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Impact of Carbon Price Policies on U.S. Industry

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RESOURCES FOR THE FUTURE

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Abstract

This paper informs the discussion of carbon price policies by examining the potential for adverse impacts on domestic industries, with a focus on detailed sector-level analysis. The assumed policy scenario involves a unilateral economy-wide \$10/ton CO_2 charge without accompanying border tax adjustments or other complementary policies. Four modeling approaches are developed as a proxy for the different time horizons over which firms can pass through added costs, change input mix, adopt new technologies, and reallocate capital. Overall, we find that a readily identifiable set of industries experience particularly adverse impacts as measured by reduced output and that the relative burdens on different industries are remarkably consistent across the four time horizons. Output rebounds considerably over longer time horizons, and the adverse impacts on profits diminish even more rapidly in most cases. Over the short term employment losses mirror output declines, while gains in other industries fully offset the losses over the longer horizons. At the same time, leakage abroad is considerable in some sectors, particularly when reductions in exports are considered.

Key Words: carbon price, competitiveness, input-output analysis

JEL Classification Numbers: F14, D 21, D57, D58, H23

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Executive Summary

As the United States moves toward mandatory action on climate change, an important consideration is the potential for new policies to cause significant declines in some domestic industries, with corresponding increases in imports and production elsewhere in the world. This is especially the case if the policy is unilateral, without a corresponding effort from U.S. trading partners.

This possibility gives rise to two serious concerns:

- potential damage to the domestic economy, especially to the subset of industries that may be vulnerable to unilateral, or near unilateral, carbon mitigation policies; and
- erosion of a domestic policy's environmental benefits if an increase in domestic production costs causes manufacturing to shift to nations that have weaker greenhouse gas (GHG) mitigation policies or none at all.

The effects of a unilateral policy placing a price on carbon dioxide (CO_2) will vary greatly across domestic industries. The industry-level impacts are fundamentally tied to the energy (more specifically, the carbon) intensity of those industries and the degree to which they can pass costs on to consumers of their products (often other industries). The strength of competition from imports and consumers' ability to substitute other, less carbon-intensive alternatives for a given product play crucial roles in determining the ultimate impacts on domestic production and employment.

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The potential economic consequences for U.S. industry are unprecedented in the history of environmental regulation due to the scale of activity affected by a unilateral, economywide CO_2 pricing policy. It would not only have significant direct impacts on coal, and other domestic energy industries, it could adversely affect the competitiveness of a number of large energy-intensive, import-sensitive manufacturing industries. Unfortunately, information concerning specific industry-level impacts associated with new carbon mitigation policies is quite limited.

The most common approach to assessing the impact of carbon-control policies is to focus on the long-run impacts, after firms have adjusted by using new energy-efficient technologies and new import patterns have been established. Such analysis, however, fails to capture an important part of the story—the short-run costs that most firms will experience. A chemical or steel plant suddenly faced with higher energy costs cannot immediately or costlessly convert to more energy-efficient methods.

From a policy perspective, the path taken to the long-run outcome is extremely important. A carbon control policy that ignores these short- and medium-term impacts will raise concerns about fairness and will likely be opposed by many stakeholders. Further, the appropriate policy response can change over time; a policy that addresses fairness questions in the initial years may not be appropriate in the future.

We recently examined how a unilateral, economywide CO_2 pricing policy would affect a large set of industries, taking into account the ways that adjustment costs may change over time. To paint a full picture, we employed four different modeling approaches using consistent assumptions in order to consider outcomes along four different time scales:

1. The very short run, where firms cannot adjust prices and profits fall accordingly.
2. The short run where firms can raise prices to reflect the higher energy costs, with a corresponding decline in sales as a result of product or import substitution.
3. The medium run, when in addition to the changes in output prices, the mix of inputs may also change, but capital remains in place, and economywide effects are considered.
4. The long run, when capital may be reallocated and replaced with more energy efficient technologies.

Impacts were measured in terms of costs, profits, employment, and trade effects, assuming a unilateral \$10/ton CO_2 price without any offsetting measures regarding permit allocation or border adjustments and without any stipulated policies by trading partners.

Findings

After examining these different time horizons and impacts, our results yield a number of observations. (For more details, see tables at end of full paper.)

- **Measured by the reduction in domestic output, a readily identifiable set of industries is at greatest risk of contraction over both the short and long terms.** Within the manufacturing sector, at a relatively aggregated, two- or three-digit standard industrial classification level, the hardest hit industries are: petroleum refining, chemicals and plastics, primary metals, and nonmetallic minerals.
- **Although the short-run output reductions are relatively large in these industries, they shrink over time as firms adjust inputs and adopt new technologies.** The industries that continue to bear the impacts are generally the same ones affected initially, albeit at reduced levels. When measured in terms of reduced profits, the rebound is especially large and, for some industries, virtually complete.
- **Focusing on the nearer-term timeframes, where certain simplifying assumptions enable us to conduct a more disaggregated analysis, we observe that the largest cost increases are concentrated in particular segments of these industries.** Using a broad definition of costs that includes capital inputs, petrochemical manufacturing and cement see very short-run cost increases of more than four percent from a modest charge of $10 per ton of CO_2, while iron and steel mills, aluminum, and lime products see cost increases exceeding two percent.
- **In the nonmanufacturing sector, we see that although the overall size of the production losses also declines over time, a more diverse pattern applies.** Specifically, the impact on electric utilities does not substantially worsen over time (compared to other industries such as mining, which experiences a continuing erosion of sales) as broader adjustments occur throughout the economy. Agriculture faces modest but persistent output declines over time, while the service sector is largely unscathed across all timeframes.
- **In terms of employment, short-term job losses are modeled as proportional to those of output.** Over the longer term, however, when labor markets are able

to adjust, the remaining, relatively small, losses are fully offset by gains in other industries.

- **Overall, the leakage rate (that is, the rate at which reductions in U.S. emissions is offset by increases in foreign emissions) is estimated to be about 25 percent**. For the three most energy-intensive sectors, chemicals, nonmetallic mineral products, and primary metals, the leakage due to imports and exports is more than 40 percent.

Policymakers have a number of tools at their disposal to address the competitiveness challenges that are likely to accompany a carbon-pricing policy. These options include: weaker overall program targets, partial or full exemption from the carbon policy, standards instead of market-based policies for some sectors, free allowance under a cap-and-trade system, and trade-related policies, including some form of border adjustment for energy- or carbon-intensive goods.

For a more in-depth discussion of policy options, see "Addressing Competitiveness Concerns in the Context of a Mandatory Policy for Reducing U.S. Greenhouse Gas Emissions," by Richard Morgenstern. Issue Brief # 8 in Assessing U.S. Climate Policy Options, *Raymond J. Kopp and William A. Pizer, editors. RFF Report, Nov. 2007. www.rff.org/Publications/Pages/CPF_AssessingUSClimatePolicyOptions_IB8.aspx*

Modeling Results

Short-Run Output Effects

In the short run, producers raise prices to cover the higher unit costs when a price is placed on carbon. Unlike a very-short term effect, which does not allow for behavioral responses by firms or individuals, here customers are able to switch to alternative goods and/or imports, leading to a fall in sales and output. The output decline varies among industries, but it can be significant for energy intensive industries like petrochemical manufacturing and fossil fuel suppliers (see Table 4 at end of full paper).

Medium and Long Term Output Effects

Over the medium term, firms can adjust their input mix to adapt to higher energy prices, thus reducing their vulnerability to the new tax. At the same time, however, consumers are adjusting their purchases to avoid the higher prices for carbon-intensive products and thus reducing their demands. The cost-reducing effect of input substitution is generally dominant (see Table 6 at end of full paper). Over time, for all but two manufacturing industries (petroleum refining and fabricated metals), the cost shock of the carbon tax is reduced, and smaller price increases are needed to cover the higher costs of carbon-intensive inputs.

A further metric of importance is the impact on employment. As is the case with output, only for petroleum refining and fabricated metals is the reduction in employment larger in the medium- and long-term horizons compared to the short-run, no-substitution case. Going from the medium to the long run where firms can switch capital, the reduction in employment diminishes in all cases. In two extreme manufacturing cases, apparel and electrical machinery, the medium-run employment reductions turn to gains in the long run. That is, the ability to substitute capital for the more expensive carbon-intensive inputs in the long run leads to bigger reductions in energy consumption and smaller reductions in labor use.

In the nonmanufacturing industries, we also see a smaller employment impact in the medium run compared to the short run except for two industries, the most interesting being electric utilities, where output falls by 1.4 percent but employment rises by 8 percent in the medium run. Going from the medium to long run, the three fossil-fuel mining industries actually see greater employment losses. That is, users of fuels substitute capital for fuel over the longer term and the demand for coal, oil, and gas falls, leading to lower employment.

Capital use in the long run is driven by two opposing effects. On one hand, outputs from carbon-intensive sectors are diminished, reducing the demand for capital. On the other, there is substitution from expensive energy to cheaper capital, which increases the demand for capital in these sectors. The net effect is negative for all but three manufacturing industries. That is, the reduction in capital demand due to the reduction in output dominates the substitution of capital for energy in most industries. The capital that moves out of the declining carbon-intensive sectors goes to services and, perhaps surprisingly, to the electricity sector. For manufacturing industries, only in the food, apparel, and electrical machinery industries are the long-run demands for capital slightly higher after a carbon tax is in place.

Trade Impacts

The trade impacts are displayed in Table 8 (at end of full paper). National domestic consumption is the sum of consumption by firms, households, and government and is equal to domestic output plus imports less exports. The second column gives the changes in consumption due to a $10/ton CO_2 tax, while the last three columns present the contributions of the changes in terms of output, imports, and exports. We can see a consistent pattern among carbon-intensive manufacturing industries: a modest increase in imports and a bigger reduction in exports. Overall, the emissions increase in the rest of the world is 26 percent of the reduction in U.S. emissions as a result of a unilateral U.S. carbon tax. This is a relatively high leakage rate but consistent with other studies.

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I. Introduction

As the United States moves toward mandatory action on climate change an important consideration is the potential for new policies to cause significant declines in some domestic industries, along with corresponding increases in production elsewhere in the world. The possibility of such impacts gives rise to at least two major concerns. The first concern involves the risk of damage to the domestic economy, especially to the subset of carbon-intensive industries that is particularly vulnerable to domestic carbon pricing policies. Unilateral or near-unilateral policies would exacerbate this risk. The second concern relates directly to the potential for emissions leakage, i.e., increases in greenhouse gas (GHG) emissions in the rest of the world in response to the domestic policy. Since climate change is driven by global emissions, the environmental benefits of a domestic policy could be substantially eroded if an increase in domestic production costs caused the manufacture of emissions-intensive goods to shift to nations that have weaker GHG mitigation policies, or none at all.

The impact of a CO_2 price on domestic industries is fundamentally tied to the energy (more specifically, the carbon) intensity of those industries, and the degree to which they can pass costs on to consumers of their products (often other industries). The effect of these characteristics on domestic production hinges on the extent to which domestically produced goods face competition from abroad and consumers' ability to substitute less carbon-intensive alternatives for a given product.

The scale of the potential impacts of a unilateral, economywide CO_2 pricing policy is unprecedented in the history of environmental regulation, as is the range of industries that would be affected. By contrast, the debate leading up to the 1990 Clean Air Act Amendments was informed by extensive analyses of the likely effects of a cap-and-trade program for sulfur dioxide emissions on a single sector, the electric power industry. These analyses were greatly simplified by the fact that the policy under consideration targeted a regulated industry that faced almost no international competition. A pricing policy for CO_2 emissions would not only have more significant direct impacts on coal and other domestic energy industries, it could also cause adverse business impacts on energy-intensive, import-sensitive manufacturing industries. Since comprehensive information concerning industry-level impacts associated with new carbon mitigation policies is quite limited, debate is often dominated by anecdotal information.

A common methodology for assessing the impact of carbon control policies is to estimate the long-run cost to consumer welfare after firms have adjusted by using new kinds of energy-efficient technologies and after new import patterns have been established. In many of these analyses, a mobile factor framework is used in which workers and capital owners do not suffer much (as producers) since they are assumed to be able to shift from the taxed sectors to the untaxed sectors. Such long-run analysis, however, fails to capture the short-run costs that most firms will experience. A chemical plant suddenly faced with higher energy costs cannot immediately and without cost convert to more energy-efficient methods. If it leaves its output price unchanged, the higher input costs will lower profits. If it tries to raise prices to cover the higher costs, it will be faced with lower sales. A carbon control policy that does not address these impacts in a fair manner will likely be opposed by many stakeholders. Further, what's fair can change over time: a policy deemed to be fair for the initial years may become unfair in the future.

This paper advances the analysis of competitiveness issues by providing relatively transparent analyses of the impacts of a unilateral, economywide \$10/ton CO_2 pricing policy on a disaggregated set of industrial sectors, taking account of time-relevant changes in adjustment costs. The analysis does *not* consider the use of *gratis* allowance allocation, trade-related measures, or other complementary policies designed to reduce the competitiveness impacts. Four time horizons are considered:

- The very short run, where output prices cannot be changed and profits fall accordingly;
- The short run, where output prices can rise to reflect the higher energy costs, with a corresponding decline in sales as a result of product and/or import substitution;
- The medium run, when in addition to the changes in output prices, the mix of inputs may also change, but capital remains in place, and economywide ("general equilibrium") effects are considered; and
- The long run, or full general equilibrium analysis, when capital may be reallocated and replaced with more energy efficient technologies.

Both the first and second time horizons are analyzed in a partial equilibrium framework with fixed input coefficients. The first one, with no changes in output prices, involves no demand adjustments whatsoever. The second time horizon requires an estimate of the demand elasticities for each industry's output, that is, how much sales fall when output prices are raised. These elasticities are estimated by simulating an economywide model under constrained conditions. Such a calculation allows us to capture the effect of customers switching to other products when output prices are raised, including the switch to imported varieties of the same product.

The third time horizon is analyzed by direct application of a relatively simple long-run computable general equilibrium (CGE) model. The use of such a model allows us to take into account the fact that the demand for steel depends not only on the price of steel but also on the price of plastics, indeed the price of everything in the economy. Higher energy prices raise the prices of steel and plastic and directly lower the demand for both. In addition, the lower demand for plastic indirectly lowers the chemical industry's demand for steel. These general equilibrium effects are not considered in the first two time horizons. At the same time, this third case continues to assume that capital is not mobile but stuck in a given industry. Therefore, when sales fall due to higher costs being passed on as higher prices, profits will also fall, leading to a lower rate of return to capital.

The fourth time horizon, the full long-run analysis, allows for capital mobility. There are no industry-specific profit effects, but simply the change in the economywide return to labor versus capital. The focus is on the long-run effects of GHG policies on consumption patterns, that is, households and other components of final demand switching to less energy-intensive products. This switch in final demand changes the structure of production and total energy consumption, but the long-run framework implies that returns to capital are equalized across industries. We should note that the "long run" may be defined in a variety of ways. Our definition is the simplest concept using a one-period model where the supply of capital is given exogenously. A model with intertemporal features that determines savings endogenously will identify an effect not considered here—that is, how the total stock of capital responds to the changes in prices due to a carbon tax.

For all four time horizons analyzed, we use a relatively disaggregated modeling framework, based on the North American Industry Classification System (NAICS) basis. For the two longer-run scenarios we use the two-digit level which allows for 21 sectors across the U.S. economy, including 13 manufacturing industries. For the first two modeling frameworks sufficient data are available to subdivide a number of the categories into finer three-digit groupings, a total of 52 industrial sectors. Estimates of carbon intensity are made for the year 2002, the most recent year of the benchmark input–output (IO) table, using industry-specific information on output, intermediate input, fossil fuel use, and emissions for that year.

The focus is on a sequence of transparent steps that allows readers to understand the analysis in a way not conveyed by the typical black box of aggregate or very long-term economic modeling. We estimate the impacts measured in terms of reduced output, profits, employment, and trade effects. Arguably, such analysis is critical to both informing the debate on competitiveness and providing guidance regarding how those concerns might be addressed, recognizing that the nature and magnitude of any new policy may depend critically on the time horizon considered. Even the ranking of industries by cost impacts should be useful for the policy challenge of assessing the need for, and nature of, any special considerations that might accompany a broad-based carbon-pricing mechanism.

The next section reviews a number of previous studies that have examined competitiveness issues at a detailed, industry-specific level. Section III describes the basic methodology used in our modeling work. Section IV describes the data sources along with the key data gaps at this level of disaggregation. A more detailed description of the data is presented in Appendix A. Section V presents the principal results, and Section VI compares the results across multiple time horizons along several different dimensions. Section VII provides cross-model comparisons, and Section VIII offers some overall conclusions.

II. Other Studies on Detailed Industry Impacts

The literature on industry impacts of carbon policies has grown considerably over the last several years, including both policy-oriented and more technical studies.[2] The technical studies build on the extensive work on the effect of environmental regulation of conventional (non-GHG) pollutants on the competitiveness of the U.S. manufacturing sector. For example, a recent paper by Levinson and Taylor (2008) examines in detail the effect of the 60 percent decline in conventional pollution from U.S. manufacturing during the period 1970–2002 concurrent with the 80 percent increase in real output during that period. Overall, the authors conclude that technological progress accounts for well over half of the observed pollution reductions and that the relocation of polluting activities overseas plays a relatively minor role. At the same time,

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[2] A recent volume by Houser et al. (2008) assesses the economics and trade flows of key carbon-intensive industries and summarizes a range of policy options under discussion in the U.S. Congress both in terms of their effectiveness in reducing emissions and addressing competitiveness issues. Overall, they argue that the impacts are relatively modest; those impacts that do exist are concentrated in a small number of industries, including steel, copper, aluminum, cement, glass, paper, and basic chemicals.

they find that the role of technology seems to be shrinking, making changes in the composition of U.S. manufacturing relatively more important for the future. Other research, based on the variation in environmental stringency across individual U.S. states, has found larger impacts (Greenstone 2002).

Whether or not U.S. firms will react to the imposition of a carbon price in the same way they have to the regulation of conventional pollution is very much an open question. Arguably, the cost of complying with carbon regulations might be higher than for conventional pollution because of the very limited applicability of end of pipe solutions such as sequestration. Thus, industries which cannot readily switch fuels or alter their production processes may face significantly higher costs. Since there is no actual experience with carbon prices in the United States, the assessment of impacts is generally based on modeling analyses—themselves derived from historical economic relationships—rather than on direct empirical observation of changes in industrial activity associated with the imposition of carbon or energy prices. The principal exception we are aware of is recent econometric work by Aldy and Pizer (2008) involving a cross-section time-series analysis of the competitiveness impacts associated with U.S. electricity prices over a 20-year period.[3] They estimate industry-specific price elasticities and calculate the likely competitiveness impacts of a unilateral U.S. carbon price of $15/ton of CO_2. The Aldy Pizer results are roughly comparable to our short and medium term cases. The remainder of this section reviews recent modeling analyses of carbon price impacts focusing on the four different time horizons considered.

Very Short–Run Time Horizon

Using IO data from four-digit U.S. manufacturing industries, Morgenstern et al. (2004) developed a simple linear model to assess the very short–run impacts on domestic manufacturing of carbon price policies. Their model, which assumes that output prices cannot be changed, is based on combustion emissions from all sources, including those associated with the purchase of electricity and other domestically produced intermediate inputs. Process emissions associated with cement production and other industrial processes are not included. Also ignored are changes in sales and output due to firms passing on the higher carbon costs, and general equilibrium

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[3] Their initial results suggest that the losses in output and employment may be somewhat higher than those reported here, although some of the differences are clearly related to their use of narrower industrial categories. Not surprisingly, the narrowness of the industry categories is a key issue throughout the literature: broad categories show smaller effects; narrow categories show larger effects.

effects such as higher natural gas prices due to fuel switching from coal, the latter creating additional competitiveness concerns for industries that use natural gas. Overall, Morgenstern et al. (2004) find a diverse pattern of impacts across the 361 individual manufacturing industries examined, with only a few of them bearing disproportionately large burdens. They also find quite different impacts for an economywide versus an electricity-only carbon price policy.

A recent paper by Hourcade et al. (2007) developed a screening model to examine competitiveness impacts on the United Kingdom manufacturing sector of phase III of the European Union Emissions Trading System (EU-ETS). Like the earlier U.S. analyses, Hourcade et al. assume that firms are unable to adjust output prices in response to higher carbon costs. Unlike the U.S. papers, however, they include process emissions in the cement and other relevant industries but exclude purchase of intermediate inputs other than electricity. Their analysis develops industry-specific information on international trade flows but does not explicitly model the output or profitability of individual industries. Like the U.S. studies, Hourcade et al. find a large divergence of impacts across the individual manufacturing industries.

Short-Run Time Horizon

On the basis of detailed case studies, two recent papers estimate the competitiveness effects of the early phases of the EU-ETS: one by McKinsey & Company and Ecofys (2006; hereafter, McKinsey) for the European Commission, and the second by Reinaud (2005) for the International Energy Agency (IEA). These studies focus on representative subsectors within particular energy-intensive manufacturing industries and explicitly consider the extent to which free permit allocation under the EU-ETS (based on direct emissions only) could mitigate estimated cost impacts.[4] Both studies start with a calculation of the cost increases that would arise from a particular CO_2 charge, including emissions-related cost increases from the combustion of fossil energy and from process emissions, as well as the indirect costs of higher

[4] While a free allocation clearly benefits shareholders, the question of whether a free allocation based on historic emissions would offset the production cost increases that are relevant for competitiveness concerns (in terms of changing prices, production, and employment) remains open. Rules that rescind allocations if a plant closes would encourage facilities to use free allowances to offset costs; rules that allow facility owners to keep free allowances when a plant closes would not.

electricity prices.[5] The indirect costs reflected in intermediate inputs other than electricity are excluded, as are the general equilibrium effects from higher natural gas prices.

