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Modeling Economywide versus Sectoral Climate Policies Using Combined Aggregate-Sectoral Models

William Pizer, Dallas Burtraw, Winston Harrington, Richard Newell, and James Sanchirico

1616 P St. NW
Washington, DC 20036
202-328-5000 www.rff.org

RESOURCES FOR THE FUTURE

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Abstract

Economic analyses of climate change policies frequently focus on reductions of energy-related carbon dioxide emissions via market-based, economywide policies. The current course of environment and energy policy debate in the United States, however, suggests an alternative outcome: inefficiently designed and/or sector-based policies. This paper uses a collection of specialized, sector-based models in conjunction with a computable general equilibrium model of the economy to examine and compare these policies at an aggregate level. We examine the relative cost of different policies designed to achieve the same quantity of emissions reductions. We find that excluding a limited number of sectors from an economywide policy does not significantly raise costs. Focusing policy solely on the electricity and transportation sectors doubles costs, however, and using nonmarket policies can raise costs by a factor of 10. These results are driven in part by, and are sensitive to, our modeling of preexisting tax distortions.

Key Words: carbon, carbon dioxide, climate change, climate policy, general equilibrium model, partial equilibrium model, cost

JEL Classification Numbers: Q25, D58, D61, Q48

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Introduction

Achieving environmental goals at lowest cost has sparked considerable interest in flexible, market-based policies that typically limit pollution by requiring emissions sources to obtain a permit for each unit of pollution released. An overall emissions cap is established by distributing a fixed number of these permits, and flexibility is introduced by allowing users to freely trade the permits in a market. Market-based policies are also currently being used to address water pollution, lead in gasoline, and overfishing.[1]

Opposition to these policies can arise because in the process of creating a permit market, substantial transfers of wealth can occur—transfers that would not occur under nonmarket-based alternatives. For instance, users who previously paid nothing to emit pollution may now face the prospect of buying permits from a competitor. In contrast, traditional regulation might limit a facility's emissions to a particular rate per unit of output, but then impose no charge or opportunity cost on emissions at that rate. Under market-based policies, people and firms who are not directly regulated may see higher prices for pollution-intensive goods compared with command-and-control policies because every unit of emission incurs an opportunity cost.[2] This is particularly true of policies to reduce carbon dioxide, the leading cause of human-induced

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[1] See Boyd et al. (2003), Stavins (2003), and chapter 6 of CEA (2002).

[2] Under some designs that involve output-based allocation of emissions allowances or refund of emissions fees within the regulated sector product prices could actually decline, compared with the absence of regulation. The reason is that the allocation of permits or revenues based on output constitutes an output subsidy that reduces variable costs of production, but it also introduces important inefficiencies in product pricing (Burtraw et al. 2001; Fischer 2001).

climate change. For example, a simple back-of-the-envelope calculation suggests that with modest reductions of 5%, the value of the wealth created by these permits is about 40 times the cost of the reduced emissions.[3] Related to this concern is the fact that market-based policies to address climate change would operate primarily by raising the cost of using fossil fuels—even as low energy prices are widely considered desirable as a means to promote economic growth (National Energy Policy Development Group 2001).

In the climate change debate, the concept of an economywide market-based program also draws criticism from some business sectors. One reason for this opposition could be that traditionally, only certain sectors—namely, transportation, electricity generation, and heavy industry—have been the target of environmental regulation on emissions. Others, such as agriculture, small businesses, and households, have typically been exempt. In many cases these exclusions are for practical reasons—direct emissions from these sources are small and diffuse, expensive to control, or difficult to regulate. As attention shifts to carbon dioxide, however, the logic behind these reasons is not so clear. For example, while direct emissions from these sectors may remain a relatively small fraction of total emissions, they may constitute a disproportionate volume of inexpensive mitigation opportunities.[4]

Given those sources of opposition, it is not surprising that most existing or proposed policy measures to reduce fossil fuel use and mitigate climate change have been sector-based, regional, and/or nonmarket policies. During the 107th Congress, two bills were introduced that would have established a cap-and-trade program for carbon dioxide emissions only from power plants. Several bills were introduced that focused on tighter fuel economy standards for automobiles.[5] The President's National Energy Policy proposed new efficiency standards and renewable energy subsidies. Only the McCain-Lieberman bill (S.139) in February 2003 proposed something approaching an economywide architecture.

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[3] That is, with 5% reductions, every ton of reduced emissions at a particular price is accompanied by 19 tons requiring permits. In a simple model with linear marginal cost, the average cost per ton reduced would be one-half the marginal cost, and the price of permits. Hence, the value of the permits would be 38 times the cost of the emissions reductions.

[4] Perhaps more importantly, carbon dioxide emissions from these small sources are in principle easy to regulate because they can be computed based on the volume of purchased fuels. Therefore, it is possible to create a permit system for regulating fossil fuel production with the same effect as a permit system on carbon dioxide emissions. Nonetheless, these small sources likely prefer to remain unregulated.

[5] See S.804, S.1923, S.1926, 107th Congress.

At the same time, state-level policies have forged ahead. California has enacted new motor vehicle efficiency requirements (State of California 2004), nine northeastern states are negotiating a regional emission cap for power plants (RGGI State Commissioners 2005), and 17 states have renewable portfolio standards (RPS), which target a specific portion of renewable generation as part of the electricity generation mix (Union of Concerned Scientists 2004).

With the divergence of most proposed policies from what is argued to be a more cost-effective economywide approach, an important policy question is just how much more expensive are sector-based, regional, and/or nonmarket policies likely to be?[6] One recent study used a rule-of-thumb approach to analyze state-level policies and concluded they would be 10 times more expensive than federal policy (Bast et al. 2003). Even as this question becomes increasingly important, most of the economic modeling has focused on economywide, market-based approaches (EIA 1998; Weyant and Hill 1999). This reflects partly the absence of suitable sectoral detail in many models, and partly the inherent difficulties in modeling nonmarket policies. It may also reflect optimism that an economywide approach may yet prevail.[7]

In this paper, we depart from the existing economic studies in important ways and examine the likely difference in costs among prominent combinations of sectoral carbon price and nonprice policies. First, we make use of detailed studies of sectoral behavior to understand and model the likely response of the electric power, household transportation, and industrial sectors to several policies to reduce carbon dioxide emissions. In addition to the standard market-based "carbon price" policies of tradable permits or carbon taxes, we consider the possibility of renewable performance standards in the power sector (minimum requirements for the share of renewable energy), fuel economy standards in the transportation sector, and uniform percentage reduction targets in the industrial sector. Second, we use these modeled responses to parameterize much simpler representations of each sector. These representations—of responses

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[6] Parry and Williams (1999) show that an economywide approach is not guaranteed to be more efficient when interactions with preexisting distortions in the economy are taken into account. This result applies to a vector of carbon reductions supplied from different sectors. Diamond and Mirrlees (1971) show that under optimal taxes, vectors of public good production can be valued at producer prices. This implies that an economywide policy is optimal, equating the marginal (producer) cost of abatement across sectors. Absent optimal taxes, however, the result is ambiguous because public goods such as CO_2 abatement cannot be valued at producer prices. Therefore, equating producer costs of abatement across sectors no longer guarantees optimality, and welfare maximization may involve higher producer costs in some sectors.

[7] Interestingly, an impetus for market-based policies came in part from various partial equilibrium studies showing the relative inefficiency of nonmarket policies. See, for example, Tietenberg (1985).

to both market and nonmarket policies—are then combined in an economywide computable general equilibrium (CGE) model. The CGE model allows us to consider effects outside the regulated market, interactions with other distortions and trade effects in the economy, as well as interactions with other carbon price and nonprice policies in different sectors.

Using the models, we make several observations. We start with a benchmark of an auctioned permit system covering all emissions and auction revenues used to cut income taxes. First, the exclusion of certain sectors—such as residential, construction, commercial, and government direct use of fossil fuels—does not noticeably affect the cost of an otherwise economywide tradable permit system covering the remaining areas of electricity production, industry, and transportation. Second, and in contrast to the first observation, a market-based policy covering just electricity and household transportation (and excluding industry and commercial transportation) costs about twice as much for a given volume of emissions reductions as an economywide approach. Finally, a national renewable portfolio standard coupled with tighter corporate average fuel economy (CAFE) standards for automobiles is more than 10 times as expensive. The increase in cost is split almost evenly between the two policies, which are designed to achieve the same fractional reduction in each sector. Although economic theory tells us that a flexible, economywide program to reduce emissions is not necessarily least-cost in an economy with existing distortions, in our simulation model we estimate that it does in fact do noticeably better than at least two competing alternatives (see footnote 6).

Those observations support several conclusions. Efforts to include all sources of carbon dioxide emissions—beyond electricity, transportation, and industry—in a flexible, economywide mitigation program may not deliver noticeably lower costs. However, the use of carbon dioxide emissions trading, rather than an RPS or CAFE, would appear to offer significant cost savings. The inefficiency of an RPS arises from its failure to encourage substitution from coal to gas for electricity generation because it does not put a price directly on emissions. And the higher costs of the CAFE are due in part to our representation of preexisting tax distortions—namely, the presence of taxes on the returns to capital invested in production by firms but the absence of taxes on returns to capital invested in "household production," in particular personal transportation. These conclusions follow, in part, from our unique use of both sectoral and aggregate CGE modeling.

The next section summarizes the model structure of the detailed electricity, household transportation, and industrial sector models we employed and describes the application of alternative climate policies to those sectors. Following this, we describe how we used the detailed sectoral results to represent these sectors in an aggregate CGE model, how we modeled nonprice policies within the CGE framework, and additional CGE modeling details. We then discuss the CGE model results, compare the partial and general equilibrium results, and offer concluding comments.

Modeling Sector-Specific Policies

Energy use can be difficult to model. In many cases, it is associated with the use of long-lived capital, ranging from automobiles with a 1five-year life, to buildings with a 50-year life, to electricity generating assets with potentially an even longer life. In addition, the markets surrounding energy use have often been regulated, ranging from electric utility regulation by public commissions to efficiency standards for building construction, home appliances, and automobile performance. In part, this regulation represents a response to various market failures that exist surrounding energy use, including natural monopolies and incomplete information. In support of and in response to policy development and evaluation, many modeling approaches have been developed by the private, government, and academic sectors to study the idiosyncrasies of energy use in particular sectors.

