EMF Report 25
Volume I
March 2011

Energy Efficiency and Climate Change Mitigation

Energy Modeling Forum
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Stanford, CA 94305-4121

Preface

The Energy Modeling Forum (EMF) was established in 1976 at Stanford University to provide a structural framework within which energy experts, analysts, and policymakers could meet to improve their understanding of critical energy problems. The twenty-fifth EMF study, "Energy Efficiency and Climate Change Mitigation," was conducted by a working group comprised of leading international energy analysts and decisionmakers from government, private companies, universities, and research and consulting organizations. The EMF 25 working group met several times and held many extensive discussions over the 2009-2010 period to identify key issues and analyze the detailed results.

This report summarizes the working group's discussions of the modeling results on the role of energy efficiency improvements in global climate change mitigation strategies. The working group is planning an additional volume of individually contributed papers on most of the models in the study. This additional report will appear as a special issue of the *Energy Journal* later this year. Inquiries about the study should be directed to the Energy Modeling Forum, Huang Engineering Center, Stanford University, 475 Via Ortega, Stanford, CA 94305-4121, USA (telephone: (650) 723-0645; Fax: (650) 725-5362). Our web site address is: *http://www.stanford.edu/group/EMF*.

We would like to acknowledge the different modeling teams that participated in the study. Their willingness to simulate the different cases and to discuss their results in detail contributed significantly to an excellent study.

This volume reports the findings of the EMF working group. It does not necessarily represent the views of Stanford University, members of the Senior Advisory Panel, any reviewers, or any organizations participating in the study or providing financial support.

EMF Sponsorship

Financial support from a wide range of affiliated and sponsoring organizations allows the Forum to conduct broad-based and non-partisan studies. During the period covering the study, the Forum gratefully acknowledges the support for its various studies from the following organizations:

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Energy Efficiency and Climate Change Mitigation

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Study Highlights

This report summarizes the major findings from an Energy Modeling Forum study on how energy-efficiency opportunities will shape future fuel and power demand in the United States over the next several decades. It also incorporates supporting information from France, Japan and Switzerland. The working group compared the results from 10 different energy-economy models from seven scenarios where all teams tried to use common assumptions for key policy and economic factors. The major findings are:

- The US economy will use energy and emit carbon emissions much less intensively (with declining heat content or emissions per dollar of output) in future years than in the past.
- The current study expects future trends without any policy changes will already incorporate many promising energy-efficiency opportunities that are often included in estimates of the economic potential for energy savings.
- Even with these adjustments, however, total emissions without a concerted policy action will hold relatively steady over time and these trends will be contrary to goals of policymakers who want a major transition towards declining emissions in the long run.
- The study considered a range of policies that could reduce energy use and total emissions: carbon pricing through a tax on emissions, mandated standards requiring more efficient appliances, buildings and automobiles, and subsidies or reductions in the upfront costs of new more energy-efficient equipment.
- Although energy use and emissions can be reduced even more with new programs, the improvements in energy efficiency in this study are more modest than estimated by other groups.
- The principal reasons for lower energy demand reductions in this study are attributable to behavioral rather than technical reasons. Other studies have focused on the economic or cost-effective potential based solely upon technology performances and costs. The current study extends the analysis to include the rate of adoption of these new technology options as well.
- The energy and emissions trends in models with explicit technology options for energy efficiency are surprisingly similar to the trends in models that focused more directly on market responses and economic equilibrium. These comments apply to the models as a group and do not describe all the models within a group. This finding suggests that how a model represents technology options does not necessarily determine whether its projections will be higher or lower than other models. Other structural model features, parameter values and assumptions about key conditioning factors appear to be primary contributors to differences in model outcomes.
- Models differed on whether carbon pricing or mandates were more effective. How consumers spent their energy savings from standards was an important issue. Standards were a less effective policy when consumers chose other goods, services and activities that required more energy use. This offsetting effect could include more purchases of the more energy-efficient activity (the direct “rebound” effect) as well as other activities requiring energy use.
- Carbon taxes and subsidies for new equipment in most models appear to be additive policy measures that do not detract from each other when combined into one package. Carbon taxes and standards may be more redundant in some models, implying that combining them may reduce their effect to some extent. This issue warrants more analysis, however, because the modeling community is only beginning to evaluate this issue.
- Although the modeling community is increasingly striving for frameworks that combine richness in technology coverage with realism in market behavioral responses, improvements are required to make the models more useful for policymaking. Many improvements require additional research on the behavior of would-be adopters of new technologies to both economic conditions and policy programs.

Introduction

The US economy grew almost six times faster than delivered energy since 1972, during a period when the standard of living improved dramatically within the United States.[1] These trends have underscored the U.S. success in improving both life styles and its environment. Success at this aggregate level is also matched at the household and firm level where many products and processes (e.g., advancements in solid-state lighting) remain waiting to be adopted.

Everyday new best practices in energy use are being adopted throughout the U.S. economy. This process will continue, perhaps stimulated further by high energy prices and government policies promoting and mandating these improvements. A central issue in energy policy is whether new policies focused on improving end-use energy efficiency will be sufficient to curtail the economy's greenhouse gas emissions sufficiently.

This report begins by describing briefly the scenarios and models included in this study. It then discusses the U.S. carbon and energy trends for the group of models, followed by the response of total delivered energy consumption by model. Central to these estimates are the models' treatment of costs, which are discussed next. Following sections include discussions of the impact of a carbon tax by model, estimates of an energy-efficiency cost curve by end-use sector, and a review of different policy options including a carbon tax, standards and equipment subsidies. A penultimate section compares carbon dioxides trends by model type and the concluding section recommends several model improvements that would make these systems more valuable for policymakers.

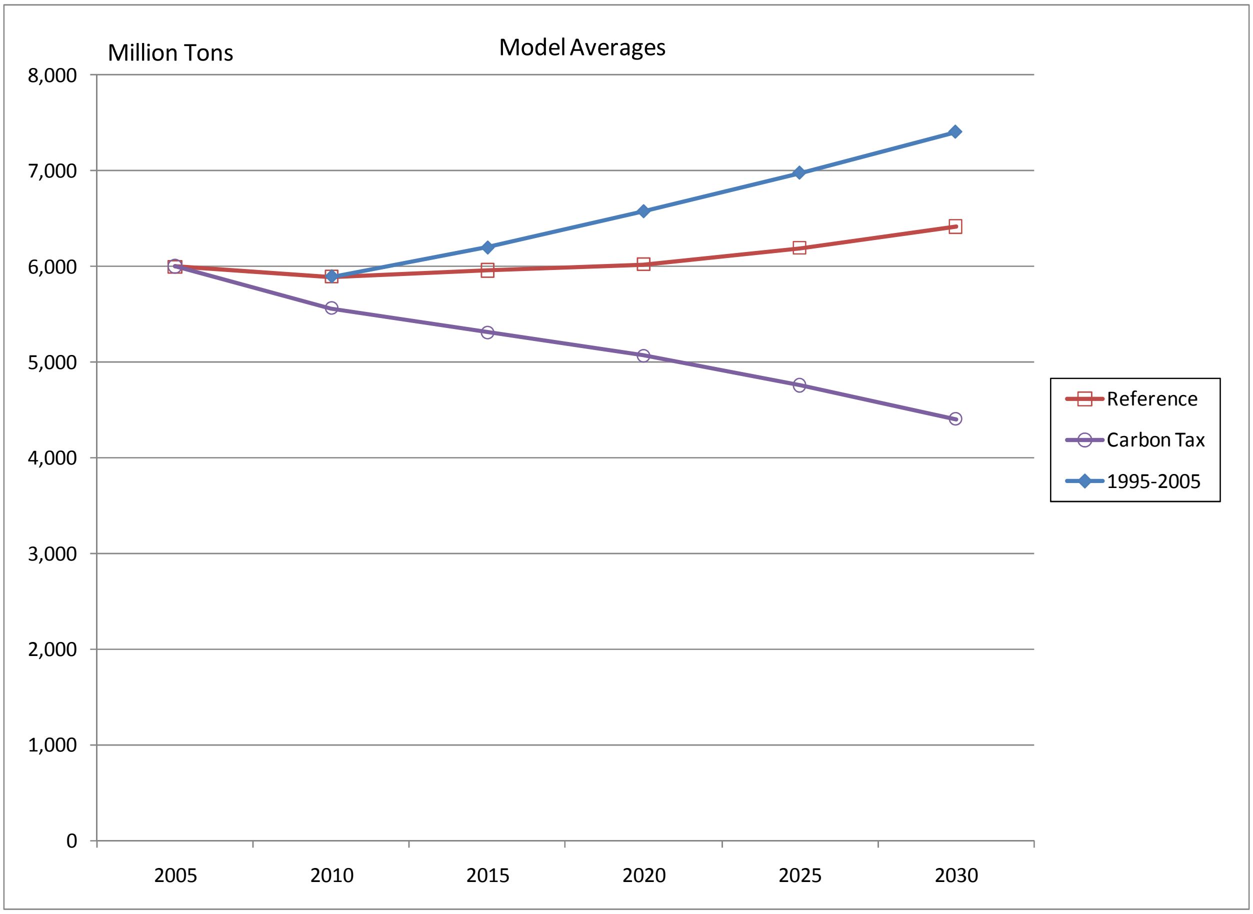
Study Organization

This report focuses on cost-effective reductions in energy demand based upon projections provided by 10 models for the United States and one model each for France, Japan and Switzerland.[2] Whenever possible, the modeling teams have used similar assumptions for representing seven different scenarios. This calibration provided the opportunity to compare the model structures to understand broad conclusions about how they as a group of models help policymakers understand complex issues like energy efficiency.

The study considers the effects of several different policies: a carbon tax that rises over the two decades from $30 to $80 per tonne carbon dioxide emissions, a comparable tax on the heat content (rather than the carbon content) of all delivered energy, a subsidy for the most energy-efficient equipment in all but the industrial sector, and a standard applied to new equipment used in households and by the commercial sector. Additionally, several cases combined the carbon tax with either the equipment subsidy or the new equipment standards.

All projections in this study are based upon a diverse set of energy-economy models that have been used for analyzing the impacts of climate-change policies. Some systems emphasize the economic relationship between markets (sometimes called "general equilibrium models") with limited technology detail for the end-use sectors. Many other models in this study choose new technologies based upon their relative costs. Rather than assuming that consumers always purchase the least-cost options, these systems use adoption rates that are more consistent with people's actual behavior. Choices about technologies within one market will also affect other energy markets in these systems and hence the relative opportunities for all technologies used throughout the economy. These "linked" or "hybrid" systems provide a degree of integration that is absent from many "bottom-up" evaluations that consider end-use decisions in isolation from each other. These models are discussed in a little more depth later in the report.

Figure 1. **U.S. CO2 Emissions With and Without Carbon Tax**



Carbon and Energy Trends: An Overview

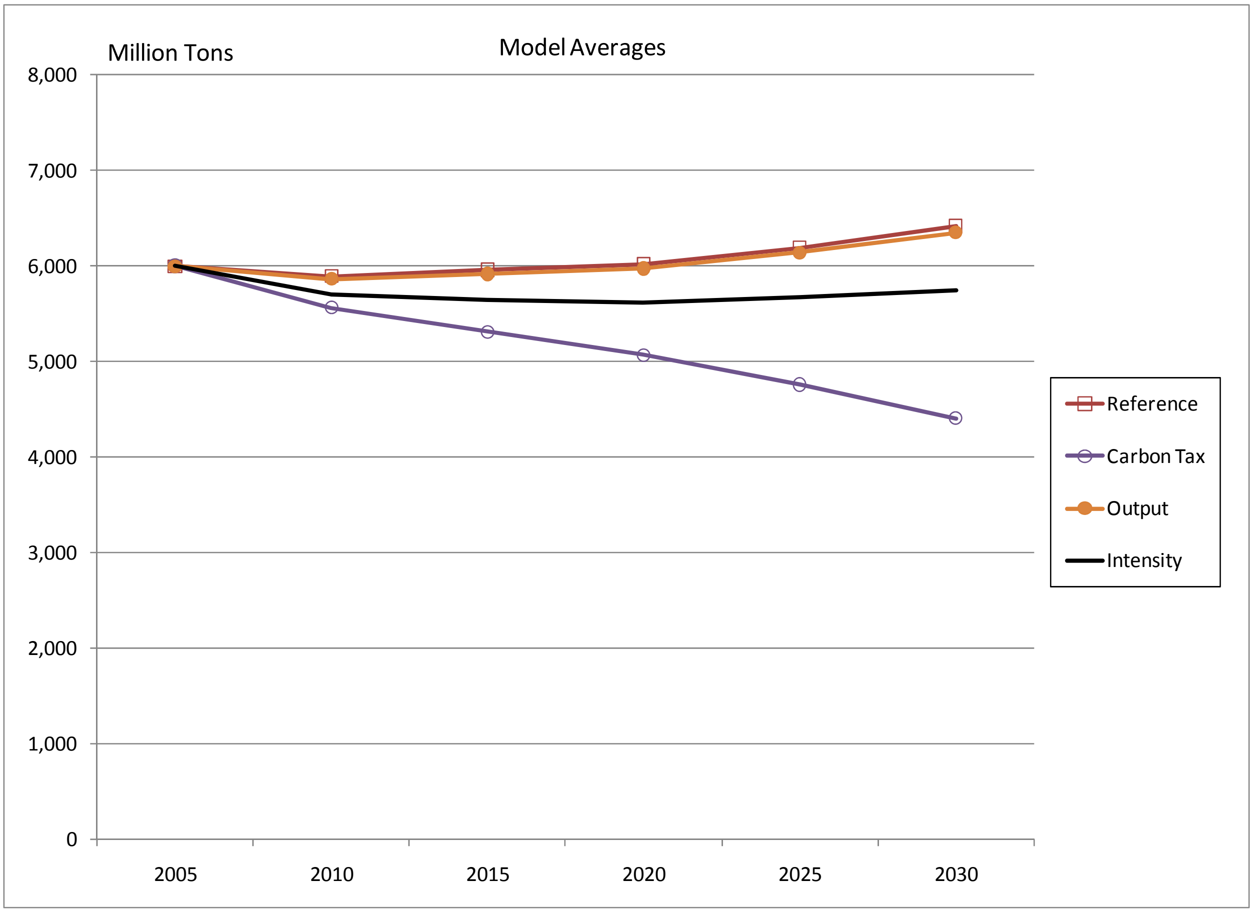
Although it is important to explore differences between model results, it is also useful to address what the models collectively reveal about critical topics. A good indicator of the collective trends in these results is the average estimate from all U.S. models. Later sections will explore some key differences between model results.

Figure 1 displays U.S. carbon dioxide emissions (including electricity losses) in the study's reference case (the middle trend labeled as "reference") and an assumed carbon tax case (the lower trend labeled as "carbon tax"). Since the opportunities for energy efficiency are greatest over the next few decades, the study emphasizes the results through 2030. Although some models have some interesting results beyond that year, only about a half of the models reported for that longer period, thus making a comparison less meaningful. For consistency across models, scenario results are reported for every five years. As a result, the trends and impacts for energy, emissions and economic activity should be viewed as long-term adjustments without any business-cycle fluctuations.

The reference conditions for each model are based upon the oil price and U.S. economic growth paths provided by the 2009 Annual Energy Outlook. In addition, no new regulatory policies were allowed after 2009. For the most part, the modeling groups have been able to standardize reasonably closely to these trends, even in situations where they derive them internally within their systems. Even with these modest efforts to standardize key input assumptions, the models varied sharply on such concepts as non-petroleum fuel prices and the costs and availability of electricity generation sources. These differences are reflected in the range of results by model shown later in this report.

In the projections, reference U.S. carbon dioxide emissions remain relatively flat over the 2005-2020 period and grow slightly between 2020 and 2030. The flatness of the carbon trend for the mature U.S. economy is noteworthy because both population and the economy are growing over this period. Even without a focused climate policy, the modeling teams expect significant reductions in carbon emissions per dollar of gross domestic product (GDP), or its carbon intensity. The projections assume that the economy begins growing again by 2010, attaining a growth rate of 2.7 percent per year through 2030. Higher energy prices and recent regulatory and policy changes in the early 2000's, followed by energy prices remaining high over the next two decades, reinforce this moderating trend in future carbon dioxide emissions. This trend dips sharply lower than the 1995-2005 historical trend for CO2 emissions shown by the top line. This historical trend for CO2 emissions has been adjusted downward from its 1995-2005 rate of increase to reflect the slightly slower economic growth in the projections relative to the 1995-2005 period (3.3 percent per year).

