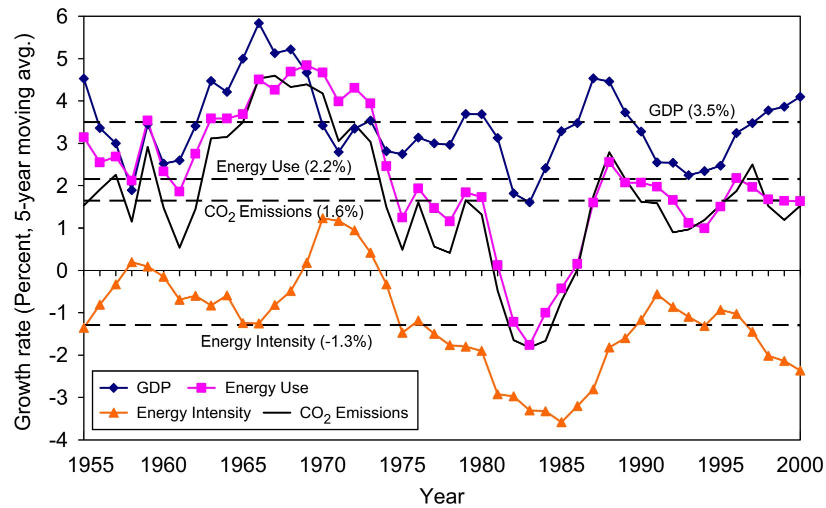

Fig. 4. Historical rates of change of GDP, energy use, energy intensity and CO_2 emissions (5-year moving averages). *Sources*: Real GDP—Bureau of Economic Analysis; Energy use—DOE/EIA (2004); CO_2 emissions—Marland et al (2003).

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	3.3	3.1	3.3	3.1	2.9	−0.2	−0.2	−0.2	3.5	3.2	3.0
II(a)	3.6	3.4	3.2	2.8	2.7	2.6	−0.7	−0.6	−0.6	2.8	2.6	2.5
III(a)	3.5	3.3	3.2	3.1	2.9	2.7	−0.4	−0.4	−0.4	3.1	2.9	2.7
IV(a)	3.5	3.2	2.9	3.9	3.9	4.0	0.4	0.7	1.0	4.1	4.2	4.2
V(a)	3.5	3.3	3.2	3.1	2.9	2.7	−0.5	−0.4	−0.4	3.1	2.9	2.7
I(b)	3.6	3.4	3.2	3.0	2.9	2.7	−0.5	−0.5	−0.4	3.1	3.0	2.8
II(b)	3.6	3.4	3.2	2.5	2.4	2.2	−1.1	−1.0	−0.9	2.4	2.3	2.2
III(b)	3.6	3.4	3.2	2.8	2.6	2.5	−0.8	−0.8	−0.7	2.8	2.6	2.5
IV(b)	3.5	3.2	2.9	3.6	3.8	4.0	0.1	0.5	1.0	3.8	4.1	4.2
V(b)	3.6	3.4	3.2	2.7	2.6	2.4	−0.8	−0.8	−0.7	2.8	2.6	2.4
I(c)	3.6	3.4	3.2	2.8	2.7	2.7	−0.7	−0.6	−0.5	2.9	2.9	2.7
II(c)	3.6	3.4	3.2	2.3	2.2	2.1	−1.3	−1.2	−1.1	2.2	2.1	2.0
III(c)	3.6	3.4	3.2	2.6	2.5	2.3	−1.0	−0.9	−0.8	2.6	2.5	2.3
IV(c)	3.5	3.2	2.9	3.4	3.7	4.0	−0.1	0.5	1.0	3.7	4.0	4.3
V(c)	3.6	3.4	3.2	2.5	2.5	2.3	−1.0	−0.9	−0.8	2.6	2.5	2.3

The specification of the AEEI does have important consequences for the growth rate of aggregate energy use, however, as panel B illustrates. Again, with the exception of Case IV(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 10 percent smaller than in Case I(a). A uniform one-percent AEEI value (Case III(a)) has the strongest influence in this regard, while for the reasons cited above technical progress alone (Case IV(a)) has the opposite effect of increasing the growth of energy use relative to the baseline.