Our effort has taken advantage of several existing lines of work. For example, the Energy Information Administration's National Energy Modeling System (NEMS) has been developed over many years for the purpose of forecasting energy prices and use at both an aggregate and a disaggregated level, resulting in publications such as the *Annual Energy Outlook*. In addition, NEMS has been employed to analyze the costs and emissions consequences of several proposed environmental initiatives, including the Kyoto Protocol (EIA 1998), multipollutant legislation (EIA 2000), and the recent McCain-Lieberman proposal (EIA 2003). As described further below, our electricity and industrial sector models build, to various degrees, on sectoral submodels within NEMS. Our electricity model also takes advantage of efforts using the Integrated Planning Model (IPM) for the power sector.[8] In the transportation sector we use a stock-flow model of the vehicle fleet similar to that developed by Berkovec (1985), informed by a discrete-continuous econometric model of vehicle ownership and use (Train 1986). More detailed technical documentation is provided in Pizer et al (2003).[9] The following subsections describe these models in greater detail.

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[8] See, for example, U.S. EPA (1998).

[9] We also developed estimates of energy-price responsiveness in the commercial sector using a discrete-continuous choice model of multifuel energy demand (Newell and Pizer 2003).

Electricity Model

The Haiku electricity sector model is a simulation model that describes regional electricity markets and interregional electricity trade with an integrated algorithm for investment and retirement of generation capacity, fuel choice, and emissions control technology choice.[10] The model uses iteration to converge to market equilibria and calculate electricity demand, electricity prices, the composition of electricity supply, and emissions of major pollutants, such as nitrogen oxides (NO_X), sulfur dioxide (SO_2), carbon dioxide (CO_2), and mercury (Hg) from electricity generation. The model solves for the quantity and price of electricity delivered in 13 regions for four time periods in each of three seasons. For each of these 156 market segments, demand is aggregated from three customer classes: residential, industrial, and commercial. Supply is aggregated from the complete set of electricity plants in the United States, which for modeling purposes are aggregated into 48 representative plants in each region. Investment in new generation capacity and retirement of existing facilities are determined in a dynamic framework, based on capacity-related costs of providing service in the future. Generator dispatch in the model is based on the minimization of short run variable costs of generation.

Interregional power trading is identified as the level of trading necessary to equilibrate regional electricity prices (accounting for transmission costs and power losses), constrained by the assumed level of available interregional transmission capability as reported by the North American Electric Reliability Council (NERC). Factor prices, such as the cost of capital and labor, are held constant. Fuel price forecasts are calibrated to match EIA price forecasts for 2002 (EIA 2001).[11] Fuel market modules for coal and natural gas calculate prices that are responsive to factor demand. Special attention is given to the flexible modeling of institutions in the electricity sector, with regard to both the way prices are set (regulated versus competitive regional electricity markets) and the design of environmental regulations.

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[10] Haiku has been used for a number of reports and articles that appear in the peer-reviewed literature. See, for example, Burtraw et al. (2003a, 2003b). The model has been compared with other simulation models as part of two series of meetings of Stanford University's Energy Modeling Forum (1998, 2001) and is documented in Paul and Burtraw (2002).

[11] More recent fuel price forecasts are similar for coal but show an increase in natural gas prices. About 40% of the increase in natural gas price forecasts that have been incorporated in EIA analysis between 2000 and 2004 were present by the forecast for 2002.

Policies in the Electricity Sector

The policies that reduce emissions at the least cost in the Haiku model of the electricity sector are an emissions tax or a cap-and-trade policy. These are equivalent policies, assuming that emissions permits are distributed initially through an auction, and assuming the absence of uncertainty and symmetric accounting rules. Hence we refer to them jointly as a “carbon price” policy. We analyze policies implemented for the year 2010. We find the carbon price produces a roughly concave marginal abatement cost schedule, as indicated in the bottom left panel of Figure 4, which illustrates a marginal cost curve conditional on a constant level of electricity demand (dashed line).

Under a carbon price policy, the largest source of emissions reductions comes from coal generation, which accounts for 86% of carbon emissions in the baseline and falls by up to one-quarter in absolute terms over the range of policies we examine. For initial (low) levels of the carbon price, reductions in emissions from coal account for about three-quarters of total reduction. At a carbon price of $100 (1999$), reductions in coal account for all emissions reductions, while natural gas emissions actually increase. At a carbon price of $100, coal still accounts for 80% of total emissions. Natural gas emissions fall initially but begin to increase at a carbon price above $40 as gas plays an increasing role in generation. We find a shift in the type of gas capacity, with substitution away from the use of existing and planned gas facilities of all types, and a general substitution away from new gas turbines in particular. There is an expansion in the use of new combined-cycle generation, which has lower emission rates. The percentage increase in combined-cycle is greater under greater carbon price levels.

We also examine a sector-specific technology policy taking the form of a renewable portfolio standard implemented at the national level. Technologies qualifying as renewable include existing and new wind and biomass electricity but exclude hydroelectric. Policy targets identified the portion of total generation to come from renewables, up to 22.5%. Tradable RPS credits effectively constitute a subsidy per kWh necessary to achieve this contribution from renewables, and reached as high as $0.20 per kWh (1999$). The charge per unit of generation from nonrenewable sources reached $0.05 per kWh at this extreme, more than doubling the price of generation from nonrenewable sources. The electricity price increases by 30% in the extreme case.[12]

The RPS is an inefficient policy for achieving reductions in carbon compared with the carbon price policy. In fact, we see some perverse consequences of the RPS. Gas-fired generation falls by 37% under the extreme policy while coal-fired generation falls by only 19%. The decline in gas is because renewables often replace gas as a way of meeting new electricity demand. Furthermore, although the effect is small, we actually see a decline in generation from relatively efficient natural gas units compared with less efficient (peaking) gas units. This is because the renewables have low variable costs and typically are used the maximum amount of time they are available, which places renewables in competition with combined-cycle units in baseload time blocks. An RPS may achieve other policy goals, such as helping to overcome inherent bias in the current configuration of the transmission grid that favors central power stations. And like a carbon price, it also leads to ancillary reductions in other air pollutants (Burtraw et al. 2003b). Nonetheless, it is less cost-effective than a carbon price in reducing carbon emissions. The relative cost-effectiveness of these policies is described in the general equilibrium analysis.

Transportation Model

The U.S. household transportation model consists of a vehicle production sector, household vehicle demand and use, and a scrappage market (Harrington et al. 2003). The model is designed to investigate both short- and long-run household responses to policies aimed at reducing carbon emissions. For example, in the short run, we would expect households to drive fewer miles if the cost per mile of travel is increased, with the magnitude of the reduction depending on the elasticity of vehicle miles traveled (VMT) with respect to price per mile. Over time, households will most likely respond to changing vehicle prices and fuel costs from carbon policies by altering the number and types of vehicles owned. In fact, many argue that CAFE standards will not only change the relative prices of new vehicles by class, but could also change the relative prices of new and used cars (Kleit 1990; Kwoka 1983; Thorpe 1997). By decreasing

[12] Palmer and Burtraw (2004) perform an analysis of an RPS using more recent and complete characterizations of renewable technology and more recent fuel prices. They find the charge per unit of generation from nonrenewable sources rises to $35 at a 20% RPS, with electricity rising by only 8%.

driving cost, furthermore, it has also been observed that higher fuel economy will lead to *increased* VMT, a phenomenon often called the rebound effect.

The dynamics of the model follow from the carryover of vehicle stocks from one period to the next. For example, part of the stock of new cars and trucks in period *T* is added to the stock of old vehicles in period *T*+1. Within each period, households demand new and old vehicles based on the relative prices and operating costs per mile. Automobile producers respond by producing new cars and trucks, where we assume that producers are price-takers and the production technology has constant returns to scale. We also simplify the producer's cost function, assuming costs vary only with changes in fuel economy. The supply functions for old vehicles are the scrappage functions, where the scrappage rate depends on the price of old vehicles and their scrap value.

Our household demand model is a simpler version of the model employed in Train (1986), which is based on expected utility theory and estimated using discrete–continuous choice econometric models (Dubin and McFadden 1984). The main simplification is that we limit the number of classes and vintages to four: new car, new truck, old car and old truck, where the truck classification includes vans, pickups, and sport utility vehicles. This simplified model is nonetheless sufficient to display the range of relevant responses of motorists to the policies of interest—that is, fuel taxes and changes to fuel economy standards.

Household vehicle demand is based on an estimated nested multinomial logit model of vehicle choice that uses data from the 1990 Nationwide Personal Transportation Survey.[13] The decision of how many vehicles to own is estimated in the top level of the nest and vehicle class-vintage choices are estimated in the second level. Using the predicted probabilities from the model estimation as a sample selection correction, we estimate VMT conditional on number of vehicles owned using a log-log specification.[14] Simultaneous estimation of this discrete-continuous model imposes some constraints on model parameters. However, our model, like almost all discrete-continuous models of vehicle stock and use, estimates the discrete model and the continuous model separately and does not impose these parameter restrictions. This greatly

[13] See Harrington et al. (2003) for more detail on the survey.

[14] We estimate the model sequentially where we first estimate a nested multinomial logit model of the number of vehicles to own (0, 1, 2, or 3) and the class and vintage of each car, and then, conditional on these choices, we estimate a model of vehicles miles traveled (Train 1986; Goldberg 1998). We also do not restrict the coefficients on the common variables to be equal across the choices (Harrington et al. 2003).

simplifies estimation, but it means that the resulting demand equation is not integrable, which in turn means that it is impossible to calculate policy costs in a theoretically consistent way.

Policies in the Transportation Sector

The dynamic household transportation model is capable of looking at many realistic scenarios associated with implementing CAFE and fuel taxes. For example, if the goal is to reach a certain emissions reduction in some year using a CAFE policy, the regulator can vary the phase-in rate to meet that goal. Because CAFE affects the use of vehicles only indirectly via changes in the vehicle stock, the phase-in rate can significantly affect the cost of the policy; faster rates of increase over shorter periods are associated with greater price increases in vehicles.

We simulate constant percentage increases in CAFE standards or fuel prices over a five-year period, after which CAFE regulations or tax rates are held constant for an additional 10 years.[15] The advantage of the detailed sector model is that it estimates readily observable physical quantities, such as change in new and old vehicles, cars and trucks, age of vehicles, and vehicle miles traveled. Along these dimensions we find qualitative differences between the two types of policies. First and foremost, CAFE and fuel taxes achieve their emissions reductions in different ways. Fuel taxes operate on three margins to reduce fuel use: total vehicle ownership, use per vehicle, and improved fuel economy. For example, a five-year annual gas price increase of 4% produces a 5% reduction in fuel use by year 15. Most (85%) of this reduction is due to reduced vehicle use. For CAFE, the 5% reduction is accomplished by a 2% annual increase in CAFE over 5 years. At the end of the period the change in fuel economy is 16% greater than the change in fuel use because vehicle use actually increases due to the rebound effect.