Figure 2. Decomposition of Carbon Tax Effect



After a carbon tax of $30 (2008 dollars) per tonne of carbon dioxide is imposed in 2010 in the second case, emissions decline throughout the period from their 2005 level. After 2010, the inflation-adjusted level of the tax increases by 5 percent each year, reaching a level of about $80 per tonne by 2030. Revenues from the tax are collected by the government but are immediately returned back to firms and households without favoring any goods and services, particular groups, or government programs. Firms and households determine how to spend the revenues generated by the tax. By 2030, carbon dioxide emissions fall below reference levels by 2012 million tonnes, or more than 30 percent, after the carbon tax has been implemented.

A number of factors contribute to this reduction in emissions due to the carbon tax. Figure 2 decomposes the difference between the reference and carbon tax trends into three components due to decreases in: (1) aggregate economic output (GDP), (2) energy intensity including structural economic shifts, and (3) the carbon intensity of the economy's energy supply. For example, the "output" line in the second figure shows the decline in emissions due to a lower long-term path for inflation-adjusted gross domestic product, holding constant energy intensity and the carbon intensity of the energy supply. The reference and output trends essentially overlap each other given the scale of this chart, because the carbon tax reduces aggregate economic output very modestly over the longer run, even in those models that allow a direct effect of the tax on economic growth.

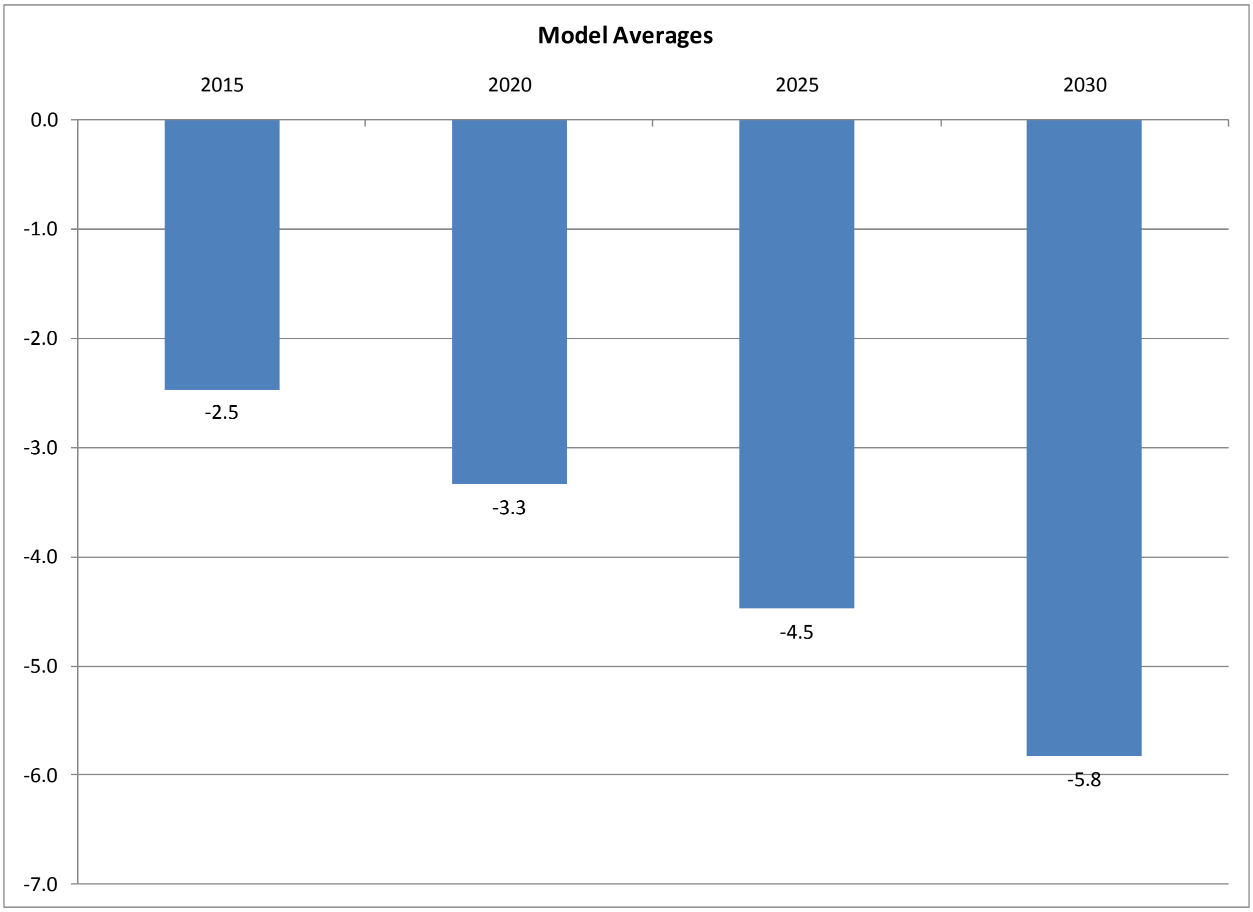
Improvements in energy efficiency play a role in reducing future U.S. greenhouse gases in this study but these improvements must be reinforced by other responses in order to achieve a significant reduction. The "intensity" line shows the declines in emissions due to lower energy intensity, holding constant aggregate output and the carbon intensity of the energy supply. Specifically, the intensity effect is the difference between the "output" and "intensity" trends in this figure. This line departs more noticeably from the "output" line, indicating that the projections expect continued energy-efficient improvements as well as possibly energy service reductions (e.g. driving less) that are stimulated by the carbon tax. However, it remains well above the carbon emissions in the carbon tax case, indicating that the output and energy intensity effects account for only part of the emissions reductions. The carbon intensity of the fuel supply, particularly within electricity generation, remains an important remaining effect in these results. Efforts to constrain energy intensity alone will miss an important avenue for reducing carbon emissions in the U.S. economy.

Impacts on Delivered Energy

Comparing these two cases also provides relevant information on additional energy efficiency improvements that are cost effective when carbon dioxide is priced initially at $30 per tonne and rises to $80 by 2030. Figure 3 shows the average reduction in U.S. delivered energy below reference levels for key years as the carbon tax makes more energy-efficiency options profitable. All models disaggregating delivered U.S. energy use by major sector (residential, commercial, industrial and transportation) are included in this group of models. As new technologies gradually penetrate the market, the effect grows continuously from 2.5 quadrillion Btus in 2015 to 5.8 quadrillion Btus in 2030.

Figure 4 shows the reductions in aggregate U.S. delivered energy below reference levels by individual models for all sectors except the transportation sector. By 2020, all demand reductions due to the carbon tax are less than 4 quadrillion Btus. By contrast, estimates from the McKinsey and Company study on energy-efficiency improvements in the residential, commercial and industrial sectors are strikingly greater for similar carbon costs. The latter study applies a "bottom-up" technology approach for estimating the economic *potential* for energy efficiency.[3] These options save 9.1 quadrillion Btus when considering options that are cost effective at no additional carbon price (the light bar). They save 10.3 quadrillion Btus when options that are cost effective at $50 per tonne are also considered. Note that $50 per tonne lies within the range used by this EMF study, where the tax begins at $30 in 2010 and rises to $80 by 2030. Although these potential energy efficiency options are based upon slightly higher reference energy trends in the 2008 rather than 2009 Annual Energy Outlook, the differences between the McKinsey and EMF model-based estimates appears significant.

Figure 3. Reductions in U.S. Delivered Energy Consumption Achievable with the Carbon Tax

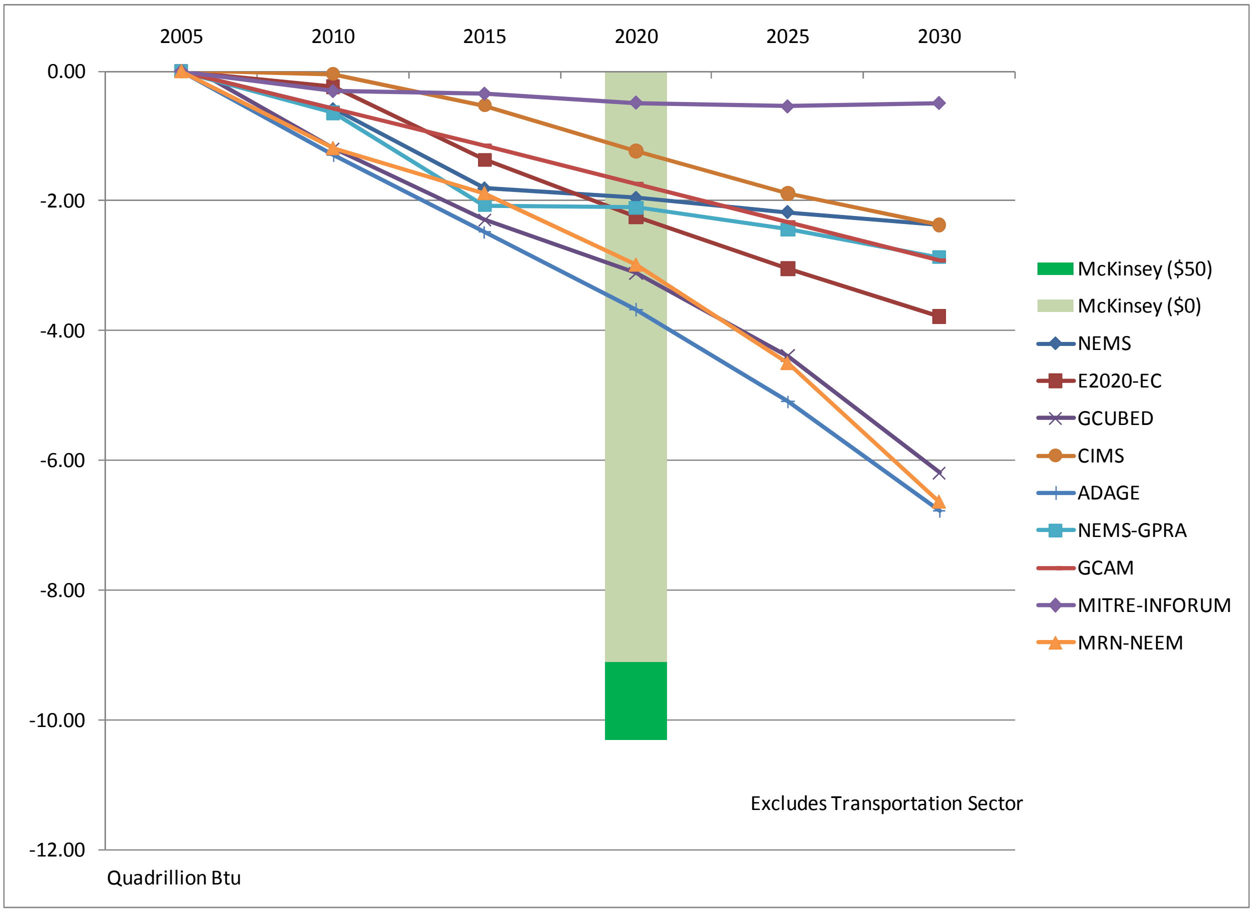


Before considering the different methodologies used by the EMF model projections and the potential energy estimates, two important observations are noticeable from this figure. First, the potential energy estimates are not only larger, but they are mostly available at no additional cost to the economy, as indicated by the lighter bar. And second, the additional effect of imposing a $50 per tonne price for carbon dioxide is relatively small, as indicated by the darker bar.

Out-of-Pocket Expenses Understate Opportunity Costs

The principal difference between the energy-economy models and potential energy studies lies in how they represent the behavior of individual investors and adopters of new technologies.[4] The potential energy approach focuses on the *optimal* energy efficiency achievable under *ideal* conditions given a specific slate of available technologies. Even if they operate with the same slate of available technologies, the EMF modeling approaches focus on what they consider to be the *most likely* energy efficiency response of investors who want other attributes besides energy efficiency and who confront more barriers and costs than under ideal conditions. The obvious resolution would be to simply remove the barriers and costs in real-time markets to make conditions appear more like those under ideal or optimal conditions. Much of the controversy between technology optimism and market realism focuses on the costs of removing these barriers.

Figure 4. Energy Demand Reductions Achievable for Similar Carbon Prices

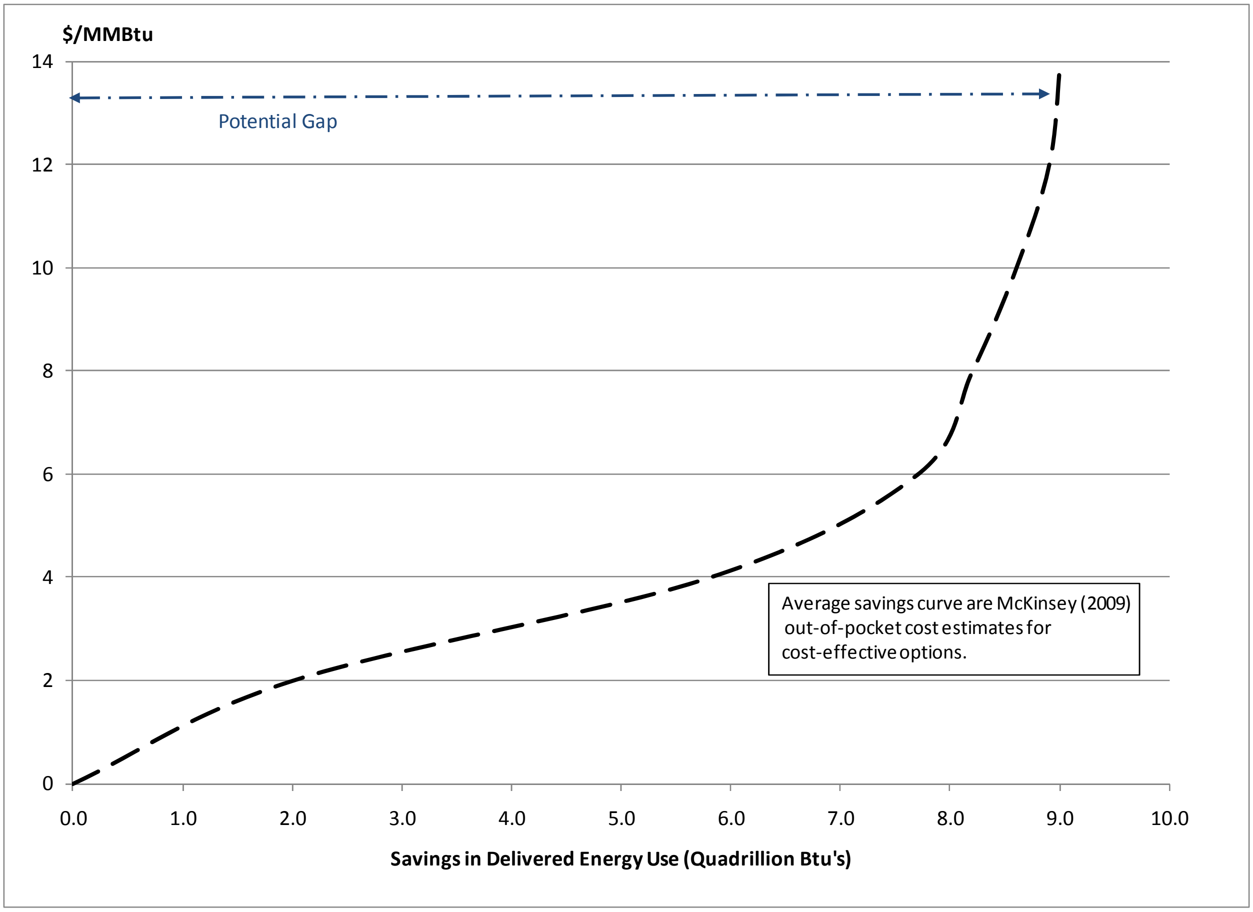


Bridging this methodological gap requires a better understanding of what these barriers are and their relative importance. One approach for exploring this issue would be to begin with the energy-efficiency cost curve provided by a potential energy study and make adjustments for various costs to observe their relative importance. One could then compare the two cost curves to understand the relative importance of these additional costs and adjustments.