The McKinsey study makes explicit assumptions about how much of any production cost increase associated with a carbon price will pass through to higher product prices in different manufacturing industries. McKinsey bases these assumptions on the published literature and its own industry expertise. However, McKinsey only goes so far as to calculate net cost impacts: effects on output are not reported. Estimated price impacts are based on the threshold change in revenue needed to keep a facility open, assuming no change in demand for the product (or facility output) in response to higher prices. Importantly, the analysis also assumes that firms will attempt to pass through all cost increases associated with the climate policy, regardless of any free allocation. In contrast, the Reinaud analysis calculates the net effect on prices and then applies demand elasticities drawn from the literature to estimate changes in output. That is, McKinsey focuses on changes in net costs while the Reinaud study attempts to explicitly trace cost impacts through to effects on output. Thus, Reinaud's approach most closely resembles what we label the short-term horizon.

The results from both European studies suggest that initial cost impacts, before adjustment for free allowance allocation or cost pass-through, are substantial in some cases and vary widely across industry subsectors. This variation reflects differences in energy intensity and, particularly in the case of cement, differences in process emissions. Both studies estimate the largest initial cost impacts in basic oxygen furnace (BOF) steel, aluminum, and cement, with relatively smaller impacts in electric arc furnace (EAF) steel.

Assuming that freely allocated allowances are incorporated directly into the firms' production cost accounting, net cost burdens fall significantly if industries are given a free allocation of allowances equivalent to 95 percent of their direct emissions. According to McKinsey, the net cost burden after free allocation for BOF steel and cement, for example, falls by 85–90 percent, an amount that reflects the substantial primary fuel consumption and only modest use of electricity that characterizes these industries. In contrast, electricity-intensive

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[5] Both studies assume the power generation industry passes on the full opportunity cost of carbon allowances. To calculate costs associated with electricity consumption, the McKinsey study assumes 0.41 tons of CO_2 emissions per megawatt-hour; the Reinaud study uses the 2001 average CO_2 intensity of grid-supplied electricity. Neither study considers how facilities might respond to a carbon price by reducing direct emissions and/or electricity consumption, thereby lessening the cost impacts of the carbon policy.

industries with significant indirect emissions from electricity use, like EAF steel, see a smaller decline (roughly 10 percent) in the net cost burden under a 95 percent free allocation based only on direct emissions.[6]

Medium- and Long-Run Analyses Based on CGE Analyses

Unlike the partial equilibrium analyses covering the very short and the short run horizons, the medium and long run analyses rely on computable general equilibrium (CGE) models of the entire economy. At the same time, most of the CGE models are quite aggregate in nature, generally containing five or fewer nonenergy sectors (Fischer and Morgenstern 2006). We are aware of only two such models used for carbon policy analysis that include extensive industry detail: the domestic-oriented Intertemporal General Equilibrium Model (IGEM) and the international-oriented Global Trade Analysis Project (GTAP). We report here on recent analyses using these models.

IGEM

IGEM is a dynamic model of the U.S. economy that describes economic growth due to capital accumulation, technical change, and population growth. Capital accumulation arises from savings of a household modeled with "perfect foresight." The production or supply side of the model identifies a total of 35 industries, of which 21 are manufacturing and 5 are energy related. Coal, refined oil, gas, and electricity are separately identified energy inputs. Domestic output is supplemented by imports from the rest of the world to form the total supply of each commodity. The key model parameters governing the behavior of producers and consumers are econometrically estimated. In a recent paper, Jorgenson et al. (2007) revised previous analyses by Ho and Jorgenson (1994) and Jorgenson and Wilcoxen (1993) to assess the economic costs of a market-based climate policy. Overall, they find that by 2020 the economic burden of a GHG mitigation policy that uses a revenue-neutral carbon tax or a cap-and-trade system to permanently constrain emissions to year 2000 levels, while measurable, is relatively small—on the order of 0.5 to 0.7 percent of the gross domestic product (GDP). Substitutions away from more costly inputs and toward relatively cheaper materials, labor, and capital, along with price-induced technical change, help to reduce the adverse impacts.

[6] This reflects the EU-ETS design, which does not address cost increases arising from higher electricity prices (where higher electricity prices reflect the indirect emissions associated with power generation).

With the exception of agriculture, food, and related activities, Jorgenson et al.(2007) project that all industries face declines in output volumes. While coal mining experiences the largest impacts on domestic output (about 15 percent in their central case), other energy-related industries, including petroleum refining, electric utilities, and gas utilities, all experience output declines of 2 to 3 percent. Metal mining, oil and gas extraction, and nonmetallic mineral mining also face significant output declines. In the manufacturing sector, the most heavily impacted industries are primary metals; stone, clay, and glass; fabricated metal products; nonelectrical machinery; motor vehicles; chemicals and allied products; rubber and plastic products; furniture and fixtures; and lumber and wood products.

GTAP

The GTAP project consists of a multisector (up to 52 industries), multiregion database of output and trade flows and a general equilibrium model of the world economy based on this database. Although the models using the GTAP data that we describe here do not project energy use into the distant future or allow for technological change, they do allow for capital reallocation. As such, the results should be considered illustrative of a hybrid of the short-, medium-, and long-term time horizons analyzed here. A recent paper by Fischer and Fox (2007) based on version 6.1 of GTAP (2001) considers how alternative permit allocation mechanisms affect the outcome of carbon policies. They examine four different allocation mechanisms: auction, grandfathering, output-based allocation tied to emissions, and output-based allocation tied to value added. They report impacts on 18 nonenergy sectors as well as 5 energy sectors.

In a policy scenario that reduces emissions by about 14 percent below baseline (roughly keyed to the goals of the proposed Lieberman-Warner legislation), Fischer and Fox (2007) estimate a relatively small reduction in overall output, on the order of 0.34 to 0.51 percent, depending on the particular allocation mechanism. The smallest output declines occur for the output-based allocation tied to emissions. Overall, output declines consistently across the industries examined, except the food products and service sectors, for all the alternative allocation mechanisms. Coal mining experiences the largest declines, on the order of 16 percent. Other energy-related industries, including electricity, natural gas, and crude oil, also experience significant declines, on the order of 5 percent. Transportation and mining are estimated to decline by 8 percent and 4 percent, respectively. The most hard-hit manufacturing industries are chemicals and iron and steel, at about one percent each. All other manufacturing industries report output declines that are generally 0.5 percent or less. Interestingly, the Fischer and Fox (2007) analysis reports total emissions leakage of about 12 to 15 percent of the overall reduction in U.S.

emissions. Although not explicitly reported in their paper, this implies dramatically higher industry-specific leakage rates for some industries. For example, the leakage rate for the energy intensive industries is on the order of 40-45 percent.[7]

Adkins and Garbaccio (2007) developed another model based on the GTAP database that covers 21 sectors and 24 regions of the world. It considers how carbon taxes interact with trade liberalization and revenue recycling. Trade liberalization raises world GDP slightly but also raises world carbon emissions, and the authors carry out a simulation where the tariff cuts are accompanied by carbon taxes that keep CO_2 emissions unchanged. They find that a system of carbon taxes, trade liberalization, and revenue recycling reduces the gains from trade liberalization quite modestly. Adkins and Garbaccio also consider a case where Annex I countries impose a carbon tax to reduce their CO_2 emissions by 5 percent and non-Annex I countries do not have a carbon constraint. They find that this leads to a net reduction in global CO_2 emissions of 2 percent, reflecting a leakage rate of 35 percent.[8]

III. Methodology to Analyze Different Time Horizons

As noted, we consider four time horizons for the analysis of the impact of carbon control policies, using an IO framework for all cases. This section describes the framework in some detail to illuminate the assumptions and simplifications made. Readers more interested in the results may skip to Section V.

We adopt fairly standard IO conventions for the notation in the following equations [see, for example, Miller and Blair (1985)]. In order to have a full accounting of all carbon sources and users we construct a complete set of accounts for all *n* industries and final demands (consumption, government, and exports).

Let p_j^X denote the price of industry *j* output to buyers, and p_j^L and p_j^K denote the price of labor and capital inputs. The value of industry *j*'s output at buyers' prices is equal to the value of inputs plus taxes on production:

(1) $$p_j^X X_j = \sum_i p_i^Q u_{ij} + p_j^L L_j + p_j^K K_j + tax_j \qquad j = 1, 2 \ldots n$$

[7] Personal communication with the authors.

[8] Adkins and Garbaccio (2007) Table 12 and personal communication with the authors.

where X_j is the quantity of output and u_{ij} is the intermediate input of commodity *i* into sector *j* purchased at prices p_i^Q. L_j and K_j are the labor and capital inputs. We denote the values of output and input by a *v* superscript: $X_j^v = p_j^X X_j$ and $u_{ij}^v = p_i^Q u_{ij}$.

Both the detailed industry accounts and IO tables distinguish between industries and commodities; they are classified by using the same names and reference numbers.[9] The electricity commodity, for example, is produced by the electric power generation industry, federal electric utilities, and state and local (S&L) government electric utilities. Each industry uses various intermediate commodity inputs, u_{ij}. A matrix whose *j*th column is the vector of commodities used by sector *j* is the "Use" matrix. In value terms this is:

(2) $$\mathbf{U}^v = [u_{ij}^v]$$

The vector of industry output is denoted by $X = (X_1, ...X_n)'$.

For calculations of emissions, we need to express emissions in terms of tons of CO_2 emitted per dollar of output. The "Activity" matrix, B, gives the amount of input *i* required for one unit of output *j*, and is simply the Use matrix divided by output:

(3) $$b_{ij} = \frac{u_{ij}^v}{X_j^v}; \quad \mathbf{B} = [b_{ij}] = \mathbf{U}^v[diag(X^v)]^{-1}$$

The symbol *diag(x)* denotes the matrix where the diagonal consists of the elements of the *x* vector and zeros in the off-diagonal. The corresponding use of labor and capital per unit output are denoted as:

(4) $$b_j^L = \frac{L_j}{X_j}; \quad b_j^K = \frac{K_j}{X_j}$$

[9] For example, the accommodation industry produces an "accommodation" commodity and a “food service” commodity. On the other side, each commodity may be produced by several industries; for example, the “food service” commodity is produced by the accommodation industry and the food service industry.

In our analysis of the very short run we assume that the input mix cannot be changed, that is, the activity matrix B is not affected by carbon control policies.

Total final demand, E_i, is the demand for domestic commodity *i* by the final users—consumption, investment, government, and net exports. This corresponds to the familiar expression for GDP: GDP = C + I + G + X – M. Thus, for commodity *i*:

(5) $$E_i = c_i + v_i + g_i + e_i - i_i \ ; \qquad E = (E_1, ...E_n)'$$

Let Q_i denote the supply of domestic commodity *i*. The supply–demand balance in quantity terms is written as:

(6) $$Q_i = \sum_j u_{ij} + E_i \qquad i = 1,2,....m \ ; \quad Q = [Q_i]$$

In vector form this becomes:

(6a) $$Q = U\iota + E = \mathbf{B}X + E$$

where ι is a vector of ones. The corresponding equation in value terms is simply $Q^v = U^v \iota + E^v$. Since each commodity may be produced by a few industries, we use the “Make” or “Supply” matrix:

(7) $$\mathbf{V}^v = [V_{ji}^v]$$

where V_{ji}^v gives the value of commodity *i* produced by industry *j*. The vector of industry output is the row sum of the Supply matrix, $X^v = \mathbf{V}^v \iota$; the vector of commodity output is the column sum, $Q^v = \mathbf{V}^v{}' \iota$. Let the share of commodity *i* produced by industry *j* be denoted by d_{ji}. Then the relation between industry output and commodity supply is given by:

(8) $$X^v = \mathbf{D}Q^v \ ; \qquad \mathbf{D} = [d_{ji}] = \mathbf{V}^v [diag(Q^v)]^{-1}$$

We also use the industry proportion matrix, C, which gives the share of industry *j*'s output going to commodity *i*:

(9) $$Q^v = \mathbf{C}X^v; \qquad \mathbf{C} = [c_{ji}] = \mathbf{V}^{v}{}'[diag(X^v)]^{-1}$$

By putting (3) and (8) into (6), we obtain the following well-known relationship between final demand and domestic output [see, e.g., Miller and Blair (1985)]:

(10) $$Q^v = (\mathbf{I} - \mathbf{BD})^{-1} E^v$$

where $\mathbf{I}$ is the identity matrix. $(\mathbf{I} - \mathbf{BD})^{-1}$ is known as the Leontief inverse, or the "commodity total requirements matrix." It tells us that to produce a vector *E* of final demand commodities, the economy must produce a vector *Q* of gross output of commodities.

In particular, this formulation expresses the additional outputs required to produce an extra unit of good *i* for final users. For example, if we want to produce one more dollar's worth of motor vehicles, the economy must produce additional steel, glass, electricity, and other necessary materials that the motor vehicle industry buys as inputs. However, steel production needs motor vehicles, electricity, coal, etc., and electricity needs steel, coal, etc. The Leontief inverse gives us the grand total of extra electricity, coal, and so on, that is required for the economy to produce one more dollar of motor vehicles. The commodity total requirements vector (i.e., the vector of additional output needed for one unit of *i*) is:

(11) $$\Delta Q^i = (\mathbf{I} - \mathbf{BD})^{-1} \mathbf{i}_i$$

where $\mathbf{i}_i$ is a vector with a one in the *i*th element and zeros everywhere else. Writing out the components of this vector explicitly gives us:

(12) $$\Delta Q^i = \begin{bmatrix} \Delta Q^i_{farm} \\ \Delta Q^i_{oil} \\ \Delta Q^i_{gas} \\ \vdots \end{bmatrix}$$

With this formulation, we can estimate the total additional CO_2 emissions due to one more unit of good *i* since the vector ΔQ^i gives us the additional coal, crude oil, and gas used.

Let θ_f be the CO_2 content per unit of fuel *f*, where the units are the base year dollars of fuel *f*. For example, $\theta_{coal} = 106923$ metric tons of CO_2 per million dollars of coal in 2002. This is derived from the energy content per unit fuel (e.g., BTUs per ton of coal), the carbon content per BTU, and the average price per unit fuel (dollars per ton). If there were no noncombustion uses of fuels, then the direct and indirect emissions due to producing one unit of good *i* may be derived simply by multiplying the primary energy elements in ΔQ^i by their respective carbon content coefficients. Let ΔC_i denote the total carbon emissions caused by producing one unit of *i*:

(13) $$\begin{aligned} \Delta C_i &= \theta_{coal}\Delta Q^i_{coal} + \theta_{oil}\Delta Q^i_{oil} + \theta_{gas}\Delta Q^i_{gas} \\ &= \theta' \Delta Q^i \end{aligned}$$

where $\theta' = (0,..,\theta_{coal},\theta_{oil},..0)$ is the vector of carbon coefficients with nonzero entries only for the primary fuels. Although the ΔQ^i vector also gives us the additional electricity and additional refined petroleum products used, we do not include them in the calculation since these are secondary products. It is the production, not the use, of electricity that generates CO_2, and that is captured by the coal, oil, and gas elements. Similarly, gasoline, kerosene, and so forth are captured at the crude oil stage.

However, oil and gas are used as feedstock in the production of chemicals and other noncombusted products, that is, their carbon is not released in the typical fashion. If the carbon policy exempts such nonfuel use then the formulas should reflect that. In this case we estimate carbon emissions from the combustion of refined petroleum products and gas utilities instead of just the primary commodities from coal, oil mining, and gas mining. We begin with expressing total national emissions as the sum over the industries and final demand use of fuel *f*, and then sum over all fuels:

(14) $$C = \sum_f \theta_f \left(\sum_j \phi_{fj} u_{fj} + E_f\right)$$

The combustion use of fuel *f* in industry *j* is the quantity used (u_{fj}) multiplied by a combustion ratio, ϕ_{fj}. National emissions also include those from households and government represented in the final demand vector *E*. In matrix notation, this is:

(15) $$\begin{aligned} C &= \theta'[(\phi \bullet \mathbf{U})i + E] \\ &= \theta'[\phi \bullet \mathbf{B}[diag(X)]\iota + E] \\ &= \theta'[\phi \bullet \mathbf{B}X + E] \\ &= \theta'[\phi \bullet \mathbf{BD}Q + E] \end{aligned}$$

where $\phi \bullet u$ is the Hadamard product and ι is a vector of ones. The vector of the change in direct and indirect CO_2 emissions due to one more unit of final demand is obtained by substituting in (11):

(16) $$\Delta C' = \begin{bmatrix} \Delta C_1 \\ \vdots \\ \ \end{bmatrix}' = \theta'[\phi \bullet \mathbf{BD}(\mathbf{I} - \mathbf{BD})^{-1} + \mathbf{I}]$$

That is, the change in emissions due to one more unit of commodity *i* used by final demand is:

(17) $$\Delta C_i = \sum_f \theta_f \left[\sum_k \phi_{fk} b_{fk} \sum_j (d_{kj} \Delta Q_j^i)\right] + \theta_i$$

We should emphasize the difference between (13) and (17), which includes the combustion ratio term. The refining sector has the smallest combustion ratio where the major part of crude input is transformed to refined products, and it is:

ϕ (oil mining, refining) = 0.067

This is very different from 1.0. Thus, (17) generates a very different estimate of the carbon intensity for some products. The construction of the combustion ratios is described in Appendix A.

Given the additional carbon embodied in one unit of commodity *i*, we may assume that a CO_2 tax at rate $\$t^C$ /ton will result in the cost of producing *i* rising by $t^C \Delta C_i$. Denote this by:

$$\Delta p_i^Q = t^C \Delta C_i \tag{18}$$

For nonfuel commodities, say for *i* = aluminum, then $\Delta p_{aluminum}^Q$ is the higher cost due to paying more for directly purchased oil and gas as well as for electricity that is generated with now more-expensive fossil inputs. For the fossil fuel commodities, say *i* = coal, the Δp_{coal}^Q expression represents the higher cost of producing coal and the carbon tax on coal.

This expression for the change in input prices is the starting point to estimate the cost of carbon mitigation policies from the twin perspectives of the initial industrial purchaser and the final end user. The additional cost to final users is the change in price multiplied by the quantity purchased of each commodity. The total cost to all final users of a $\$t^C$ carbon tax (before any changes in behavior) is the sum over all *m* commodities:

$$\Delta COST^{FD} = \sum_{i=1}^{m} \Delta p_i^Q E_i \tag{19}$$

The change in costs of industry *j* is the change in the prices of inputs multiplied by the quantity of inputs that are assumed to be unchanged in the very short–run (*VS*) case. The total increase in current costs per dollar of output *j* is:

$$\Delta COST_j^{VS} = \sum_i \Delta p_i^Q B_{ij} \phi_{ij} \tag{20}$$

We allow for the option that the carbon tax only applies to the combusted portion by multiplying the input matrix B by the combustion ratio ϕ.

We also want to separate out the total effect into the contribution of primary fuels, electricity, and all other intermediate inputs. To do this we compute the carbon contributions of the primary fuels and electricity from the energy consumption data given in Table A2 of Appendix A. That is, we have, θ_j^{DC} = CO_2 per dollar of industry output due to the direct combustion (*DC*) of fossil fuels, and θ_j^{EL} = CO_2 per dollar due to electricity (*EL*) consumption. The total effect is thus the sum of the direct combustion, electricity, and indirect intermediate input (*IN*) contributions:

(20a)
$$\Delta COST_j^{VS} = \Delta COST_j^{DC} + \Delta COST_j^{EL} + \Delta COST_j^{IN}$$
$$\Delta COST_j^{DC} = t^C \theta_j^{DC}$$
$$\Delta COST_j^{EL} = t^C \theta_j^{EL}$$

We are interested in the total effect on an industry and need to distinguish between quantities and values, sales revenues and profits. The gross sales revenue is $P_j^X X_j$, and net sales revenue is the gross minus “taxes on production” (sales tax). Denoting the tax rate by t_j^X, net sales revenue for industry *j* is:

(21)
$$\text{sales revenue} = P_j^{XO} X_j = \frac{P_j^X X_j}{1+t_j^X}$$

where P_j^{XO} denotes the revenue received per unit of output by the producer, that is, the “seller’s price.” Let π_j denote the gross return to capital, that is, net sales revenue minus intermediate input costs and labor costs of industry *j*:

(22)
$$\pi_j = p_j^{XO} X_j - \sum_i p_i^Q B_{ij} X_j - p_j^L L_j$$

Very Short–Run Horizon Where Quantities Cannot Be Changed

In the very short–run scenario we calculate the effect of the carbon charge on profits for *j* as if customers do not buy less due to higher prices, that is, there are no changes in the quantity of output or inputs. This is best regarded as a very short–run, partial equilibrium view of the effects. Here we only focus on industry *j* and how the higher input prices of all non-*j* commodities affect its profits. We also regard labor prices to be unchanged in this very short–run horizon case. The change in gross profit to the producer is:

(23)
$$\begin{aligned}\Delta\pi_j^{VS} &= \Delta p_j^{XO} X_j - \sum_i \Delta p_i^Q B_{ij}\phi_{ij} X_j - \Delta p_j^L L_j \\ &= -\sum_i \Delta p_i^Q B_{ij}\phi_{ij} X_j \\ &= -\Delta COST_j^{IM} X_j\end{aligned}$$

That is, under the assumption that quantities are unchanged and the output price is fixed, the change in profits is simply the per dollar change in cost given in (20) multiplied by total output quantity. This definition of changes in very short–run profits is somewhat inconsistent since we consider how the carbon tax results in higher input prices, p_i^Q, while at the same time assuming that output prices, p_j^{XO}, are unchanged for all industries. We define it in this manner to reflect the arguments often made by industry representatives: "our costs will rise due to a carbon fee and we will not be able to raise prices or change input quantities." This setup also has the advantage of being a simple, transparent representation of the maximum impact on profits from the higher costs. This is a simple partial equilibrium representation, ignoring the fact that input commodity *i* is some other industry's output.