CAFE and fuel taxes also differ in their effect on the structure of the fleet. Both have slight negative effects on the number of vehicles, but the reductions differ across the vehicle stock. For instance, we find that in the gasoline tax scenarios, the number of cars stays constant or increases slightly; the entire decline in number of vehicles comes from trucks, especially older trucks. In the CAFE scenarios, there is a substantial increase in old trucks and a corresponding decrease in new cars. Old cars and new trucks are largely unaffected. As a result of these fleet

[15] See Harrington et al. (2003) for additional analysis and discussion of policy simulations. The waiting period allows time for the CAFE policies to ripple through the vehicle stock. The longer the period until the evaluation occurs (after the ramp-up period), the lower the costs of CAFE in meeting a certain target level of emissions.

shifts, the life expectancy of both cars and trucks increases under CAFE and declines in the fuel tax scenarios. CAFE raises new vehicle prices substantially, reflecting the improvements in fuel economy. As Kleit (1990) predicts, used-car prices also rise, with increases on the order of 14% for cars and 8% for trucks. Finally, because of stock turnover rates and rebound effects, a major difference between CAFE and fuel economy policies is the speed with which the policies achieve a certain level of emissions reduction.

Industrial Sector Model

The industrial sector model is based on the National Energy Modeling System's industrial sector demand module.[16] The industrial sector model distinguishes 15 industry groups, for which it forecasts the demand for 13 main fuels in four geographic regions. The model covers energy demand from both manufacturing (SIC 20–39) and nonmanufacturing sectors (SIC 1–2, 10–17), with industry group classifications chosen to be as consistent as possible with the Manufacturing Energy Consumption Survey. The model estimates consumption of each fuel along with nonutility electricity generation and corresponding steam production. Unlike the electricity and transportation models, the industrial sector model takes output levels as fixed. The model calculates carbon emissions based on the carbon contents of the fuels used.

We chose to base the industrial sector on the National Energy Modeling System for several reasons. First, the NEMS module has, to our knowledge, undergone more development effort, peer review, and testing than any other model of U.S. industrial energy demand. It also offers a straightforward platform for assessing the carbon reductions associated with a carbon price or carbon permit system. Finally, the module's technology and sectoral detail is sufficiently disaggregated to allow estimation of the emissions and fuel use consequences of nonprice policies (e.g., uniform performance standards) and price and nonprice policies targeted to specific sectors or components of energy demand.

Policies in the Industrial Sector

The model is capable of computing any number of different carbon price scenarios, as well as uniform percentage emissions reduction standards by industry. The carbon price is levied on fuel use, and reflected in fuel prices, as if levied on fuel suppliers, but they are able to pass on

[16] See the NEMS documentation (EIA 1999) for detail on the model structure.

100% of the carbon price to their industrial consumers. To approximate the effects of foresight, which is not included in the model, we levy the carbon price beginning in the year 2000 and evaluate results as of 2010.

We use the industrial sector model to simulate both a uniform carbon price and a "uniform percentage rollback" in the industrial sector. Figure 1 illustrates our results for the costs of carbon mitigation for the industrial sector. The results show that for a carbon price policy, based on either a carbon tax or a tradable permit system, the marginal cost of carbon mitigation rises at an increasing rate, with a 5% reduction in emissions costing about $65 per ton ($1997). The "uniform percentage rollback" policy evaluates a series of percentage emissions reductions by industry group for manufacturing industries. Policy costs and emissions changes are calculated for each percentage level for each industry group. The resulting marginal cost curve for all of industry is higher than for the more efficient price policy—about 50% more expensive on the margin for a 5% reduction in emissions, reflecting the difference in the cost of carbon reduction across industrial sectors.

Adopting Detailed Sectoral Models for General Equilibrium Use

Economywide general equilibrium models long have been the workhorses of economic studies of carbon price policies (i.e., taxes or tradable permit systems). The reasons for using such models have been frequently noted: they allow us to study the effects of carbon prices in the economy in a way that is consistent with economic theory, consistent across sectors, and cognizant of inter sectoral interactions across goods and factor markets.

However, this strength becomes somewhat of a handicap when attempting to deal with more disaggregated sectoral price policies that do not price carbon consistently across sectors, or with nonprice policies that encourage, mandate, or forbid certain choices. Energy efficiency standards are a canonical example. As we discuss further below, in principle any such policy can be reduced to an equivalent set of price distortions, but without a fair amount of sectoral detail, it may be far from easy to ascertain the relevant price-equivalent representation.

General equilibrium models applied to energy-economy-CO_2 analysis differ considerably in their details (for discussion of model differences, see Weyant and Hill (1999) and Ghersi and Toman (2003)). Some of these models were originally developed mainly to study energy-related issues; they are relatively detailed in their description of energy supply but have little breakdown of the rest of the economy. Other models have relatively less energy detail (e.g., describing electricity supply) but more detail on other goods markets. In either case, however, what is often lacking in the models is a detailed and more technology-rich description of energy demand (e.g., for personal transport or in buildings). This implies, as noted above, that the models have a limited ability to handle policies that do not readily reduce to a carbon price.

Detailed sectoral models have the advantage of facilitating analysis of such policies by replicating more fully the critical technology choices and institutions and features associated with particular types of economic activity. With further elaboration—incorporating factor supply and output demand—these sectoral models can attempt to show what would likely happen in these sectors under various policy scenarios. However, it is hard to use these models to develop a picture of overall economic impacts or impacts in other sectors. Specifically, sectoral models cannot calculate overall policy costs simultaneously in all markets.

Ideally, one might imagine patching together a collection of detailed sectoral models into a single, economywide model capturing simultaneous equilibria in all markets. Unfortunately, this is not entirely practical. First, model inputs and outputs do not naturally match up—commodity definitions and the level of detail vary. The Haiku electricity model described above predicts generation at the facility level and tracks 156 time-, season-, and regionally differentiated kinds of electricity for three customer classes. Meanwhile, the transport model predicts vehicle choice and use for a large sample of representative households.

Second, it is not feasible to solve all the models simultaneously. Detailed sectoral models are usually a combination of simulation and optimization. Simulation models allow policy effects to propagate through a very large number of relationships in an iterative calculation. Coupling such models with similarly detailed models in other sectors and searching for a simultaneous equilibrium are unrealistic because of computational requirements.

Even if it were practical to put all these detailed models together, it is not clear that the detail contained in the sectoral models is necessary for the kinds of economywide questions we might be asking. The advantage of putting the detailed models together is the calculation of overall policy costs—more detailed impacts in a particular sector can be understood through simulation of the stand-alone sectoral models.[17] By avoiding “kitchen sink” models that attempt to do everything, results also tend to be more transparent.

[17] In sectoral models where aggregate economic conditions are exogenous, it is possible to consider changes in those conditions by iterating simulation of the sectoral model and an aggregate economic model. See, for example, EIA (1998).

Modeling Integration

For each detailed sectoral model, our approach is first to construct a similar *reduced-form* sectoral model based on the benchmark 1992 National Income and Product Accounts of the United States (Lawson 1997). We then use simulations of the detailed sectoral models to calibrate elasticities in the reduced-form model. We use a nested constant elasticity of substitution (CES) functional form for the reduced-form models, as in many other CGE models (Perroni and Rutherford 1995). The top nest involves substitution between capital, labor, energy, and materials (KLEM). Energy inputs—coal, petroleum, natural gas, and electricity—constitute one subnest. The remaining commodities make up the material subnest. We assume that materials have zero elasticity of substitution among one another and use simulations of the detailed sectoral models to determine the energy (σ_e) and KLEM (σ_{top}) elasticities.[18] The nested CES model is diagrammed in Figure 2.

To determine the elasticities in the electricity, household transportation, industry, and commercial building sectors, we simulate the effect of a carbon price on use of fossil fuels and electricity in the appropriate detailed sectoral models. With multiple data points between zero and about $60 per ton of carbon, we attempt to match these detailed sectoral model results with the percentage changes in fuel demand predicted by the reduced-form model using the same percentage changes in fuel prices. Elasticities are chosen for each sector to minimize the sum of squared errors in percentage changes in fuel and other available inputs given by the reduced-form model compared with the detailed sectoral model results, weighting by expenditure. That is, we choose the elasticities σ_e and σ_{top} to minimize

$$\sum_{e,n}\left(w_e\left(x_{e,n}-\overline{x}_{e,n}\right)\right)^2, \qquad (1)$$

by searching over various combinations of these parameters. Here the summation is over both e inputs (including coal, oil, natural gas, and electricity) and n distinct simulated carbon

[18] Household transportation is treated differently because it does not exist in the input-output accounts. We create it from a combination of household purchases of gasoline and an imputed capital stock. Household purchases of gasoline are separated from home heating oil based on Table 2.2, 1992 National Income and Product Accounts (from the BEA website; see BEA 2002). The imputed capital stock of household vehicles is based on the ratio of consumer vehicles capital stock to total private capital in 1992 from Table 1.1 of the detailed data on fixed assets and consumer durable goods (from the BEA website; see Herman 2000).

prices.[19] The variable $x_{e,n}$ is the percentage change in use of input e for carbon price n predicted by the reduced-form model, $\bar{x}_{e,n}$ is similarly the predicted change in the detailed sectoral model, and w_e is the expenditure on input e in the reduced-form model (from the input-output tables). The household transportation sector is somewhat different from the others in that we use detailed sectoral model results to estimate a KLEM elasticity and an elasticity of substitution between household transportation and consumption of other market goods. Estimated elasticities are shown in Table 1.

Although we fit changes in individual fuel use based on changes in fuel prices, our ability to match the carbon dioxide abatement schedule is important, given our interest in policies to reduce carbon dioxide emissions. Even with a close fit based on Equation (1), deviations are possible because the reduced-form model necessarily uses cruder measures of carbon content. Whereas the detailed sectoral models track physical quantities, the reduced-form model relies on input-output accounts that contain only dollar flows. Carbon content is assigned to the dollar flows coming from coal, natural gas utilities, and petroleum refining based on emissions data by fuel and major sector—transportation, residential, commercial, industry, and electricity.[20] It is also possible that the mix of fuels differs between the reduced-form model, based on the 1992 input-output tables, and the detailed sectoral models, based on a variety of more detailed sources.