In a study focused on energy efficiency, McKinsey and Company developed a total cost curve for all energy-efficiency investments that would produce more net energy savings than the initial cost of the equipment. Their criterion of negative net costs for the investor is introduced in Figure 5 by noting that the total costs are all below their estimate of the avoided costs of $13.70 per million Btu in their reference case (based upon the 2008 Annual Energy Outlook including the economic stimulus package that was produced by the US Energy Information

Administration). Although this cost curve for aggregate energy should be considered as illustrative, a comprehensive evaluation of these opportunities requires that the specific avoided cost for each fuel type be considered. This cost curve shows the economic potential for energy-efficiency improvement, but it ignores the likely rate of adoption. It represents an "out-of-pocket expense" curve because it focuses exclusively on the direct equipment and operating costs and ignores any indirect costs that are important for many decisions made in the economy, particularly when people are considering new technologies that have yet to prove themselves. The chart shows that fully employing all these options could potentially save 9.1 quadrillion Btu annually by 2020.

Figure 5. Energy Efficiency Cost Curve (Based Upon Potential Energy Estimates)



The models in this EMF study show that a smaller set of these options will be adopted. Even if an energy-economy model and an economic potential study use the same technology assumptions, the estimates for achieved energy efficiency may be considerably smaller in the energy-economy model, often because they include behavioral assumptions that make it more difficult for new technologies to penetrate the market.

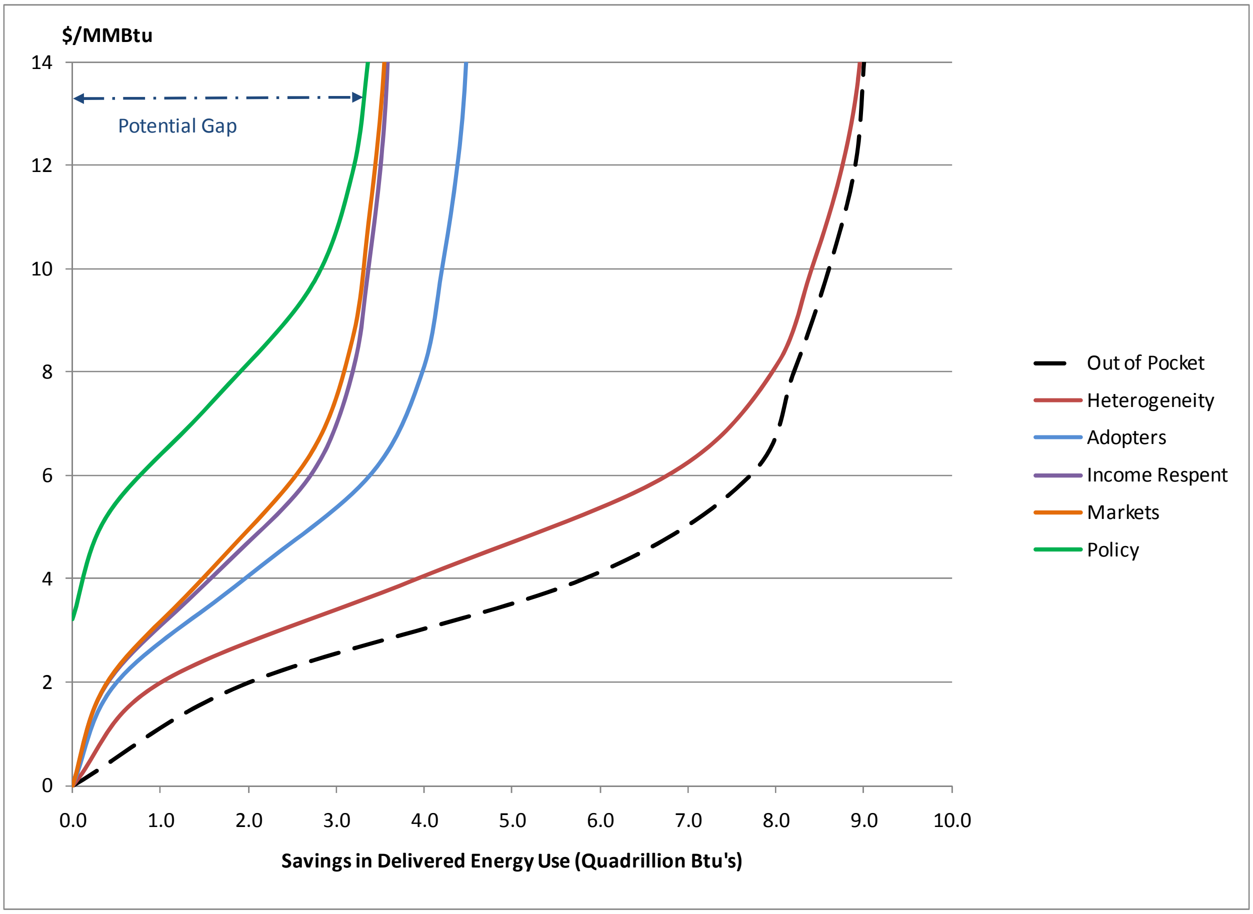
Figure 6 illustrates the difference between the estimates after adjustments are made for market rather than ideal conditions.[5] It shows the effect of including some important behavioral and policy costs into the energy efficiency cost curve in order to represent the broader cost concept represented in many of the models. Often, these costs are incorporated simply by an assumption that people appear to place little value on future energy savings. Instead, this figure assumes that investors are using the relatively low, risk-free rate of 7 percent for discounting future energy savings. The adjusted curve shows that much of the apparently high observed rate for discounting future energy savings may actually reflect higher indirect costs that are excluded from what the consumer pays for equipment and energy. All cost curves assume that the technology performance and costs are the same as in the potential energy analysis. Adjustments are made conservatively, often taking lower values to minimize these effects. It should be emphasized that models will differ about which effects they incorporate and also how important they are.

Below are listed several adjustments to the original economic potential curves that will move those estimates closer to those representing achievable energy efficiency improvements.

1. A “flaw of averages” exists in potential energy studies when everybody is assumed to adopt based upon the average investment costs for the whole group. For example, home owners in San Francisco use much less energy for air conditioning than home owners in California’s central valley. Although the two homeowners may pay similar amounts for a more efficient air conditioner, the San Francisco one will have a much smaller benefit due to its substantially lower cooling requirements. As a result, its costs per unit of saved energy will be higher than the average costs for all customers in the group. No such investment bias exists for the low-cost customer, who will continue to invest because its costs per unit of saved energy will be less than average costs.
2. Adoption of even the best new technologies is seldom universal. Furthermore, the diffusion often takes many decades. The McKinsey study focuses on improvements that are potentially cost effective (the *economic potential*) but does not discuss the diffusion of new technologies. Moreover, energy consumers reach this potential within the next ten years. The following chart assumes that 20 percent of the energy consumers who could buy the more energy-efficient options in the “out-of-pocket” cost group actually accept the new technology within the next 10 years. This assumption for constructing the “adopters” line remains quite optimistic for a relatively short period.
3. Households may use their furnaces or vehicles more intensively because the equipment is cheaper to operate when they are more energy efficient (the so-called “rebound” effect). More importantly, they will use their energy savings on these activities to buy other goods that will use energy. The “income respent” line shows the combined effect of both responses by assuming that 20 percent of the initial energy savings are lost.
4. When consumers invest in energy efficiency, they set off a number of effects that are transmitted through many different energy markets. For example, major demand reductions will reduce energy prices in the aggregate and make each individual’s efficiency investments less profitable (the “markets” line). This effect is the “fallacy of composition” that occurs when collective decisions by many investors significantly reduce the profitability of the original opportunity for each investor.
5. Many government programs for setting standards and monitoring efficiency investments are costly to implement (the “policy” line). Although some policies are inexpensive to implement, the utility administrative program costs (excluding rebates)

> have been estimated at 1.1 cents per kilowatt hour. The figure incorporates policy costs for all energy-efficient improvements with this average estimate, although actual administrative costs for any individual policy could be above or below this level.

Figure 6. Energy Efficiency Cost Curve After Adjustments (for 2020)



The cost curves in Figure 6 have been added incrementally to these out-of-pocket expenses to form new energy-efficiency cost curves that move leftward with each adjustment. Not all experts agree on the relative size of these effects, but all effects reduce the size of profitable investments from the economic potential. The cost curves are illustrative and may not include all adjustments that might be appropriate. For example, many new technologies are riskier with a greater failure rate, which can make adoption of capital-intensive options very expensive because energy savings disappear completely once the equipment has failed. Despite this limitation, the stacked cost curves emphasize that behavioral assumptions for adopting new technologies can be very critical.

When these indirect costs are aggregated, the cost curves become higher and the energy-efficiency gap (the area left of the adjusted cost curve) smaller. How much the curve shifts will depend upon critical assumptions about behavior and institutions that can vary across different experts. Even if the models in this study used the same technology cost curves as a potential energy study, their full costs would be higher than the direct “out-of-pocket” costs for the behavioral, institutional and policy reasons identified above. Accordingly, cost-effective energy efficiency would be less.

If the government were to adopt energy-efficiency programs that were relatively expensive to implement and monitor, the larger policy component would shift the cost curve further to the left. These conditions would reduce the potential gap for achieving energy efficiency that was cost effective. If research and government agencies could identify those programs that imposed less costs, these opportunities would expand. Identifying how people respond to different program provisions and the administrative costs for each program is a high-priority issue for better public decision making in this area.

A set of conditions – called market failures – could prevent the gap in potential energy efficiency from closing completely. These factors are discussed in greater detail in the background material at the end of this report. These obstacles cannot be overcome by simply pricing energy higher, because the institutions do not exist to allow consumers to see the appropriate incentives. These types of market failures are very different from another set of market failures that exist because society simply does not place a value on the damages caused by greenhouse gas emissions. These problems can be resolved with a carbon tax or cap-and-trade program, provided consumers and producers respond appropriately to energy and carbon price changes. This second market failure is evaluated in greater depth in the next section, where more emphasis is placed on the results by model.

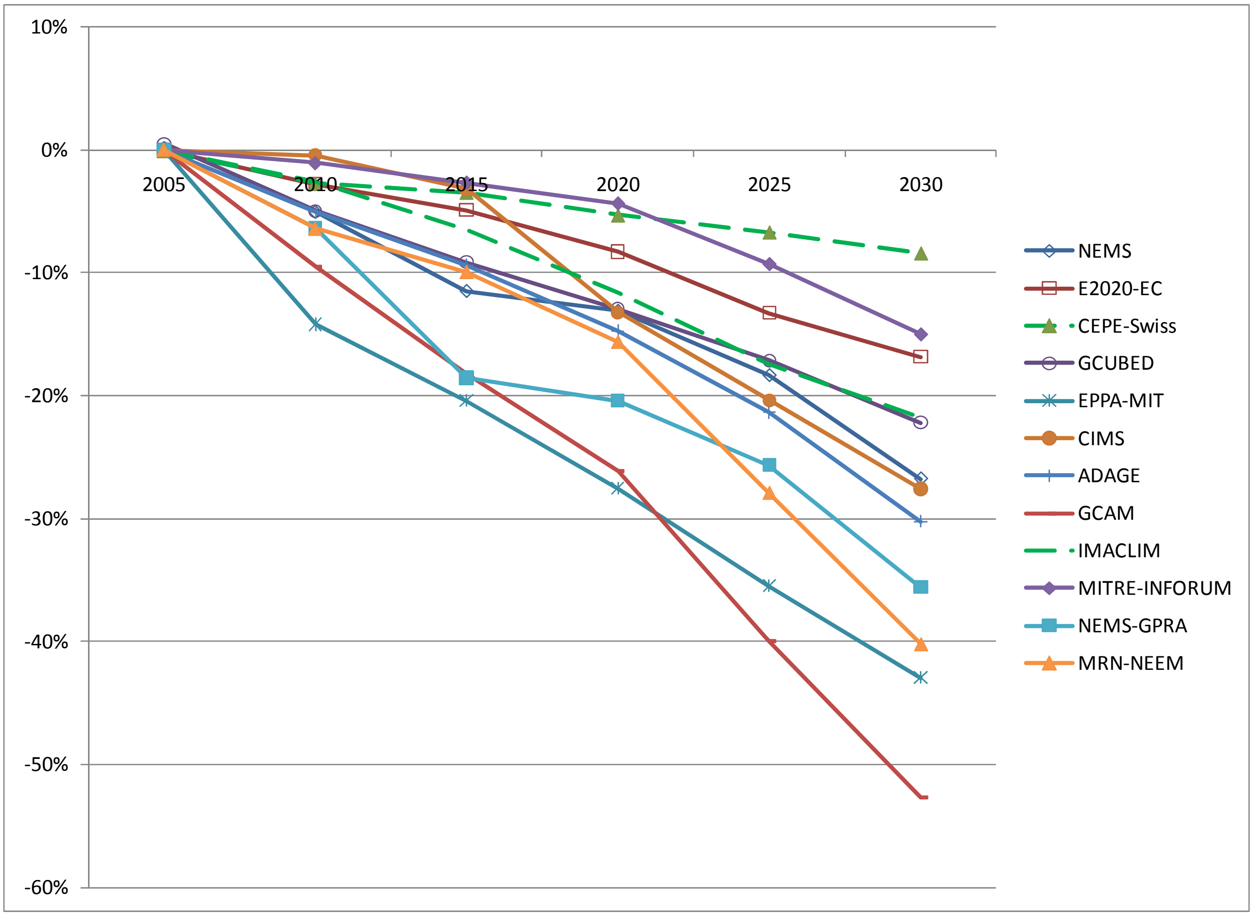
Major Effects of a Carbon Tax

Two ways to provide incentives for reducing carbon dioxide emissions are a "cap-and-trade" program for allocating carbon dioxide emissions and a carbon tax. Although they are implemented differently, the two approaches have many similarities. A carbon tax was chosen to avoid any potential confusion in what modeling teams should assume for offsets, exemptions and other provisions that often play important roles in carbon-trading schemes. The same tax rate is applied to each activity and no exceptions are allowed for any sectors in these simulations. In this sense, the carbon tax represents the highest direct costs of any observed reduction in carbon emissions. If economically motivated, energy users will reduce their carbon emissions only if the abatement costs are equal to or less than the tax level. Otherwise, they pay the tax.

A carbon tax raises the cost of fossil fuels relative to carbon-free energy sources. As energy prices in different fuel markets rise as a result of the tax, consumers will shift their consumption patterns by reducing total energy use and by shifting to energy sources whose prices do not rise as much. Generators and energy suppliers will also adjust their decisions, resulting in a set of energy prices and quantities that are likely to be much different than without the tax.

Carbon dioxide emissions in these projections decline over the next several decades with the carbon tax. Figure 7 reveals a wide range in the response of carbon dioxide emissions (including those generated from electricity) to this carbon tax. Model results for foreign countries are included as dashed lines in order to emphasize that the energy, regulatory and economic conditions in different geographical settings may be important conditioning factors in this response. Excluding the two foreign models, the carbon tax reduces carbon dioxide emissions by 15 to 53 percent by 2030, if U.S. policymakers applied a tax of $30 per tonne of carbon dioxide in 2010 and escalated it by 5% each year. As will be shown, this range reflects much more than differences in the energy-efficiency improvements adopted by each model.