The percentage change in very short–run profits is simply the weighted share of the percentage change in input prices:

(24)
$$\frac{d\pi_j^{VS}}{\pi_j} = \frac{-\Delta COST_j^{VS} X_j}{\pi_j} = \frac{-\sum_i dp_i^Q B_{ij}\phi_{ij} X_j}{\pi_j} = -\sum_i \frac{dp_i^Q}{p_i^Q}\frac{\phi_{ij}\alpha_{ij}}{\alpha_{Kj}}$$

where the α s denote the cost shares:

(25)
$$\alpha_{ij} = \frac{p_i^Q u_{ij}}{p_j^{XO} X_j} \quad \text{i=1,2,…m}$$

$$\alpha_{Kj} = \frac{p_j^K K_j}{p_j^{XO} X_j}$$

Short-Run Horizon with Higher Output Price and Lower Sales

In this next case we consider the situation where the producers raise their output prices to cover the higher costs and customers react by switching to substitute goods or substitute suppliers such as imports. Let the demand elasticity for output *j* be:

(26) $$\eta_j = \frac{p_j^X}{X_j}\frac{dX_j}{dp_j^X}$$

That is, for each percentage point increase in price, the producer *j* will make and sell η_j percent less. That is, the percent change in sales and output due to an increase in price to cover the higher cost $\Delta COST_j^{VS}$ is:

(27) $$\frac{dX_j}{X_j} = \eta_j \frac{dp_j^X}{p_j^X} = \eta_j \Delta COST_j^{VS}$$

As in the first case, we assume that labor prices are unchanged. However, we allow a certain level of adjustment for inputs—all input quantities other than capital input may change in proportion to the reduction in output, but not due to price-induced factor substitution. Let dX_j denote the change in the quantity of output produced. The change in intermediate input *i* and labor use are given by:

(27a) $$dU_{ij} = B_{ij}dX_j = B_{ij}\eta_j X_j \frac{dp_j^X}{p_j^X}$$

$$dL_j = b_j^L dX_j = b_j^L \eta_j X_j \frac{dp_j^X}{p_j^X}$$

The no-substitution assumption means that the amount of input per unit output is fixed, that is, $dB_{ij} = 0$. This setup is also not guaranteed to be internally consistent, since the total change in purchases calculated from (27) is independent of the change given by η_j, which is estimated from a model simulation where substitution is allowed. That is, while we allow the customers of *j* to respond to higher prices, producers of *j* are still unable to adjust the input mix by substituting cheaper inputs for the more expensive carbon-intensive ones. The customers are, however, simply other producers. We frame the short-run effect in this manner to show a partial equilibrium effect in the simplest way possible. This framework addresses the issue of pass-through, that is, how much producers can pass on their higher costs in the short run. It allows a generous estimate of the damage to sales due to price changes and, correspondingly, a generous estimate of the impact on profits.

In this short-run case we assume that producers raise the output price by the amount of the increase in unit cost due to the carbon tax:

(28) $$dp_j^{XO} = \Delta COST_j^{VS}$$

The price to buyers is changed by this higher seller's price plus the new carbon tax:

(29) $$\begin{aligned} p_j^X &= p_j^{XO}(1+t_j^X) + t^C\theta_j \\ &= p_j^{XO}(1+t_j^X + \tau_j^C) \end{aligned} \quad j = 1,\ldots 52$$

$$\tau_j^C = t^C\theta_j / p_j^{XO}; \quad j = \text{coal, crude oil, gas, refined petroleum, gas utilities}$$

where τ_j^C is the carbon tax rate. The carbon tax is positive only for the energy industries j = coal, oil mining, gas mining, gas utilities, and refined petroleum. The change in price is:

(30) $$dp_j^X = dp_j^{XO} + t^C\theta_j$$

And in percentage terms:

(31) $$\frac{dp_j^X}{p_j^X} = \frac{dp_j^{XO}}{p_j^{XO}} + \tau_j^C$$

The change in profits in this short-run (*SR*) case is the change in revenues less the change in costs, both of which are split into price change and quantity change:

(32)
$$\begin{aligned} d\pi_j^{SR} &= dp_j^{XO} X_j + p_j^{XO} dX_j - \sum_i dp_i^Q B_{ij} X_j - \sum_i p_i^Q B_{ij} dX_j - dp_j^L L_j - p_j^L dL_j \\ &= dp_j^{XO} X_j + \frac{\eta_j X_j p_j^{XO}}{p_j^X} dp_j^X - \sum_i dp_i^Q B_{ij} X_j - \sum_i p_i^Q B_{ij} \eta_j X_j \frac{dp_j^X}{p_j^X} \\ &\quad - p_j^L b_j^L \eta_j X_j \frac{dp_j^X}{p_j^X} \end{aligned}$$

Recall that the value share of profits in sales revenue is denoted by α_{Kj}, and the value share of labor and intermediate inputs are α_{Lj} and α_{ij}, respectively. Substituting (30) into (31), the percentage change in gross profits may be expressed as:

(33)
$$\begin{aligned} \frac{d\pi_j^{SR}}{\pi_j^{SR}} &= dp_j^{XO} \frac{X_j}{\pi_j} + \frac{\eta_j X_j p_j^{XO}}{\pi_j} \left(\frac{dp_j^{XO}}{p_j^{XO}} + \tau_j^C\right) - \sum_i dp_i^Q B_{ij} \frac{X_j}{\pi_j} - \sum_i p_i^Q B_{ij} \eta_j \frac{X_j}{\pi_j} \left(\frac{dp_j^{XO}}{p_j^{XO}} + \tau_j^C\right) \\ &\quad - p_j^L b_j^L \eta_j \frac{X_j}{\pi_j} \left(\frac{dp_j^{XO}}{p_j^{XO}} + \tau_j^C\right) \\ &= \frac{dp_j^{XO}}{p_j^{XO}} \frac{1}{\alpha_{Kj}} + \frac{\eta_j}{\alpha_{Kj}} \left(\frac{dp_j^{XO}}{p_j^{XO}} + \tau_j^C\right) - \sum_i \frac{dp_i^Q}{p_i^Q} \frac{\alpha_{ij}}{\alpha_{Kj}} - \left[\sum_i \eta_j \frac{\alpha_{ij}}{\alpha_{Kj}} - \eta_j \frac{\alpha_{Lj}}{\alpha_{Kj}}\right] \left(\frac{dp_j^{XO}}{p_j^{XO}} + \tau_j^C\right) \\ &= \frac{dp_j^{XO}}{p_j^{XO}} \frac{1}{\alpha_{Kj}} \left[1 + \eta_j \left(1 - \sum_i \alpha_{ij} - \alpha_{Lj}\right)\right] + \frac{\eta_j \tau_j^C}{\alpha_{Kj}} \left(1 - \sum_i \alpha_{ij} - \alpha_{Lj}\right) - \sum_i \frac{dp_i^Q}{p_i^Q} \frac{\alpha_{ij}}{\alpha_{Kj}} \\ &= \frac{dp_j^{XO}}{p_j^{XO}} \frac{1 + \eta_j \alpha_{Kj}}{\alpha_{Kj}} + \eta_j \tau_j^C - \sum_i \frac{dp_i^Q}{p_i^Q} \frac{\alpha_{ij}}{\alpha_{Kj}} \end{aligned}$$

Compared to the change for the very short–run horizon case given in (24), the above expression has an additional term for the effect of higher output prices on quantities of input and output. For the fossil fuel industries, there is also another term, $\eta_j \tau_j^C$, for the direct effect of carbon taxes on the quantities of outputs and inputs in these sectors. That is, the customers of fossil fuel industries not only face more costly fuels due to the higher costs of producing fuels, but also the carbon tax on the fuels.

Medium-Term Horizon When Input Mix May Be Changed

Beyond the short run we would expect firms to adapt their production processes to the higher prices of fossil fuels. There may be fuel switching toward lower-carbon fuels, or using less energy-intensive intermediate inputs, or substituting labor for energy. In this scenario, which we refer to as the medium run, we allow these changes but assume that capital stocks are not changed. We estimate the effects of these changes in variable input use by using a three-region general equilibrium model developed by Adkins and Garbaccio (2007).

Long-Run Horizon When Capital May Be Reallocated

Over time we may see more changes in production technology than changes in the mix of intermediate inputs, for example, the use of more capital-intensive, fuel-efficient technologies. Unlike the medium-term horizon case, where we hold the capital stocks in each sector fixed at the base case, in this long-run horizon we allow all factors to be mobile.

IV. Implementation: Data Construction and Simulation Model

Data

To obtain accurate estimates of the industry-specific burdens of a CO_2 pricing policy, it is essential to calculate the carbon usage of each industry, including both direct combustion and the purchase of electricity and other intermediate inputs. Thus, two types of information are required: IO data on the interindustry flows and outputs measured in value terms; and industry-specific estimates of the physical quantities of the different fuels consumed. Unfortunately, the available value and energy data are not designed to complement each other. While the industry economic data are collected in terms of the NAICS, only the energy data for manufacturing are collected on the NAICS basis. Energy data for transportation and services are collected on an end-use basis. Accordingly, a key challenge is to develop a consistent set of fuel use estimates across all sectors. We briefly describe here how the energy and emissions estimates by industry are assembled. Details of the calculations are presented in Appendix A.

The 2002 benchmark IO table is the most recent version produced by the U.S. Department of Commerce, providing the interindustry flows for 426 sectors, plus information on consumption, government, exports, and imports. Development of the industry-specific CO_2 use involves linking this highly disaggregated value information to the more aggregated fuel data. This is accomplished by aggregating the former to match the categorization scheme of the latter. At the same time, the list of 426 sectors is not sufficiently detailed for the purpose of identifying precisely the use of coal, oil, and natural gas. Thus, we split oil and gas extraction into oil mining and gas mining, and petroleum refineries into natural gas liquids (NGL) refining and other petroleum refining, and government enterprises into government electric utilities and other government enterprises. We had hoped to explicitly identify all the high energy–cost industries in the set of IO industries; however, the energy data available restricted us to a smaller group. The final list of 52 industries consists of (a) six-digit NAICS industries that have high energy costs and have the energy quantity data available; (b) the energy-supplying industries with coal, oil, and gas separated; and (c) the remaining industries aggregated to the three- or four-digit level. The identified industries are displayed in Table 1.

The consumption of energy for the manufacturing industries is taken from the 2002 Manufacturing Energy Consumption Survey (MECS). This data set provides information for a detailed group of industries on combustion and nonfuel use of various energy inputs, including residual fuel oil, distillate fuel oil, natural gas, LPG, coal, coke, and electricity. Unfortunately, for confidentiality reasons, the data for a number of industries are suppressed and we have to make alternative estimates as explained in Appendix A. Fossil fuel consumption for the electric utility industry is from the Annual Energy Review (AER 2006). Energy use for agriculture is provided by the Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA). Energy use for the other industries is inferred from the value data.

The methodology assumes that all buyers pay the same price for a ton of coal, a kilowatt-hour of electricity, or a unit of any other commodity. However, as shown in Tables A3a and A3b (Appendix A), there are significant differences between the MECS and the industry-specific fuel quantities implied by the IO value data. Thus, we use the MECS, AER and ERS data to develop estimates of the quantities of the different fuels used by the reporting sectors. For other industries, the quantities of the different fuels are inferred, based on a residuals calculation constrained by national quantities of the fuels. The results of our calculations of energy use by the 52 industries are given in Tables A4–A9.

Given the energy input quantities, we estimate the direct carbon emissions by using the carbon coefficients, θ_f. Indirect carbon emissions for electricity consumption are based on the carbon embodied in the average kilowatt-hour. The carbon emissions per unit of industry output are given in Table A10, and the direct and indirect emissions are displayed in Table A11.

Multisector General Equilibrium Model

Key to the analysis are our estimates of the elasticity of demand for industry output, η. This is the effect of a higher industry output price on customers' demand for alternative commodities or imports. Since we are not aware of any comprehensive and consistent estimate of such elasticities for all industries, we estimate them from a multisector model of the U.S.

economy. Thus, we derive the demand elasticity for each industry from a common (and consistent) framework.

To develop these elasticity estimates we turn to the model described in Adkins and Garbaccio (2007) and Adkins (2006). This model identifies 21 industries, including 5 energy industries—coal, oil, gas, petroleum products, and electricity. The production functions used are constant elasticity of substitution (CES), where capital and labor form a "value-added" aggregate input, and there is substitution between value-added inputs and the energy bundle (see Appendix B).

To estimate the output elasticity for industry *j*, η_j, we simulate the model by putting a small tax on the output of *j* and recording the effect of X_j. This is the general equilibrium effect of the tax, allowing all intermediate and final demand users to substitute with alternative commodities. The estimated demand elasticities are then applied to all the subindustries in our list of 52 industries. The elasticity estimated for, say, chemicals, using the Adkins–Garbaccio model is applied to all six subindustries in the chemicals group. An exception to this is the petroleum refining industry. Here we impose a short-run elasticity of demand that is smaller than that generated by simulating the CGE model. We did this because we believe the short-run response is significantly smaller than the long-run response to gasoline price changes.

For the medium- and long-run scenarios, we simulate a carbon tax and use the full Adkins–Garbaccio model to estimate the effects on the outputs and inputs of each industry, allowing for a full set of substitutions. The quantity of labor demanded, which forms the basis of our estimates of job losses, is one of the key factor inputs.

The regions identified in the model are the United States, the rest of Annex I, and the rest of the world.[10] The model also calculates the effects of the CO_2 tax on industry-specific exports and imports, where the tax is defined as a levy on both domestic fuel producers and importers. The model simulations presented below do not include a border adjustment or "carbon content tax" on imported steel or other energy-intensive manufactures.

[10] Annex I refers to those countries that have explicit CO_2 targets under the Kyoto Protocol.

V. Industry Patterns of Output, Energy Use, Carbon Intensity, and Imports

Energy Consumption Patterns and Carbon Intensity

We first describe the energy consumption patterns and carbon content of the 52 industries considered in the short-run analyses. Table 1 presents the summary energy consumption information for these industries—energy costs as a share of total costs are given for electricity, fossil fuel (combusted portion only), and total energy, including noncombustion use of fossil fuels. The term “total costs” is defined as the total value of all inputs for industry *j* given in the *j*th column of the “Use” table which, as shown in (1), is also equal to the value of industry output.

As shown, the relative importance of energy, including feedstocks, as a contributor to total costs varies quite widely across the different manufacturing industries, ranging from more than 60 percent in the petroleum industry to less than 1 percent in miscellaneous manufacturing, motor vehicles, and other transportation equipment. Outside of manufacturing a similarly wide range exists, from a high of about 42 percent in gas utilities to 0.2 percent in finance and insurance. Even when energy costs are restricted to the combusted portion, the cost share ranges from 15 percent in cement to 0.9 percent in transportation equipment. Of the 33 manufacturing industries identified here, 15 of them have energy costs exceeding 6 percent of total costs.

Within the manufacturing sector, the contributors to energy costs also vary greatly. For many industries, including petroleum refining, petrochemical manufacturing, other basic organic chemical manufacturing, and fertilizer manufacturing, more than 70 percent of the energy costs are associated with direct fuel combustion. For others, such as other basic inorganic chemical manufacturing, alumina refining and primary aluminum production, and ferrous metal foundries, electricity accounts for more than 70 percent of total energy costs.

Outside of manufacturing, electricity generation (private and government utilities) clearly has the highest energy cost share at 13 percent, followed by air transportation services with 9 percent and farms with 6 percent.

Table 2 presents the energy consumption data for the 52 industries in physical quantity terms: tons of coal, barrels of oil, cubic feet of natural gas, and kilowatt-hours of electricity. It also presents the value of industry output and the primary CO_2 content per dollar of output, that is, the primary CO_2 intensity. Primary CO_2 includes only the carbon in the fossil fuel combusted and in the electricity used: CO_2 embodied in intermediate inputs and biomass is excluded. As explained in Appendix A, we define industry output as the value contained in the benchmark IO table, less the intraindustry transactions given in the diagonal of the IO matrix.

Ranked by the value of output, the biggest manufacturing industries are food manufacturing, other chemicals and plastics, and computer and electrical equipment. These are about 50 times larger than small, energy-intensive industries such as fertilizer, glass, and cement. Within manufacturing, the biggest users of coal are iron and steel, and paper mills; the biggest user of petroleum products is petrochemical manufacturing; and the biggest users of natural gas are food manufacturing, refining, and other basic organic chemicals. Other chemicals and plastic is the biggest user of electricity, followed by food manufacturing.

Industry-specific estimates of primary CO_2 intensity are displayed in the last column of Table 2. Clearly, electricity has the highest CO_2 intensity among the 52 industries. Within manufacturing, cement manufacturing has the highest at 5,100 tons of CO_2 per million dollars of output, followed by petrochemical manufacturing with 4,100 tons and alumina refining and primary aluminum with 2,700 tons of CO_2 per million dollars of output. At the other extreme, the machinery, electrical machinery, and transportation equipment industries have carbon content that is less than 120 tons of CO_2 per million dollars of output.

Import Exposure

While the vulnerability to import competition is not necessarily related to the average level of import penetration, a high import share does indicate greater competition for domestic producers. The last column of Table 1 gives the import share of total U.S. consumption by value. The contribution of imports to total supply of manufactures in the U.S. market also varies greatly, ranging from 73 percent for apparel and 50 percent for computer and electrical equipment on the high end to zero for nonferrous metal foundries. In the results presented in the next section, the vulnerability to imports or international leakage associated with a unilateral increase in the domestic CO_2 price depends on the import substitution elasticity, as embodied in the Adkins–Garbaccio model, and the import share.

VI. Effects of a Carbon Tax over Different Time Horizons

This section presents the results of our four different modeling frameworks. The most comprehensive results are available for industrial output, while industry-specific estimates for profits, employment, and trade effects are presented for some but not all of the modeling horizons. To illustrate the effects of a carbon policy, cap-and-trade, or carbon taxes, we simulate the effects of an economywide carbon tax (t^C) of \$10/ton CO_2 (2005\$). This tax is first converted to 2002 levels to match our base year data. In the first two time horizons, the very short run and the short run, we compute the effects on costs by using equations (20) and (20a) for each of the 52 industries.

Effects on Costs and Output—Very Short–Run Horizon

The estimates of $\Delta COST_j^{VS}$ (the percent change in unit costs) are displayed in the first column of Table 3, while the remaining columns display the direct combustion, electricity, and other intermediate input components: $\Delta COST_j^{DC}$, $\Delta COST_j^{EL}$, and $\Delta COST_j^{IN}$. Recall that in this very short–run scenario, firms are regarded as being unable to raise prices, adjust output, change input mix, or adopt new technologies. Since the full costs of the carbon charge would be reflected in reduced profits, this can be considered a worst-case assessment.

The most highly affected sector is electricity generation, where costs rise by 8.3 percent. Of the 33 manufacturing industries, two (petrochemical manufacturing and cement) are estimated to face increases in production costs (reductions in profits) of 4 percent or more. Three more manufacturing industries face cost increases exceeding 2 percent—lime and gypsum, iron and steel mills, and alumina refining. An additional 14 manufacturing industries and one nonmanufacturing industry (air transportation) face production cost increases of 1 to 2 percent. The machinery, transportation equipment, and apparel industries have the lowest cost increases at less than half a percent. We should emphasize that these are the effects of a \$10/ton tax. If they are scaled up proportionately to, say, \$50/ton of CO_2, the costs for iron and steel mills and alumina refining will also rise by a factor of five to more than 11 percent.

Given the mix of energy inputs used in U.S. industry, it is not surprising that the contributions of direct combustion, electricity, and other intermediate inputs vary considerably across sectors. The most highly affected manufacturing sector, cement, uses large amounts of fossil fuel and electricity. It is also responsible for significant carbon emitted in the production of key intermediate inputs. Petrochemical manufacturing costs rise by 3.4 percent due to direct combustion but only by 0.4 percent each due to electricity and intermediate inputs. Of the 2.6 percent increase in costs for alumina refining, 1.8 percentage points—about 70 percent—is due to electricity use. Electricity is a similarly big contributor for other basic inorganic chemicals and mineral wool.