Figure 4 compares the CO_2 marginal abatement cost schedules from the detailed sectoral models with the schedules from the reduced-form models for the four sectors we fit. The reduced-form schedules for commercial buildings and transportation come out slightly less elastic than the detailed model results; industry is a bit more elastic. The errors in marginal cost for a given level of reductions are on the order of a few percentage points in buildings and transportation and closer to 25% for industry. The reduced-form marginal cost schedule for electricity does not provide as good a representation of the cost curve from the detailed electricity sector model. Although they match at around $60 per ton, the detailed model shows a concave schedule and the reduced-form a convex schedule. The concave schedule arises in the

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[19] We match output on capital for both the electricity and household transportation models; we match other inputs (labor) for the electricity model.

[20] Based on our assignment of carbon flows from the Annual Energy Review to sectoral $ flows from NIPA, carbon content for coal ranges from 21 to 29 tons per thousand dollars, for petroleum from 0.7 to 8.0 tons per thousand dollars, and for natural gas from 0.9 to 9.0 tons per thousand dollars. The value depends on the quality of the product (for example, gasoline is a higher-quality product than fuel oil) and the bargaining power of the purchaser (coal and natural gas prices are lower for electricity generators than for industrial users).

detailed electricity model because significant supply-side reductions do not begin to appear until the relative cost of coal rises sufficiently to encourage fuel switching (see discussion in the electricity modeling section). Yet a CES production function cannot capture a concave schedule.

Non-Carbon-Price Sectoral Policies

In addition to using the detailed sectoral models of electricity, household transportation, commercial buildings, and industry to fit elasticities in reduced-form nested CES models, we also develop an approach to model nonprice policies, including CAFE standards, industrial performance standards, and renewable electricity performance standards. It is relatively straightforward to simulate these policies in the detailed models, but previously it has not been clear how can they be represented in a reduced-form CES model. By suggesting a way to model them in a reduced-form manner, our approach opens the door for substantial further analysis.

Simulation results from the detailed models provide data on how production changes in response to these policies—that is, changes in inputs and outputs at different levels of CAFE or an RPS. There are several ways we could imagine replicating these results in a reduced-form model. Without changing the model parameters, we could impose constraints that shift production while prices remain the same. For example, fuel economy requirements on automobiles and renewable electricity standards both suggest a maximum ratio of fossil fuel to output.

We could also imagine using a different production technology to generate the new policy outcome. That is, we could change the technology of production by changing the CES parameters (elasticities, initial input shares, or productivity) so that the new RPS or CAFE outcome arose at benchmark prices. Both of these approaches require us to change the shape of the production possibility frontier, either explicitly or through constraints, to cause input use to shift in response to nonprice policies.

Rather than changing the production frontier, suppose we imagine instead that firms suddenly see the internal cost of using particular inputs diverging from market prices. For example, a fuel economy standard would make transportation fuel use *appear* more costly (relative to capital) to firms and households because fuel consumption uses up flexibility with respect to the standard. Perhaps a better example is an RPS, where the use of fossil fuels to generate electricity actually becomes relatively more costly than capital-intensive renewables because the former require RPS credits and the latter generate them.

All of this suggests modeling nonprice policies as a change in the prices contemplated by the firm, even as the market prices and underlying technology remain unchanged. This is straightforward to implement as taxes and subsidies on inputs that create no net revenue —for example, taxing fuel and subsidizing output in such a way that they balance out. If no net revenue is generated, net price continues to equal net input costs. This is true even though the taxes and subsidies change the implicit prices used by the firm to configure their production strategy.

We call these *shadow* taxes because they do not really tax the firm on net; rather, they change the relative prices of inputs. In this approach we can further allow for a Hicks neutral productivity shock—requiring proportionally more inputs for a given output level—because in some cases policies might not only shift input usage along a production frontier but also lead to inefficient use of existing technology. The shadow taxes move the choice of inputs along the production function, and the productivity shock shifts production to an interior, inefficient level of output.[21]

The shadow tax approach seems particularly appropriate for flexible performance standards, like tradable CAFE[22] and an RPS, where the policies place no limit on the scaling up or down of total production. Instead, these policies pressure input usage in particular directions. The idea that such policies appear, from the producers' perspective, as an effective tax on fuel use and subsidy to capital use actually makes sense (Fischer and Newell 2004). A crucial feature of both the policies and the shadow tax approach is that, unlike cap-and-trade or carbon tax policies directed at emissions, these policies do not price inframarginal emissions.

In practice, we estimate the vector of taxes, subsidies, and productivity shocks in a manner analogous to estimation of the CES elasticities. Data from each of the detailed models are matched, as closely as possible, to predictions from the reduced-form model by minimizing the squared error in Equation (1) through the choice of a set of taxes, subsidies, productivity shocks, and scaling factors, given the previously estimated CES elasticities. The scaling factors allow us to use data from a range of stringency scenarios associated with each policy, jointly scaling the shadow taxes and subsidies for each scenario. Note that the estimated parameters,

[21] As we note below, we do not find evidence of such negative productivity shocks when we examine the sectoral data.

[22] See NRC (2002).

shown in Table 2, reflect the nonprice policy operating at a particular level. In our CGE simulations, as in the fitting exercise, we jointly scale the input taxes and subsidies to achieve different emissions goals, while the output tax or subsidy endogenously adjusts to maintain zero-net revenue from the distortions.

The results indicate no productivity effects associated with the various inefficient policies—only shifts along the production frontier due to the shadow taxes and subsidies. This may be because there are, in fact, no productivity effects. It may also arise because in some of the detailed models (household transportation and industry) we do not have measures of overall cost—only responses for a subset of inputs and outputs.[23] This makes it more difficult to identify lost productivity. The productivity effects may also be small relative to the shifts along the production frontier. Effects on the remaining inputs are sensible. Energy prices increase relative to other inputs. For industry performance standards, coal prices increase more than oil, which increases more than natural gas. For the RPS, we see that coal prices increase less than oil and gas—reflecting the earlier observation that an RPS tends to displace gas rather than coal.

Additional CGE Model Details

The description so far has focused on our modeling of four sectors—electricity, industry, commercial buildings, and household transportation—and on the application of policies to three of those sectors.[24] To complete the CGE model, we need to model other productive sectors, including the fossil fuel supply sectors; final demand from consumers, investment, and government; foreign supply and demand; and factor supply.

The CGE model is centered on eight production sectors, distinct household and government agents, investment, and a standard model of relatively inelastic import supply and elastic export demand. The eight production sectors provide particular detail on fossil fuel use (coal, petroleum, natural gas) in order to monitor carbon dioxide emissions. The structure separates electricity generation, industry, commercial buildings, household and commercial transportation for more detailed policy modeling. Our household transportation sector combines household capital (cars), gasoline, and retail services into a good consumed exclusively by the

[23] The household transportation model does not provide a sectoral output measure—e.g., transportation services—and makes predictions holding income constant. Without a utility measure, there is no analog to cost.

[24] We built a model of commercial building energy demand but did not consider policies in that sector.

household. This allows us to model CAFE policies. The exact composition of these sectors based on input-output classification codes is given in Pizer et al. (2003), along with the intersectoral flows of goods. The model is benchmarked to the 1992 National Income and Product Accounts (from the BEA website; see BEA 2002).

In its comprehensive representation of the U.S. economy, this model captures all energy and fossil fuel use, even those uses that have not been the focus of our more detailed modeling efforts. Government use of energy, for example, is captured along with commercial transportation, and investment (mostly construction).

Following Kehoe and Kehoe (1994), we use a static model holding capital fixed and modeling saving as another element of final demand. With a few exceptions (noted below), we allow capital to be fully malleable among sectors. Along with the fact that our sectoral policy simulations are typically modeled 10 years into the future, this has the effect of mixing short-, medium-, and long-term assumptions about capital: aggregate capital is fixed, the sectoral results used to calibrate elasticities and nonprice policies allow moderate capital turnover, and capital can shift costlessly among sectors. We believe that this combination represents a reasonable trade-off between simplicity and policy relevance, allowing us to get at our interest in the interactions among policies without the overhead of a complex dynamic CGE model.[25]

Labor supply is endogenous; we use an elasticity of 1.7 between leisure and other goods.[26] Real government spending is held fixed across simulations, with government revenue coming from indirect business taxes (modeled as output taxes), income tax on labor and capital, and any revenue from carbon pricing. In this way, our simulation of carbon price policies is best thought of as either a carbon tax or an auctioned permit system, with all revenue being recycled into cuts in the income tax.

We assume elastic exports (elasticity of 10) and relatively inelastic imports (elasticity of 0.465). Imports are elastically substitutable with domestic goods in the production of a composite domestic-import good according to a standard Armington model with elasticities of 3.0 based on Ballard et al. (1985). The foreign exchange rate adjusts to maintain a fixed level of real foreign saving.

[25] Expanding the model to represent multiple periods would be an interesting area for further work.

[26] This is based on an uncompensated labor supply elasticity of 0.2 (Fuchs et al. 1998) and a compensated elasticity of 0.35 (Blundell and McCurdy 1999).

We use estimates of elasticities of substitution among fuels and among capital, labor, energy, and materials from McKibbin et al. (1999) for those sectors where we do not work with detailed sectoral models (coal, oil, gas, and commercial transportation).[27] For coal and natural gas production, we deviate from our assumption of fully malleable capital and assume fixed, sector-specific stocks. This allows us to better match expected supply response suggested by the detailed model of the electricity sector, which includes natural gas and coal supply models. We also use a lower KLEM elasticity for coal (0.334) than McKibbin et al. to better match the coal supply results from the detailed electricity sector model.

We use a tiered structure for household consumption (see Figure 3) that incorporates the elasticities for leisure and household transportation, noted earlier, as well as residential energy use.[28] We use an elasticity of 0.25 between energy and other goods based on an average of previous studies (Dahl 1993) while our elasticity of 0.05 among fuels was informed by historical data.[29] Domestic savings is combined with household consumption to define household utility (with unit elasticity). Final demand for investment and government goods are modeled as Cobb-Douglas. Demand for both is fixed in real terms with income taxes adjusting endogenously to meet the government budget constraint.

Equilibrium in the model is defined as supply meeting demand for all goods, zero profit in all sectors, and a binding income constraint for households. Additional details about the model, including programming code, are available from the authors (see Pizer et al. 2003).