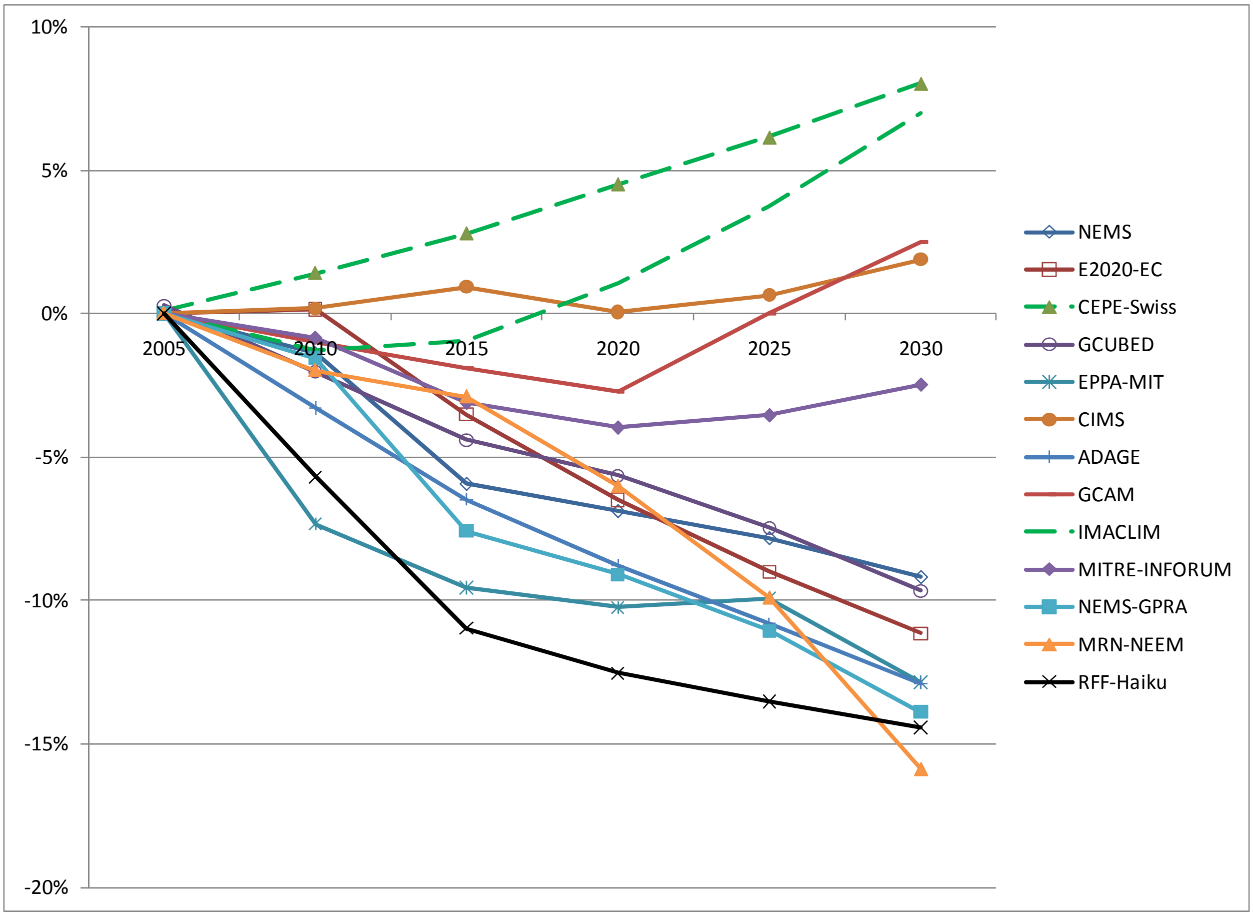
Figure 7. Carbon Tax Effect on CO2 Emissions, including Electricity (%)



A major difference happens within the electric generation system. If regional electricity prices are based upon average costs, generation costs will rise according to the generation mix in that region. More carbon-free sources will prevent electricity prices from rising as much, as long as these more capital intensive options remain cost effective under the carbon tax conditions. If regional electricity prices are instead based upon the additional costs of providing more power rather than the average cost, generation costs will rise more if the incremental power is provided from coal rather than nuclear, solar, wind or other generation sources that emit less carbon. Whether average-cost pricing applies to the electricity sector and what the prospects are for nuclear power and carbon capture and sequestration can be very important determinants of the carbon tax's impact.

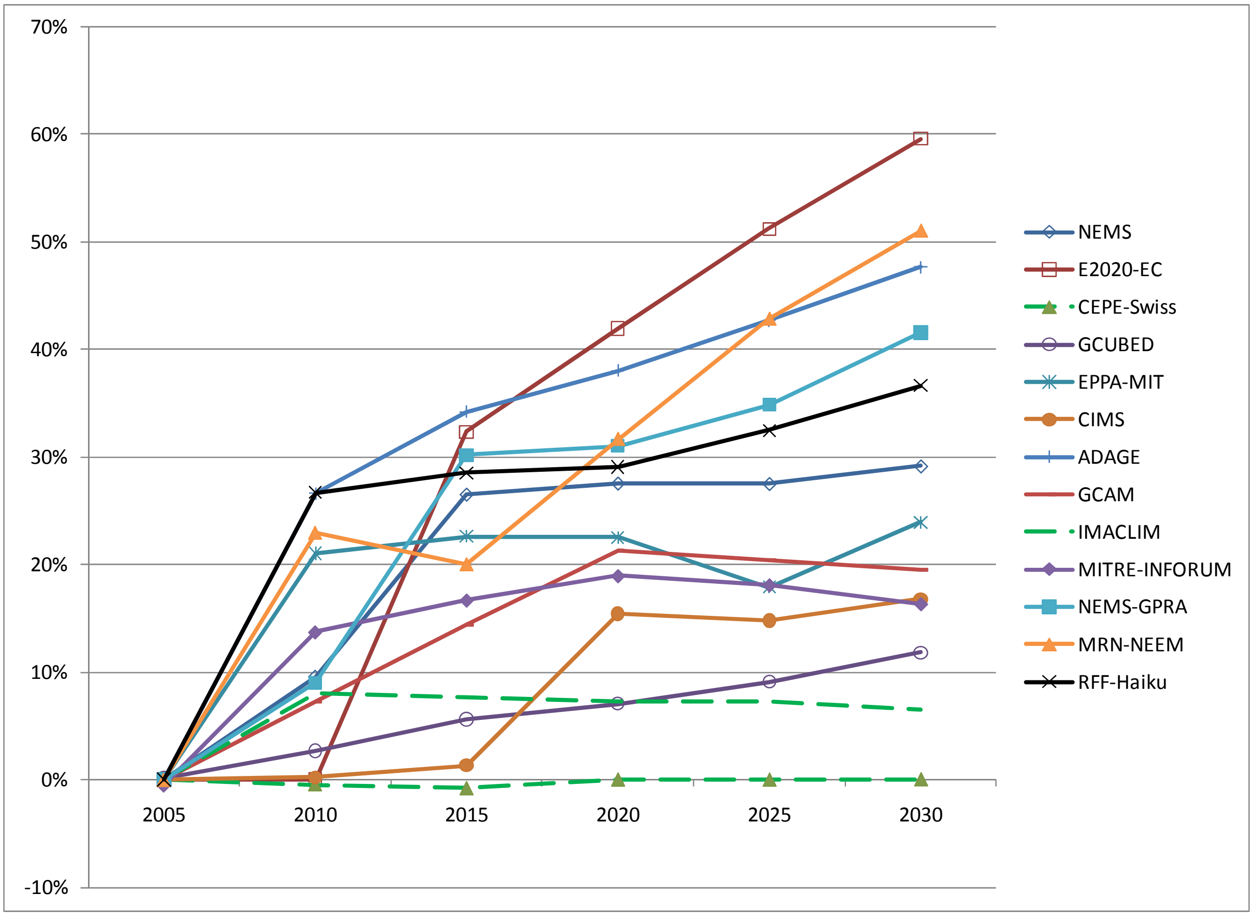
The carbon tax effects on total electricity markets are much milder in CEPE and IMACLIM, because electricity in these two European countries becomes more competitive with other direct use of fossil fuels after the carbon tax. Existing nuclear and hydropower generation in Switzerland and nuclear generation in France tend to insulate electricity prices from the carbon tax as revealed by the very mild responses in electricity prices due to the carbon tax in Figure 9. Electricity consumption rises in these two countries (models) in Figure 8, while many of the other electricity consumption results for the United States decline often by 10-15 percent by 2030.

Figure 8. Carbon Tax Effect on Total Electricity Sales (%)



Substitution between direct energy use and electricity is also an important factor explaining the effects on electricity consumption for the U.S. models. A separate analysis pooled the responses from all models into one large data set or meta-system.[6] This approach focused on what all the models as a group revealed about the response of electricity consumption to electricity prices, natural gas prices and commercial sector floor space. As an example, commercial sector electricity consumption over a 20-year period declined 0.53 percent for each one percent increase in electricity prices and increased 0.27 for each one percent increase in natural gas prices. Thus, electricity consumption in the commercial sector would decline 0.26 percent if both electricity and natural gas prices rose by one percent.

Figure 9. Carbon Tax Effect on Electricity Prices (%)



Energy-Efficiency Cost Curves by Sector

The carbon tax simulations provide important insights into the energy-efficiency cost curves by energy end-use sectors in the models. In each case energy intensity is defined as the total delivered energy (quadrillion Btu) divided by activity in that sector. As the carbon tax rises from $30 per tonne in 2010 to about $80 per tonne in 2030, energy intensity declines from its reference path. These adjustments occur on top of energy intensity reductions that are already happening in the reference scenario.

In the top panel of Figure 10, residential energy intensity between 2005 and 2030 declines by 13.0 percent for the median result in the reference case.[7] The total median decline with the carbon tax is 19.6 percent below the 2005 level by 2030. Thus, the carbon tax reduces the residential energy intensity by 6.6 percent below the reference level in 2030. In this sector, intensity is measured as total delivered energy (quadrillion BTU) divided by total households.

The bottom panel of Figure 10 shows that many of the individual models indicate that the carbon tax reduces residential energy intensity by 5 to 10 percent below reference levels. An important reason for this modest additional decline is that high energy prices and aggressive policy actions since 2003 have already pushed households strongly towards new energy-efficient options.

Figure 10. Residential Energy Intensity (%) in Response to Carbon Tax

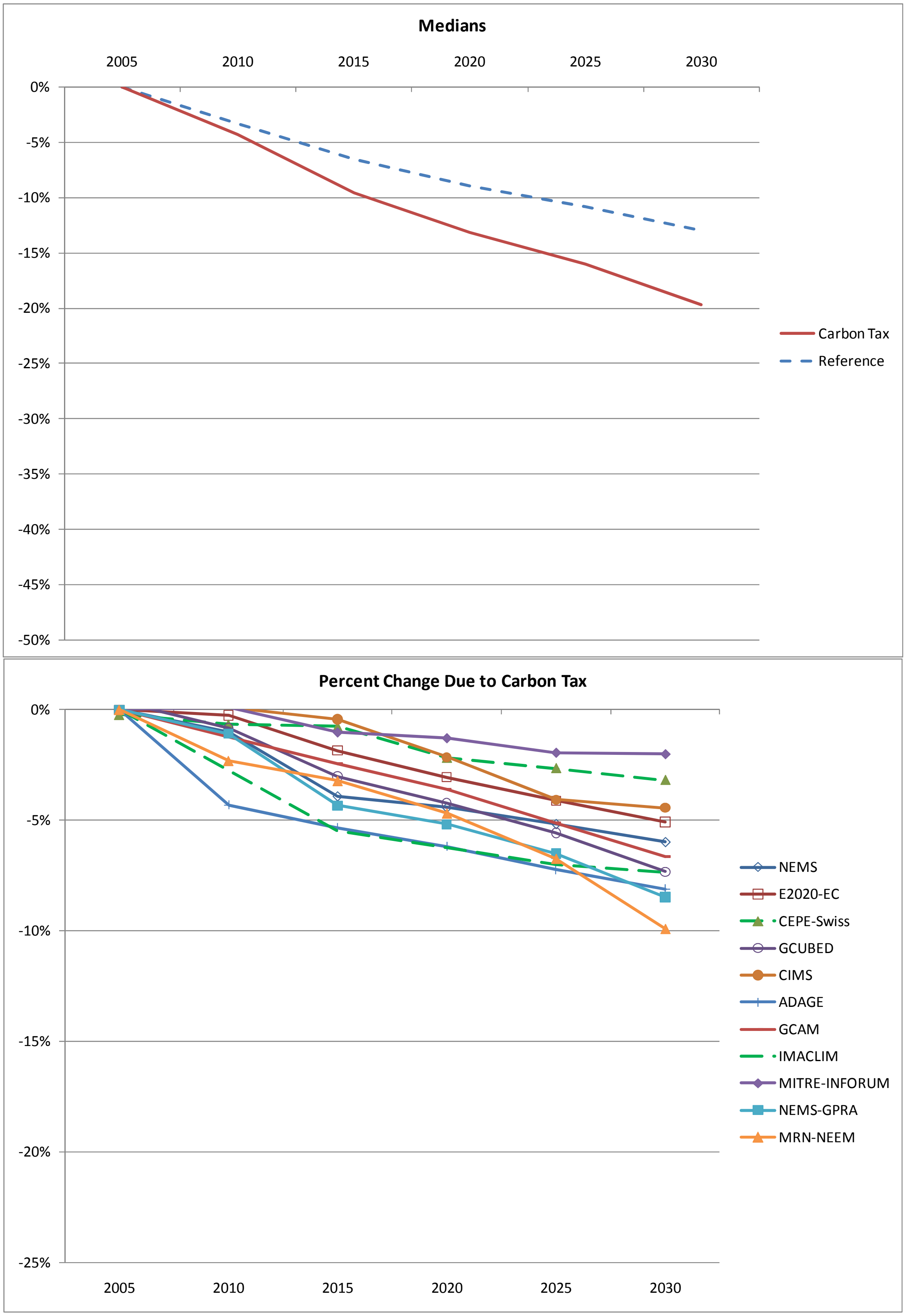


Figure 11 duplicates the same two panels for the commercial end-use sector.[8] Commercial energy intensity between 2005 and 2030 declines by 5.5 percent for the median result in the reference case. It declines further with the carbon tax, reaching 11.5 percent below the 2005 level in 2030. Thus, the carbon tax reduces the commercial energy intensity by 6.0 percent below the reference case in 2030. In this sector, intensity is measured as total delivered energy (quadrillion BTU) divided by total square footage of commercial floorspace.

Many models in the lower panel show a further decline of 5 to 10 percent due to the carbon tax. The tax does not change commercial floor space very much. As with the residential sector, an important reason for this modest intensity decline is that new energy-efficient options enter the market even prior to the carbon tax (in the reference case).

In Figure 12, industrial energy intensity between 2005 and 2030 declines by 27.1 percent for the median result in the reference case.[9] The deep recession significantly influences the intensity trend in 2010, as output declines are not matched by energy demand reductions. The longer-term trend in total industrial energy intensity reflects the substantial post-1995 growth in the computer and other less-energy-intensive industries that are expected to continue in the future. In this sector, intensity is measured as total delivered energy (quadrillion BTU) divided by total industrial sector shipments. This activity measure does not allow one to separate the effect of changes in the composition of industrial activity within this sector from energy-efficiency improvements within an industry. There was insufficient standardization across the models in their reporting of industry-specific activity.

On top of this decrease, the median intensity declines by only 2.8 percent more by 2030 due to the carbon tax. Although two economic equilibrium models show larger intensity reductions due to the carbon tax in the lower panel, many models indicate a relatively modest impact for the carbon tax.

Within the transportation sector, energy efficiency improvements are measured as total miles per gallon in vehicles that are on the road. These vehicle fuel efficiency improvements decrease the energy intensity in this sector and thus are comparable to declining energy intensities observed in the other end-use sectors. On-road light-duty vehicle fuel efficiency between 2005 and 2030 improves dramatically by 49.6 percent for the median result in the reference case. On top of this improvement, Figure 14 indicates that the median vehicle efficiency improves 4.1 percent more by 2030 due to the carbon tax relative to the reference case.[10] These improvements through 2030 are generally less than 5 percent in most models in the lower panel. Carbon taxes have a relatively modest impact on vehicle efficiency in these models, because legislated mandated efficiency improvements are already having a pronounced effect in the reference case.

In summary, significant declines in energy intensity are already happening in the reference case. Additionally, a carbon tax of $30 in 2010 and rising to almost $80 by 2030 reduces energy intensity by another 10 percent or less in the residential, commercial, industrial and transportation sectors.