As indicated in Panel C, these changes in energy use generally 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 relative prices of energy inputs to production and consumption, which induces substitution toward non-energy commodities. As with total energy, the largest reductions in intensity occur in the early periods before onset of the deceleration in GDP growth. By the end of the simulation horizon, an AEEI of one percent (Case II(a)) results in the largest decline in intensity, while setting the AEEI at the rate attributed to technical progress alone (Case IV(a)) generates a sizeable intensity increase.

The effects of the AEEI on the growth of CO_2 emissions, shown in Panel D, are similar to its influences on energy. Like aggregate energy use, declining growth rates of emissions occur everywhere except case IV. Emissions grow fastest when 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 when structural and efficiency changes are attributed to the AEEI, while setting the AEEI to one percent yields the slowest growth in emissions.

An interesting feature of the table is that the simulated growth rates of aggregate variables in Cases III and V are almost identical. This result suggests that our empirically based estimates produce different trajectories of energy use and emissions because of the difference in the magnitude of their aggregate energy-saving effect, as opposed to the manner in which such influences are distributed across sectors with heterogeneous demands for fossil fuels with different carbon contents.

Overall, the model results are more consistent with historical average growth rates in their projections of GDP than either energy use or CO_2 emissions. Such overestimation of energy and emissions relative to historical trends is precisely the problem that motivates the need for the AEEI, and is an issue to which we return below.

First, however, we examine the results of the simulations in which the value of the AEEI for the final consumption of energy goods was set at one percent (the (b) cases). 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–V 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, the growth of energy use and emissions slows by 6–7 percent and the rate of decline in energy intensity more than doubles relative to the corresponding scenarios with a household sector AEEI of zero. In Case IV, there is a substantial attenuation of growth in the level and intensity energy use early in the simulation, but not in later periods. Setting industries' AEEI values at one percent results 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 structural and efficiency change (Case III(b)) slows the increase of energy and emissions by 10–14 percent relative to the corresponding earlier case.

The resulting 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 away from energy. The simulated rates of growth of energy use are within a few tenths of a percent of the historical long-run average, especially in Case II(b). However, simulated trajectories of emissions still increase at rates 35–165 percent faster than projections based on history would suggest.

The last five rows of Table 4 summarize the effects 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 patterns in these results mirror those just discussed for the (b) cases, GDP growth rates remain essentially unchanged, while the growth rates of aggregate energy use and emissions slow by a further 2–6 percent. As before, the results of Case II(c), in which the combined effects of structural change and efficiency improvement are attributed to the AEEI, match the historical growth of energy use most closely. But even here the simulated growth rates of emissions remain some 25–167 percent higher than seen in recent history.

Despite the fact that the trends in the aggregate variables simulated in the Case (c) model runs 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 (Fig. A-2), final demands account for half of total electricity use, one third of total petroleum and natural gas use and only a negligible fraction of coal use. The large values for the AEEI in the household sector therefore directly influence only a fraction of the least polluting components of aggregate energy demand (i.e., petroleum and natural gas), while their strongest influence on carbon emissions remains indirect, reducing the demand for electricity generated from coal.

Our assessments of the agreement between historical trends and the GDP, energy use and emissions series produced by the model under the various parameter assumptions are summarized in Table 5. Our goodness-of-fit statistic 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.[10]

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 six percent, as indicated by panel A of

[10]A more traditional method of establishing the consistency between the model's solution and historical trends is backcasting analysis (see, e.g., Dowlatabadi and Oravetz, 2006). We do not undertake such analysis here due to the considerable effort necessary to make valid comparisons between model results and observations. Of particular concern is the need to control for factors that CGE simulations will have difficulty capturing endogenously, such as historical shifts in industry structure, exogenous price shocks, or non-market influences such as regulatory changes. To fully elucidate the implications of these forces for model construction and calibration requires a separate investigation, which we defer to future research.

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)	0.062	0.487	−0.893	1.041
II(a)	0.056	0.274	−0.527	0.643
III(a)	0.058	0.375	−0.698	0.834
IV(a)	0.105	0.848	−1.601	1.611
V(a)	0.058	0.372	−0.692	0.828
I(b)	0.056	0.358	−0.660	0.865
II(b)	0.051	0.116	−0.239	0.423
III(b)	0.053	0.232	−0.439	0.636
IV(b)	0.096	0.777	−1.467	1.518
V(b)	0.053	0.228	−0.432	0.629
I(c)	0.055	0.291	−0.550	0.781
II(c)	0.051	0.039	−0.105	0.305
III(c)	0.052	0.155	−0.312	0.535
IV(c)	0.094	0.747	−1.415	1.480
V(c)	0.052	0.150	−0.305	0.528

[a]Coefficient of variation $= 1/\tilde{x}\sqrt{\sum_{t=1}^{T}(x_t - \tilde{x})^2/(T-1)}$, where x is the simulated average annual rate of change for the variable in question, $\tilde{x}$ is the corresponding historical average rate of change from Fig. 4, and $t = \{1,\ldots, T\}$ is the number of future periods projected by the model.

the table. Nonetheless, we consider our results to be a reasonable approximation, considering the limitations of our empirical estimates and modeling approach.