General Equilibrium Results

The advantage of a general equilibrium (GE) model is that it allows us to compute a broader concept of policy cost that includes effects in other markets. A GE model also accounts

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[27] Generally, we use a KLEM elasticity of 0.5 and an energy elasticity of 0.2. Gas has a KLEM elasticity of 0.8 and an energy elasticity of 0.9.

[28] Our tiered structure follows most existing models, assuming that leisure is an average substitute for consumption of other goods. This implies that rising energy prices will shift consumption toward leisure, reduce the labor supply, and exacerbate tax distortions in the labor market (e.g., see Goulder et al. 1999). Recent work suggests that energy products, particularly gasoline, may be a leisure complement and reverse this effect (Williams and West 2004).

[29] Absent estimates in the existing literature for the elasticity among fuels, we fit our nested model to historic time series data on energy use and prices from 1983 to 2000. The model estimated an elasticity of 0.10 (0.08) between energy and other goods and 0.01 (0.05) among fuels (standard errors in parentheses). Because the existing literature suggested a higher value for the energy–other good elasticity than we estimated, though still within a 95% confidence interval, we used a slightly higher value (0.05) for the elasticity among fuels.

for what happens when all markets equilibrate, which may be different from partial equilibrium assumptions that necessarily hold certain features constant. With the completed model in hand, we can now take advantage of this capacity to evaluate a menu of policy options as well as compare partial with general equilibrium results.

Comparison of Policies to Reduce Carbon Emissions

Most economic studies of climate change policy focus on the cost of reducing emissions through an economywide carbon pricing policy (an emissions tax or cap-and-trade program). We also consider three alternative policies: (1) a more limited economywide carbon pricing policy that excludes residential, commercial buildings, investment, and government emissions; (2) a trading program that includes only electricity and household transportation (and thus excludes industry, commercial transport, and primary fuel extraction); and (3) a combination of non-carbon-price policies—that is, CAFE standards in the household transportation sector and an RPS in the electricity sector. In the carbon pricing policies, we assume all revenue goes to the government and is used to cut income taxes. This places the market-based policies in the best possible light and sets us up to measure the largest possible discrepancy with nonprice policies.[30] For the nonprice policies, we assume proportional reductions in both household transportation and electricity enforced by CAFE and an RPS.

Although the economywide carbon pricing policy would need to be implemented upstream to capture the myriad small sources, the other two carbon pricing policies are designed to consider the likely implementation of a mostly downstream trading program with transportation handled upstream (e.g., the architecture suggested by S.139, the McCain-Lieberman Climate Steward Act). Downstream programs are limited to large sources and would inevitably exclude households and many commercial and government buildings. At the same time, transportation is about 40% of total emissions and would need to be covered in any meaningful program. Household transportation emissions are about two-thirds of total transportation.

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[30] We set the exercise up in this way to highlight costs relative to the most cost-effective solution. Assuming auction revenue is returned to households in a lump-sum fashion (or alternatively, that permits are grandfathered) would raise the cost of the market-based policies (Goulder et al. 1999). Examining this question of handling permit revenues has been discussed extensively in the “double dividend” literature and is not the goal of our analysis.

The nonprice policy focuses on possibilities suggested by recent events. First, more than 17 states have enacted requirements that a certain share of their electricity generation be supplied by renewable sources (Union of Concerned Scientists 2004), and the U.S. Senate has twice passed legislation to establish a federal RPS. Second, we have seen both federal and state efforts to improve fuel economy (Pickler 2002; Booth 2002). Proposals for more comprehensive legislation are unlikely to progress very far in the near term, however (Pianin 2003). With this in mind, we consider a policy that implements an RPS at the national level alongside increased fuel economy standards. In particular, we consider a policy that imposes uniform reductions in both the household transportation and the electricity sectors in order to compare aggregate impacts with the other three policies.

Figure 5 shows the marginal welfare cost ($ per ton carbon) for the four alternative policies and a range of emissions reductions from 0 to 10% of total emissions; Table 3 summarizes permit prices and GDP costs for a fixed reduction of 5%. Our economywide policy suggests that a 5% reduction can be obtained with a $19 per ton carbon price. Before comparing alternative market and nonmarket sectoral policy results, it is useful to first note that this economywide result falls squarely in the middle of the estimates reported by Weyant and Hill (1999; see Figure 10(a)). This suggests aggregate results broadly consistent with previous work.

Comparing policies, the economywide and industry-transportation-electricity carbon pricing policies have nearly identical welfare costs. Meanwhile the transportation-electricity carbon pricing policy has roughly double the costs of the economywide program, and the RPS–CAFE policy has roughly 10 times the cost. The simple message from these results would be that excluding some sectors from a market-based policy, up to a fifth of emissions representing commercial buildings, households, government, and investment, does not substantially raise costs (see Figure 7). Even focusing just on electricity and transportation, which account for just under 50% of emissions, only doubles the cost. What truly drives up costs is the use of substantially less-efficient RPS and CAFE policies.

The simple message may be that RPS and CAFE are particularly inefficient, but more subtle messages also emerge from the results—as well as explain the simple message. First, Table 3 reveals that although dropping several sectors of the economy from an otherwise economywide program raises the carbon price by 40% (from $19 to $27 per ton), welfare costs rise only very slightly (from $24 to $26 per ton, remaining at about 0.016% of GDP). This relates to the early observation that in an economy with existing distortions, producer prices are not always appropriate for valuing public goods. Here, the culprit is property, excise, and other indirect business taxes (IBT) in the commercial building sector—7.3% compared with 1.3% in industry and 6.4% in electricity.[31] Including commercial buildings in a trading program may expand the opportunities to reduce emissions (thereby lowering the permit price), but equating the market price of carbon across sectors leads to welfare losses because of the particularly adverse interaction with IBT in the commercial building sector (e.g., see Goulder 1995; Parry 1997). This is exacerbated by disproportionate reductions in this sector: as Figure 8 indicates, a 5% economywide emission reduction leads to 8% reductions in the commercial building sector.

The effect of removing industry stands in contrast to the effect of removing commercial buildings (along with households, investment, and government). Whereas commercial buildings represent a relatively distorted sector in terms of IBT, industry is relatively undistorted. Removing commercial buildings from the carbon pricing policy maintains roughly the same aggregate costs, but further removing industry doubles costs.

Second, the RPS is particularly expensive as a CO_2 mitigation policy because it leads to a relative shift from gas to coal as overall fossil generation declines. As noted in the earlier discussion on the electricity sector, this arises from institutional features in the electricity market that place some types of gas generators more at the margin relative to coal, and because an RPS does nothing to penalize coal relative to gas. The failure to emphasize reductions in coal use makes an RPS a very inefficient tool for reducing carbon emissions; it is actually hard to push an RPS to achieve more than 20% reductions in CO_2 because of this failure.[32]

Third, CAFE is expensive for an entirely different reason related to our modeling of taxes on capital. In our model, factor inputs of labor and capital are taxed at a rate of about 15%. However, we do not tax the use of capital to provide household transportation. Much like owner-occupied housing (which is not addressed in our model), the implied return from owner-driven vehicles flows directly to consumers without any tax on the capital return. This leads to a distortion among capital uses, with a relatively high amount of household vehicles and relatively

[31] Note that our model, like most CGE models, treats indirect business taxes as taxes on output.

[32] Palmer and Burtraw (2004) find a knee of the curve in the cost-effectiveness of an RPS policy between 15% and 20% goals for the year 2020. They find partial equilibrium welfare cost per ton of carbon reduced to be 50% greater than the cost of a carbon trading policy with emissions allowances distributed on an updated share of generation. Elsewhere (Burtraw et al. 2001) this type of policy is shown to be two to three times less efficient than a policy with permits auctioned and revenues distributed lump-sum. The CGE model takes another step that cannot be captured by these detailed partial equilibrium models by accounting for the role of previous distortions away from economic efficiency. The tax policy we model recycles revenues to reduce preexisting taxes.

low amount of all other, taxed capital (which must have a 15% higher pretax return to balance its after-tax return with untaxed returns to household vehicles).[33]

CAFE requirements further exacerbate this distortion between vehicle and other types of capital by drawing in more vehicle capital to produce more fuel-efficient household transportation. Indeed, even though CAFE contributes less than a third of the reductions arising under the RPS, it is responsible for about half of the added welfare costs (both policies are set up to achieve the same percentage reductions, but electricity production generates more than three times the emissions associated with household transportation). Under a carbon pricing policy, there is still a relative shift from energy to capital in household transport, but there is a much greater reduction in household transportation services owing to increased costs of production associated with pricing inframarginal emissions. That is, although CAFE shifts household transport toward more capital and less fuel, there is no increased cost (such as a fuel tax or required permit) associated with the gasoline that is still used. A carbon-pricing policy, through greater reductions in overall consumption of household transport, reduces the distortion associated with household transport capital.

Summarizing, our simulations show minimal consequences associated with excluding a few relatively small sectors from an otherwise economywide cap-and-trade program. This is particularly true for sectors with relatively high taxation. Costs double when the cap-and-trade is limited to power plants and household transportation, partly because of the significant reduction in access to mitigation options but also because of the relatively low existing distortions in industrial production that make them a particularly appealing sector to include. Costs go up by a factor of 10 when, instead of market-based carbon pricing, we apply an RPS and a CAFE to the electricity and transportation sectors. Here, the story is about both the inefficiency of policies that do not directly target emissions as well as preexisting taxes and their capacity to dramatically alter the costs of a program.

Comparison of Partial and General Equilibrium Results

It is useful to recap the performance of general versus partial equilibrium analyses. This paper was motivated by the fact that general equilibrium analysis provides full cost estimates that

[33] Note that we do not model any market imperfections due to consumer undervaluation of future energy savings, which would tend to imply underinvestment in energy efficiency and at least partially offset the above effect.

are unavailable in a partial equilibrium analysis. Previous studies have found that partial equilibrium analyses, even with extensions to other markets, do poorly at capturing real welfare costs (Kokoski and Smith 1987). This paper is no different. However, partial equilibrium analysis *does* do a reasonable job of predicting emission responses. Consider the panels in Figure 6. For the four sectors where we calibrated production elasticities, we show the reduction supplied (horizontal axis) at different carbon prices (vertical axis). We show these schedules based on both a simple partial equilibrium analysis that holds input prices and output level constant (solid lines), and for our general equilibrium analysis where all markets equilibrate (short dashed lines). Note that both schedules are based on the fitted reduced-form model—unlike Figure 4, where we compare detailed and reduced-form models. What we see is that in three out of four cases, the partial equilibrium schedule closely matches the general equilibrium schedule. That is, a partial equilibrium analysis does a good job of predicting emissions response to a particular carbon price in that sector. The one exception is electricity, where reductions in output are responsible for an increasing share of emissions reductions as prices rise. Holding output constant in the reduced form partial equilibrium analysis misses those opportunities, leaving the partial equilibrium schedule to the left of the general equilibrium schedule.[34]

Although partial equilibrium analysis effectively captures the emissions response as well as the immediate policy costs in that sector, it does a poor job of measuring the impact on consumers and overall welfare. The third line (long dash) in each of the panels in Figure 6 shows the marginal *welfare* cost of the reductions under carbon price policies—that is, the marginal equivalent variation in household income associated with each ton of reductions in a particular sector. There we see that welfare costs are about $10 to $15 per ton of carbon higher than costs measured by the permit price in the buildings and electricity sectors, but about $10 per ton lower in the industry sector and $50 per ton lower in household transportation under carbon price policies.