Figure 11. Commercial Energy Intensity (%) in Response to Carbon Tax

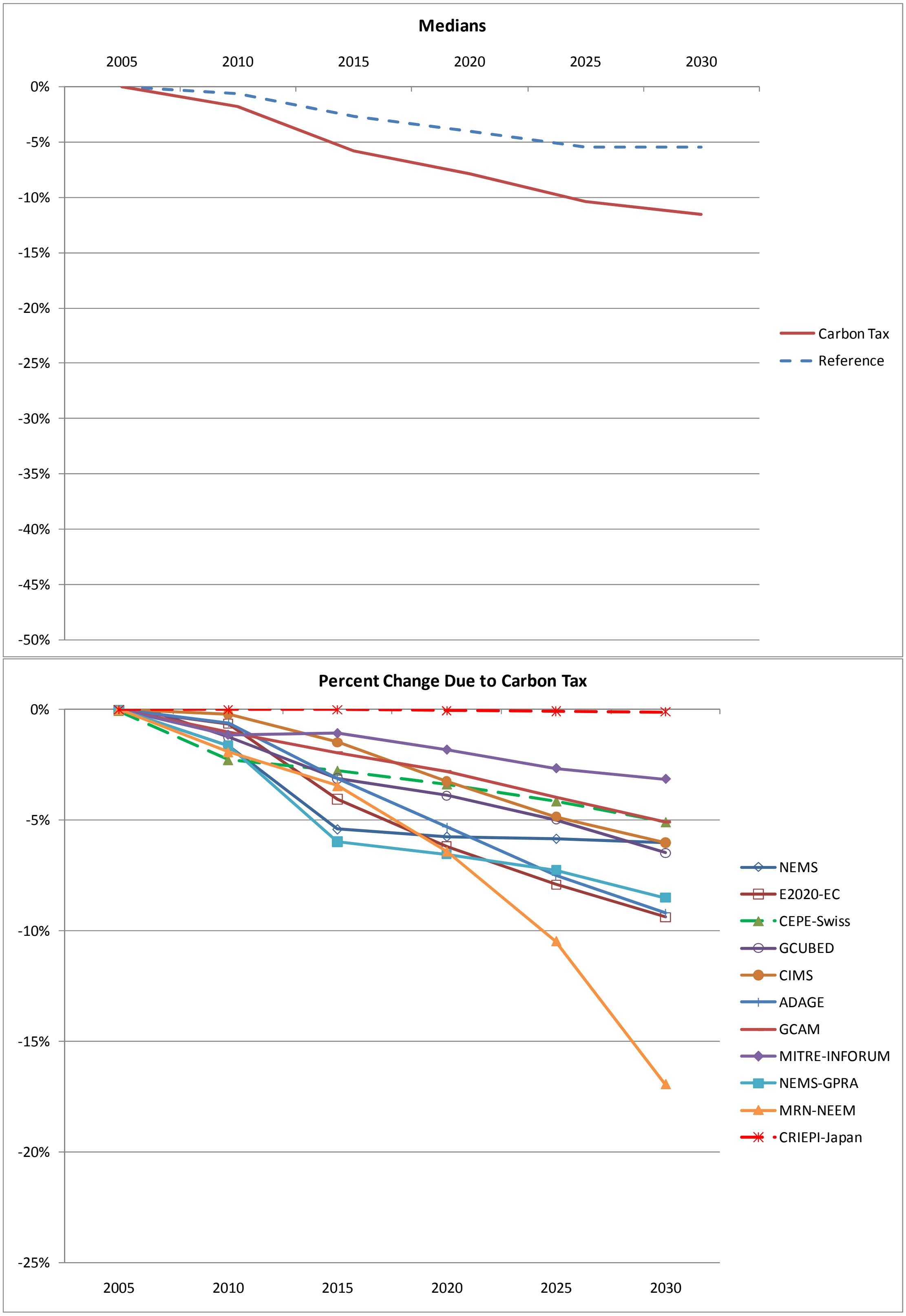


Figure 12. Industrial Energy Intensity (%) in Response to Carbon Tax

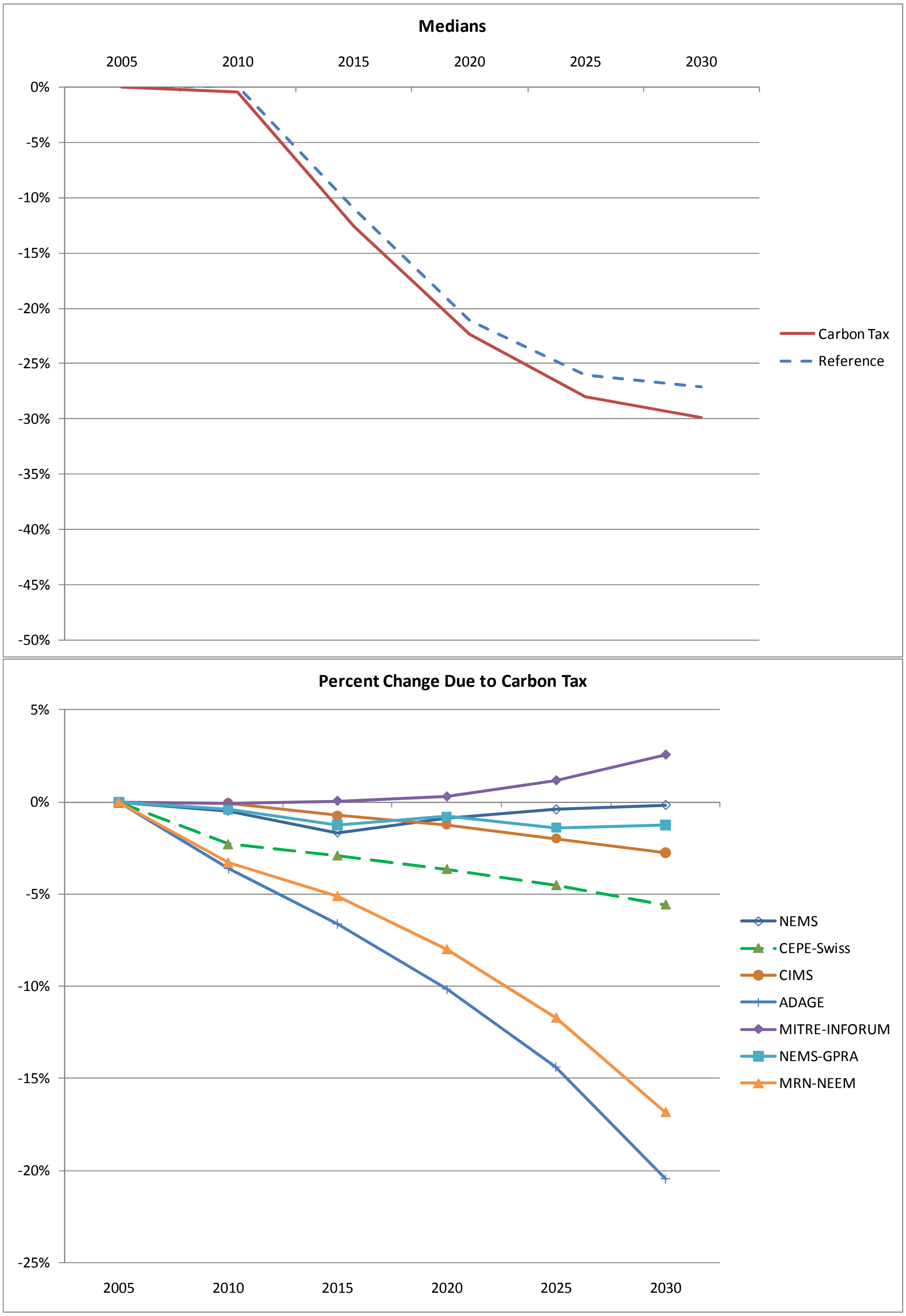
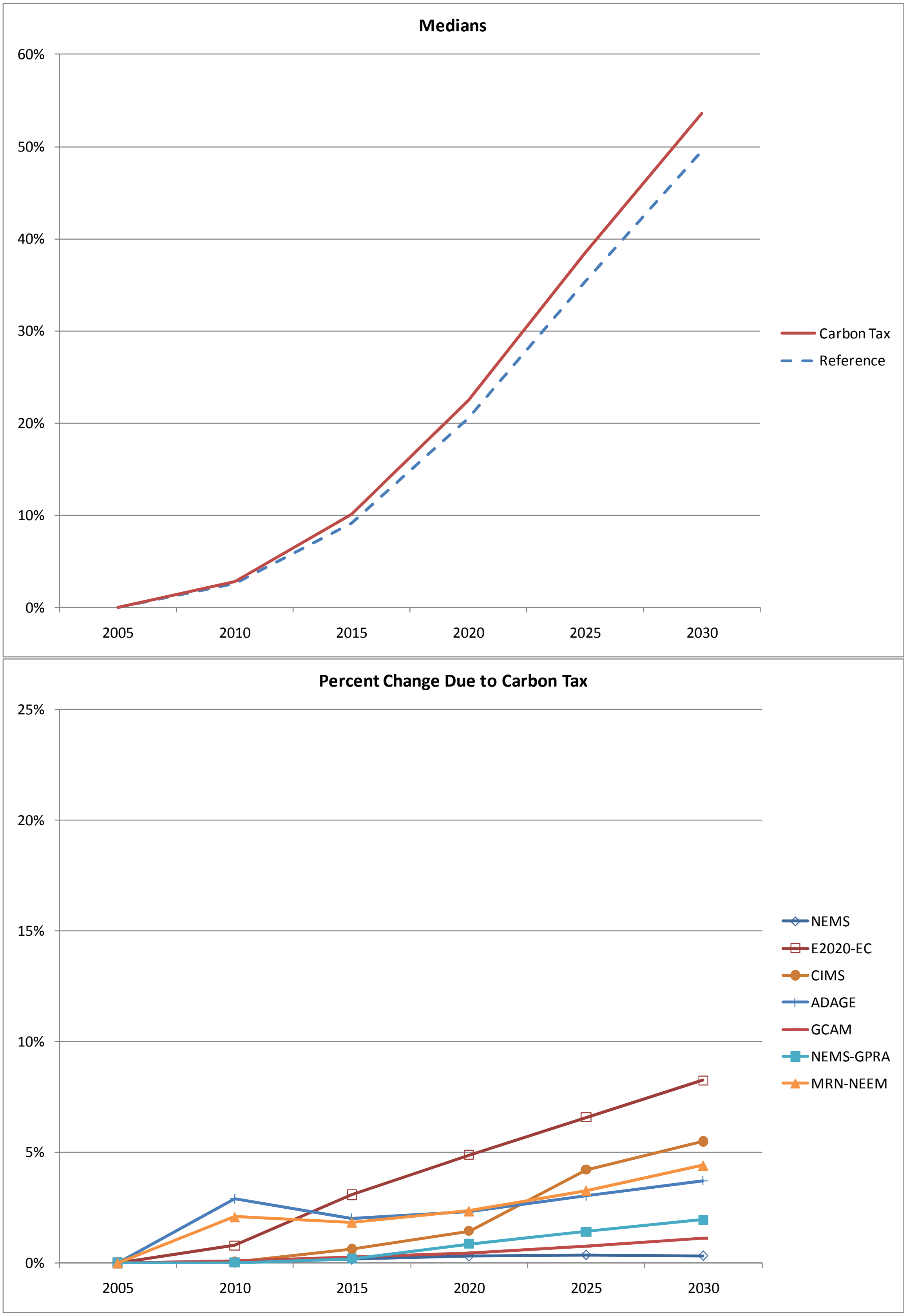


Figure 13. Transportation On-Road Vehicle Efficiency (%) in Response to Carbon Tax



Stand-Alone and Combined Policies

Standards and Carbon Tax

The working group considered both mandated standards and a carbon tax as alternative policy instruments for improving energy efficiency. The ideal standards scenario would be one that imposed the same costs on consumers that the carbon tax does. Comparison of the energy intensity trends in the two cases would then reveal which policy reduced energy demand more for similar costs.

Unfortunately, it is very difficult to obtain information about the costs imposed by standards in the real world and there is often very little agreement among experts. For the same reasons, most models do not explicitly include this information. To the extent that they do, the models often report different costs from each other. Thus, it is often impossible to calibrate a common set of cost assumptions that each model could use.

Instead the working group standardized on specific efficiency improvements in the residential, commercial and transportation sectors. The scenario increased building codes as specified in the Waxman-Markey Bill, improved energy-efficiency standards for selected new building and equipment, and increased light vehicle fuel economy standards. These standards could be a stand-alone policy or they could be combined with a carbon tax.

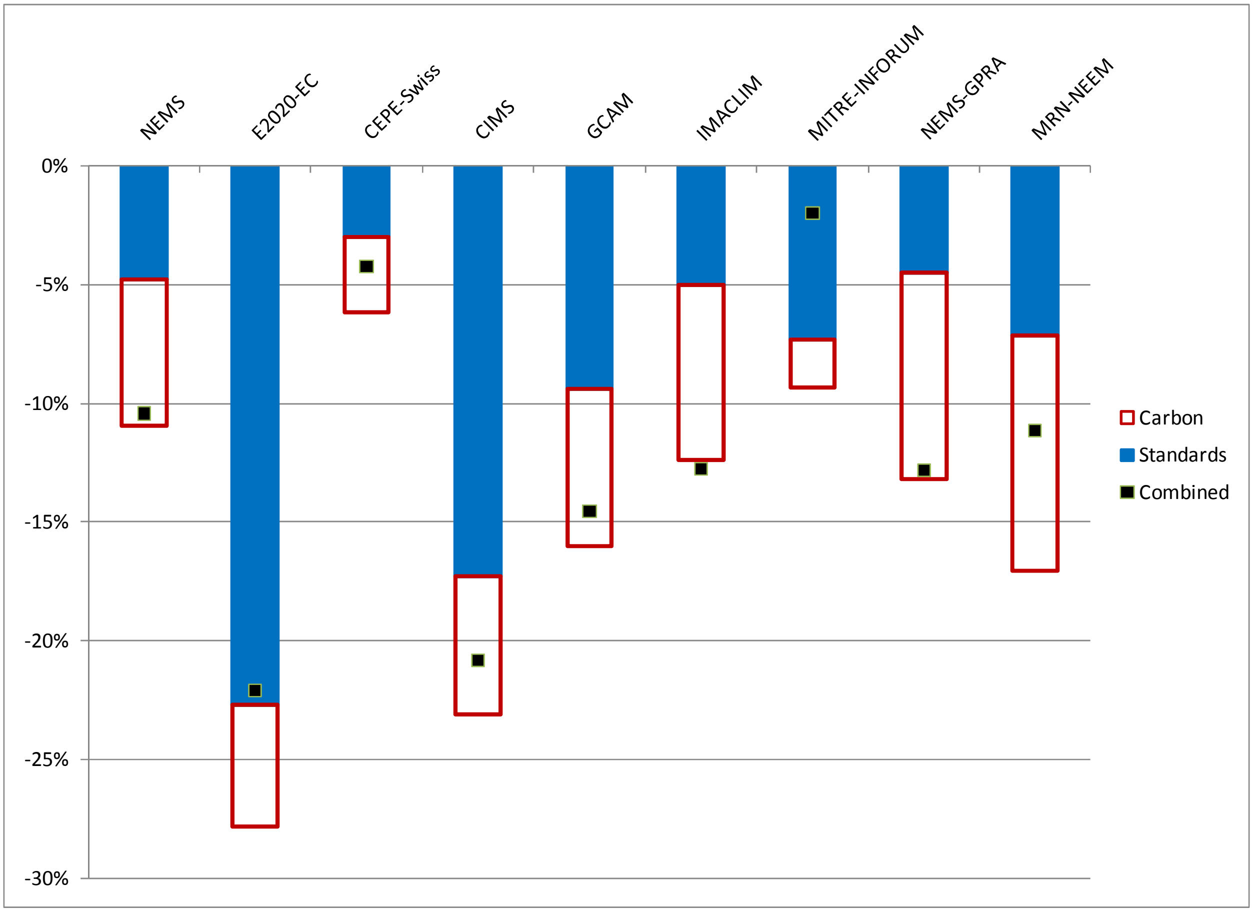
If a carbon tax and standards operate on energy efficiency through similar mechanisms, they may each be redundant because they are good substitutes for each other. Whatever reductions can be achieved through a carbon tax can also be implemented through standards. On the other hand, if they operate through different mechanisms, they may be less than ideal replacements for each other. Under these conditions, the two policies may be more additive because one policy does not repeat what the other policy does. It may be that standards are superior to carbon taxes in adopting more energy-efficient vehicles and other equipment. On the other hand, carbon taxes may be a more effective approach for changing people's driving patterns and operating other energy-using equipment. Whether policies are redundant or additive is very important when designing overall policy strategies.