By comparison, panel B indicates much less agreement between the simulated trajectory of energy use and the historical trend. Across cases I–V 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 have prevailed historically. This phenomenon is most apparent 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 one-percent consensus value, or where it is attributed to sub-sectoral changes in the energy intensity within industries. Viewed in the context of Eq. (7), 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 in the model. A household sector AEEI value of zero gives rise to CVs on the order of 27–85 percent. Increasing the value of this parameter to one percent lowers the range of average deviations to 11–77 percent, while specifying the AEEI as the historical rates of change of energy expenditure shares gives rise to deviations of 4–75 percent. As the results in panel C illustrate, the implication is that these AEEI values in the household sector 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.

We 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 work.

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 shifts toward more carbon-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 understand the origins of this phenomenon we examine the details of the model's solutions.

Table 6 summarizes the average rates of growth of the prices and quantities of energy commodities across our suite of model runs. The prices of energy commodities tabulated in panel A change very little over time. In all cases, the price of electricity declines and the price of coal increases monotonically throughout the simulation. The patterns of growth in coal and electricity prices are largely insensitive to the different specifications of the AEEI in the household sector. However, the latter is much more responsive to the specification of the AEEI across industries. The price indices for petroleum, natural gas and aggregate energy behave similarly to one another. In the absence of an AEEI in the household sector, these prices generally increase, where the AEEI for industries is zero or energy-using (Cases I and VI) and for the most part decline where it is energy-saving (Cases II, III and V), but exhibit 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 the quantities of energy commodities tabulated in panel B explain the progressive increase in CO_2 emissions relative to energy use. Despite the rapid rise in coal's price, demand for that fuel increases substantially in the majority of simulations. The origin of this behavior is the high value of the resource supply elasticity parameter in the coal sector relative to that for crude oil and gas mining.[11] Additionally, the low value of this elasticity in

[11]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

Table 6
Simulated average annual growth rates of prices and quantities for Armington energy commodities (percent)

	A. Prices					B. Quantities			
	Coal	Electricity	Gas	Oil	Fossil fuel[a]	Coal	Electricity[b]	Gas	Oil
I(a)	0.33	−0.38	0.06	0.01	0.08	3.3	2.3	3.2	3.3
II(a)	0.07	−0.57	−0.03	−0.10	−0.11	2.1	2.7	2.9	2.9
III(a)	0.20	−0.48	0.01	−0.05	−0.02	2.7	2.5	3.0	3.1
IV(a)	0.68	−0.25	0.20	0.16	0.33	4.7	2.2	4.0	3.7
V(a)	0.19	−0.49	0.01	−0.05	−0.03	2.7	2.6	3.0	3.1
I(b)	0.29	−0.38	0.00	−0.06	0.02	3.0	2.2	2.9	3.0
II(b)	0.02	−0.57	−0.11	−0.20	−0.19	1.8	2.5	2.4	2.6
III(b)	0.15	−0.48	−0.06	−0.13	−0.09	2.4	2.4	2.6	2.8
IV(b)	0.66	−0.25	0.16	0.12	0.31	2.4	2.4	2.6	2.8
V(b)	0.14	−0.48	−0.06	−0.13	−0.09	2.4	2.4	2.6	2.8
I(c)	0.28	−0.38	−0.04	−0.10	−0.01	3.0	2.2	2.6	2.9
II(c)	0.00	−0.57	−0.16	−0.26	−0.23	1.8	2.4	2.1	2.4
III(c)	0.14	−0.48	−0.10	−0.18	−0.13	2.4	2.4	2.3	2.6
IV(c)	0.65	−0.24	0.14	0.09	0.00	4.5	2.2	3.7	3.4
V(c)	0.13	−0.48	−0.10	−0.19	−0.13	2.4	2.4	2.3	2.6

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

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 prices, the growth rates of the quantities of coal and primary electricity are insensitive to the magnitude 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 Case II, 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. Interestingly, the growth rates of petroleum and natural gas use are similar when the household sector's AEEI is zero, but when this parameter increases the growth rates diverge, with a clear substitution away from natural gas. 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 examine the influence of the nested structure of production and the values of the elasticities of substitution on the emission intensity of energy use. However, in the interest of conserving space we leave such experiments to future research.