Intermediate inputs other than electricity constitute the biggest share in only a few of the high carbon–input industries—plastic material (0.7 out of 1.4 percent), artificial and synthetic fibers (0.8 out of 1.6 percent), and other nonmetallic mineral products (0.6 out of 1.0 percent). For the low CO_2–content industries such as machinery and transportation equipment, other intermediate inputs are the major contributors to the increased costs of a CO_2 charge. We should note again here that process emissions have not been included in our analyses. If included they would have changed the picture considerably for some sectors, for example, for the nonmetallic mineral products group. We should also note that pulp mills represent a special case since biomass is a major energy input, although it is ignored in our analysis here. Clearly, the treatment of biomass as an energy source would have to be specified under any new policy.

For the nonmanufacturing group, the cost increases for electric utilities and transportation are due mostly to the fossil fuel input. In contrast, for the other nonmanufacturing sectors, the CO_2 embodied in intermediate inputs is the big source of the burden.

Effects on Costs, Profits, and Output—Short Run versus the Very Short Run

In the short-run horizon we assume that producers raise prices to cover the higher unit costs. Thus, the change in unit costs is the same as that estimated in the very short–run scenario. Unlike the very short–run case, however, where sales and output are fixed, in this scenario the higher prices lead to a fall in sales and output as customers switch to alternative goods or imports. As described previously, to determine the sales response we estimated the elasticity of demand for each industry using the 21-sector, three-region world model. Multiplying the elasticities by the percent change in costs due to a $10/ton carbon tax gives our estimate of the decline in sales and output (equation 27), as reported in Table 4.

The reduction in output is large where there is either a large cost change or a highly elastic demand response. Among the manufacturing industries, the biggest fall in output is in petrochemical manufacturing (–7.7 percent), since it has both a large 4.2 percent increase in costs from a $10/ton tax and a large demand elasticity. This is followed by cement with a 4.1 percent decline in output due to the 5.0 percent increase in costs. Within the chemicals group, other basic organic chemicals, plastic materials, and fertilizer are all estimated to experience output declines exceeding 3.5 percent due to cost increases of almost 2 percent and a relatively high demand elasticity.

Among the nonmanufacturing industries, the fuel-producing industries subject to the carbon tax see the biggest increase in price (to the buyer, not the producer) and the biggest declines in sales. Coal mining, oil mining, and gas utilities experience output declines exceeding

5 percent. Electric utilities see the biggest increase in costs and a big reduction in output (1.4 percent), followed by the transportation industries.

A useful set of comparisons can be made from examining the impact of a CO_2 charge on the profits of different industries. Table 5 displays the percentage change in profits in both the very short–run and the short-run models derived from (24) and (33). Recall from Section III that we define profits as the gross return to capital, that is, sales revenue less intermediate and labor costs. Expressed in this way, in the very short–run two industries, other basic organic chemicals and basic inorganic chemicals, face a fall in profits of more than 8 percent from this modest carbon tax. Artificial and synthetic fiber manufacturing, and fertilizer also see relatively large reductions in profits, exceeding 4 percent.

However, as firms attempt to pass along the higher costs, even with some reduction in sales, a large portion of these losses are recouped for those industries facing inelastic demands, that is, for those most able to pass through the higher costs. For example, the 9.4 percent reduction in profit in other basic inorganic chemicals in the very short run is reduced to a loss of 0.2 percent in the short run. That is, about 98 percent of the increased costs may be recouped once we relax the constraint on cost passthrough. Similar patterns are seen in most of the other manufacturing industries. Those least able to pass on the higher costs are cement (short run loss of 0.4 percent compared to very short–run loss of 1.5 percent) and computer and electrical equipment (0.10 percent versus 0.22 percent).

The situation in the fossil fuel producing industries, however, is quite different. In these industries the very short–run assumption of no change in output quantities means a smaller loss compared to the short-run assumption, when the consumers of fossil fuels react to the carbon tax by buying less fuel. In the case of coal mining, in the very short–run horizon we see a 0.30 percent fall in profits, but when we account for the much lower use of coal after prices rise, the fall in profits is 1.1 percent. Similarly, oil mining experiences a fall in profits of 0.51 percent when we account for the higher oil prices to consumers compared to the very short–run decline of 0.11 percent.

The other nonmanufacturing industries experience effects similar to those in the manufacturing group. For example, truck transportation experiences a very short-run loss of 0.56 percent compared to a short-run loss of 0.07 percent.

It is clear from these results that the extent of the variation in both output and profit impacts is quite sensitive to the breadth of the industrial categories considered. Within the chemicals group (NAICS 325) the very short–run change in profits ranges from 0.3 percent in other chemicals and plastics to 9.4 percent in other basic inorganic chemicals, more than an order of magnitude difference. If we had averaged over the whole group, the low estimate for other chemicals and plastics would have dominated the results (see the output values in Table 2.) In earlier work, Morgenstern et al. (2004) found that subindustry impacts estimated at a four-digit classification scheme (based on the Standard Industrial Classification) can be an order of magnitude larger those estimated at the two-digit classification level. This is consistent with the analysis presented here that also includes some six-digit industries. As discussed in Appendix A, here our choice of aggregation level is dictated by the availability of consistent information to serve as inputs to the relevant models.

A further issue involves the scaling of results to different CO_2 price levels. Since the calculations for the very short– and the short-run are based on a relatively simple linear model, they can be readily scaled up or down to reflect different assumptions about CO_2 prices. However, one has to be careful about the application of the calculated demand elasticities, η_j , as these are derived from the parameters in the multisector CGE model and are strictly intended for marginal analyses. How the system would respond to large increases in prices is an issue that should be carefully considered. In the medium- and long-run horizons examined below, the model explicitly involves nonlinearities that cannot be so readily scaled.

Effects on Output over the Four Time Horizons

As noted in Section III, the CGE model that we use to consider the longer horizons only identifies three-digit–level industries for manufacturing. The complete data for trade flows and production parameters allow for a total of 21 sectors instead of the 52 sectors analyzed for the very short– and short-run models. To compare the output responses to the more detailed results in the short-run scenario we first aggregate the results for the 52 industries in Table 4 to the same 21 industrial categories. Table 6 displays the effects of a \$10/ton of CO_2 (2005\$) tax on output derived from the medium- and long-term models as well as the aggregated short-run effects.

It should be obvious that the aggregation process results in the loss of quite a bit of information. For example, the output effects for the nonmetallic minerals group range from –0.88 for other nonmetallic mineral products to –4.06 for cement. The group average output effect is the 1.2 percent for nonmetallic minerals given in the first column of Table 6. By their very nature, the group averages are smaller than the largest effects detected at the more disaggregated level and larger than the smallest effects detected at the more aggregated level.

Recall that in the medium run producers may substitute among all inputs except for capital. Thus, for example, firms may substitute labor for energy or gas for coal. Only in the long-run horizon can capital move to other sectors and substitute for energy or labor. Furthermore, in the general equilibrium framework both producers and purchasers are changing their behavior, and these may have opposing effects on output over time. On one hand, producers are substituting inputs to reduce costs and hence prices. Over time, lower prices should help raise sales and output. On the other hand, customers are making substitutions to avoid the higher prices for carbon-intensive products and thus reducing their demands.

Looking across the columns of Table 6, from short run to long run, we see these opposing effects. The magnitudes of the output reductions generally decline, but not uniformly. That is, the cost-reducing effect of input substitution is generally, but not completely, dominant. Over time, for all but two manufacturing industries, the cost shock of the carbon tax is reduced, and smaller price increases are needed to cover the higher costs of carbon-intensive inputs. Excluding the two exceptions, on average, the output losses in the manufacturing industries are reduced by about 16 percent between the short and medium time frames and by a further 1 percent between the medium- and long-run time frames.[11] For example, output losses in the transportation equipment industry decline from 1.1 percent in the short run to 0.28 percent in the medium term and 0.23 percent in the long run. For primary metals the output loss falls from 1.6 percent to 1.3 percent in the medium run and to 1.2 percent in the long run.

For two manufacturing industries, petroleum refining and fabricated metals, the flexibility associated with longer time horizons does not lead to reduced impacts. In fabricated metals, the short-run reduction in output was estimated to be 0.33 percent, and in the medium run it is 0.44 percent. Recall that the short-run effect was estimated by simply multiplying the elasticity η_j by the percent change in unit costs. This is the effect of a simple change in the price of good j. The general equilibrium effects considered in the medium run seem to dominate the effect of the industry's own effort to lower costs and prices; the customers' response to changes in all prices is to lower demand for fabricated metals by more than the effect of lower fabricated metal prices. That is, the shift in the demand curve is bigger than the movement along the demand curve caused by lower prices. From Table 3 we saw that changes in unit costs can vary

[11] These calculations are based on an output-weighted average of the individual industry-level estimates.

substantially across sectors; for example, the electricity price rises substantially, while the relative price of wood falls.

Recall that petroleum refining is a special case, where we imposed a smaller elasticity in the short run. Thus, the output effect in the medium run is much bigger than the short-run effect.

Among the nonmanufacturing industries we also see both patterns of diminished and expanded output effects over time. For the fossil fuels sectors and services, the effect of producers adapting inputs to lower costs dominates, and output losses diminish over time. For the other industries, the general equilibrium effects of customers switching even more to substitute products dominate, and output declines further over time.

The changes in industry level outputs as we move from the world of from fixed capital in the medium term to one of mobile capital in the long run are quite varied. In three of the twelve manufacturing industries, apparel, primary metals, and transportation equipment, the long-run effects on output are smaller than those in the medium run. That is, the ability to substitute capital for other inputs leads to both lower costs and lower prices, dampening the initial effect of the carbon tax. In five industries, food, textiles, lumber, fabricated metals, and other machinery, the response is essentially unchanged. That is, the effect of lowering costs by substituting capital is canceled out by the general equilibrium effects of all the other changes in the prices. In three industries (refining, chemicals, and nonmetallic mineral products) the output reduction in the long run is slightly bigger than the medium run. These are the most energy- and carbon-intensive industries, and their products experience the biggest price increases. In the medium run their customers are limited to substituting alternative intermediate inputs and labor, but in the long run they may substitute capital, thereby reducing the demand for these high-carbon content intermediate inputs even further. For example, in the medium run nonmetallic mineral products experience a 1.14 percent reduction in sales and output, but in the long run they see a 1.20 percent reduction.

For one manufacturing industry, electrical machinery, output rises slightly in the long run even though it falls in the medium run. This is due to the full-employment assumption; factors that are reallocated out of the declining industries have to go somewhere, and some ended up in electrical machinery and services. Labor supply is elastic and falls slightly, but the national capital stock is assumed to be fixed.

Employment and Capital Utilization over Time

Recall that we have defined the short-run horizon as the period where producers are unable to change inputs per unit output, that is, the employment output ratio is fixed. Thus, the percentage change in employment due to the imposition of a carbon price is equal to the percentage change in output, as shown in Table 3 for the detailed 52 industries and in Table 6 for the aggregated 21 industries. The employment results for the 21 aggregated industries are shown in the first column of Table 7.

In the medium-run case producers may substitute among intermediate inputs and labor, while over the long run all inputs, including capital, may be substituted for each other. Thus, in both the medium- and long-run cases, labor demand depends on both the output level and the degree of substitution among inputs. Clearly, one would expect the impacts to be smaller than in the short-run, no-substitution case. Capital use in the long run is driven by two opposing effects. On one hand, the outputs of the carbon-intensive sectors are reduced, reducing the demand for capital. On the other hand, there is substitution from expensive energy to cheaper capital, which increases the demand for capital in these sectors.

The effects on employment and capital use for the medium- and long-run horizons estimated from simulating the general equilibrium model are shown in Table 7. The results comparing the short-run to the medium- and long-run cases for employment are similar but not identical to the output effects shown in Table 6. In all but two manufacturing industries, the reduction in employment is smaller in the medium and long term horizons compared to the short-run, no-substitution case. For example, in chemicals the short-run reduction of 1.7 percent is reduced to 0.81 percent in the medium run and to 0.47 percent in the long run. In primary metals the corresponding reductions range from –1.57 percent to –1.10 percent to –0.69 percent, respectively.

Comparing the change in employment to the change in output given in Table 6, we see that in more than half the manufacturing industries, the percentage reduction in employment is smaller than the reduction in output, indicating some substitution of labor for carbon-intensive inputs. In four other manufacturing industries the percentage reduction in labor exceeds the reduction in output due to the substitution between capital and labor. Since capital is assumed fixed in this scenario, the industry is unable to shed capital given the reduction in sales and output. Thus, it makes larger reductions in employment. The higher elasticity of capital–labor substitution for petroleum refining leads to the biggest fall in employment of any industry. In the case of food manufacturing, employment in the medium run actually rises by a small amount despite the reduction in output, likely due to the small output effect and the strong substitution away from carbon-intensive intermediate inputs. Not surprisingly, this is an industry where the carbon embodied in the other intermediate inputs is greater than the carbon in the fossil fuel used or electricity used.

Another exception to the general pattern occurs in the case of fabricated metals. Here the greater labor reduction in the medium run follows the unusual pattern of a larger output reduction in the medium run. Petroleum refining is also a special case that has a greater medium-run output reduction due to the use of more elastic parameters in the general equilibrium calculation.

Going from the medium to the long run, the reduction in employment diminishes in all cases. In two extreme manufacturing cases, apparel and electrical machinery, the medium-run employment reductions turn to gains in the long run. That is, the ability to substitute capital for the more expensive carbon-intensive inputs in the long run lead to bigger reductions in energy consumption and smaller reductions in labor use.

As noted above, there are two opposing effects on capital use, and the net the effect is negative for all but three manufacturing industries. That is, the reduction in capital demand due to the reduction in output dominates the substitution of capital for energy in most industries. Only in the food, apparel, and electrical machinery industries are the long-run demands for capital slightly higher after a carbon tax is in place.

In the nonmanufacturing industries we also see a smaller employment impact in the medium run compared to the short run except for two industries. In the gas industry and other mining, the output reduction is bigger in the medium run compared to the short run, and employment follows the same pattern. The two fossil fuel mining industries continue to see large reductions in employment, albeit smaller than the short-run impacts.

In the medium run, we assume full employment. Thus, labor that is released from the declining sectors moves to the expanding sectors. Services is the big recipient of this released labor; the small 0.18 percent change is multiplied by a very large number of workers there. The most interesting industry is electric utilities, where output falls by 1.4 percent but employment rises by 8 percent in the medium run. This is due to the high value-added substitution elasticity for this industry (see Appendix B, Table B5, σ^{v}); the system is trying to substitute away from fossil fuel inputs, and since capital is fixed in the medium-run case, the demand for labor increases to replace fossil fuels.

Going from the medium to long run, the three fossil fuel mining industries actually see greater employment losses. That is, the users of fuels substitute capital for fuel over the longer term and the demand for coal, oil, and gas falls, leading to lower employment. For agriculture, construction, and transportation, the impact is softened over time, as capital moves out of the declining sectors and firms move toward the now relatively cheaper labor. The capital that moves out of the declining carbon-intensive sectors goes to services and, perhaps surprisingly, to the electricity sector. However, given the nest of substitution possibilities in the electricity industry this should be expected: the cost of fuel inputs has risen substantially, and the system substitutes value added for it, which raises both capital and labor demands.

The changes due to the carbon tax calculated by the general equilibrium model depend, of course, on the functional forms used and the elasticities imposed. Our calculations here are certainly not the only plausible ones; other flexible functional forms would have generated a different pattern of changes. The key point is that output and employment responses change over time and they change due to actions taken by both producers and customers. The adjustments by customers may well overwhelm the actions taken by producers to reduce long-run costs, thus generating bigger losses over the long run.

Trade Impacts

We turn now to the impacts of CO_2 pricing on international competitiveness. Up to this point we have been discussing the effects on output, profits, and employment. Competitiveness is a demand-side issue, that is, how domestic and foreign customers choose between or among different suppliers. Domestic consumption is supplied by domestic output less the exported portion, plus imports. “Leakage” refers to emissions increases in the rest of the world as a result of the domestic policy. The way we use the term, industry specific leakage is a measure of the percent reduction in domestic output that is made up by a change in net imports as a result of the domestic policy. Using this definition, we are recognizing changes in global output flows, but not any changes in the carbon intensity of those flows.[12]

In simulating the medium- and long-run horizons with the CGE model, we impose a carbon tax on fossil fuel consumption that is equivalent to a tax on both domestic fuel output and

[12] In a case where all domestic output losses were fully offset by increased foreign output and the CO_2 emissions intensity was greater than the domestic intensity, global emissions could increase. In the absence of specific data on the CO_2 intensity of foreign-produced goods, we do not explicitly examine this case.

imported fuels. However, we do not tax imports of manufactured goods to offset the effects of the tax on domestic manufacturers. In this framework there is no leakage of carbon reductions due to imported coal and oil, but some leakage due to increased imports of manufactured goods. The results are displayed in Table 8.

The first column of Table 8 presents the model base year values for domestic consumption of the 21 commodities. National domestic consumption is the sum of consumption by firms, households, and government and is equal to domestic output plus imports less exports (ignoring changes in inventories, which are not modeled). The second column gives the changes in consumption due to a \$10/ton CO_2 tax, while the last three columns present the contributions of the changes in terms of output, imports, and exports.

We observe a similar, albeit varied, set of trade impacts across the different industries. In the case of chemicals, for example, consumption falls by 0.62 percent. Of that amount, the fall in domestic output contributes 1.30 percentage points. However, this output reduction is offset by an increase in imports of 0.18 points and a reduction in exports of 0.50 points [–0.62 = –1.30 + 0.18 – (–0.50)]. Stated alternatively, the large fall in output of 1.1 percent (see Table 6), does not lead to a large fall in consumption, as imports rise to make up about 14 percent of the output reduction, and the diversion of previous exports to domestic use makes up another 38 percent. The result is that consumption of chemicals falls by only 0.62 percent, that is, the reduction in global carbon emissions due to a fall in chemical output is not the large 1.1 percent reduction in U.S. chemicals–related emissions, but only a 0.62 percent chemicals-related reduction in the United States plus a very small reduction in the rest of the world due to more expensive U.S. chemical exports. The leakage for chemicals is thus a substantial 52 percent, more (less) if the production in the rest of the world is more (less) carbon intensive than U.S. production.

We can see a similar pattern for the other carbon-intensive manufacturing industries: a modest increase in imports and a bigger reduction in exports. Of the 0.49 percent reduction in consumption of nonmetallic mineral products, the rise in imports contributed 0.13 points and exports contributed 0.29 points (a 46 percent leakage). Of the 0.66 percent reduction in primary metals use, imports contributed 0.16 points and exports 0.30 points (a 41 percent leakage).

Overall, the emissions increase in the rest of the world is 26 percent of the reduction in U.S. emissions as a result of a unilateral U.S. carbon tax. This is a relatively high leakage rate but consistent with other studies. World Bank (2008) first cites the IPCC 2001 report as estimating leakages in the order of 5-20 percent, and then, after examining the historical shifts in trade, concluded there is "some evidence…of leakage of carbon- and energy-intensive industries to developing economies." Babiker (2005) reports that most studies find leakage rates associated with the Kyoto Protocol of 5-25 percent. Babiker's own calculations, based on a highly aggregated model (7 goods, 7 regions), suggests aggregate leakage rates ranging from 20-130 percent from the Kyoto Protocol. These studies are not directly comparable to our unilateral U.S. policy, but do give a sense of the range of possibilities. Fisher and Fox (2007) analyze a unilateral policy but consider a complex combination of carbon tax and output subsidies. They report an aggregate leakage rate of 12-15 percent. As previously noted, at the industry level there is quite a wide range, for example, for the energy intensive industries the leakage rate is 40-45 percent. Similarly, the leakage rate in Adkins and Garbaccio (2007) is 35 percent.[13]

In this simple one-period model, the trade deficit of each region is held fixed, that is, the carbon tax scenario has the same deficit as the base case. The increase in imports and reduction of exports of the carbon-intensive commodities are offset by a reduction in imports and an increase in exports of other commodities induced by the endogenous exchange rate to maintain the trade deficits. The electrical machinery industry actually experiences both a reduction in imports and a rise in exports. Recall that petroleum product imports are also subject to a carbon tax, and imports of that commodity also fall.

These trade effects are sensitive to the import elasticities assumed. Since the CGE model is quite aggregated with only 12 manufacturing sectors, some of the elasticities are smaller than might be appropriate for a more disaggregated set of industries. That is, if we were able to conduct this medium-run exercise for the 52 industries that were used for the short-run analysis, we would likely see a bigger import response for some commodities and an even bigger degree of leakage. Of course, this would be offset by smaller impacts (leakage) in other industries.

VII. Cross-Model Comparisons

Debate on the impact on industry of an economywide carbon tax or cap-and-trade system has, quite naturally, focused on the most adversely affected industries. In that context it is useful to compare the relative rankings of the different industries across the four modeling horizons considered here. Comparing all four time horizons according to the 21 industry classifications

[13] Our results differ from those of others for various reasons, including the fact that other models may have different amounts of regional detail than ours. Also, some include output subsidies and consider a higher tax rate than we do. Since the models are non-linear, our relatively smaller tax may be expected to generate larger leakages compared to others.

used in our modeling, it appears that the relative rankings are reasonably consistent across all horizons, with only a few exceptions (Table 9).[14] Thus, among manufacturing industries, primary metals, nonmetallic minerals, petroleum refining, and chemicals and plastics rank relatively high across all four time horizons, while food, electrical machinery, and apparel rank relatively low. The Spearman rank correlation coefficient between the very short run and the short run is 0.37; between the short and medium run the correlation is 0.46; and between the medium and long runs, the coefficient is 0.97. For nonmanufacturing industries, a roughly similar pattern applies. The corresponding Spearman rank coefficients are –0.33, 0.68, and 0.98, respectively.