The study results on the combined policy cases are preliminary and depend very much on the types and stringency of the policies simulated in this model comparison. Results showing policies to be additive or replacements for each other do not necessarily carry over to other similar policies considered by each model. Additional analysis is clearly warranted, because the modeling community is only beginning to evaluate this issue.

The range of outcomes in 2030 for these two separate policies for standards and a carbon tax is shown for the residential sector by the stacked bars in Figure 15. The solid bar indicates the reduction in delivered energy consumption due to the standards, while the white bar reveals the reduction due to the carbon tax. The small rectangle for each model in the figure shows the effect on delivered energy consumption in 2030 of combining both approaches into a single policy package. When the small rectangle is closer to the bottom of the stacked bars, the two policies are more additive and complement each other.[11] When the small rectangle is more inside the stacked bars, the policies are more redundant because one of the policies is incorporating some of the effect of the other policy. Under the latter conditions, combining policies will cause a smaller impact than the sum of the two separate policies because the effect of this first policy is muted to some extent by the second policy.

Energy 2020, CIMS, GCAM, MITRE and MRN-NEEM are the five models in Figure 15 showing reductions in residential delivered energy consumption of more than 5 percent by 2030 due to the standards. They are also systems that display at least some degree of redundancy between standards and the carbon tax. Other models show smaller consumption effects from the standards and very little redundancy between standards and the carbon tax. Appendix A includes some important caveats on the relative size of the impacts from standards and carbon taxes and on the approach for combining policies that are particularly relevant for interpreting the results from the Energy 2020, IMACLIM, and MRN-NEEM models. Overall, the results suggest that standards and carbon taxes may not be completely additive, but the outcome depends upon the model.

Figure 15. Effect of Carbon Tax and Standards on Residential Energy Consumption, 2030 (%)

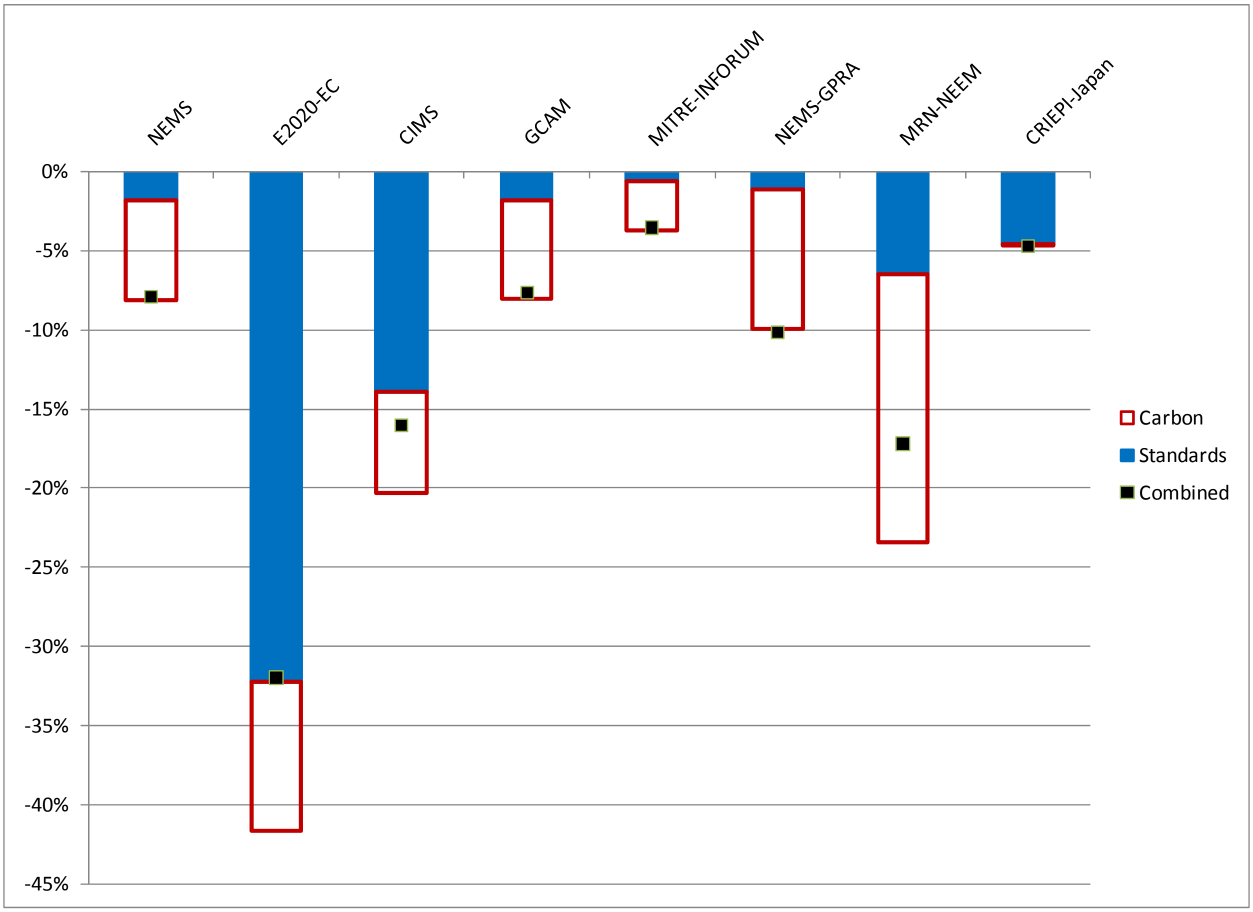


Similar results for delivered energy consumption in the commercial sector are shown in Figure 16. Energy 2020, CIMS and MRN-NEEM are three models displaying large effects (more than 5 percent) on energy use due to standards. These models also indicate some degree of redundancy. The effect of standards in the CRIEPI model is nearly as large but it indicates almost no effect from the carbon tax because energy in Japan is already taxed quite highly in the reference case. Other models show smaller effects from standards and no apparent redundancies between policies.

Figure 17 summarizes the responses within the transportation end-use sector. Energy 2020, CIMS, GCAM and MRN-NEEM are four models that report reductions in energy consumption due to the more stringent standards that are three percent or more by 2030. All but

GCAM reveal some degree of redundancy. The other models have smaller effects from standards and very little redundancy between the two policies.

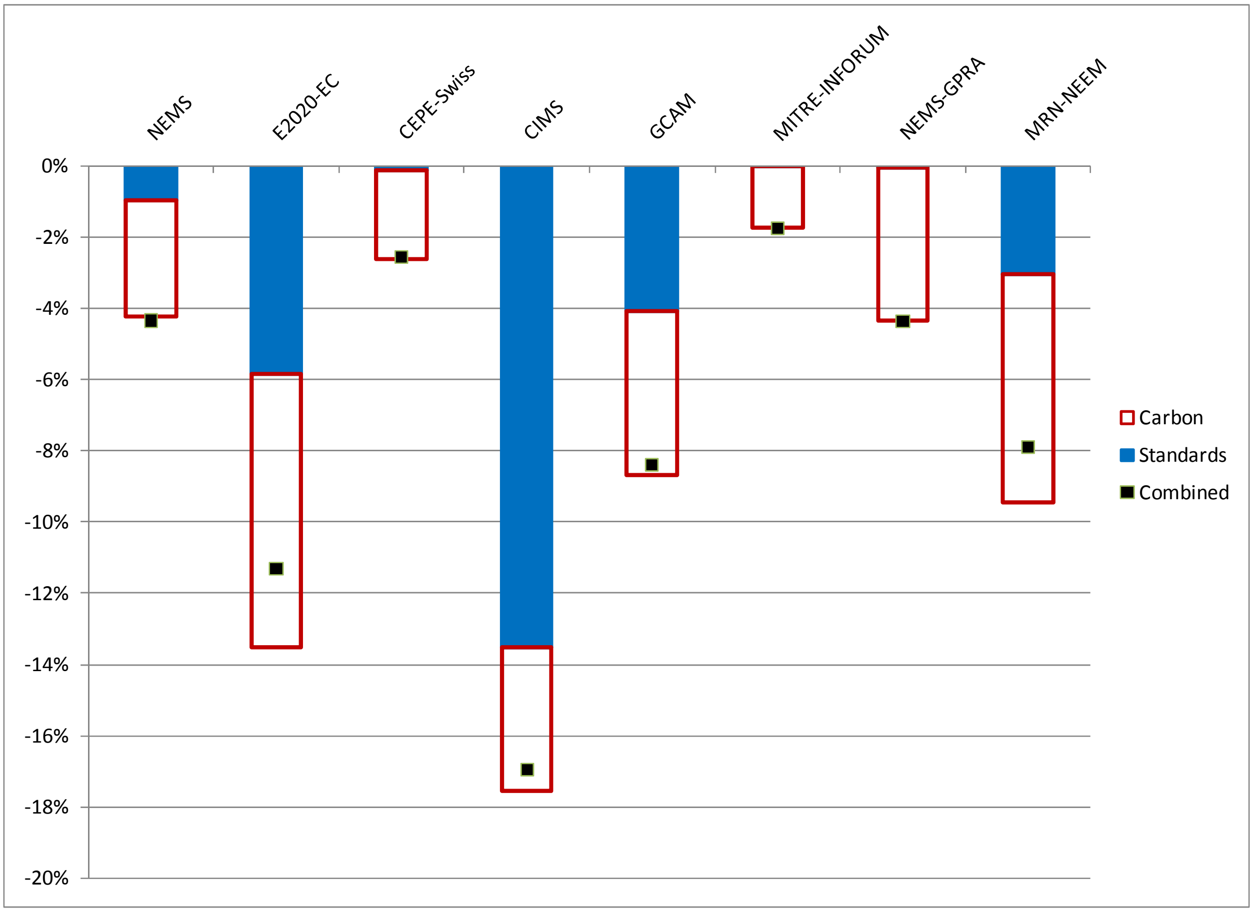
Figure 16. Effect of Carbon Tax and Standards on Commercial Energy Consumption, 2030 (%)



Equipment Subsidy and Carbon Tax

The study also considered the effects of lower upfront costs for the most energy-efficient equipment available to residential and commercial consumers. No such adjustments were implemented in the industrial and transportation sectors. In this case, the most energy-efficient equipment in each end-use class had its costs lowered by one-half of the differential between its cost and the cost of the least energy-efficient equipment type. It was not pre-determined whether this cost reduction resulted from a direct government or utility subsidy or from a successful research and development program. In neither case were the subsidy or program costs included. As with the standards case, direct comparison of the energy efficiency improvements in this case cannot be compared with the carbon tax results, because their costs may vary.

Figure 17. Effect of Carbon Tax and Standards on Transportation Energy Consumption, 2030 (%)



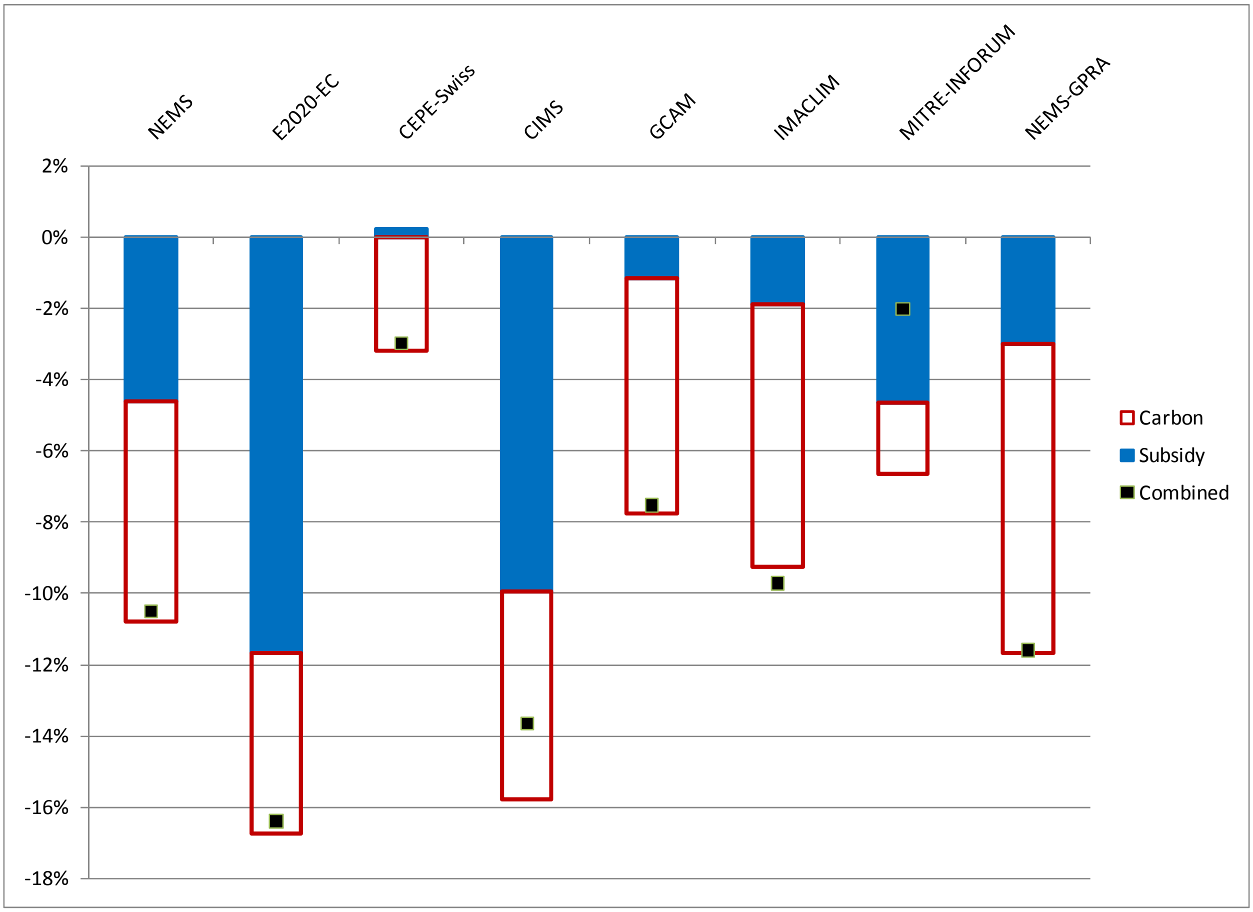
The equipment subsidies as specified in this study provide less reductions in residential energy consumption below reference levels than do the standards. The solid bars are smaller in Figure 18 than they are in Figure 15. Moreover, equipment subsidies and carbon taxes appear to be more uniformly additive than standards and carbon taxes. Figure 18 shows for each model the 2030 effect in the residential sector of combining the two policies into one package (indicated by the small rectangle) relative to the sum of the two separate stand-alone policies. Energy 2020 and CIMS have relatively large responses to the equipment subsidy relative to other models. Most models show the two policies to be mostly additive with little redundancy except for CIMS and MITRE.

Figure 19 compares the same two policies for the commercial sector. Subsidies and carbon taxes have many of the same effects in the commercial sector as they do in the residential sector. Reductions in delivered energy consumption due to the subsidy exceed 5 percent in Energy 2020 and CIMS. Carbon taxes and subsidies appear to be additive in all models, with little redundancy between the two policies.

Equipment Costs and Energy Prices

Since the subsidy case affects upfront costs, there was some interest in exploring how the response to subsides compared with higher energy prices. If consumers place very high discount rates on future energy savings, they may respond much less to energy prices than to equipment subsidies. This effect may be more pronounced in some models compared to others.