The final step in our analysis is to examine the implications for projections of energy use and emissions, which are summarized in Fig. 5. Short dashes indicate the series corresponding to AEEI values which reflect the joint effect of sub-sectoral structural and efficiency changes (Case III). Long dashes identify the series with the slowest increases of energy and emissions, which correspond to the one-percent value for the AEEI (Case II). Solid lines identify the series with the fastest increases of energy and emissions, which reflect the isolated technological component of efficiency changes in detailed industries (Case IV). Squares, diamonds and triangles indicate, respectively, the series for which the rate of decline of the coefficient on energy goods in the household sector is zero, one percent, or given by the historical averages in Table 2.E. By way of comparison, the crosses illustrate the 5-year data points of the reference case energy and emissions forecasts from the 2007 Annual Energy Outlook (DOE/EIA, 2007), while the heavy solid lines are the projections of these variables from benchmark levels using the corresponding historical rates of growth.

The ranges of projections of energy use and emissions are spanned by Cases II and IV, in 2050 extending from 310 to 706 exajoules (EJ) of energy and 16.5–44.6 GT of CO_2. This divergence indicates the importance of assumptions about the character and magnitude of non-price influences, and suggests that the effect on aggregate energy use and emissions of the AEEI within sectors is six times as large as that of the AEEI in consumption. Even so, our model projections are uniformly higher than EIA's forecasts, which, notably, lie below the historical trends. By 2050, the latter predict energy use of 138 EJ and CO_2 emissions of 8 GT for the US economy. In that year, the gap between the projection of history and the closest simulated trajectory (Case II(c)) for energy is 62 EJ, or 31 percent of the historical benchmark, while for emissions the

(*footnote continued*)
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). To test whether the results were being driven by this parameter, we simulated the cases discussed in the text with η_R set to 0.5, or 25 percent of its benchmark value. The resulting growth rates of aggregate energy use were only slightly smaller than those reported in the text.