As another cross check, we compare the relative rankings of published U.S. and European analyses for manufacturing industries (Table 10). Although the industry boundaries are not identical across the different studies, the rankings appear roughly similar, with a few notable exceptions. For the U.S. studies, the results are quite close, reflecting the common data and definitions used in the analyses. When comparing the U.S. and European results, however, the differences appear somewhat greater. Most significant is the cement industry, which ranks number one in the European case studies prepared by McKinsey (2006) and by Reinaud (2005) and number two in the cross-industry study of the United Kingdom developed by Hourcade et al. (2007). In contrast, cement is roughly in the top quarter in the U.S. analyses. One possible explanation for these differences is the inclusion of process emissions in the European analyses. On the assumption that a U.S. emissions control policy would eventually include process emissions from cement and other relevant industries, one would expect these industries to move up in the rankings to more closely resemble their European counterparts.

A further difference between the U.S. and European analyses can be seen in the analyses of the petroleum refining industry, which ranks high in the United States and only appears in one of the European studies. In fact, neither the Reinaud (2005) nor the Hourcade et al. (2007) analyses even analyzed petroleum refining. McKinsey (2006) did include it and found that it ranked number two behind cement. While petroleum refining is an important industry worldwide, it is also a particularly complex one to analyze given the lack of a consensus on the short- and long-run demand elasticities for petroleum products. We have used a relatively low elasticity for our short-run estimate and thus put the output fall at a modest 0.8 percent per

[14] Most notable among the rank changes is petroleum refining, which moved up from roughly the middle of the pack in the very short–run and short-run analyses to the most adversely impacted sector in the long run.

\$10/ton CO_2 tax. When we use the CGE model with larger elasticities, however, the output effects are larger, almost 5 percent. This is due to several different effects: the substitution by users toward capital and other inputs and the influence of higher petroleum prices on the price of oil-intensive commodities; for example, the higher price of transportation fuels reduces the use of these fuels.

VIII. Conclusions

Any broad-based CO_2 pricing policy will have disproportionate impacts on carbon-intensive, import-sensitive industries. Two key challenges for policy development are to identify the hardest hit industries and to understand the full extent and likely duration of the impacts. Defining carbon intensity to include the emissions associated with direct combustion as well as the purchase of electricity and other intermediate inputs, we use four modeling approaches as a proxy for the time horizons over which firms can pass through added costs, change input mix, adopt new technologies, and reallocate capital. While our modeling analyses are based on a fairly detailed list of industries, further disaggregation would certainly show an even broader range of responses. With this caveat in mind, examination of the results of a \$10/ton CO_2 charge over what we label the very short–, short-, medium-, and long-run horizons yields a number of observations:

- Measured by the reduction in domestic output, a readily identifiable set of industries is at greatest risk of contraction over both the short and long terms. Within the manufacturing sector, at a relatively aggregate, two- or three-digit industry classification level, the hardest hit industries are petroleum refining, chemicals and plastics, primary metals, and nonmetallic minerals.

- Although the short-run output reductions are relatively large in these industries, they shrink over time as firms adjust inputs and adopt new technologies. The industries that continue to bear the impacts are the same ones affected initially, albeit at reduced levels. When impacts are measured in terms of reduced profits, the rebound is especially large and, for some industries, virtually complete.

- Focusing on the nearer-term time frames, where certain simplifying assumptions enable us to conduct a more disaggregated analysis, we observe that the greatest harm is concentrated in particular sub-segments of these industries. Petrochemical manufacturing and cement see very short–run cost increases of more than 4 percent, while iron and steel, aluminum, and lime products see cost increases exceeding 2 percent.

- Turning to the nonmanufacturing sector, we see that while the overall size of the production losses also decline over time, a more diverse pattern applies. Specifically, the impact on electric utilities does not substantially worsen over time compared to other industries such as mining, which experiences a continuing erosion of sales, as broader adjustments occur throughout the economy. Agriculture faces modest but persistent output declines over time, while the service sector is largely unscathed across all time horizons.

- In terms of employment, the short-term job losses are modeled as proportional to those of output. Over the longer term, however, when labor markets are able to adjust, the remaining losses are fully offset by gains in other industries.

- Our analysis of trade effects at the relatively aggregate two- or three-digit classification level assumes that manufactured products are subject to increased foreign competition but fuels are not. That is, while out baseline includes some form of border adjustment for fuels *per se*, no such mechanism is assumed for manufactured goods. We find that pricing CO_2 emissions increases manufactured imports and reduces manufactured exports in parallel with reducing domestic output. Overall, the leakage rate in the long run is 26 percent when viewed across the entire economy, that is, increases in emissions in the rest of the world offset about a quarter of the U.S. reductions. Not surprisingly, the leakage rate for the three most energy-intensive sectors – chemicals, nonmetallic mineral products, and primary metals – is considerably higher. The leakage rate for these top three industries is more than 40 percent.

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Tables

Table 1. Import Shares and Energy Cost As Share of Total Costs

	Share of Total Costs (%)				
	Electricity	Fuel combustion	Total energy (including noncombustible)	Intermediate inputs	Import
Manufacturing industries					
Food	1.0	0.9	1.9	66.9	8.3
Textile	3.3	1.1	4.5	60.2	27.2
Apparel	0.6	0.3	0.9	57.7	73.4
Wood and furniture	1.4	0.4	1.7	57.9	21.8
Pulp mills	3.0	5.6	8.8	64.5	45.8
Paper mills	4.9	3.7	8.6	55.2	20.6
Paperboard mills	5.1	5.8	11.0	57.4	0.5
Other papers	1.1	0.4	1.5	57.4	4.5
Refining–LPG	1.3	7.0	69.8	88.1	0.0
Refining–other	1.3	7.0	69.9	88.1	12.3
Petrochemical manufacturing	5.3	26.4	46.5	77.6	10.0
Other basic inorganic chemical mfg.	11.2	1.8	13.9	67.0	28.4
Other basic organic chemical mfg.	3.8	6.8	22.4	80.3	25.7
Plastics material and resin mfg.	2.7	3.8	21.9	81.4	15.3
Artificial and synthetic fibers, filaments	2.5	4.1	6.7	78.7	13.8
Fertilizer manufacturing	3.6	13.3	36.0	80.3	26.7
Other chemical and plastics	1.8	0.7	2.7	52.2	20.8
Glass container manufacturing	5.9	6.3	12.2	49.2	13.5
Cement manufacturing	11.6	11.3	23.4	49.5	14.3
Lime and gypsum product mfg.	1.8	4.6	6.6	58.6	2.1
Mineral wool manufacturing	5.1	4.0	9.2	53.5	7.3
Other nonmetallic mineral	1.9	2.7	4.7	53.8	18.1
Iron and steel mills, ferroalloy mfg.	9.0	5.9	15.6	59.4	22.1
Alumina refining, primary aluminum	19.8	7.3	27.6	51.6	29.8
Ferrous metal foundries	3.7	1.1	4.8	45.3	3.1
Nonferrous metal foundries	1.9	1.4	3.3	59.3	0.0
Other primary metals	4.4	1.9	6.3	61.6	41.1
Fabricated metals	1.4	0.5	1.9	52.6	12.7
Machinery	0.7	0.2	0.9	57.3	29.3
Computer and electrical equipment	0.9	0.3	1.2	52.9	49.8
Motor vehicles	0.7	0.3	1.0	62.6	41.9
Other transportation equipment	0.7	0.2	0.9	54.5	27.8
Miscellaneous manufacturing	0.6	0.2	0.7	46.6	40.1
Nonmanufacturing industries					
Farms	1.5	2.2	3.9	58.5	8.5

Forestry, fishing, and hunting	0.2	1.6	1.9	37.6	22.0
Oil mining	1.3	1.1	2.4	48.0	59.8
Gas mining	1.3	1.1	2.4	48.0	33.1
Coal mining	2.0	1.8	3.9	45.2	3.4
Other mining activities	2.4	2.6	5.1	48.8	0.8
Electric utilities (including government enterprises)	0.0	13.1	13.2	31.7	0.5
Gas utilities	0.0	0.1	43.4	66.5	0.0
Construction	0.3	2.2	2.7	50.0	0.0
Trade	0.8	0.3	1.2	31.4	–1.2
Air transportation	0.1	9.5	10.4	45.7	17.8
Truck transportation	0.3	5.6	6.4	51.3	1.2
Other transportation	0.7	3.7	4.6	37.0	–2.8
Information	0.3	0.3	0.6	34.2	0.6
Finance and insurance	0.2	0.1	0.2	21.1	2.5
Real estate and rental	0.8	0.1	0.9	22.2	0.0
Business services	0.4	0.7	1.1	22.9	0.5
Other services	1.1	0.4	1.5	39.0	0.1
Government excluding electricity	0.5	1.9	2.6	37.8	0.0

Table 2. Combusted-Only Energy Consumption and CO_2 Intensity, 2002

	Output (billion $)	Coal (million short tons)	Crude oil (million bbls)	Petroleum–LPG (million bbls)	Petroleum–other (million bbls)	Gas (billion cu. ft.)	Electricity (billion kWh)	CO_2 intensity (ton CO_2 /million $)
Manufacturing industries								
Food	470.4	9.1	0.0	1.4	21.2	605.0	75.2	224.9
Textile	59.7	1.0	0.0	0.6	3.5	100.0	30.1	461.9
Apparel	44.1	0.0	0.0	0.0	0.3	20.0	4.3	88.2
Wood and furniture	136.1	0.0	0.0	1.5	2.2	80.0	28.0	168.1
Pulp mills	3.4	0.3	0.0	0.0	2.1	23.0	1.6	1050.2
Paper mills	45.3	13.2	0.0	0.4	8.2	216.0	34.0	1362.5
Paperboard mills	21.1	3.8	0.0	0.1	5.6	183.0	16.4	1409.4
Other papers	173.3	0.2	0.0	1.3	1.0	113.0	28.3	142.1
Refining–LPG	21.0	1.0	40.2	0.0	0.0	94.1	4.1	1280.6
Refining–others	169.8	11.6	325.1	6.0	0.0	759.9	33.1	1327.8
Petrochemical manufacturing	14.7	1.1	2.2	156.5	7.3	168.0	11.9	4118.3
Other basic inorganic chemical mfg.	15.2	0.9	0.2	0.8	0.9	66.5	25.9	1444.1
Other basic organic chemical mfg.	47.6	7.1	2.1	32.2	11.0	479.0	27.5	1474.5
Plastics material and resin mfg.	44.8	1.2	1.4	10.0	0.2	291.2	18.6	731.5
Artificial and synthetic fibers, filaments	7.7	0.5	0.0	0.0	0.8	55.2	2.9	792.0
Fertilizer manufacturing	8.2	0.0	0.0	0.0	0.6	203.0	4.5	1716.6
Other chemicals and plastics	403.1	3.5	0.1	5.1	15.4	473.0	109.9	267.6
Glass container manufacturing	4.4	0.0	0.0	0.0	0.0	51.0	3.9	1197.3
Cement manufacturing	7.1	10.6	0.0	0.0	16.1	21.0	12.5	5080.7
Lime and gypsum product mfg.	4.9	3.0	0.0	0.0	4.4	7.0	1.4	1775.0
Mineral wool manufacturing	4.8	0.0	0.0	0.0	0.2	34.0	3.8	884.6
Other nonmetallic mineral	67.0	0.3	0.0	0.6	6.8	297.0	19.9	477.7
Iron and steel mills, ferroalloy mfg.	41.9	19.0	0.0	0.0	1.9	383.5	57.5	2242.7
Alumina refining, primary	18.8	0.0	0.0	0.1	22.9	127.0	56.7	2717.7

aluminum								
Ferrous metal foundries	14.7	0.2	0.0	0.2	0.3	26.9	8.2	477.1
Nonferrous metal foundries	11.4	0.0	0.0	0.1	0.0	30.0	3.2	321.0
Other primary metals	28.4	0.6	0.0	0.7	2.2	84.0	18.9	645.7
Fabricated metals	219.3	0.0	0.0	0.9	1.4	204.0	47.1	186.8
Machinery	221.6	0.1	0.0	1.1	1.0	80.0	24.6	91.5
Computer and electrical equipment	363.6	0.0	0.0	0.4	12.0	114.0	52.3	119.1
Motor vehicles	326.2	0.0	0.0	0.9	3.8	154.1	36.3	99.7
Other transportation equipment	134.5	0.0	0.0	0.0	2.1	43.5	14.2	89.2
Miscellaneous manufacturing	115.1	0.0	0.0	0.2	0.4	31.0	10.4	72.1
Nonmanufacturing industries								
Farms	177.3	0.1	0.0	0.0	119.9	58.0	41.1	430.5
Forestry, fishing, and hunting	34.4	0.0	0.0	0.0	18.1	1.4	0.9	227.4
Oil mining	61.1	0.1	0.0	0.0	8.7	71.7	12.4	248.8
Gas mining	41.1	0.1	0.0	0.0	5.9	48.3	8.3	248.8
Coal mining	19.3	0.0	0.0	0.0	5.2	36.3	5.8	394.8
Other mining activities	57.1	0.2	0.0	0.0	22.4	151.1	21.0	533.1
Electric utilities (including government enterprises)	259.6	977.5	0.0	0.0	91.4	5,676.8	0.0	8647.6
Gas utilities	82.6	0.0	0.0	0.0	2.2	0.0	0.4	13.7
Construction	966.9	0.0	0.0	0.0	669.2	123.4	44.7	310.2
Trade	1,850.5	0.0	0.0	0.0	145.5	349.7	232.8	119.1
Air transportation	99.3	0.0	0.0	0.0	311.0	0.8	1.2	1250.7
Truck transportation	194.7	0.0	0.0	0.0	357.0	23.0	8.4	760.7
Other transportation	329.3	0.0	0.0	0.0	337.2	634.0	32.9	573.5
Information	824.0	0.0	0.0	0.0	32.4	275.0	42.3	65.5
Finance and insurance	1,138.7	0.0	0.0	0.0	14.7	45.5	26.1	21.4
Real estate and rental	1,932.0	0.1	0.0	0.0	59.3	172.2	222.3	88.0
Business services	1,710.9	0.1	0.0	0.0	352.6	307.7	100.1	127.8
Other services	2,370.2	0.0	0.0	0.0	106.1	1,079.7	403.6	147.7
Government excluding electricity	2,043.1	0.1	0.0	0.0	910.4	2,795.9	159.3	300.0

Note: CO_2 intensity is derived from fossil fuels combusted and electricity use.

Table 3. Very Short–Run Time Horizon: Estimated Percent Increase in Production Costs per $10/ton CO_2 (2005$)

	Total cost	Fuel cost	Purchased electricity	Indirect cost
Manufacturing industries				
Food	0.6	0.1	0.1	0.4
Textile	0.8	0.1	0.3	0.4
Apparel	0.4	0.0	0.1	0.3
Wood and furniture	0.4	0.0	0.1	0.3
Pulp mills	1.3	0.7	0.3	0.3
Paper mills	1.6	0.8	0.4	0.3
Paperboard mills	1.6	0.9	0.5	0.2
Other papers	0.6	0.0	0.1	0.5
Refining–LPG	1.4	1.1	0.1	0.1
Refining–others	1.4	1.1	0.1	0.1
Petrochemical mfg.	4.2	3.4	0.5	0.4
Other basic inorganic chemical mfg.	1.6	0.4	1.0	0.2
Other basic organic chemical mfg.	2.0	1.1	0.3	0.6
Plastics material and resin mfg.	1.4	0.4	0.2	0.7
Artificial and synthetic fibers, filaments	1.6	0.5	0.2	0.8
Fertilizer manufacturing	1.8	1.3	0.3	0.2
Other chemical and plastics	0.7	0.1	0.2	0.4
Glass container manufacturing	1.3	0.6	0.5	0.1
Cement manufacturing	5.0	3.8	1.0	0.2
Lime and gypsum product mfg.	2.1	1.5	0.2	0.5
Mineral wool manufacturing	1.1	0.4	0.5	0.3
Other nonmetallic mineral	1.0	0.3	0.2	0.6
Iron and steel mills, ferroalloy mfg.	2.3	1.3	0.8	0.2
Alumina refining, primary aluminum	2.6	0.8	1.8	0.1
Ferrous metal foundries	0.7	0.1	0.3	0.2
Nonferrous metal foundries	0.8	0.1	0.2	0.5
Other primary metals	1.0	0.2	0.4	0.4
Fabricated metals	0.6	0.1	0.1	0.4
Machinery	0.4	0.0	0.1	0.3
Computer and electrical equipment	0.3	0.0	0.1	0.2
Motor vehicles	0.5	0.0	0.1	0.4
Other transportation equipment	0.3	0.0	0.1	0.3
Miscellaneous manufacturing	0.3	0.0	0.1	0.3

Nonmanufacturing industries				
Farms	0.7	0.3	0.1	0.3
Forestry, fishing, and hunting	0.4	0.2	0.0	0.2
Oil mining	0.4	0.1	0.1	0.2
Gas mining	0.4	0.1	0.1	0.2
Coal mining	0.6	0.2	0.2	0.2
Other mining activities	0.7	0.3	0.2	0.2
Electric utilities (including government enterprises)	8.3	8.2	0.0	0.1
Gas utilities	0.1	0.0	0.0	0.1
Construction	0.5	0.3	0.0	0.2
Trade	0.2	0.0	0.1	0.1
Air transportation	1.4	1.2	0.0	0.3
Truck transportation	1.0	0.7	0.0	0.3
Other transportation	0.7	0.5	0.1	0.1
Information	0.2	0.0	0.0	0.1
Finance and insurance	0.1	0.0	0.0	0.1
Real estate and rental	0.1	0.0	0.1	0.1
Business services	0.2	0.1	0.0	0.1
Other services	0.2	0.0	0.1	0.1
Government excluding electricity	0.4	0.1	0.0	0.1

Table 4. Short-Run Time Horizon: Effect of a $10/ton CO_2 Charge on Output (percent change)

	Short-run partial equilibrium effect only
Manufacturing industries	
Food	–0.38
Textile	–1.13
Apparel	–1.03
Wood and furniture	–0.34
Pulp mills	–1.00
Paper mills	–1.08
Paperboard mills	–1.11
Other papers	–0.46
Refining–LPG	–0.68
Refining–others	–0.79
Petrochemical mfg.	–7.65
Other basic inorganic chemical mfg.	–1.92
Other basic organic chemical mfg.	–3.66
Plastics material and resin mfg.	–3.95
Artificial and synthetic fibers, filaments	–1.83
Fertilizer manufacturing	–3.58
Other chemical and plastics	–1.00
Glass container manufacturing	–1.04

Cement manufacturing	–4.06
Lime and gypsum product mfg.	–1.73
Mineral wool manufacturing	–0.97
Other nonmetallic mineral	–0.88
Iron and steel mills, ferroalloy mfg.	–2.06
Alumina refining, primary aluminum	–2.42
Ferrous metal foundries	–0.68
Nonferrous metal foundries	–0.78
Other primary metals	–1.08
Fabricated metals	–0.33
Machinery	–0.76
Computer and electrical equipment	–1.00
Motor vehicles	–1.24
Other transportation equipment	–0.89
Miscellaneous manufacturing	–0.65
Nonmanufacturing industries	
Farms	–0.56
Forestry, fishing, and hunting	–0.41
Oil mining	–5.09
Gas mining	–6.34
Coal mining	–11.01
Other mining activities	–0.49
Electric utilities (including government enterprises)	–1.35
Gas utilities	–4.95
Construction	–0.42
Trade	–0.16
Air transportation	–1.05
Truck transportation	–0.72
Other transportation	–0.52
Information	–0.13
Finance and insurance	–0.06
Real estate and rental	–0.10
Business services	–0.15
Other services	–0.21
Government excluding electricity	–0.31

Table 5. Very Short Run versus Short Run: Effect on Profits of a $10/ton CO_2 Tax (percent change)