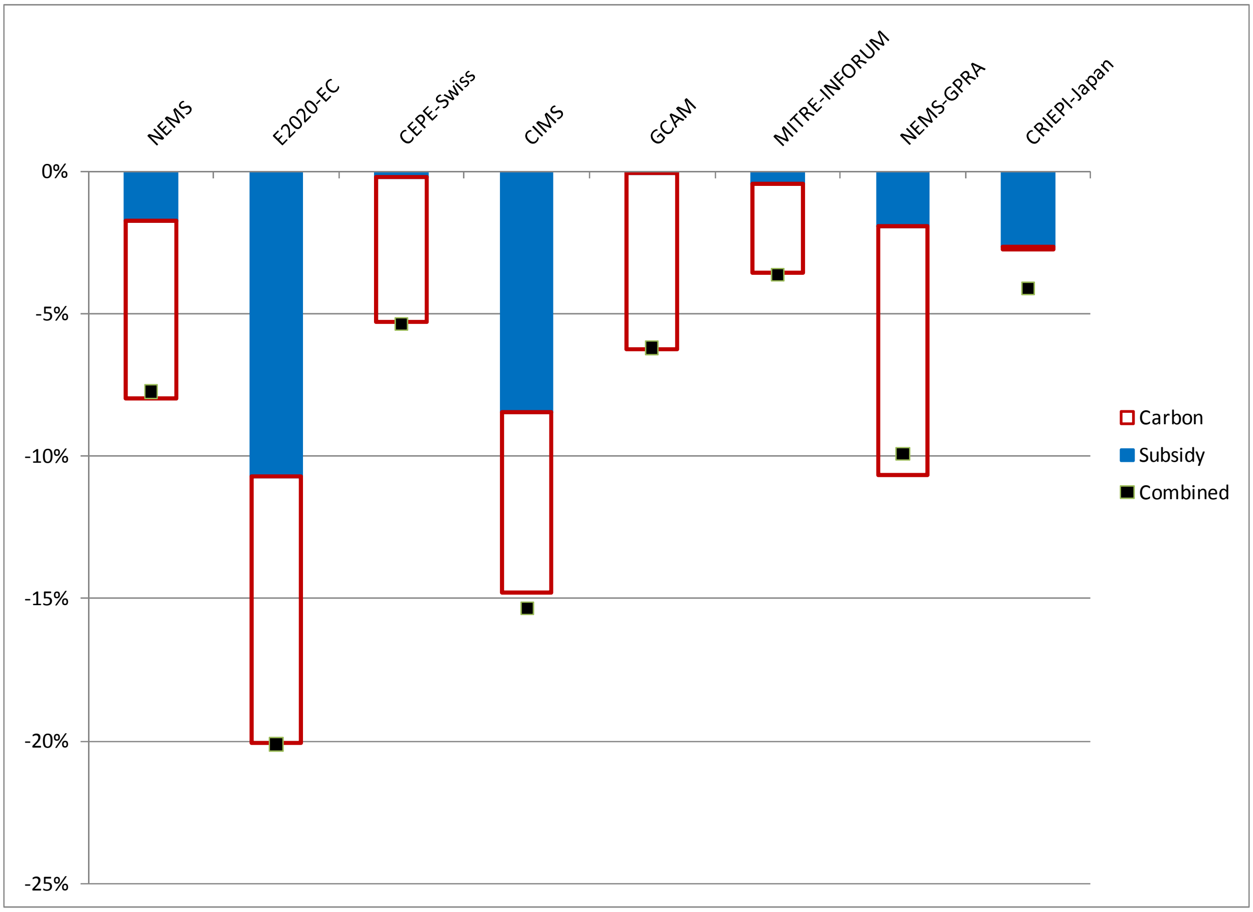
Figure 18. Effect of Equipment Subsidy and Carbon Tax on Residential Energy Consumption (%)



The subsidy case was compared to another scenario in which the inflation-adjusted BTU prices for all energy forms increased by 15 percent above the reference price paths. Although the size of the subsidy was not calibrated to the size of the energy price increases, some models with higher discount rates may respond relatively more strongly in the equipment subsidy case than in the energy price case. This result was not observed for several reasons. The equipment cost reduction was not sufficiently standardized across models because it was calibrated to the cost differential between equipment types *within a model*. Additionally, each model applied these cost reductions to different end uses, depending upon which applications had technology choice. A significant portion of electricity demand is in miscellaneous end-uses which are often not modeled with technology choice and hence not impacted by the subsidies.

The energy price increases were significant and had relatively large impacts. By 2030, the average reduction in residential energy consumption was 5.2 percent below reference levels compared to 4.6 percent in the subsidy case. The comparable average reduction in commercial energy consumption was 5.9 percent below reference levels compared to 3.4 percent in the subsidy case.

Figure 19. Effect of Equipment Subsidy and Carbon Tax on Commercial Energy Consumption (%)



The modeling teams were also offered the opportunity to evaluate energy market conditions where consumers evaluated future energy savings at 7 percent. Many groups did not evaluate these conditions because the higher discount rates in many models are proxy variables for market barriers. Reducing these rates to 7 percent provides an unrealistic assessment for policymakers, because this approach ignores what many experts think are substantial costs in removing these barriers.

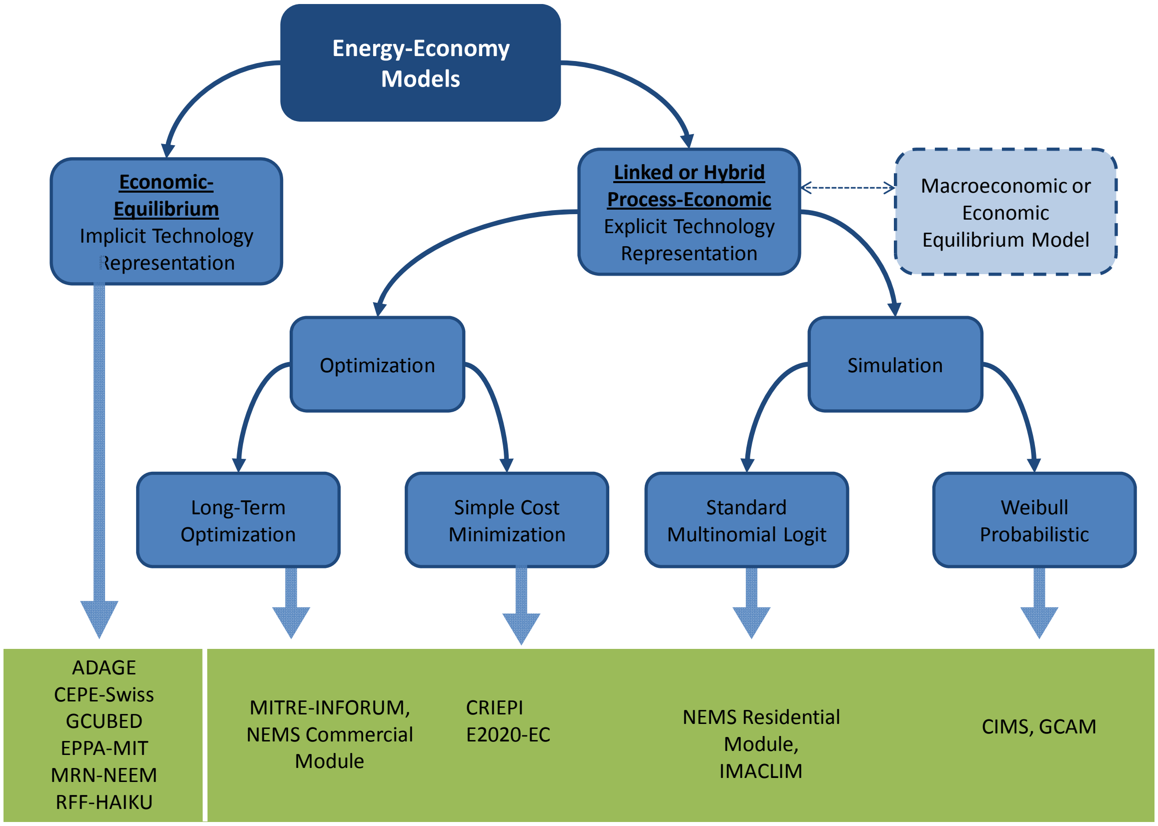
Trends by Model Type

All projections in this study are from energy-economy models that have been used for analyzing the impacts of climate-change policies. Despite this commonality, however, the EMF 25 modeling participants operate a diverse set of energy-market and climate-policy frameworks. Although energy and power supply sectors are represented explicitly with resource curves and specific technologies, demand trends often are incorporated with considerably less detail.

From the energy demand perspective, the distinguishing trait that separates these models is whether end-use technologies are represented implicitly or explicitly (see Figure 20).[12] In models representing energy-use technologies implicitly, substitution parameters govern the ease with which fuels and power can replace each other as well as labor and capital. Non-price-induced changes in energy intensities are introduced through parameters for aggregate energy-efficiency improvements (or AEEI) that decouple fuel use from service activity, either at the major sectoral level like commercial or major end-use category like lighting. This model type is often labeled as "general equilibrium" and is used frequently for integrated assessments of climate change policy. These models will be listed as economic equilibrium and are listed in the bottom far left of Figure 20.

Other models represent energy-use technologies explicitly through different capital-stock vintages. Each new vintage offers the opportunity to reduce energy intensity in a specific end-use activity. Technologies compete with each other on the basis of their relative costs to meet the demands created for a particular end-use activity. Different functional forms can govern this competition. Logit-choice specifications allow heterogeneity among consumers and the market conditions influencing their decisions. Linear or nonlinear cost-minimization programming approaches will aggregate consumers into a more typical agent facing a uniform set of conditions for each particular end-use. Although the NEMS commercial model is more similar to a programming approach, it differs in some important respects. The model optimizes within market segments by minimizing annualized life-cycle costs, but with logistic elements in the hurdle rate calculation and a two stage decision process for some decisions.

Figure 20. End-Use Technology Competition Frameworks

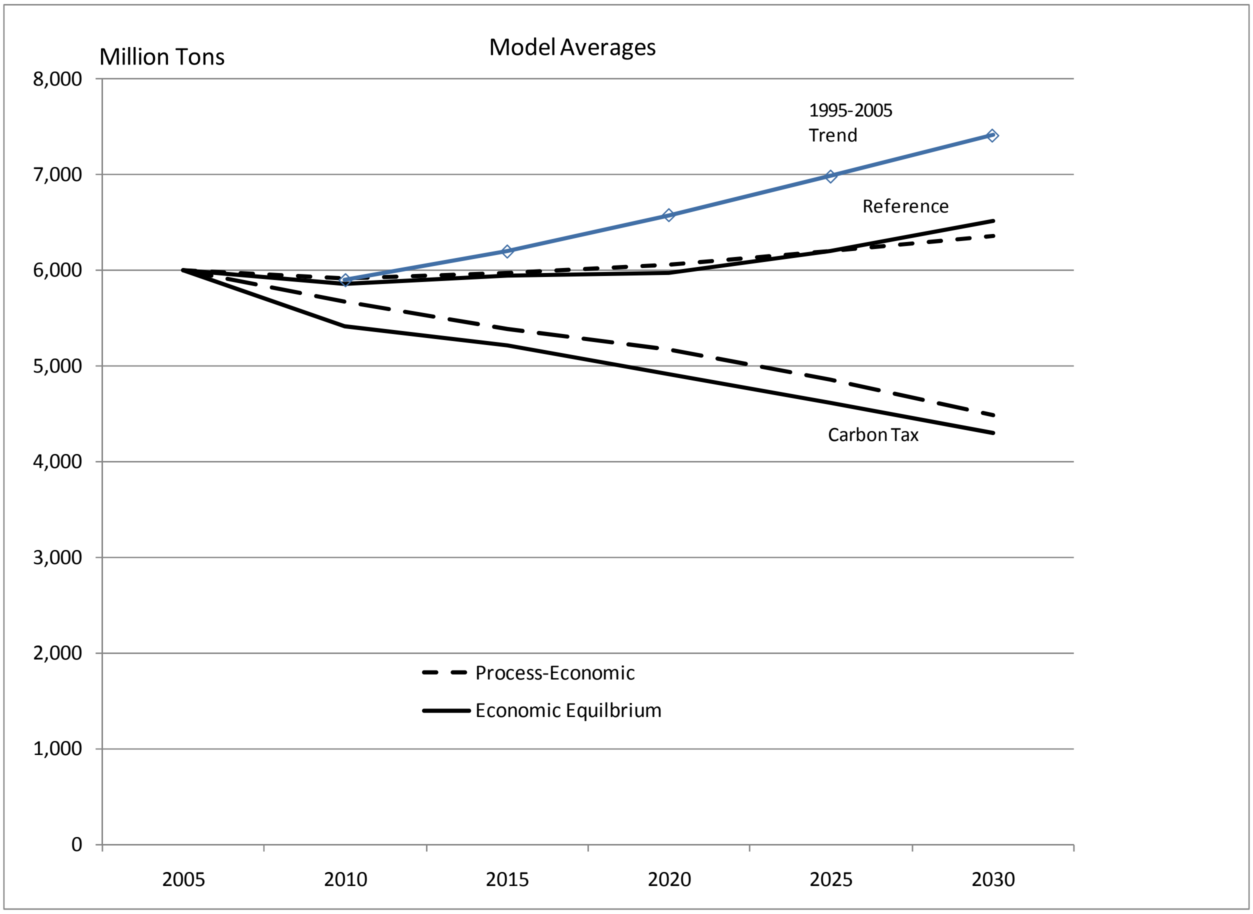


None of the technology-explicit systems included in this study are pure "bottom-up" approaches that optimize on a solution to determine energy outcomes on the lowest-cost options. The MITRE system uses an optimization approach for energy (MARKAL) but merges it with a macroeconomic model (INFORUM). CIMS adopts a "hybrid" approach that is technologically explicit but also behaviorally realistic in that these parameters are based upon empirical verification. NEMS and NEMS-GRPA incorporate detailed behavioral rules and links to a macroeconomic model. These models are sometimes called "linked" and other times called "hybrid", but they are all quite different from the approach used in potential energy studies. These models will be referenced as linked or hybrid process-economic frameworks and are listed at the bottom of Figure 20 under each solution type.

A particularly striking conclusion from this study is that models with very different technology detail display similar trends in CO2 emissions for the simulated cases. Models with explicit end-use energy efficiency technologies generally tend to show modest differences in CO2 emissions from models with implicit technologies.