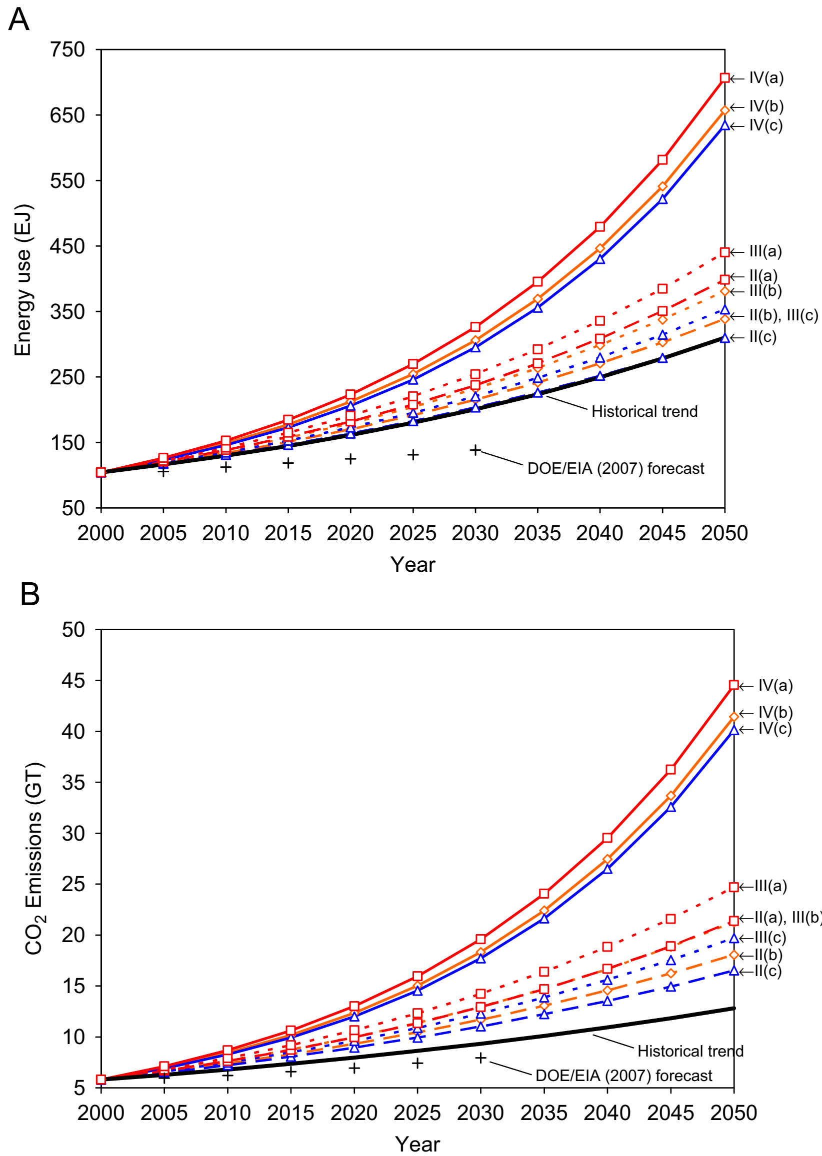

Fig. 5. The range of uncertainties in model projections: (A) energy use and (B) emissions.

more carbon-intensive fuel mix accounts for a minimum deviation of 3.1 GT of emissions, or 33 percent of the historical benchmark.

These results suggest that the disposition of future energy supplies is likely to result in significantly higher CO_2 emissions than has been the case in recent history, despite substantial energy-saving structural and technological change. Of course, there are numerous reasons why one might expect the future to differ from the past. If technological progress in oil and gas mining does not keep pace with the depletion of the petroleum resource base then the long-run marginal costs and relative prices of these commodities will rise over time, inducing firms to substitute toward coal. One might also expect less vigorous substitution of less carbon-intensive forms of energy for coal in the future due to the low likelihood of additional environmental restrictions on coal use on the scale of those in the past 50 years.[12]

Nevertheless, we cannot rule out the possibility that this puzzling feature of our simulation is simply the result of misspecification of the CGE model's structure and parameters, especially if projections based on history are considered "truth". We have noted that our empirical estimates do not resolve the technological components of structural change, either at the sub-sectoral level or across broad sectors. Remedies for these shortcomings await further econometric investigation. An additional issue, which we have not discussed is embodied technical change. Our previous econometric research found that the accumulation of certain types of capital—particularly information

[12]E.g., outright bans on the use of coal in the household sector.

technology and electrical equipment—were associated with substantial energy efficiency improvements within detailed industries. Integrating these kinds of estimates into our simulations must await the construction of a more complicated CGE model capable of resolving several classes of capital assets in each sector.

5. Conclusions

Our main results may be summarized as follows. First and foremost, in multi-sectoral top-down emission projection models, the customarily employed values for the AEEI—whether differentiated by industry sector or specified as a "one-size-fits-all" parameter—are unlikely to generate trajectories of energy use and CO_2 emissions which are consistent with historical trends. Although changes in both the price- and non-price components of movements in energy intensity within detailed industry groupings exhibit substantial inter-sectoral variability, which suggests that the AEEI is more appropriately modeled as a vector of values with heterogeneous signs and magnitudes applied to different industries, our simulation results indicate that the AEEI's aggregate energy-saving impact (not its inter-industry distribution) exerts a far larger influence on energy and emission projections.

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 structural changes appear to play an important role in not only reducing aggregate energy intensity but also moderating the growth of CO_2 emissions. When we incorporate our empirical results into a CGE model of the US economy, the influence of disembodied technological change on aggregate trends in energy use and CO_2 emissions is the opposite of the conventional one percent per year value of the AEEI. Conversely, attributing sub-sectoral changes in structure and efficiency to the AEEI generates faster reductions in aggregate energy and emissions than does its conventional counterpart.

Third, projections of energy use and emissions are sensitive to changes in the mix of broad sectors in the economy, an influence which is parameterized via the AEEI in 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 widens the gap between the results generated using the conventional AEEI and those arising from its specification purely as an industry phenomenon. Across the range the computational experiments conducted, the simulations that included an AEEI for the household sector exhibited trends of energy use that were consistent with projections of historical rates of growth.