	Very short run (quantities fixed)	Short run (output changed)
Manufacturing industries		
Food	–0.39	–0.04
Textile	–0.80	–0.11
Apparel	–0.24	–0.10
Wood and furniture	–0.49	–0.03
Pulp mills	–0.85	–0.10
Paper mills	–0.61	–0.11
Paperboard mills	–0.63	–0.11
Other papers	–0.47	–0.05
Refining–LPG	–1.59	–0.07
Refining–others	–1.92	–0.08
Petrochemical mfg.	–2.26	–0.76
Other basic inorganic chemical mfg.	–9.38	–0.19
Other basic organic chemical mfg.	–8.64	–0.37
Plastics material and resin mfg.	–3.70	–0.40
Artificial and synthetic fibers, filaments	–6.51	–0.18
Fertilizer manufacturing	–4.71	–0.36
Other chemical and plastics	–0.34	–0.10
Glass container manufacturing	–0.50	–0.10
Cement manufacturing	–1.52	–0.41
Lime and gypsum product mfg.	–0.94	–0.17
Mineral wool manufacturing	–0.51	–0.10
Other nonmetallic mineral	–0.64	–0.09
Iron and steel mills, ferroalloy mfg.	–1.34	–0.21
Alumina refining, primary aluminum	–1.10	–0.24
Ferrous metal foundries	–0.43	–0.07
Nonferrous metal foundries	–1.36	–0.08
Other primary metals	–0.81	–0.11
Fabricated metals	–0.51	–0.03
Machinery	–0.35	–0.08
Computer and electrical equipment	–0.22	–0.10
Motor vehicles	–0.33	–0.12
Other transportation equipment	–0.28	–0.09
Miscellaneous manufacturing	–0.17	–0.06
Nonmanufacturing industries		
Farms	–0.21	–0.06
Forestry, fishing, and hunting	–0.18	–0.04

Oil mining	–0.11	–0.51
Gas mining	–0.11	–0.63
Coal mining	–0.30	–1.10
Other mining activities	–0.36	–0.05
Electric utilities (including government enterprises)	–2.11	–0.14
Gas utilities	–0.06	–0.49
Construction	–0.44	–0.04
Trade	–0.11	–0.02
Air transportation	–1.11	–0.10
Truck transportation	–0.56	–0.07
Other transportation	–0.41	–0.05
Information	–0.05	–0.01
Finance and insurance	–0.02	–0.01
Real estate and rental	–0.02	–0.01
Business services	–0.09	–0.01
Other services	–0.20	–0.02
Government excluding electricity	–0.39	–0.03

Table 6. Effect on Output of a $10/ton CO_2 Tax (percent change)

	Short-run partial equilibrium effect only	Medium-run general equilibrium effects with fixed capital	Long-run general equilibrium with reallocation of capital
Manufacturing industries			
Food	–0.38	–0.11	–0.12
Textile	–1.13	–0.51	–0.50
Apparel	–1.03	–0.18	–0.07
Lumber, wood, paper	–0.53	–0.32	–0.32
Petroleum refining	–0.78	–4.72	–5.36
Chemical and plastics	–1.74	–1.11	–1.26
Nonmetallic mineral	–1.20	–0.86	–0.94
Primary metals	–1.57	–1.30	–1.21
Fabricated metals	–0.33	–0.44	–0.43
Transportation equipment	–1.14	–0.35	–0.27
Electrical machinery	–1.00	–0.13	0.08
Other machinery and miscellaneous mfg.	–0.72	–0.50	–0.49
Nonmanufacturing industries			
Agriculture	–0.54	–0.58	–0.68
Coal mining	–11.01	–4.89	–7.85
Oil mining	–5.60	–1.02	–2.09
Gas	–4.95	–5.33	–10.04
Other mining	–0.49	–0.74	–1.06
Electric utilities	–1.35	–1.37	–1.17
Construction	–0.42	–0.32	–0.39
Transportation	–0.67	–1.02	–1.15
Services	–0.17	0.05	0.06

Table 7. General Equilibrium Effects on Employment and Capital of a \$10/ton CO_2 Tax (percent change)

	Employment			Capital
	Short run	Medium run	Long run	Long run
Manufacturing industries				
Food	–0.38	0.06	0.08	0.02
Textile	–1.13	–0.52	–0.32	–0.38
Apparel	–1.03	–0.10	0.05	0.00
Lumber, wood, paper	–0.53	–0.25	–0.10	–0.18
Petroleum refining	–0.78	–5.64	–3.86	–3.93
Chemical and plastics	–1.74	–0.81	–0.47	–0.55
Nonmetallic mineral	–1.20	–0.67	–0.42	–0.49
Primary metals	–1.57	–1.10	–0.69	–0.77
Fabricated metals	–0.33	–0.44	–0.30	–0.37
Transportation equipment	–1.14	–0.32	–0.15	–0.23
Electrical machinery	–1.00	–0.05	0.21	0.13
Other machinery and miscellaneous mfg.	–0.72	–0.55	–0.33	–0.41
Nonmanufacturing industries				
Agriculture	–0.54	–0.12	–0.09	–0.09
Coal mining	–11.01	–8.12	–10.15	–10.13
Oil mining	–5.60	–2.14	–2.77	–2.80
Gas	–4.95	–5.71	–9.15	–9.17
Other mining	–0.49	–0.80	–0.99	–0.98
Electric utilities	–1.35	8.08	3.52	3.44
Construction	–0.42	–0.35	–0.33	–0.40
Transportation	–0.67	–0.46	–0.34	–0.43
Services	–0.17	0.18	0.16	0.07

Table 8. Long-Run Trade Effects of CO_2 Tax on Domestic and Imported Fuels

	Base case domestic consumption* (million $)	Domestic consumption with CO_2 tax (% change)	Contribution**		
			Output	Imports	Exports
Manufacturing industries					
Food	5,556	–0.03	–0.12	0.03	–0.06
Textile	1,232	–0.30	–0.45	0.05	–0.11
Apparel	1,605	0.10	–0.05	0.12	–0.02
Lumber, wood, paper	5,006	–0.25	–0.31	0.02	–0.05
Petroleum refining	1,579	–5.88	–5.61	–0.28	0.00
Chemical and plastics	5,569	–0.62	–1.30	0.18	–0.50
Nonmetallic mineral	967	–0.49	–0.91	0.13	–0.29
Primary metals	2,182	–0.66	–1.11	0.16	–0.30
Fabricated metals	2,278	–0.40	–0.43	–0.01	–0.03
Transportation equipment	5511	–0.22	–0.25	–0.02	–0.06
Electrical machinery	3,368	–0.19	0.07	–0.14	0.12
Other machinery and miscellaneous mfg.	7,014	–0.39	–0.47	–0.04	–0.12
Nonmanufacturing industries					
Agriculture	2,452	–0.27	–0.72	0.11	–0.34
Coal mining	253	–17.24	–10.15	–0.44	6.65
Oil mining	1067	–5.51	–1.07	–4.32	0.12
Gas	463	–10.68	–9.50	–1.22	–0.05
Other mining	275	–0.96	–1.03	–0.02	–0.09
Electric utilities	2,344	–1.00	–1.17	0.13	–0.04
Construction	9,936	–0.39	–0.39	0.00	0.00
Transportation	5,352	–0.76	–1.18	0.08	–0.33
Services	80,941	0.05	0.06	0.00	0.01

* From Adkins and Garbaccio (2007) model using a 1997 base year.

** Domestic consumption = output + imports – exports.

Table 9. Ranking Order of Impacts across Four Modeling Time Horizons

	Percentage increase in production costs per \$10/ton CO_2 tax (2005\$)	Effect on output of a \$10/ton carbon tax (percent change)		
	Very short–run effect	Short-run partial equilibrium effect only	Medium-run general equilibrium effects with fixed capital	Long-run general equilibrium with reallocation of capital
Manufacturing industries				
Primary metals	1	1	2	3
Nonmetallic mineral	2	4	4	4
Petroleum refining	3	8	1	1
Chemical and plastics	4	3	3	2
Textile	5	5	5	5
Lumber, wood, paper	6	10	9	8
Fabricated metals	7	12	7	7
Food	8	11	12	10
Transportation equipment	9	2	8	9
Other machinery and miscellaneous mfg.	10	9	6	6
Apparel	11	6	10	11
Electrical machinery	12	7	11	12
Spearman rank correlation				
Very short vs. short run		0.37		
Short vs. medium run			0.46	
Medium vs. long run				0.97
Nonmanufacturing industries				
Electric utilities	1	4	3	4
Transportation	2	8	5	5
Other mining	3	7	6	6
Agriculture	4	6	7	7
Coal mining	5	1	2	2
Construction	6	9	8	8
Oil mining	7	2	4	3
Services	8	5	9	9
Gas	9	3	1	1
Spearman rank correlation				
Very short vs. short run		–0.33		
Short vs. medium run			0.68	
Medium vs. long run				0.98

Table 10. Comparison with Other Studies: Most Affected Manufacturing Industries by Output

Study No.	Jorgenson et al.	Fischer–Fox	Hourcade et al.	McKinsey	Reinaud
1	Coal mining	Coal	Lime	Cement	Cement
2	Gas utilities (services)	Electricity	Cement	Refining	BOF steel
3	Petroleum refining	Petroleum and coal products	Basic iron and steel	BOF steel	newsprint
4	Electric utilities (services)	Other mining and metals	Refined petroleum products	Primary Aluminum	Aluminum
5	Primary metals	Transport equipment	Fertilizers and nitrogen compounds	Paper	EAF steel
6	Nonmetallic mineral mining	Agriculture	Aluminum	EAF steel	
7	Metal mining	Construction	Other inorganic basic chemicals		
8	Stone, clay, and glass products	Chemistry industry	Pulp, paper, and paperboard		
9	Motor vehicles	Food products	Malt		
10	Nonelectrical machinery	Paper–pulp–print	Coke oven products		
11	Chemicals and allied products	Crude oil	Industrial gases		
12	Fabricated metal products	Iron and steel industry	Nonwovens		
13	Crude oil and gas extraction	Textiles–wearing apparel–leather	Household and sanitary goods		
14	Electrical machinery	Natural gas	Finishing of textiles		
15	Furniture and fixtures	Transport equipment	Hollow glass		
16	Lumber and wood products	Other machinery	Rubber tires and tubes		
17	Rubber and plastic products	Wood and wood products	Retreading and rebuilding of rubber tires		
18	Construction	Services (excluding transport)	Veneer sheets, plywood, etc.		
19	Instruments	Other services	Flat glass		
20	Other transportation equipment	Other manufacturing	Other textile weaving		
21	Textile mill products	Trade, wholesale and retail	Copper		
22	Paper and allied products		Throwing preparation		
23	Miscellaneous		Casting of iron		

	manufacturing
24	Wholesale and retail trade
25	Transportation and warehousing
26	Printing and publishing
27	Leather and leather products
28	Government enterprises
29	Finance, insurance, and real estate
30	Apparel and other textile products
31	Communications
32	Personal and business services
33	Agriculture, forestry, fisheries
34	Food and kindred products
35	Tobacco manufactures

BOF = basic oxygen furnance; EAF = electric arc furnace.

Appendix A. Data

The primary data for our analysis is drawn from the 2002 IO table for the U.S. and manufacturing energy use data from the Energy Information Administration (EIA). In this appendix we describe how we estimate the outputs and inputs, including energy inputs, for the 52 industries identified in our study from these primary data. In doing this we highlight weaknesses in the primary data that, hopefully, can be strengthened in future versions.

A.1 Constructing an Input–Output Matrix for 2002

The Bureau of Economic Analysis produced 2002 benchmark IO data with detailed information on output and intermediate inputs for 428 commodities and 426 industries**.** From the 2002 benchmark based on the NAICS classification, we aggregated the entire IO table into a 50-commodities and 50-industries "Use" matrix as well as a 50-industries and 50-commodities "Make" matrix. The electric utility sector includes electric power generation, transmission, and distribution; federal electric utilities; and state and local government electric utilities. Oil and gas mining is one sector in the original IO table. We split the commodity of oil and gas mining into two, oil mining and gas mining, on the basis of the commodity proportions. We also split the petroleum industry into refining–liquefied petroleum gas (LPG) and refining–others by using the same procedure. In the end, we have 52 industrial/commodity sectors. We update the IO values of seven fuels, including coal, crude oil, gas mining, refining–LPG, refining–others, and natural gas, by using EIA's MECS data. (We discuss the process of updating the seven individual fuel commodities later in this appendix.) We rebalance the Use matrix for the cells not in the seven fuel commodities constrained on the row (intermediate commodity consumption) and column (intermediate industrial output) sums. We follow a similar procedure for the Make matrix.

The resulting 52 industrial sectors are displayed in the first column of Table A1. The values of industry and commodity output from IO tables (in millions of dollars) for our 52 industries are given in the second and third columns of Table A1 (in millions of dollars). These are domestic industry output values; the U.S. accounts distinguish between industries and commodities—each industry may make several commodities and each commodity may be made by a few industries. The domestic output classified by commodities is given in the third column in Table A1. Domestic consumption of commodities is output plus imports, less exports, plus inventory change. Consumption levels are displayed in the last column of Table A1. We can see that total consumption is close to domestic output (i.e., net imports are small) for most items, but large for oil mining and apparel.

Total consumption is the sum of intermediate input purchases by industries and final demand. Final demand refers to purchases for consumption, investment, government, and exports. Given the focus on energy inputs, we provide the detailed estimates of input values of the seven energy commodities (oil mining, gas mining, coal mining, electric utilities, gas utilities, refining–LPG, and refining–others) for each of the 52 industries and final demand in Table A2. We note that these are gross purchases used for feedstocks and for combustion. They should not be simply added to obtain total national consumption. For example, petroleum refining buys a lot of crude oil from "oil and gas mining," and its output is purchased by all 52 industries and final demand.

A.2 Energy Use

We estimate CO_2 emissions for the 52 industrial sectors by using quantities of fuel combusted. We consider seven different types of energy sources: coal, crude oil, natural gas from gas mining, natural gas from gas utility, refining–LPG, refining–others, and electricity. The quantities of these energies are mainly from the MECS, the *Annual Energy Review* (AER), the IO table, the USDA, and our own estimates. MECS is our major source of energy consumption quantity data for manufacturing sectors. It is complemented by AER and USDA energy quantity data. We then use economywide energy consumption value data from the IO table and quantity data from AER to estimate energy consumption quantity data for other sectors. In the following section, we discuss the development of price and quantity data for these seven energy sources.

One common way of estimating the quantity of energy use at this level of aggregation is to assume that every purchaser pays the same economy average price and to apply that price to the values in the IO table. As we noted earlier in Morgenstern et al. (2004), that is a poor assumption for some industries (e.g., aluminum smelting pays a much lower average price for electricity than other industries). We thus turn to independent measures of energy use quantities to compare with the estimates derived from IO dollar values.

A.2.1 Manufacturing Energy Consumption Survey

MECS is the federal government's most comprehensive source of information on energy use by U.S. manufacturing. MECS collects data on energy consumption and expenditures, fuel-switching capability, onsite generation of electricity, by-product energy use, and other energy-related topics. The manufacturing sector is defined according to NAICS. The manufacturing sector (NAICS Sectors 31–33) consists of all manufacturing establishments in the 50 states and the District of Columbia. Our analysis is based on 2002 data.

MECS reports the quantities of coal, coke, residual fuel oil, distillate fuel oil, natural gas, LPG and NGL, and net electricity for the manufacturing industries at the six-digit NAICS level.[15] Specifically, the 2002 MECS Table 1.1 gives the information of Consumption of Energy for All Purposes (First Use); Table 2.1 gives information of Energy Used as a Nonfuel (Feedstock); and Table 3.1 provides data on Energy Consumption as a Fuel. Some energy quantity data are either too small (*) or withheld (W, Q). We treat the small numbers as zeros. For data which were withheld, we scale from available information. We also adopt other methods to estimate missing values, for example, energy balance. We use the totals for the three-digit industries corresponding to our manufacturing industrial list. The total quantities of coal, oil, and gas for our 32 manufacturing industries are given in Tables A3a. We estimate the feedstock ratios by using MECS Tables 1.1 and 2.1. For comparison, we also derive the quantity of energy combusted in Table A3b, using IO and estimated average price data. As we can see, the combusted quantities derived using IO table are not proportional to the quantities from MECS.

We regard the quantities from MECS and the USDA as the best estimates and thus assume that these industries paid different average prices. For the other industries we have to assume a common price. This common price is derived by first subtracting the quantity used in the manufacturing group and agriculture from the national total. The value of consumption outside of these two groups is then divided by this residual quantity to give the common price. The use of coal, oil, and gas for each industry outside of manufacturing and agriculture is then the Use table value divided by the common price. In the following sections we discuss how we derive the total consumption and combusted quantity of various fuels.

A.2.2 Coal

We obtained the national quantity of coal (1,066.4 million short tons) consumed in the United States in 2002 as well as the quantity of coal consumed by the electric power sector (977.5 million short tons) from the AER (2006).[16] We also obtained the quantity of coal consumed by the manufacturing sector from MECS. We then used the IO value to estimate the quantities of coal consumption for nonmanufacturing sectors. We divided the intermediate value

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[15] The MECS for 2002 was downloaded from http://www.eia.doe.gov/emeu/mecs/mecs2002/data02/shelltables.html.

[16] AER (2006); Table 7.3 gives the data for coal.

by the intermediate quantity to give the intermediate implicit price. We used this price along with the quantity of coal to update the IO values. Total coal consumption and combusted coal are displayed in Table A4.

A.2.3 Oil

For 2002, total U.S. domestic crude oil consumption is 5,433 million barrels, which includes 2,097 million barrels[17] from domestic production and 3,336 million barrels[18] from imports. The petroleum industry consumes more than 99.9 percent (5,427 million barrels) of domestic consumption. However, most of the crude oil is consumed as feedstock to produce petroleum products. According to our estimate made by using MECS data, only about 365 million barrels (6.7%) are combusted. The balance (93.3 percent) is used as feedstock. The total consumption and combusted crude oil are listed in Table A5.

A.2.4 Petroleum

For 2002, total domestic consumption of petroleum is about 7,177 million barrels, which include 6,305 million barrels of domestic refinery production and 872 million barrels of refinery imports. The farm sector consumes about 130.1 million barrels of petroleum.[19] Electricity utilities consume about 99.2 million barrels of petroleum.[20] We also obtained the petroleum consumption of manufacturing sectors by using MECS data. We then estimated petroleum consumption for other nonmanufacturing sectors by using the petroleum implicit price derived from the IO values and petroleum quantities.

The total consumption and combusted petroleum–LPG and petroleum–others are listed in Tables A6 and A7, respectively.

A.2.5 Natural Gas

The sources of domestic natural gas consumption in the IO table include natural gas mining and gas utility. The total amount of U.S. domestic natural gas consumption in 2002 is about 23,007 billion cubic feet.[21] We first estimated natural gas consumption from natural gas

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[17] AER (2006); Table 5.1 gives the data for crude oil domestic production.

[18] AER (2006); Table 5.3 gives the data for crude oil imports.

[19] James Duffield, Economic Research Service, USDA.

[20] EIA *Electric Power Annual* (2006); http://www.eia.doe.gov/cneaf/electricity/epa/epat4p1.html.

[21] AER (2006); Table 6.1 gives the data of natural gas consumption.

mining. Electric utilities consume about 5,672 billion cubic feet of natural gas (assumed to be from gas mining).[22] We used total domestic and electric utility consumption quantities (noted above) as well as natural gas mining consumption value data from the IO table to estimate natural gas consumption quantity data for all industrial sectors (electric utility). On the basis of this procedure, we estimate that gas utility purchased about 14,996 billion cubic feet of natural gas from gas mining. We know that the farm sector consumes about 58 billion cubic feet of natural gas.[23] For the manufacturing sector, we know the amount of natural gas consumed from gas utilities by subtracting natural gas consumption (from natural gas mining) from total natural gas consumption (obtained from MECS). Using these quantities and the value of gas utility consumption information from the IO table, we estimate the amount of natural gas consumption for other nonmanufacturing sectors. We then recalculate the IO values for natural gas mining and gas utility by using their respective intermediate implicit prices. The total consumption and combusted natural gas are listed in Table A8.

A.2.6 Electricity

MECS (2002, Table 1.1) also gives the quantity of electricity consumed by each of the manufacturing industries. This is reproduced in Table A3a. There are no equivalent surveys for nonmanufacturing industries that we are aware of. The National Agriculture Statistics Service collects data on energy expenses and prices at the regional level. The detailed data are not published, but a summary is given in the *Farm Production Expenditures Annual Summary*.[24] James Duffield of the Economic Research Service used these data together with electricity price data from other sources to make an unofficial estimate of Agriculture carbon emissions and kindly shared his calculations with us. From his estimates we obtain the electricity consumption given in Table A9.

We first compare this estimate of electricity consumption from MECS to the one in the 2002 IO table. Since neither source is based on a full census, the degree of consistency between these two sources would give us an idea of their reliability. To derive the quantities from the IO data we first need prices.

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[22] AER (2006); Table 6.5.

[23] James Duffield, Economic Research Service, USDA.

[24] The *Farm Production Expenditures Annual Summary* is available at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1066.

AER[25] gives the total national consumption in 2002 at 3,632 billion kWh. Applying this figure to the IO table value of electricity and electricity consumption by manufacturing industries, we estimate electricity consumption for other nonmanufacturing sectors. We then use a common price to rescale the electricity consumption IO values.

A.3 CO_2 Emissions and Intensity

We estimate CO_2 emissions in the United States at 5,752 million metric tons, representing about 85 percent of total U.S. GHG emissions. Most CO_2 is emitted as a result of the combustion of fossil fuels and is highly correlated with energy use. In this research we consider primary CO_2 emissions from coal, oil, petroleum, and natural gas. We also consider total CO_2 emissions, which include primary emissions plus emissions due to electricity consumption for individual sectors. Table A10 shows our estimates of total CO_2 emissions, CO_2 emissions from direct combustion of primary fuels, and CO_2 emissions due to electricity consumptions for individual sectors. Table A11 shows total and primary CO_2 emissions intensities; data are derived from dividing emissions by industrial output.