As noted earlier, these distinctions arise because of the pattern of preexisting taxes. Indirect business taxes explain the differential pattern between commercial buildings and electricity, which have relatively high IBT, and industry, which has relatively low IBT. The income tax on capital, which is not applied to household transportation capital (in the same way it does not apply to owner-occupied housing), explains the dramatic effect on transportation

[34] Note that the Haiku model includes demand response and calculates welfare measures within the electricity sector for exactly these reasons.

capital. In theory, knowing the source of the distortions driving these distinctions would allow an extended-market analysis—but often it will be as hard to know these sources as to build a general equilibrium model.[35] The panels also show the even higher general equilibrium welfare costs of the CAFE and RPS policies.

Before concluding, a word of caution is in order: these additional costs or benefits attributed to preexisting distortions require that these distortions be modeled carefully. For example, our model of taxes is stylized—we do not attempt to replicate the complexity of the U.S. tax system. We have ignored nonlinearities in the income tax, payments to Social Security, and the double taxation of corporate profits. Most general equilibrium models are not designed to capture the plethora of existing tax rules.[36] Nor are many economists likely to agree on the assumptions necessary to pin down the distortions. For instance, policies that exclude household capital (homes and automobiles) from taxation lead to distortions in the allocation of capital among sectors but also may contribute to community stability and/or progressivity in the tax system. There is also a question of whether to use environmental policy to undo tax policy when this might be undone by actual tax reform. These concerns suggest that although general equilibrium exercises are a useful source of qualitative information and gross quantitative information, one should recognize that they inject a large number of additional assumptions into analysis that might otherwise be well served by a partial equilibrium analysis more fully grounded in institutional details.

Conclusions

Existing studies of climate change policy costs have tended to focus on efficient, economywide cap-and-trade or carbon tax approaches. In reality, a more limited cap-and-trade or even a disconnected set of nonmarket policies is more likely to arise in public policy. To study such approaches requires a general equilibrium model that can mimic non-carbon-price policies in particular sectors; otherwise, important interactions among policies are likely to be overlooked.

This paper presented a model that uses detailed sectoral models to calibrate behavior in simpler, reduced-form specifications that are combined in a computable general equilibrium

[35] See discussion in Kopp and Pizer (forthcoming).

[36] Studies that explicitly consider tax reform are an exception; see Jorgenson and Yun (1991).

framework. The calibration involved finding elasticities to match market response and sets of price distortions and productivity shocks to represent nonmarket policies. The result is a CGE model capable of considering renewable portfolio standards in the electricity market, fuel economy standards for cars and light trucks, and uniform performance standards for industry.

The model was applied to four polices: (1) an economywide carbon pricing policy, (2) a carbon pricing policy that excludes residential, commercial buildings, investment, and government emissions, (3) a carbon pricing policy for electricity and transportation only, and (4) combination of an RPS in the electricity sector and CAFE standards for automobiles. Compared with the economywide policy, we find that the exclusion of residential, commercial buildings, investment, and government emissions makes virtually no difference in the cost of the carbon policy. Accounting for only 20% of emissions and having either inelastic emissions (residential) or high costs due to preexisting distortions (commercial), costs are almost unchanged or even marginally lower (at reduction levels below 4%) when these sources of emissions are excluded from the program. However, limiting the program to only electricity generation and transportation more than doubles costs in our analysis. In this case, significant reduction opportunities are given up in the industrial sector and services.

We find that costs rise by a factor of 10 when fuel economy standards and a renewable portfolio standard for power plants are imposed (with both sectors facing equal percentage reductions). Each policy contributes roughly half of the noted increase in costs, even though fuel economy standards achieve about one-third as many reductions. In the case of an RPS for electricity, the policy fails to distinguish between coal and gas despite the roughly double emissions from coal per million Btus. In the case of fuel economy standards for light-duty vehicles, there is a significant preexisting distortion among capital uses owing to the absence of taxes on household capital services (e.g., cars and owner-occupied housing). This distortion means relatively more investment in cars and relatively less investment in other, taxed uses from the perspective of economic efficiency. Unlike carbon pricing policies (taxes and permits), fuel economy standards dictate more capital-intensive transport without increasing the price of gasoline and depressing overall driving; the net effect is an increase in vehicle capital that worsens the preexisting distortion.

Despite these dramatic and intuitive results, we would caution leaning too much on the quantitative analysis. The representation of taxes in the model is necessarily crude and the cost of distortions in other markets is only as accurate as the parameterization in those markets. Although detailed models based on empirical data have been used in the partial equilibrium analysis, other parts of the model have been parameterized from literature surveys and other information.

Even with those caveats, we demonstrate the capability to compare a variety of non-carbon-price, sector-specific policies that may be components of actual public policy and evaluate the relative efficiency cost compared with least-cost strategies. The result that policies like an RPS and CAFE turn out to be considerably more expensive than broad-based market alternatives should be a signal to decisionmakers who favor narrower, nonprice policies. Policymakers may be unaware of the relative cost of these policies, or it may be that other concerns trump economic efficiency. In either case, the information we develop about relative cost-effectiveness can benefit the shaping of public policy.

Tables and Figures

Table 1: CGE Elasticities Estimated from Detailed Sectoral Models

Sector	*KLEM elasticity*	*Energy elasticity*
Electricity	0.09	0.07
Industry	0.15	0.29
Commercial buildings	1.19	0.29
Transportation*	0.24	0.00

*Note that the elasticity between household transportation and consumption of other market goods, also estimated from the detailed transportation model, is 0.34.

Table 2: Ad Valorem Shadow Taxes (+) and Subsidies (–) for Simulating Nonprice Policies

	CAFE standards	*Renewable electricity standards*	*Industry uniform % reduction standards*
Coal	n/a	0.83	0.82
Oil	0.25	4.2	0.096
Natural gas	n/a	4.8	0.18
Electricity	n/a	n/a	0.31
Capital	–0.24	–0.66	–0.0054
Labor and materials	n/a	–0.48	–0.0054
Output	0.00	0.04	0.00
Productivity shock	0	0.08	0
Policy level (% carbon reduction)	9%[1]	7%[2]	6%

[1]The reference CAFE policy is a 22% increase in fuel economy, to roughly 29 mpg fleet average.

[2]The reference RPS policy is a 10% renewable electricity standard.

[3]The output tax/subsidy is reported for reported given policy level but is endogenously determined as other taxes and subsidies are scaled.

Table 3: Simulation Results for 5% Aggregate Reductions Through Alternative Policies

Policy	*Cost (% GDP)*	*Permit price ($/ton of carbon)*	*Marginal welfare cost ($/ton of carbon)*
Carbon price; economywide	0.016%	$19	$24
Carbon price; industry, transport, and electricity	0.016%	$27	$26
Carbon price; transport and electricity sectors only	0.038%	$53	$58
Renewable electricity portfolio and CAFE standards	0.19%	n/a	$240

Figure 1: Marginal Cost of Carbon Reductions in U.S. Industrial Sector

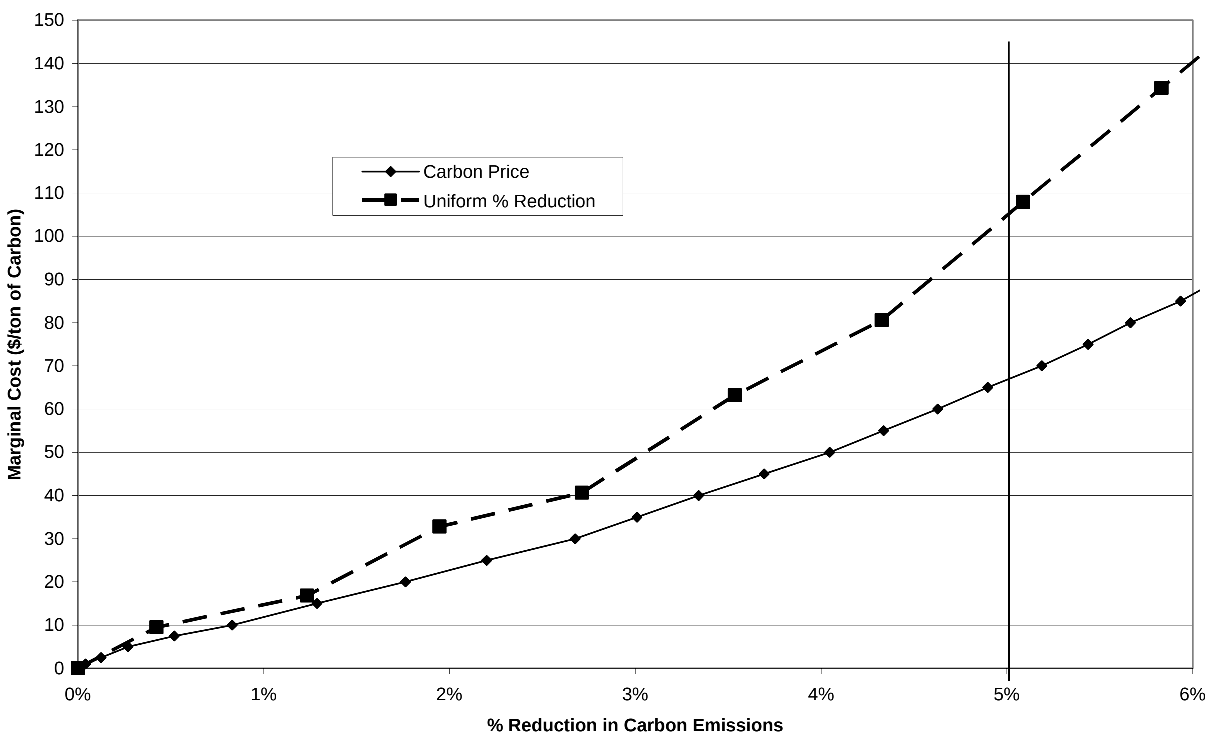
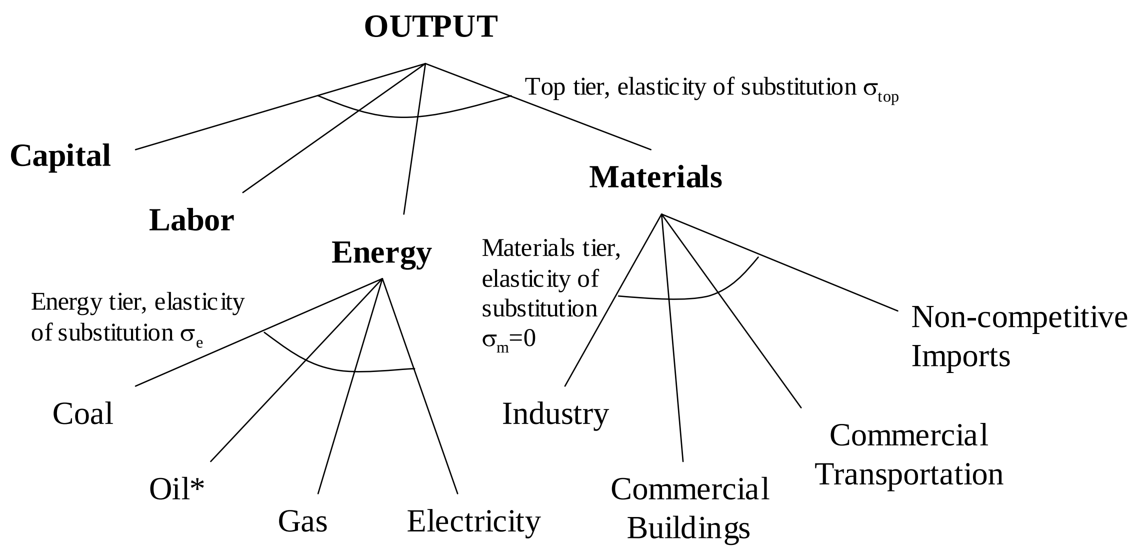