Fourth, even in the latter cases, emissions might still increase much more rapidly compared to 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 based on a variety of factors it seems 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 general cautions for modelers from this exercise. In models with highly aggregated sectors, which employ the conventional specification for the AEEI, the inability to represent inter-sectoral differences in the drivers and effects of sub-sectoral structural change may well result in biased estimates of the future decline in aggregate energy intensity. The implications for CO_2 emission projections are equivocal, because they depend on the way in which the AEEI interacts with the details of model's sectoral aggregation, as well as the structural and parametric attributes of the model's production and demand functions. 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 one percent AEEI value may drastically overstate potential reductions in energy intensity, biasing emission projections downward.

Finally, these conclusions are subject to the caveats that the empirical estimates incorporated into our model do not resolve the technological components of structural change, either at the sub-sectoral level or across broad sectors, nor do they capture the influence of embodied technical change at the sectoral level. Addressing these limitations will likely prove a fruitful area for future econometric and simulation studies.

Acknowldgements

ISW was supported by US Department of Energy Office of Science (BER) Grants nos. DE-FG02-02ER63484 and DE-FG02-06ER64204, as well as a REPSOL-YPF Harvard Kennedy School Energy Fellowship. This paper has benefited from comments and suggestions by Philippe Thalmann, Jake Jacoby, Laurent Viguier, an anonymous referee, and participants at the NCCR Climate Symposium on 3–5 March 2005 in Interlaken, Switzerland, at which a preliminary version was presented. Errors and omissions remain the sole responsibility of the authors.

Appendix A

The simulations in the paper are constructed using a simple recursive-dynamic CGE simulation of the US 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 5-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 the one used in Sue Wing (2007), which models the US as an open economy in the same way as 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, the demand for which is assumed to evolve exogenously at the rate of GDP growth. Aggregate investment and government output are produced according to CES 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 Fig. A1, 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 $\sigma_{F\text{–}NF} \gg 1$, 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 and Hansen, 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 non-linear 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.