Appendix A. Tables

Table A1. Value of Industry and Commodity Output from IO Tables, 2002 (million $)

Sector	Industry output	Commodity output	Commodity domestic consumption
Farms	177,337	171,482	168,532
Forestry, fishing, etc.	34,382	41,502	48,460
Oil mining	61,093	51,295	126,146
Gas mining	41,144	35,996	52,569
Coal mining	19,269	19,172	18,881
Other mining activities	57,139	57,729	56,813
Electric utilities (including government enterprises)	259,603	250,078	250,852
Gas utilities	82,614	92,965	92,926
Construction	966,919	1,031,693	1,031,627
Food	470,396	474,835	486,680
Textile	59,670	53,357	62,447

[25] EIA (2005); Table 8.1. Available at http://www.eia.doe.gov/aer/.

Apparel	44,078	41,737	133,149
Wood and furniture	136,132	133,874	164,005
Pulp mills	3,443	5,197	5,177
Paper mills	45,319	45,945	52,514
Paperboard mills	21,095	19,847	19,882
Other papers	173,273	145,200	145,197
Refining–LPG	21,023	15,558	15,558
Refining–other	169,836	177,511	191,641
Petrochemical mfg.	14,743	18,531	18,270
Other basic inorganic chemical mfg.	15,177	17,270	17,745
Other basic organic chemical mfg.	47,573	49,531	47,725
Plastics material and resin mfg.	44,832	44,611	38,808
Artificial and synthetic fibers, filaments	7,651	12,359	12,508
Fertilizer manufacturing	8,239	8,575	9,195
Other chemical and plastics	403,058	398,920	448,400
Glass container manufacturing	4,367	4,361	4,861
Cement manufacturing	7,058	7,022	8,132
Lime and gypsum product mfg.	4,900	4,818	4,837
Mineral wool manufacturing	4,834	4,810	4,787
Other nonmetallic mineral	67,020	65,907	74,686
Iron and steel mills, ferroalloy mfg.	41,942	52,665	62,903
Alumina refining, primary aluminum	18,765	18,104	22,262
Ferrous metal foundries	14,700	14,413	14,545
Nonferrous metal foundries	11,420	11,158	11,142
Other primary metals	28,403	21,628	29,823
Fabricated metals	219,291	212,025	225,327
Machinery	221,635	221,818	228,125
Computer and electrical equipment	363,578	352,482	466,241
Motor vehicles	326,173	323,386	450,146
Other transportation equipment	134,524	131,718	105,557
Miscellaneous manufacturing	115,134	112,248	158,471
Trade	1,850,478	1,733,304	1,645,222
Air transportation	99,315	102,362	102,147
Truck transportation	194,732	200,162	187,881
Other transportation	329,317	331,215	297,242
Information	824,047	648,073	625,365
Finance and insurance	1,138,654	1,083,077	1,074,983
Real estate and rental	1,931,963	1,997,938	1,953,017
Business services	1,710,859	1,975,840	1,927,957
Other services	2,370,176	2,728,059	2,729,030
Government excluding electricity	2,043,064	1,682,805	1,682,805

Table A2. Value of Energy Commodity Inputs for Industries, 2002 (million $)

Sector	Oil mining	Gas mining	Coal mining	Electric utilities	Gas utilities	Refining–LPG	Refining–other
Farms	0	0	3	2,696	312	0	3,950
Forestry, fishing, etc.	0	0	0	61	8	0	595
Oil mining	0	0	2	813	386	0	288
Gas mining	0	0	1	548	260	0	194
Coal mining	0	0	0	379	195	0	171
Other mining activities	0	1	3	1,376	812	0	740
Electric utilities (including government enterprises)	0	13,536	17,752	0	26	0	3,011
Gas utilities	0	35,789	0	28	0	0	72
Construction	0	0	0	2,934	665	0	22,053
Food	0	6	165	4,932	3,282	28	700
Textile	0	2	18	1,978	539	12	117
Apparel	0	0	0	282	108	1	11
Wood and furniture	0	6	0	1,840	416	29	72
Pulp mills	0	0	5	104	123	0	70
Paper mills	0	2	240	2,231	1,159	7	269
Paperboard mills	0	2	69	1,074	981	2	185
Other papers	0	1	3	1,855	606	25	32
Refining–LPG	13,880	0	25	269	507	0	0
Refining–other	112,126	0	203	2,171	4,093	118	0
Petrochemical mfg.	51	131	20	783	802	4,707	369
Other basic inorganic chemical mfg.	5	134	15	1,700	98	55	103
Other basic organic chemical mfg.	49	471	130	1,806	2,400	3,693	2,108
Plastics material and resin mfg.	32	99	22	1,218	1,645	6,553	252
Artificial and synthetic fibers, filaments	0	16	8	193	270	0	27
Fertilizer manufacturing	0	38	0	297	2,612	0	21
Other chemical and plastics	3	231	64	7,215	2,241	217	1,088
Glass container manufacturing	0	0	0	258	275	1	0
Cement manufacturing	0	0	193	818	113	0	530
Lime and gypsum product mfg.	0	0	54	89	38	0	144
Mineral wool manufacturing	0	0	0	246	189	1	8
Other nonmetallic mineral	0	1	6	1,305	1,597	13	224
Iron and steel mills, ferroalloy mfg.	0	1	345	3,771	2,222	1	188
Alumina refining, primary aluminum	0	3	0	3,719	704	3	754
Ferrous metal foundries	0	0	3	539	145	7	17
Nonferrous metal foundries	0	0	0	213	162	1	0
Other primary metals	0	0	10	1,240	452	14	71
Fabricated metals	0	2	0	3,092	1,094	18	45
Machinery	0	3	1	1,612	424	22	32

Computer and electrical equipment	0	0	0	3,429	625	8	395
Motor vehicles	0	3	0	2,380	825	20	143
Other transportation equipment	0	1	0	934	232	0	69
Miscellaneous manufacturing	0	1	0	681	165	3	14
Trade	0	147	0	15,278	1,552	0	4,795
Air transportation	0	0	0	76	4	0	10,248
Truck transportation	0	0	0	551	124	0	11,764
Other transportation	0	1,156	0	2,161	806	0	11,112
Information	0	97	0	2,774	1,262	0	1068
Finance and insurance	0	7	0	1,713	229	0	485
Real estate and rental	0	33	1	14,586	852	0	1,956
Business services	0	186	1	6,567	1,238	0	11,618
Other services	0	292	1	26,481	5,156	0	3,498
Government excluding electricity	0	2,504	3	10,453	9,408	0	30,002
C	0	0	14	107,106	38,490	0	68,191
I	0	–2,338	–498	0	0	0	–2,228
G	0	0	0	0	0	0	0
X	626	853	938	427	39	0	9,430
M	–75,477	–17,426	–647	–1,201	0	0	–23,560
Total commodity	51,295	35,996	19,172	250,078	92,965	15,558	177,511
Total domestic consumption	126,146	52,569	18,881	250,852	92,926	15,558	191,641

Table A3a. Fuel Inputs from the Manufacturing Energy Consumption Survey, 2002

Sector	**Coal (1,000 short tons)**	**Residual fuel oil (1,000 bbl)**	**Distillate fuel oil (1,000 bbl)**	**Natural gas (billion cu. ft.)**	**LPG and NGL (1,000 bbl)**	**Electricity (million kWh)**
Food	9,066	2,399	3,430	605	1,568	75,160
Textile	1,005	925	342	100	662	30,146
Apparel	0	71	291	20	34	4,304
Wood and furniture	0	155	1,811	80	1,583	28,047
Pulp mills	279	1,490	806	23	26	1,579
Paper mills	13,207	8,164	704	216	389	34,005
Paperboard mills	3,759	5,392	661	183	128	16,369
Other papers	167	891	167	113	1,370	28,264
Petroleum	569	3,995	2,821	854	6,106	37,186
Petrochemical mfg.	1,115	506	41	167	695	11,938
Other basic inorganic chemical mfg.	851	304	351	67	46	25,904
Other basic organic chemical mfg.	7,135	2,108	341	479	4,354	27,521
Plastics material and resin mfg.	1,198	87	251	339	125	21,495

Artificial and synthetic fibers, filaments	463	11	27	29	23	4,956
Fertilizer manufacturing	33	182	165	202	4	4,521
Other chemical and plastics	3,507	4,464	1,569	476	4,477	109,950
Glass container manufacturing	0	0	13	51	52	3,932
Cement manufacturing	10,633	106	967	21	17	12,471
Lime and gypsum product mfg.	2,958	46	210	7	8	1,353
Mineral wool manufacturing	0	0	260	34	47	3,750
Other nonmetallic mineral	336	307	3,916	297	705	19,887
Iron and steel mills, ferroalloy mfg.	1,824	96	1,776	384	39	57,470
Alumina refining, primary aluminum	0	0	203	127	145	56,673
Ferrous metal foundries	49	0	87	27	105	8,211
Nonferrous metal foundries	0	0	12	30	82	3,247
Other primary metals	323	46	482	84	438	18,901
Fabricated metals	35	0	959	204	965	47,123
Machinery	51	7	371	80	664	24,563
Computer and electrical equipment	20	159	279	114	419	52,253
Motor vehicles	0	990	552	197	1,090	50,508
Other transportation equipment	0	0	0	0	0	0
Miscellaneous manufacturing	0	36	71	31	183	10,374
Total Manufacturing	58,583	26,679	12,209	3,477	17,113	35,1395

Note: These are numbers for the combusted fuels, not all-purpose or consumed fuels.

Table A3b. Fuel Inputs Derived from IO Dollar Values, 2002

Sector	Coal (1,000 tons)	Crude oil (1,000 bbl)	NGL (1,000 bbl)	Petroleum (1,000 bbl)	Natural gas (billion cu. ft.)
Food	17,539	0	0	27,065	858
Textile	1655	0	0	2,226	109
Apparel	91	0	0	725	68
Wood and furniture	223	0	0	8,658	110
Pulp mills	908	0	0	766	31
Paper mills	7,369	0	0	10,631	256
Paperboard mills	5,924	4	0	5,077	206
Other papers	1,849	0	0	11,834	123
Petroleum	6,153	424,000	4,252	0	783
Petrochemical mfg.	1,113	282	0	19,145	193
Other basic inorganic chemical	320	288	0	2,322	56

mfg.					
Other basic organic chemical mfg.	2,123	1,011	0	18,733	373
Plastics material and resin mfg.	850	213	0	1,451	101
Artificial and synthetic fibers, filaments	143	35	0	7,683	19
Fertilizer manufacturing	337	82	0	11,129	129
Other chemical and plastics	3,071	497	0	78,201	350
Glass container manufacturing	1,741	0	0	804	39
Cement manufacturing	3,870	0	0	1,275	86
Lime and gypsum product mfg.	2,957	0	0	948	66
Mineral wool manufacturing	1,199	0	0	463	26
Other nonmetallic mineral	8,293	0	0	3,961	184
Iron and steel mills, ferroalloy mfg.	73,936	0	0	1,982	232
Alumina refining, primary aluminum	3,938	0	0	835	85
Ferrous metal foundries	1,513	0	0	206	34
Nonferrous metal foundries	1,107	0	0	333	25
Other primary metals	2,352	0	0	3,749	53
Fabricated metals	143	0	0	10,391	246
Machinery	205	0	0	11,812	92
Computer and electrical equipment	103	0	0	14,865	138
Motor vehicles	479	0	0	3,757	191
Other transportation equipment	143	0	0	1,545	54
Miscellaneous manufacturing	0	0	0	3,369	39
Total manufacturing	46,597	425,914	4,252	127,445	3,415

Table A4. Total Consumption and Combusted Fuel: Coal (million short tons)

Sector	Total consumption	Combusted
Farms	0.1	0.1
Forestry, fishing, etc.	0.0	0.0
Oil mining	0.1	0.1
Gas mining	0.1	0.1
Coal mining	0.0	0.0
Other mining activities	0.2	0.2
Electric utilities (including government enterprises)	977.5	977.5
Gas utilities	0.0	0.0
Construction	0.0	0.0
Food	9.1	9.1
Textile	1.0	1.0
Apparel	0.0	0.0

Wood and furniture	0.0	0.0
Pulp mills	0.3	0.3
Paper mills	13.2	13.2
Paperboard mills	3.8	3.8
Other papers	0.2	0.2
Refining–LPG	1.0	1.0
Refining–other	11.6	11.6
Petrochemical mfg.	1.1	1.1
Other basic inorganic chemical mfg.	0.9	0.9
Other basic organic chemical mfg.	7.1	7.1
Plastics material and resin mfg.	1.2	1.2
Artificial and synthetic fibers, filaments	0.5	0.5
Fertilizer manufacturing	0.0	0.0
Other chemical and plastics	3.5	3.5
Glass container manufacturing	0.0	0.0
Cement manufacturing	10.6	10.6
Lime and gypsum product mfg.	3.0	3.0
Mineral wool manufacturing	0.0	0.0
Other nonmetallic mineral	0.3	0.3
Iron and steel mills, ferroalloy mfg.	19.0	19.0
Alumina refining, primary aluminum	0.0	0.0
Ferrous metal foundries	0.2	0.2
Nonferrous metal foundries	0.0	0.0
Other primary metals	0.6	0.6
Fabricated metals	0.0	0.0
Machinery	0.1	0.1
Computer and electrical equipment	0.0	0.0
Motor vehicles	0.0	0.0
Other transportation equipment	0.0	0.0
Miscellaneous manufacturing	0.0	0.0
Trade	0.0	0.0
Air transportation	0.0	0.0
Truck transportation	0.0	0.0
Other transportation	0.0	0.0
Information	0.0	0.0
Finance and insurance	0.0	0.0
Real estate and rental	0.1	0.1
Business services	0.1	0.1
Other services	0.0	0.0
Government excluding electricity	0.1	0.1

Table A5. Total Consumption and Combusted Fuel: Crude Oil (million bbl)

Sector	Total consumption	Combusted
Farms	0.0	0.0
Forestry, fishing, etc.	0.0	0.0
Oil mining	0.0	0.0
Gas mining	0.0	0.0
Coal mining	0.0	0.0
Other mining activities	0.0	0.0
Electric utilities (including government enterprises)	0.0	0.0
Gas utilities	0.0	0.0
Construction	0.0	0.0
Food	0.0	0.0
Textile	0.0	0.0
Apparel	0.0	0.0
Wood and furniture	0.0	0.0
Pulp mills	0.0	0.0
Paper mills	0.0	0.0
Paperboard mills	0.0	0.0
Other papers	0.0	0.0
Refining–LPG	597.9	40.2
Refining–other	4,829.4	325.1
Petrochemical mfg.	2.2	2.2
Other basic inorganic chemical mfg.	0.2	0.2
Other basic organic chemical mfg.	2.1	2.1
Plastics material and resin mfg.	1.4	1.4
Artificial and synthetic fibers, filaments	0.0	0.0
Fertilizer manufacturing	0.0	0.0
Other chemical and plastics	0.1	0.1
Glass container manufacturing	0.0	0.0
Cement manufacturing	0.0	0.0
Lime and gypsum product mfg.	0.0	0.0
Mineral wool manufacturing	0.0	0.0
Other nonmetallic mineral	0.0	0.0
Iron and steel mills, ferroalloy mfg.	0.0	0.0
Alumina refining, primary aluminum	0.0	0.0
Ferrous metal foundries	0.0	0.0
Nonferrous metal foundries	0.0	0.0
Other primary metals	0.0	0.0
Fabricated metals	0.0	0.0
Machinery	0.0	0.0
Computer and electrical equipment	0.0	0.0
Motor vehicles	0.0	0.0

Other transportation equipment	0.0	0.0
Miscellaneous manufacturing	0.0	0.0
Trade	0.0	0.0
Air transportation	0.0	0.0
Truck transportation	0.0	0.0
Other transportation	0.0	0.0
Information	0.0	0.0
Finance and insurance	0.0	0.0
Real estate and rental	0.0	0.0
Business services	0.0	0.0
Other services	0.0	0.0
Government excluding electricity	0.0	0.0

Table A6. Total Consumption and Combusted Fuel: Refining–LPG (million bbl)

Sector	Total consumption	Combusted
Farms	0.0	0.0
Forestry, fishing, etc.	0.0	0.0
Oil mining	0.0	0.0
Gas mining	0.0	0.0
Coal mining	0.0	0.0
Other mining activities	0.0	0.0
Electric utilities (including government enterprises)	0.0	0.0
Gas utilities	0.0	0.0
Construction	0.0	0.0
Food	1.6	1.4
Textile	0.7	0.6
Apparel	0.0	0.0
Wood and furniture	1.6	1.5
Pulp mills	0.0	0.0
Paper mills	0.4	0.4
Paperboard mills	0.1	0.1
Other papers	1.4	1.3
Refining–LPG	0.0	0.0
Refining–other	6.5	6.0
Petrochemical mfg.	260.0	156.5
Other basic inorganic chemical mfg.	3.0	0.8
Other basic organic chemical mfg.	204.0	32.2
Plastics material and resin mfg.	362.0	10.0
Artificial and synthetic fibers, filaments	0.0	0.0

Fertilizer manufacturing	0.0	0.0
Other chemical and plastics	12.0	5.1
Glass container manufacturing	0.1	0.0
Cement manufacturing	0.0	0.0
Lime and gypsum product mfg.	0.0	0.0
Mineral wool manufacturing	0.0	0.0
Other nonmetallic mineral	0.7	0.6
Iron and steel mills, ferroalloy mfg.	0.0	0.0
Alumina refining, primary aluminum	0.1	0.1
Ferrous metal foundries	0.4	0.2
Nonferrous metal foundries	0.1	0.1
Other primary metals	0.8	0.7
Fabricated metals	1.0	0.9
Machinery	1.2	1.1
Computer and electrical equipment	0.4	0.4
Motor vehicles	1.1	0.9
Other transportation equipment	0.0	0.0
Miscellaneous manufacturing	0.2	0.2
Trade	0.0	0.0
Air transportation	0.0	0.0
Truck transportation	0.0	0.0
Other transportation	0.0	0.0
Information	0.0	0.0
Finance and insurance	0.0	0.0
Real estate and rental	0.0	0.0
Business services	0.0	0.0
Other services	0.0	0.0
Government excluding electricity	0.0	0.0

Table A7. Total Consumption and Combusted Fuel: Refining–Others (million bbl)

Sector	Total consumption	Combusted
Farms	130.1	119.9
Forestry, fishing, etc.	19.6	18.1
Oil mining	9.5	8.7
Gas mining	6.4	5.9
Coal mining	5.6	5.2
Other mining activities	24.4	22.4
Electric utilities (including government enterprises)	99.2	91.4
Gas utilities	2.4	2.2
Construction	726.6	669.2
Food	23.1	21.2
Textile	3.9	3.5
Apparel	0.4	0.3
Wood and furniture	2.4	2.2
Pulp mills	2.3	2.1
Paper mills	8.9	8.2
Paperboard mills	6.1	5.6
Other papers	1.1	1.0
Refining–LPG	0.0	0.0
Refining–other	0.0	0.0
Petrochemical mfg.	12.1	7.3
Other basic inorganic chemical mfg.	3.4	0.9
Other basic organic chemical mfg.	69.5	11.0
Plastics material and resin mfg.	8.3	0.2
Artificial and synthetic fibers, filaments	0.9	0.8
Fertilizer manufacturing	0.7	0.6
Other chemical and plastics	35.8	15.4
Glass container manufacturing	0.0	0.0
Cement manufacturing	17.5	16.1
Lime and gypsum product mfg.	4.7	4.4
Mineral wool manufacturing	0.3	0.2
Other nonmetallic mineral	7.4	6.8
Iron and steel mills, ferroalloy mfg.	6.2	1.9
Alumina refining, primary aluminum	24.9	22.9
Ferrous metal foundries	0.6	0.3
Nonferrous metal foundries	0.0	0.0
Other primary metals	2.3	2.2

Fabricated metals	1.5	1.4
Machinery	1.1	1.0
Computer and electrical equipment	13.0	12.0
Motor vehicles	4.7	3.8
Other transportation equipment	2.3	2.1
Miscellaneous manufacturing	0.5	0.4
Trade	158.0	145.5
Air transportation	337.7	311.0
Truck transportation	387.6	357.0
Other transportation	366.1	337.2
Information	35.2	32.4
Finance and insurance	16.0	14.7
Real estate and rental	64.4	59.3
Business services	382.8	352.6
Other services	115.3	106.1
Government excluding electricity	988.5	910.4

Table A8. Total Consumption and Combusted Fuel: Natural Gas (billion cu. ft.)