Figure 2: Nested CES Structure for Each Production Sector



* Oil is included in the materials tier for the household transportation services sector to allow fuel and fuel delivery services to be combined in a subtier before being combined with capital in the top tier.

Figure 3: Structure of Household Demand

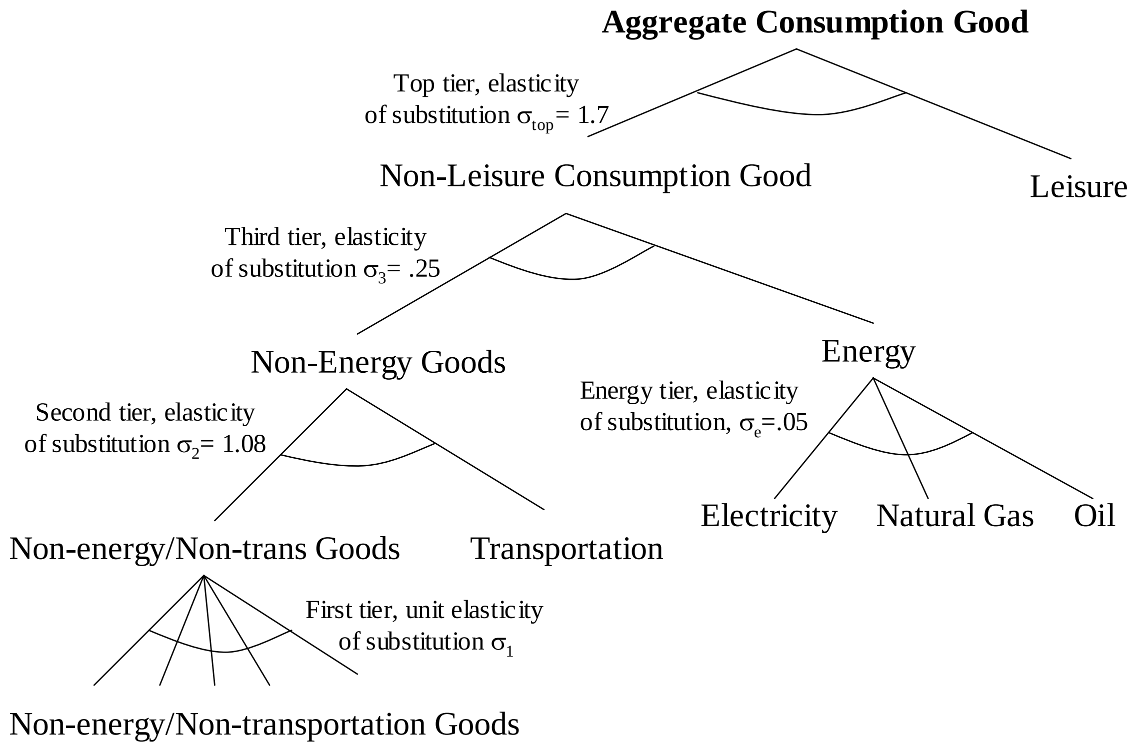


Figure 4: Comparison of Emissions Reduction Schedules for Reduced-Form and Detailed Sectoral Models