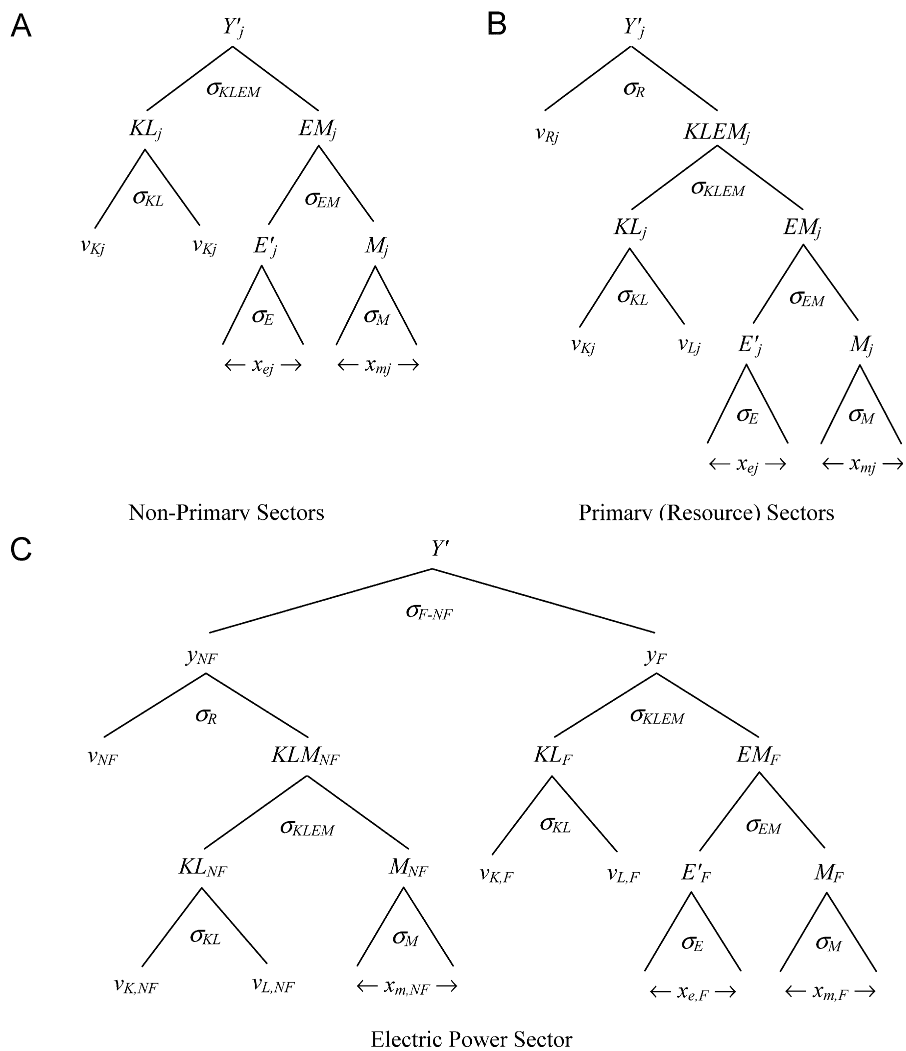

Fig. A1. . Structure of production in the CGE Model.

The equilibrium system described above is numerically calibrated on a social accounting matrix (SAM) for US economy in the year 2000, using values for the elasticities of substitution (based on Bovenberg and Goulder, 1996) and factor supply summarized in Table A1. 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 US 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 Fig. A2, along with the parameters in Table A1, 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).

Table A1
Substitution and supply elasticities

Sector	σ_{KL}[a]	σ_E[b]	σ_A[c]	σ_R[d]	η_R[e]	χ_E[f]	χ_C[g]	All sectors	
Agriculture	0.68	1.45	2.31	0.4	0.5	–	–	σ_{KLEM}[h]	0.7
Crude oil and gas	0.68	1.45	5.00	0.4	1.0	–	–	I_{EM}[i]	0.7
Coal	0.80	1.08	1.14	0.4	2.0	1.0956	0.0969	I_M[j]	0.6
Refined oil	0.74	1.04	2.21	–	–	0.2173	0.0131	I_T[k]	1.0
Natural gas	0.96	1.04	1.00	—	–	0.2355	0.0116	η_L[l]	0.3
Electricity	0.81	0.97	1.00	0.4	0.5	0.2381	–	Electricity	
Energy intensive mfg.	0.94	1.08	2.74	–	–	–	–	I_{F-NF}[m]	10
Transportation	0.80	1.04	1.00	–	–	–	–	Final demand	
Manufacturing	0.94	1.08	2.74	–	–	–	–	I_C[n]	0.5
Services	0.80	1.81	1.00	–	–	–	–	I_I[o]	0.5
Rest of the economy	0.98	1.07	1.00	0.4	1.0	–	–	I_G[p]	0.5

[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.
[n]Elasticity of substitution among inputs to consumption.
[o]Elasticity of substitution among inputs to investment.
[p]Elasticity of substitution among inputs to government activity.

	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

Fig. A2. . Year 2000 social accounting matrix for the US (2000 Dollars × 10^{10}).

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[13]

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

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

$$KS(t + 1) = I(t) + (1 - \delta)KS(t), \tag{A-2}$$

in which I denotes the value of the supply of investment. In each period, the demands for investment and the government good are specified within the static equilibrium sub-problem through an ad-hoc side-constraint that attempts to maintain the economy on a balanced growth path

$$\frac{C(t)}{C(0)} = \frac{I(t)}{I(0)} = \frac{G(t)}{G(0)}, \tag{A-3}$$

where C and G denote aggregate final consumption and government output, respectively.

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 Fig. 4.[14]

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 (χ_E) and emissions-output factors (χ_C), 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 carbon emission content of these goods in the benchmark year.[15] The resulting coefficients, whose values are shown in Table A1, are applied to the quantities of the corresponding Armington energy goods solved for by the model at each time-step.

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

[14]Other forecasts such as the Annual Energy Outlook (DOE/EIA, 2007) typically embody slower rates of GDP growth, on the order of 2.5–3 percent per annum.

[15]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, US primary energy demands for coal, petroleum and natural gas and electricity were 23.9, 40.5, 25.2, and 14.8 EJ, 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

Armington, P.S., 1969. A theory of demand for products distinguished by place of production. IMF Staff Papers 16, 159–178.

Bernstein, P.M., Montgomery, W.D., Rutherford, T.F., 1999. Global impacts of the Kyoto agreement: results from the MS-MRT model. Resource and Energy Economics 21 (3–4), 375–413.

Bovenberg, A.L., Goulder, L.H., 1996. Optimal environmental taxation in the presence of other taxes: general-equilibrium analyses. American Economic Review 86 (4), 985–1000.