Sector	Total consumption	Combusted
Farms	58.0	58.0
Forestry, fishing, etc.	1.4	1.4
Oil mining	71.7	71.7
Gas mining	48.3	48.3
Coal mining	36.3	36.3
Other mining activities	151.1	151.1
Electric utilities (including government enterprises)	5,676.8	5,676.8
Gas utilities	0.0	0.0
Construction	123.4	123.4
Food	612.0	605.0
Textile	101.0	100.0
Apparel	20.0	20.0
Wood and furniture	80.0	80.0
Pulp mills	23.0	23.0
Paper mills	216.0	216.0
Paperboard mills	183.0	183.0
Other papers	113.0	113.0
Refining–LPG	94.1	94.1
Refining–other	759.9	759.9
Petrochemical mfg.	204.0	168.0

Other basic inorganic chemical mfg.	74.5	66.5
Other basic organic chemical mfg.	643.0	479.0
Plastics material and resin mfg.	347.0	291.2
Artificial and synthetic fibers, filaments	57.0	55.2
Fertilizer manufacturing	501.0	203.0
Other chemical and plastics	513.0	473.0
Glass container manufacturing	51.0	51.0
Cement manufacturing	21.0	21.0
Lime and gypsum product mfg.	7.0	7.0
Mineral wool manufacturing	35.0	34.0
Other nonmetallic mineral	297.0	297.0
Iron and steel mills, ferroalloy mfg.	413.0	383.5
Alumina refining, primary aluminum	132.0	127.0
Ferrous metal foundries	27.0	26.9
Nonferrous metal foundries	30.0	30.0
Other primary metals	84.0	84.0
Fabricated metals	204.0	204.0
Machinery	80.0	80.0
Computer and electrical equipment	116.0	114.0
Motor vehicles	154.5	154.1
Other transportation equipment	43.5	43.5
Miscellaneous manufacturing	31.0	31.0
Trade	349.7	349.7
Air transportation	0.8	0.8
Truck transportation	23.0	23.0
Other transportation	634.0	634.0
Information	275.0	275.0
Finance and insurance	45.5	45.5
Real estate and rental	172.2	172.2
Business services	307.7	307.7
Other services	1,079.7	1,079.7
Government excluding electricity	2,795.9	2,795.9

Table A9. Consumption of Electricity (million kWh)

Sector	Electricity consumption
Farms	41,080
Forestry, fishing, etc.	926
Oil mining	12,391
Gas mining	8,345
Coal mining	5,774
Other mining activities	20,975
Electric utilities (including government enterprises)	0

Gas utilities	430
Construction	44,720
Food	75,160
Textile	30,146
Apparel	4,304
Wood and furniture	28,047
Pulp mills	1,579
Paper mills	34,005
Paperboard mills	16,369
Other papers	28,264
Refining–LPG	4,096
Refining–other	33,090
Petrochemical mfg.	11,938
Other basic inorganic chemical mfg.	25,904
Other basic organic chemical mfg.	27,521
Plastics material and resin mfg.	18,559
Artificial and synthetic fibers, filaments	2,936
Fertilizer manufacturing	4,521
Other chemical and plastics	109,950
Glass container manufacturing	3,932
Cement manufacturing	12,471
Lime and gypsum product mfg.	1,353
Mineral wool manufacturing	3,750
Other nonmetallic mineral	19,887
Iron and steel mills, ferroalloy mfg.	57,470
Alumina refining, primary aluminum	56,673
Ferrous metal foundries	8,211
Nonferrous metal foundries	3,247
Other primary metals	18,901
Fabricated metals	47,123
Machinery	24,563
Computer and electrical equipment	52,253
Motor vehicles	36,269
Other transportation equipment	14,239
Miscellaneous manufacturing	10,374
Trade	232,839
Air transportation	1,157
Truck transportation	8,390
Other transportation	32,927
Information	42,277
Finance and insurance	26,102
Real estate and rental	222,291
Business services	100,087
Other services	403,573
Government excluding electricity	159,306

Table A10. CO_2 Emissions from Total and Direct Combustion of Fossil Fuels (metric tons)

Sector	Total combustion	Direct combustion	Combustion due to electricity
Farms	76,342,617	51,021,942	25,320,676
Forestry, fishing, etc.	7,818,166	7,247,670	570,496
Oil mining	15,199,727	7,562,082	7,637,645
Gas mining	10,236,725	5,092,918	5,143,807
Coal mining	7,605,875	4,046,747	3,559,127
Other mining activities	30,464,207	17,535,745	12,928,461
Electric utilities (including government enterprises)	2,244,924,377	2,244,924,377	0
Gas utilities	1,129,501	864,717	264,784
Construction	299,969,872	272,405,637	27,564,235
Food	105,811,684	59,484,956	46,326,728
Textile	27,560,253	8,979,019	18,581,234
Apparel	3,886,867	1,233,990	2,652,877
Wood and furniture	22,887,813	5,600,349	17,287,463
Pulp mills	3,617,342	2,644,086	973,256
Paper mills	61,749,898	40,790,074	20,959,824
Paperboard mills	29,733,835	19,644,396	10,089,439
Other papers	24,620,526	7,199,310	17,421,217
Refining–LPG	26,924,219	24,399,365	2,524,853
Refining–other	225,505,256	205,109,597	20,395,659
Petrochemical mfg.	60,723,541	53,365,278	7,358,263
Other basic inorganic chemical mfg.	21,917,603	5,951,031	15,966,572
Other basic organic chemical mfg.	70,150,790	53,187,334	16,963,456
Plastics material and resin mfg.	32,794,581	21,355,304	11,439,277
Artificial and synthetic fibers, filaments	6,060,475	4,250,776	1,809,699
Fertilizer manufacturing	14,144,832	11,358,202	2,786,630
Other chemical and plastics	107,856,621	40,086,323	67,770,298
Glass container manufacturing	5,229,726	2,806,140	2,423,586
Cement manufacturing	35,867,253	28,180,443	7,686,810
Lime and gypsum product mfg.	8,695,133	7,861,178	833,955
Mineral wool manufacturing	4,276,876	1,965,471	2,311,405
Other nonmetallic mineral	32,017,530	19,759,685	12,257,845
Iron and steel mills, ferroalloy mfg.	94,066,181	58,643,123	35,423,058
Alumina refining, pri aluminum	50,999,622	16,067,814	34,931,808
Ferrous metal foundries	7,013,271	1,952,218	5,061,053
Nonferrous metal foundries	3,665,182	1,663,813	2,001,369
Other primary metals	18,339,751	6,689,651	11,650,100
Fabricated metals	40,968,644	11,923,216	29,045,429
Machinery	20,275,004	5,134,991	15,140,014
Computer and electrical equipment	43,299,123	11,091,692	32,207,431
Motor vehicles	32,511,385	10,156,205	22,355,181
Other transportation equipment	11,994,983	3,218,306	8,776,676
Miscellaneous manufacturing	8,296,281	1,902,009	6,394,272

Trade	220,432,836	76,916,723	143,516,113
Air transportation	124,208,958	123,495,630	713,329
Truck transportation	148,141,226	142,970,008	5,171,218
Other transportation	188,861,573	168,565,943	20,295,630
Information	53,973,358	27,915,133	26,058,225
Finance and insurance	24,419,924	8,331,599	16,088,325
Real estate and rental	170,098,400	33,084,106	137,014,294
Business services	218,603,298	156,912,035	61,691,264
Other services	350,013,486	101,261,300	248,752,185
Government excluding electricity	612,819,746	514,627,589	98,192,158

Table A11. Total and Primary CO_2 Emissions Intensity (metric tons/million $)

Sector	Total CO_2 intensity	Primary CO_2 intensity
Farms	430.5	287.7
Forestry, fishing etc	227.4	210.8
Oil mining	248.8	123.8
Gas mining	248.8	123.8
Coal mining	394.8	210.0
Other mining activities	533.1	306.9
Electric utilities (including government enterprises)	8,647.6	8,647.6
Gas utilities	13.7	10.5
Construction	310.2	281.7
Food	224.9	126.5
Textile	461.9	150.5
Apparel	88.2	28.0
Wood and furniture	168.1	41.1
Pulp mills	1,050.2	767.7
Paper mills	1,362.5	900.0
Paperboard mills	1,409.4	931.2
Other papers	142.1	41.5
Refining–LPG	1,280.6	1,160.5
Refining–other	1,327.8	1,207.7
Petrochemical mfg.	4,118.3	3,619.3
Other basic inorganic chemical mfg.	1,444.1	392.1
Other basic organic chemical mfg.	1,474.5	1,118.0
Plastics material and resin mfg.	731.5	476.3
Artificial and synthetic fibers, filaments	792.0	555.5
Fertilizer manufacturing	1,716.6	1,378.5
Other chemical and plastics	267.6	99.5
Glass container manufacturing	1,197.3	642.5
Cement manufacturing	5,080.7	3,991.8

Lime and gypsum product mfg.	1,775.0	1,604.7
Mineral wool manufacturing	884.6	406.5
Other nonmetallic mineral	477.7	294.8
Iron and steel mills, ferroalloy mfg.	2,242.7	1,398.1
Alumina refining, primary aluminum	2,717.7	856.2
Ferrous metal foundries	477.1	132.8
Nonferrous metal foundries	321.0	145.7
Other primary metals	645.7	235.5
Fabricated metals	186.8	54.4
Machinery	91.5	23.2
Computer and electrical equipment	119.1	30.5
Motor vehicles	99.7	31.1
Other transportation equipment	89.2	23.9
Miscellaneous manufacturing	72.1	16.5
Trade	119.1	41.6
Air transportation	1,250.7	1,243.5
Truck transportation	760.7	734.2
Other transportation	573.5	511.9
Information	65.5	33.9
Finance and insurance	21.4	7.3
Real estate and rental	88.0	17.1
Business services	127.8	91.7
Other services	147.7	42.7
Government excluding electricity	300.0	251.9

Appendix B. Adkins–Garbaccio CGE Model

In this Appendix we describe the multisector, multiregion model that is used to simulate the effects of the medium-run and long-run horizons. It is also used to generate the demand elasticities for industry output, η_j . The model is described in detail in Adkins and Garbaccio (2007) and Adkins (2006), and we only discuss the main features here.

The model is based on the GTAP (v6) database and is aggregated to three world regions: the United States, the rest of Annex I, and the rest of the world (Table B1). The rest of Annex I comprises the other developed countries that essentially have had a very different pattern of exports and imports with the U.S. compared with the rest of the world. In particular, the rest of the world exports oil to the United States.

GTAP identifies 52 industries, many of which are in the agriculture group. These are aggregated to 21 industries as shown in Table B2.

The model is a one-period (long-run) model where the labor supply is elastic. The production functions are CES nested functions; at the top tier the value-added energy bundle is substitutable with all other intermediate inputs. The second tier is a CES function of the value-added bundle and the energy bundle. Value added is a CES function of capital, labor, and land. The energy bundle is a function of coal mining, gas, petroleum products, and electricity. The main equations of the model are listed in Table B3, with the variable description given in Table B4. The elasticities of substitution are given in Table B5.

Appendix B. Tables

Table B1. Regions in Model

Abbreviation	Region
USA	United States
AN1	Australia Austria Belarus Belgium Bulgaria Canada Croatia Czech Republic Denmark Estonia Finland France Germany Greece Hungary Iceland Ireland Italy Japan Latvia Lithuania Luxembourg Netherlands New Zealand Norway Poland Portugal Romania Russia Slovakia Slovenia Spain Sweden Switzerland Turkey Ukraine United Kingdom
XRW	Rest of the world

Table B2. Sectors in Model

Abbreviation	No.	Sector
AGR	1	Agriculture
COA	2	Coal
OIL	3	Oil mining
GAS	4	Natural gas
OMN	5	Other minerals
FBT	6	Food, beverages, and tobacco
TEX	7	Textiles
WAP	8	Wearing apparel and leather goods
LUM	9	Wood and paper products
PCP	10	Petroleum and coal products
CRP	11	Chemicals, rubber, and plastics
NMM	12	Other nonmetallic mineral products
MET	13	Ferrous and nonferrous metals
FMP	14	Fabricated metal products
MVH	15	Motor vehicles and other transport equipment
ELE	16	Electronic goods
OME	17	Other machinery, equipment, and manufactures
ELY	18	Electricity
CNS	19	Construction
TRN	20	Transportation services
SER	21	Services

Table B3. Equation for Producer Model

$$PTC_{t,r} = \left(\frac{1}{aa_{t,r}}\right)\cdot\left[\zeta_{t,r}^{\sigma_{t,r}^{n}} \cdot PN_{t,r}^{\left(1-\sigma_{t,r}^{n}\right)} + \left(1 - \zeta_{t,r}\right)^{\sigma_{t,r}^{n}} \cdot PVE_{t,r}^{\left(1-\sigma_{t,r}^{n}\right)}\right]^{\frac{1}{1-\sigma_{t,r}^{n}}} \quad (5)$$

$$PVE_{t,r} = \left(\frac{1}{ee_{t,r}}\right)\cdot\left[\eta_{t,r}^{\sigma_{t,r}^{ve}} \cdot PEN_{t,r}^{\left(1-\sigma_{t,r}^{ve}\right)} + \left(1 - \eta_{t,r}\right)^{\sigma_{t,r}^{ve}} \cdot PVC_{t,r}^{\left(1-\sigma_{t,r}^{ve}\right)}\right]^{\frac{1}{1-\sigma_{t,r}^{ve}}} \quad (6)$$

$$PVC_{t,r} = \left(\frac{1}{a_{t,r}}\right)\cdot\left[\sum_f \delta_{f,t,r}^{\sigma_{t,r}^{v}} \cdot PF_{f,r}^{\left(1-\sigma_{t,r}^{v}\right)}\right]^{\frac{1}{1-\sigma_{t,r}^{v}}} \quad (7)$$

$$PEN_{t,r} = \left(\frac{1}{kk_{t,r}}\right)\cdot\left[\sum_{t5} \kappa_{t5,t,r}^{\sigma_{t,r}^{en}} \cdot PX_{t5,r}^{\left(1-\sigma_{t,r}^{en}\right)}\right]^{\frac{1}{1-\sigma_{t,r}^{en}}} \quad (8)$$

$$PN_{t,r} = \sum_{t6} PX_{t6,r} \cdot io_{t6,t,r} \quad (9)$$

$$P_{t,r} \cdot Q_{t,r} = PN_{t,r} \cdot NX_{t,r} + PEN_{t,r} \cdot EN_{t,r} + PVC_{t,r} \cdot VA_{t,r} + ty_{t,r} \cdot P_{t,r} \cdot Q_{t,r} \quad (49)$$

$$VE_{t,r} = \left(\frac{1}{aa_{t,r}}\right)^{1-\sigma_{t,r}^{n}} \cdot \left[\left(1 - \zeta_{t,r}\right)\cdot\frac{PTC_{t,r}}{PVE_{t,r}}\right]^{\sigma_{t,r}^{n}} \cdot Q_{t,r} \quad \text{value-added energy bundle} \quad (13)$$

$$VA_{t,r} = \left(\frac{1}{ee_{t,r}}\right)^{1-\sigma_{t,r}^{ve}} \cdot \left[\left(1 - \eta_{t,r}\right)\cdot\frac{PVE_{t,r}}{VC_{t,r}}\right]^{\sigma_{t,r}^{ve}} \cdot VE_{t,r} \quad (14)$$

$$EN_{t,r} = \left(\frac{1}{ee_{t,r}}\right)^{1-\sigma_{t,r}^{ve}} \cdot \left[\eta_{t,r} \cdot \frac{PVE_{t,r}}{PEN_{t,r}}\right]^{\sigma_{t,r}^{ve}} \cdot VE_{t,r} \quad (15)$$

$$NX_{t,r} = \left(\frac{1}{aa_{t,r}}\right)^{1-\sigma_{t,r}^{n}} \cdot \left[\zeta_{t,r} \cdot \frac{PTC_{t,r}}{PN_{t,r}}\right]^{\sigma_{t,r}^{n}} \cdot Q_{t,r} \quad \text{total interim input} \quad (16)$$

$$IX_{t5,t,r} = \left(\frac{1}{kk_{t,r}}\right)^{1-\sigma_{t,r}^{en}} \cdot \left[\kappa_{t5,t,r} \cdot \frac{PEN_{t,r}}{PX_{t5,r}}\right]^{\sigma_{t,r}^{en}} \cdot EN_{t,r} \quad (17)$$

$$IX_{t6,t,r} = io_{t6,t,r} \cdot NX_{t,r} \quad \text{Leontief demand for nonenergy} \quad (18)$$

$$DF_{f,t,r} = \left(\frac{1}{a_{t,r}}\right)^{1-\sigma_{t,r}^{v}} \cdot \left[\delta_{f,t,r} \cdot \frac{PVC_{t,r}}{apf_{ftr} PF_{f,r}}\right]^{\sigma_{t,r}^{v}} \cdot VA_{t,r} \quad (19)$$

Table B4. Model Variable Listing

$PWE_{t,s,r}$ World price (seller price FOB)

$PE_{t,r}$ Exported goods price

$PWM_{t,s,r}$ Buyer price (CIF)

$PM_{t,r}$ Aggregate imported goods price

$PX_{t,r}$ Composite goods price

$PD_{t,r}$ Domestic goods price

$P_{t,r}$ Average output price

$PTC_{t,r}$ TCP Sectoral unit cost of production

$PVE_{t,r}$ Value-added energy composite price

$PVC_{t,r}$ VC Value-added composite price

$PEN_{t,r}$ Energy composite price

$PN_{t,r}$ Intermediate good composite price

$PFN_{f,r}$ Factor price (net of tax)

$PF_{f,r}$ Factor price (gross of tax)

$PC_{t,r}$ Consumer purchase price

CPI_{r} Consumer price index

ERT_{r} Exchange rate

$VE_{t,r}$ Value-added energy composite good

$VA_{t,r}$ Value-added composite

$EN_{t,r}$ Energy composite

$VC_{t,r}$ Sectoral variable production cost

$NX_{t,r}$ Composite intermediate good

$IX_{t,k,r}$ Intermediate demand

$DF_{f,t,r}$ Sectoral factor demand

$C_{t,r}$ Household consumption

$GC_{t,r}$ Government consumption

$ID_{t,r}$ Investment demand

$SUPY_{r}$ Household consumption above subsistence level

$SX_{t,r}$ Composite good supply

$DX_{t,r}$ Domestic sales of domestically made good

$X_{t,s,r}$ Trade flows

$EX_{t,r}$ Exports

$MX_{t,r}$ Sectoral imports by region

$TRQS_r$ International shipping supply by region

PTR International shipping service price

$TRQD_{t,r}$ International shipping demand by region

TRQ Total international transport supply

HDI_r Household disposable income

SAV_r Household savings

$GREV_r$ Government revenue

$TARIFF_r$ Tariff revenue

$ETAX_r$ Export tax revenue

$PTAX_r$ Output tax revenue

$CTAX_r$ Consumption tax revenue

$FTAX_r$ Factor tax revenue

$HTAX_r$ Household tax revenue

$NETINFL_r$ Net capital inflow by country

$CO2TAXF_{t1,r}$ Carbon tax per fuel

$CO2TAX_r$ Country carbon tax

$CO2TAXR_r$ Country carbon tax revenue

$CO2TOT_r$ Total CO_2 emissions by country

$GDPR_r$ GDP (final demand)

$GDPVA_r$ GDP (value added)

$PINDEX_r$ GDP deflator (*numeraire*)

$Q_{t,r}$ Sectoral output

$FS_{f,r}$ Factor endowment by region

INV_r Gross investment by region

$GSAV_r$ Government savings

$GPUR_r$ GSP Government purchases

$GTRANS_r$ Net government transfers

Table B5. Elasticities of Substitution

σ^n SGN 0.15 all industries

σ^{ve} SVE 0.5 all industries

σ^v SGV 0.2(COA, OIL, GAS), 1.1, 1.3(PCP, ELY), 1.4

σ^{en} SEN 0.5 all industries

σ^e SGE –2.1, –3.5, –5.6, –7.2

σ^m SGM 1.9, 2.1, 2.3(PCP), 2.8(COA, OIL, GAS), 4.0(WAP), 5.2(MVH)

Table B6. Demand Elasticity for Output

Sectors	Elasticity
Farms	-0.812
Forestry, fishing etc	-0.812
Oil mining	-0.296
Gas mining	-0.296
Coal mining	-0.106
Other mining activities	-0.633
Electric Utilities (inc govt enterprises)	-0.160
Gas Utilities	-0.566
Construction	-0.774
Food	-0.638
Textile	-1.139
Apparel	-2.418
Wood & Furniture	-0.698
Pulp mills	-0.698
Paper mills	-0.698
Paperboard mills	-0.698
Other papers	-0.698
Refining-LPG	-0.071
Refining-Other	-0.071
Petrochemical mfg	-0.987
Other basic inorg. chemical mfg	-0.987
Other basic organic chemical mfg	-0.987
Plastics material and resin mfg	-0.987
Artificial & syn fibers, filaments	-0.987
Fertilizer manufacturing	-0.987
Other Chemical & Plastics	-0.987
Glass container manufacturing	-0.827
Cement manufacturing	-0.827
Lime and gypsum product mfg	-0.827
Mineral wool manufacturing	-0.827
Other Nonmetallic mineral	-0.827
Iron & steel mills, ferroalloy mfg	-0.953
Alumina refining, primary aluminum	-0.953
Ferrous metal foundries	-0.953
Nonferrous metal foundries	-0.953
Other Primary metals	-0.953
Fabricated metals	-0.505
Machinery	-1.662
Computer & Electrical Equip	-2.596

Motor vehicles	-2.485
Other transportation Equip	-2.485
Misc manufacturing	-1.662
Trade	-0.745
Air transportation	-0.833
Truck transportation	-0.833
Other transportation	-0.833
Information	-0.745
Finance and Insurance	-0.745
Real estate and rental	-0.745
Business services	-0.745
Other services	-0.745
Govt exc. Electricity	-0.745