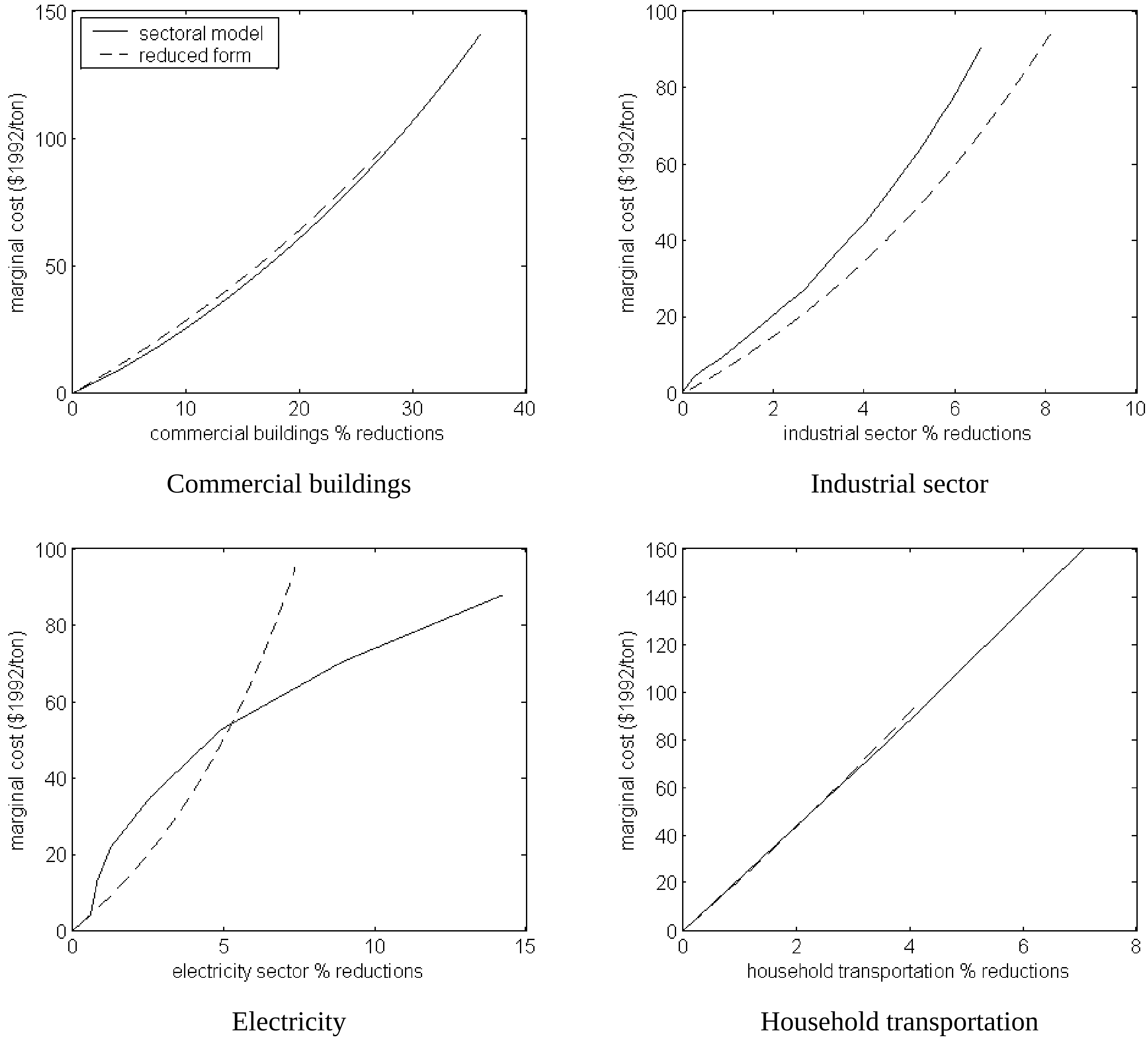


Figure 5: Cost of Alternative Policies to Reduce Carbon Dioxide Emissions

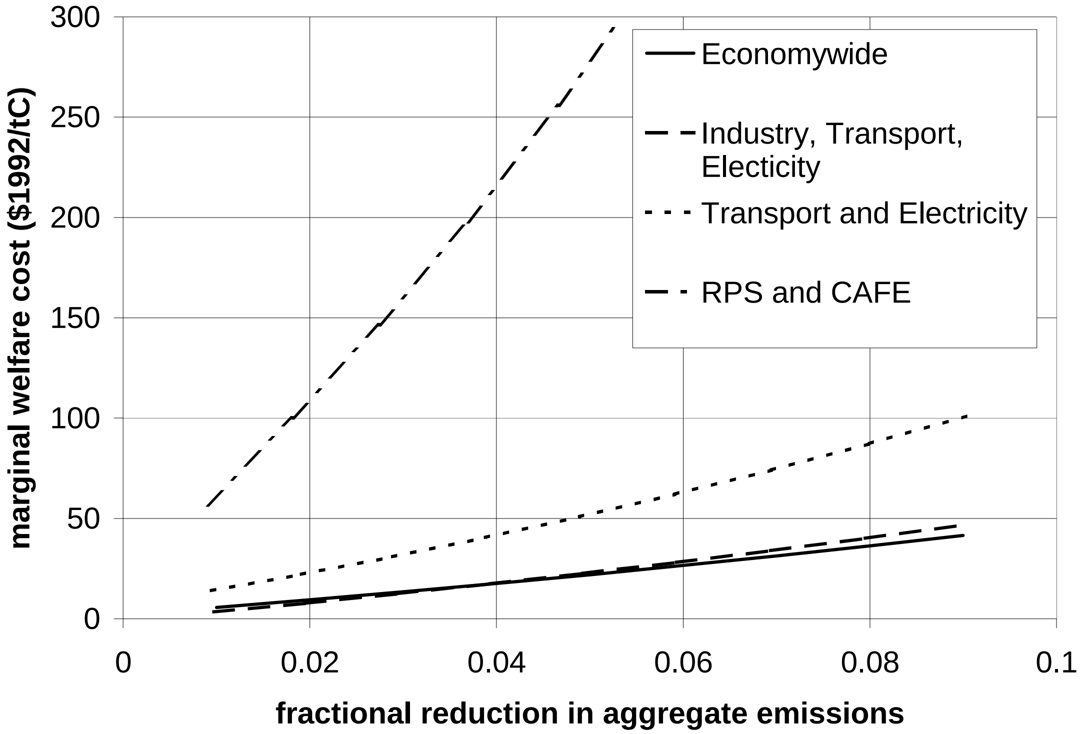
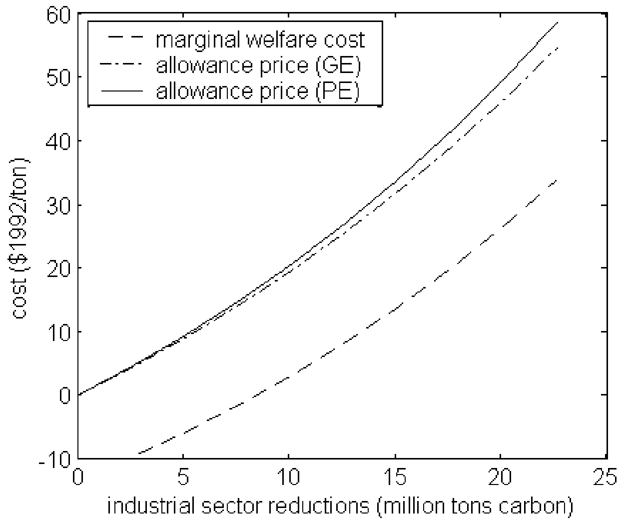
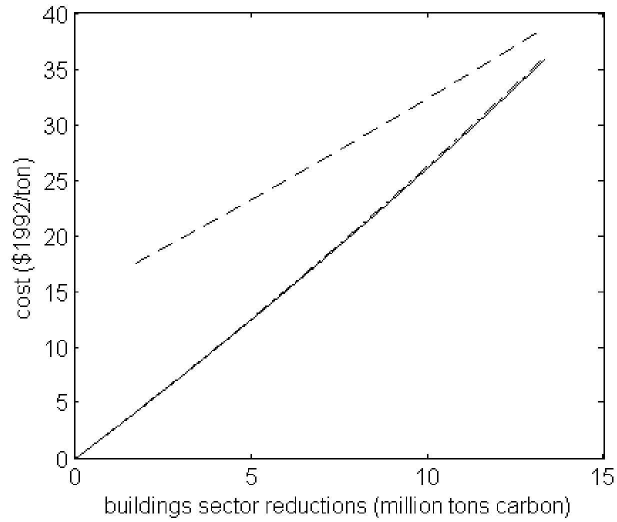


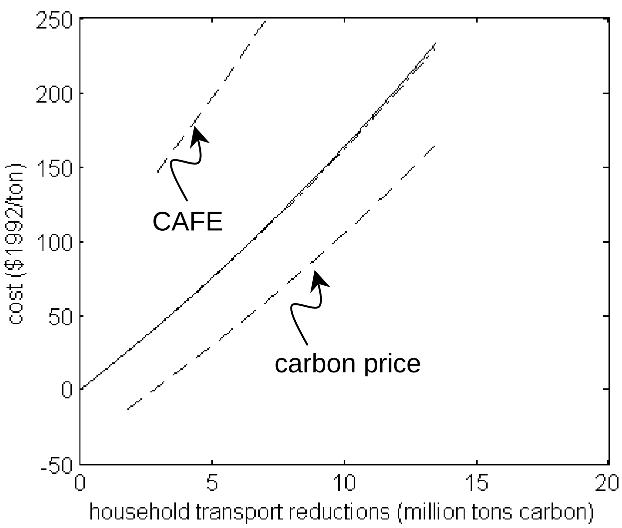
Figure 6: General and Partial Equilibrium Abatement Schedules and Welfare Cost



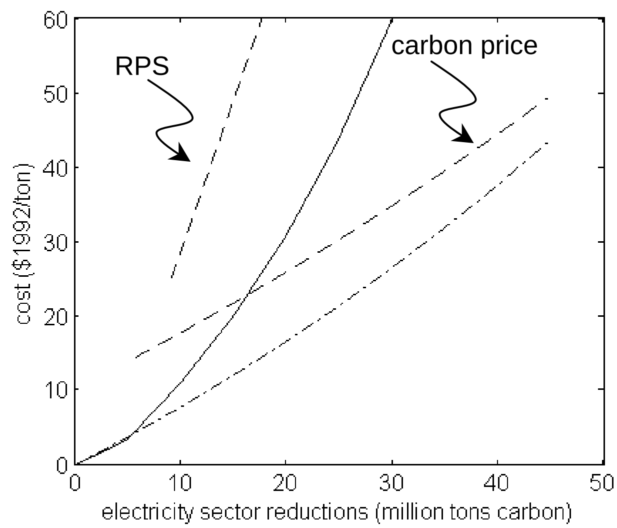
Industrial sector



Commercial buildings



Household transportation



Electricity

Figure 7: Emissions Shares in Reference Case

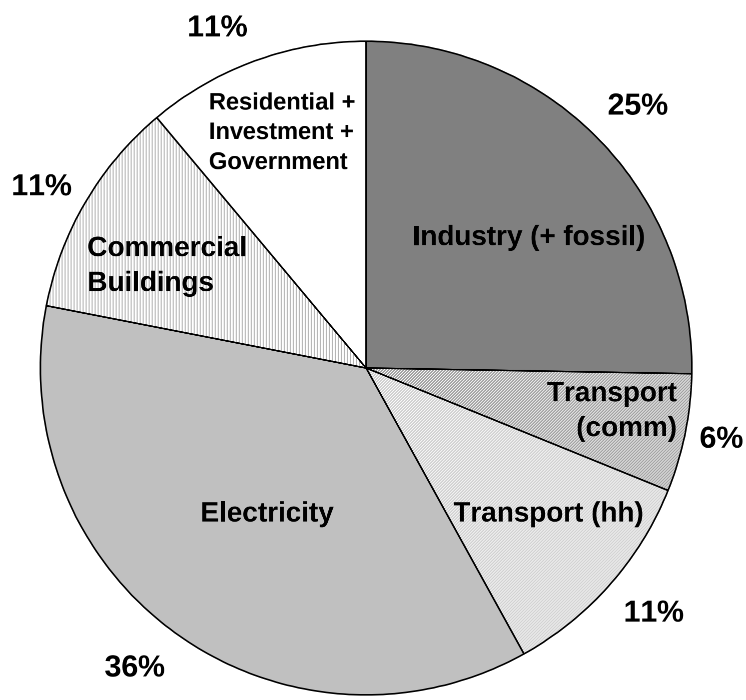
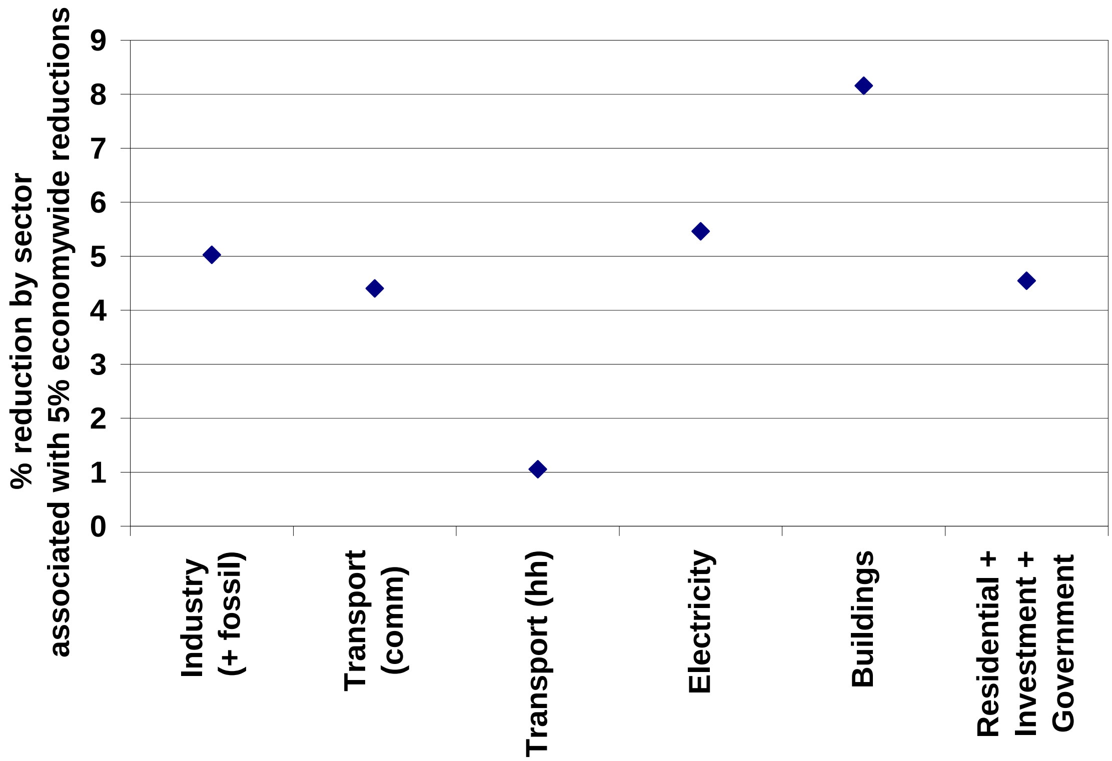


Figure 8: Sectoral Reductions Associated with 5% Economywide Policy



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