Boyd, G.A., Roop, J.M., 2004. A note on the fisher ideal index decomposition for structural change in energy intensity. Energy Journal 25 (1), 87–101.

Brooke, A., Kendrick, D., Meeraus, A., Raman, R., 1998. GAMS: A User's Guide. GAMS Development Corp, Washington, DC.

Dahl, C.A., Duggan, T.E., 1996. US energy product supply elasticities: a survey and application to the US oil market. Resource and Energy Economics 18 (3), 243–263.

Dirkse, S.P., Ferris, M.C., 1995. The PATH solver: a non-monotone stabilization scheme for mixed complementarity problems. Optimization Methods and Software 5, 123–156.

DOE/EIA, 2003. Emissions of Greenhouse Gases in the United States 2002. DOE/EIA-0573(2002), Washington, DC.

DOE/EIA, 2004. Annual Energy Review 2003. DOE/EIA-0384(2003), Washington, DC.

DOE/EIA, 2007. Annual Energy Outlook 2007. DOE/EIA-0383(2007), Washington, DC.

Dowlatabadi, H., Oravetz, M.A., 2006. US long-term energy intensity: backcast and projection. Energy Policy 34, 3245–3256.

Edmonds, J., Reilly, J.M., 1985. Global Energy: Assessing the Future. Oxford University Press, New York.

Harrison, G.W., Rutherford, T.F., Tarr, D.G., 1997. Quantifying the Uruguay Round. Economic Journal 107 (444), 1405–1430.

Hogan, W.W., Jorgenson, D.W., 1991. Productivity trends and the cost of reducing carbon dioxide emissions. Energy Journal 12 (1), 67–85.

Hollmann, F.W., Mulder, T.J., Kallan, J.E., 2000. Methodology and Assumptions for the Population Projections of the United States: 1999–2100. US Census Bureau, Population Division Working Paper No. 38.

Jorgenson, D.W., 1984. The role of energy in productivity growth. In: Kendrick, J.W. (Ed.), International Comparisons of Productivity and Causes of the Slowdown. Ballinger, Cambridge, MA, pp. 279–323.

Jorgenson, D.W., Fraumeni, B.M., 1981. Relative prices and technical change. In: Berndt, E., Field, B. (Eds.), Modeling and Measuring Natural Resource Substitution. MIT Press, Cambridge, MA, pp. 17–47.

Manne, A.S., Richels, R.G., 1990. CO_2 emission limits: an economic cost analysis for the USA. Energy Journal 11 (2), 51–74.

Marland, G., Boden, T.A., Andres, R.J., 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 National Laboratory, Oak Ridge, TN.

Mathiesen, L., 1985a. Computational experience in solving equilibrium models by a sequence of linear complementarity problems. Operations Research 33, 1225–1250.

Mathiesen, L., 1985b. Computation of economic equilibria by a sequence of linear complementarity problems. Mathematical Programming Study 23, 144–162.

McFarland, J., Reilly, J.M., Herzog, H.J., 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Economics 26 (4), 685–707.

Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J., Sarofim, M., Asadoorian, M., Babiker, M., 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, MIT Joint Program on the Science and Policy of Global Change Report No. 125.

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.

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

Schafer, A., Jacoby, H.D., 2005. Technology detail in a multi-sector CGE model: transport under climate policy. Energy Economics 27, 1–24.

Sue Wing, I., 2001. Induced technical change in computable general equilibrium models for climate policy analysis. Unpublished Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

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.

Sue Wing, I., 2007. The synthesis of bottom-up and top-down approaches to climate policy modeling: electric power technologies and the cost of limiting US CO_2 emissions. Energy Policy, in press.

Sue Wing, I., Eckaus, R.S., 2004. Explaining long-run changes in the energy intensity of the US economy. MIT Joint Program on the Science and Policy of Global Change Report No. 116, Cambridge, MA.

Weyant, J.P., 2000. An Introduction to the economics of climate change policy. Pew Center on Global Climate Change Report.

Williams, R.H., 1987. A low energy future for the United States. Energy 12, 939–944.

Williams, R.H., 1990. Low-cost strategies for coping with CO_2 emission limits. Energy Journal 11, 35–59.

Williams, R.H., Larson, E., Ross, M., 1987. Materials, affluence, and industrial energy use. Annual Review of Energy 12, 99–144.