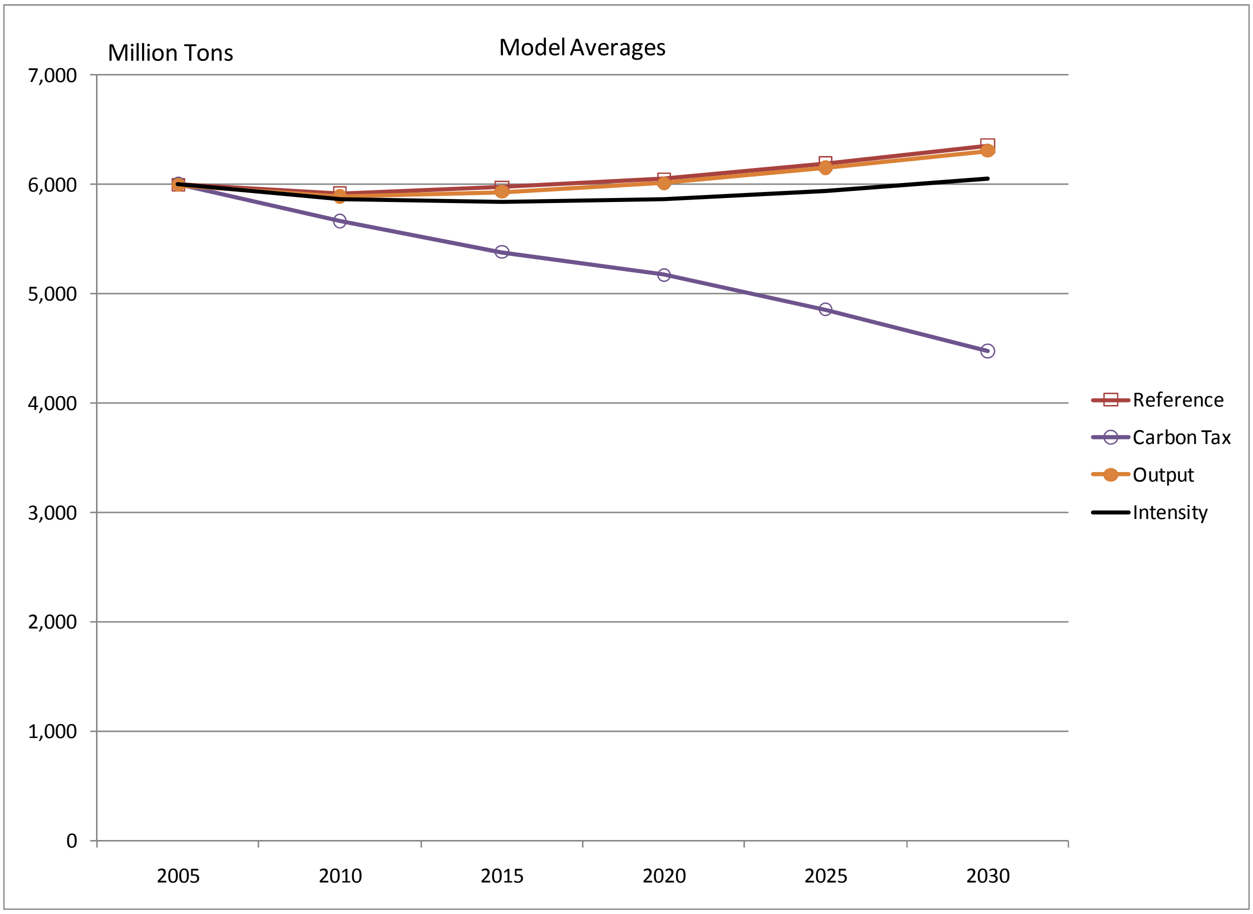
Figure 21 compares the average trends for emissions in the reference and carbon tax cases for each group. Reference emissions for each group are comparable until 2030, when the path becomes modestly lower in the "linked" or "hybrid" process-economic models with explicit technologies. By 2030, differences in reference emissions between the two groups are only about 165 million tonnes (or 2.6 percent). This trend suggests that greater technology detail allows these linked or hybrid models to find modestly more opportunities to replace carbon under baseline conditions, but these differences are not stark.

Figure 21. Trends in CO2 Emissions by Model Type



Meanwhile, emissions with the $30 per tonne carbon tax show the reverse; process-economic models with explicit technology reveal the higher emissions levels for the tax. By 2030, differences in emissions with the carbon tax are only 173 million tonnes (or 3.9 percent) between the two types of models. As a result, the carbon tax produces a smaller reduction in carbon emissions in linked or hybrid models compared to the models with implicit technologies. One explanation for the latter effect may be that some models with explicit technologies use more of the energy-efficient options in the reference case and have fewer options available in the carbon tax, given the technology slates represented in their systems. Another possibility is that models without explicit technologies allow greater flexibility to adopt different technologies implicitly through their response parameters than do those models with discrete technologies. These comments apply to the models as a group and do not describe all the models in the group.

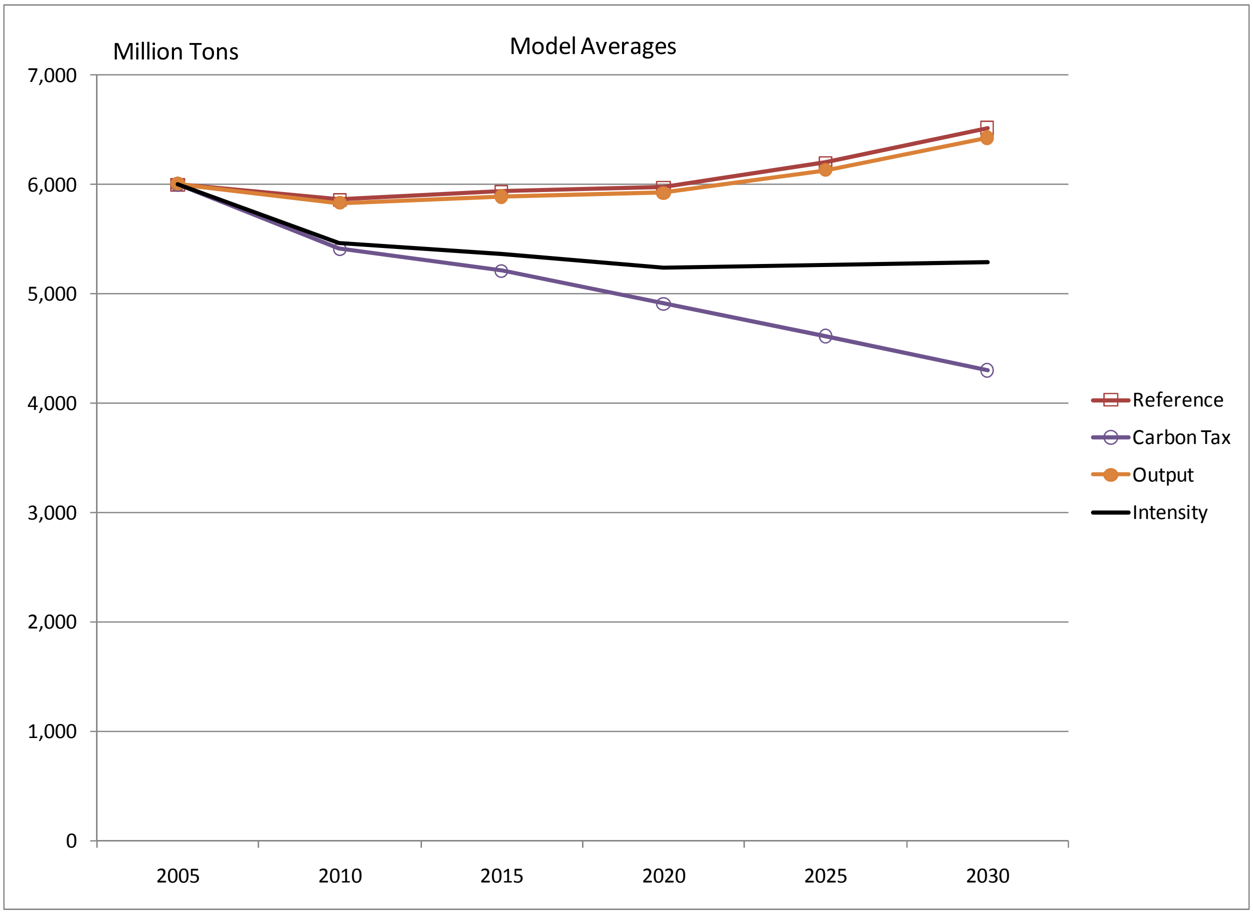
Figure 22. Decomposition of CO_2 Trends Within Process-Economic Models



The net effect of the carbon tax on emissions for each group can be decomposed into output, energy intensity and carbonization trends as was done for all U.S. models in the beginning of the report. Once again, averages of all models in each group are compared. Within the models with explicit technology shown in Figure 22, quite a bit of the smaller total decline in emissions due to the carbon tax occurs because the energy intensity effect (indicated by the "intensity" trend) is also smaller. This effect, however, is offset by a relatively large impact of the carbon tax on decarbonizing the fuel supply, or the difference between the intensity and carbon tax trends. Within the models with implicit technology shown in Figure 23 the intensity component is larger and the effect of decarbonizing the fuel supply is smaller than with the first group of models. The full impact of the carbon tax is marginally larger than those for models with explicit technology representations.

The study did not include scenarios to explain why the intensity effect was larger and the decarbonizing trend was smaller in one group of models rather than in the other. It may be that decarbonizing options were more difficult and costly and therefore shifted more of adjustment to end-use adjustments in consumption in the models with implicit technology representations. It would be interesting to resolve this issue in future studies where the focus was more broadly directed towards a range of climate change mitigation strategies rather than on energy efficiency alone.

Figure 23. Decomposition of CO_2 Trends Within Economic Equilibrium Models



Improving Models for Evaluating Energy Efficiency

Energy-economy models can contribute to better policymaking if they apply similar assumptions consistently to all supply and demand options that compete with each other in fuel and power markets. The role for each technology will depend upon the assumptions used for evaluating all other energy sources as well as energy-efficiency improvements. Somewhat belated, proprietors of large-scale climate change policy and energy modeling have recognized the need for expanding their representation of end-use processes.

There has been a recent shift to models that link energy processes with economic markets. Some models link the energy and economic processes through fully comprehensive "hybrid" systems representing the major options throughout the economy. Other systems employ a suite of models where satellite subsystems for sectors like transportation, buildings or the power sector are linked to integrating frameworks. Both approaches try to introduce more technical details and realism into systems that preserve the important economic interactions between markets. Either approach is quite different from the pure top-down or bottom-up approaches that have traditionally been applied to the energy markets.

These approaches will be successful for policymaking only if several advancements are realized over the coming years. First, data on technology costs and performances need to be fully vetted in open forums and made publicly available. Policymakers should be critical of results based upon proprietary data. Any well-constructed data collection effort can provide some important policy insights without sacrificing the confidentiality of individual units. As part of this study, the Lawrence Berkeley National Laboratory (LBNL) and the American Council for an Energy-Efficient Economy (ACEEE) combined efforts to provide some initial technology cost and performance data for a few key applications in the residential, commercial and industrial sectors. A more comprehensive effort, however, requires substantially more funding if this barrier is to be overcome.

Second, improving both modeling and policy analysis requires much further study into the process of adopting new technologies. Carefully constructed research experiments should be undertaken to determine behavior in sufficient detail to know who adopts new processes and under what conditions.[13] Unlike studies of the economic potential for energy-efficiency improvements, the models in this study allow market diffusion to play a critical role in determining future trends. But these efforts will not be successful unless they improve their representation of these relationships.

Third, there is a critical need for better information on program costs. The direct costs for taxes or emissions-trading schemes are often readily apparent from the costs paid by market participants. When a program operates through non-market channels, it too will involve costs associated with its implementation and monitoring as well as its indirect effects (such as whether the program creates "free riders" or "free drivers"). Unless these costs are properly accounted for, no model will be able to tell policymakers which programs will produce the largest improvements for each dollar spent.

And fourth, disclosure of key model responses is critical if models are to be applied effectively for resolving important debates. With advanced computing power and programming techniques, models today are much more complex and complicated than they were previously. Key responses in today's computational models often cannot be reduced to a few parameters, as may have been the case in the past. Modeling groups need to begin providing reliable summary measures of these responses in their systems in ways that will bridge the communication gap between credible modeling practices and robust policy decisions.

Background Notes

[1] Total U.S. delivered energy grew by 0.5 percent per year between 1972 and 2008 (see Appendix A), relative to an economic growth rate of 2.9 percent per year for the same period.

[2] Supporting information is provided on key concepts and measurements (Appendix A), the design of scenarios and key assumptions in the study design (Appendix B), and a list of participating modeling teams (Appendix C). The reference case (without the carbon tax) is based upon the Annual Energy Outlook 2009 AEO stimulus reference case produced by the U.S. Energy Information Administration.

[3] There have been a number of important studies on the economic potential for energy-efficiency improvements, including the comprehensive evaluation by Interlaboratory Working Group (1997). The main text discusses several more recent studies by the McKinsey and Company (2007) report on climate change and the McKinsey and Company (2009) report on energy efficiency.

[4] Energy Modeling Forum (1996) and many of the articles by technologists and economists contained in Huntington, Schipper and Sanstad (1994) provide good discussions of the conditions leading to the "energy-efficiency gap." More recent contributions include Gillingham *et al* (2006, 2009) and Stavins *et al* (2007).

[5] The discussion of Figure 6 refers to the work of a number of other researchers. Savage (2009) provides an interesting and often amusing discussion of the "flaw of averages", the problem associated with representing unknown variables with averages rather than their distribution. Although the "respent income" adjustment is much broader than the rebound effect investigated by a number of different researchers, Figure 6 bases the percent of energy savings lost (20%) as the midpoint between the 10-30 percent range suggested by Sorrell *et al* (2009) for the rebound effect. This adjustment conceptually includes not only the additional driving with a more fuel-efficient vehicle but also the broader issue of how consumers respend their savings on other activities and goods. The full "markets" effect is based upon an assumption that energy prices decrease by 1 percent for each 1 percent reduction in energy use. Such a price reduction would be consistent with the sum of the long-run elasticities of supply and demand being equal to one. And finally, the costs of government programs are based upon Sathaye and Phadke (forthcoming), who estimate the administrative costs for California electric utilities to be as high as 1.1 cents per kilowatt hour (or about $3.20 per million Btu). This estimate provides a useful lower bound for administrative policy costs in a state with considerable experience with these utility programs. One might also want to add additional utility costs for rebates (as done by Gillingham et al, 2006) and the effects of spillovers and free riders, but these adjustments would require some controversial assumptions. Program costs are often not trivial, e.g., see Stavins *et al* (2007).

[6] The estimates of the response in the commercial sector's electricity consumption to electricity and natural gas prices on pages 10 and 11 are based upon a simple, statistical meta-analysis that pooled all of the model results for all of the scenarios. Electricity consumption in this sector was the dependent variable. In addition to sectoral electricity and natural gas prices, the log-linear fitting equation also included commercial floor space, projected year and a constant (or indicator variable) for each model. All variables were statistically significant at the 1 percent level.

[7] Figure 10 compares changes in the residential energy intensity due to the carbon tax. Since the reported number of households did not change with the carbon tax, the figure reports the change in delivered energy for those several models that did not report households. These models

include: E2020-EC, CEPE-Swiss and GCUBED. Figures 10-13 consistently used medians because they represented the sectoral results from all the models slightly better than did the averages.

[8] Figure 11 compares changes in the commercial energy intensity due to the carbon tax. Since floor space changed very little with the carbon tax, the figure reports the change in delivered energy for those models that did not report floor space. These models include: E2020-EC, CEPE-Swiss, GCUBED and MITRE-INFORUM.

[9] Figure 12 compares changes in the industrial energy intensity due to the carbon tax. Since industrial output changed more visibly with the carbon tax than did households and floorspace, the figure includes only those models that also reported industrial output.

[10] For similar reasons, Figure 13 includes only those models that report fuel efficiency (miles per gallon) for light-duty vehicles.

[11] Again, results for these specific policy packages do not necessarily apply to other similar policy analysis conducted by any of the models. For example, the additive results for the IMACLIM model in Figure 15 are not systematic responses but instead depend upon the types of policies and conditions that are simulated. They report results where the policies are not additive in an article on their specific model prepared during the study.

[12] Figure 20 represents the two basic modeling approaches used in this study. Good examples of the economic-equilibrium approach appear in many of the articles contained in the special issue on a previous Energy Modeling Forum study edited by Clarke, Böhringer and Rutherford (2009). The process-economic approach for energy analysis was pioneered by Hoffman and Jorgenson (1977) and has seen a recent resurgence in the articles contained in Hourcade, Jaccard, Bataille and Ghersi (2006), who describe this approach as being “hybrid” between purely top-down and bottom-up models.

[13] Some researchers (e.g., see Axsen *et al* (2009) and Horne *et al* (2005)) have begun to provide empirical estimates on how end-use consumers react to product quality and risks, interactions between consumers and other important drivers of new investment decisions. This work needs to be supported and continued in order to provide a richer understanding of the complexity of the investment decisions for energy consumers.

References

Axsen, J., Mountain, D. and M. Jaccard (2009). “Combining Stated and Revealed Choice Research to Simulate Preference Dynamics: The Case of Hybrid-Electric Vehicles.” *Resource and Energy Economics,* 31(3), 221-238.

Clarke, Leon, Christoph Böhringer and Tom F. Rutherford, editors (2009). International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22, *Energy Economics*, Volume 31, Supplement 2, December.

Energy Modeling Forum (1996). *Markets for Energy Efficiency*, Stanford University, Stanford, CA.

Gillingham, Kenneth, Richard G. Newell, and Karen Palmer (2009). “Energy Efficiency Economics and Policy,” *Annual Review of Resource Economics* 1: 14.1–14.23.

Gillingham, Kenneth, Richard G. Newell, and Karen Palmer (2006). “Energy Efficiency Policies: A Retrospective Examination,” *Annual Review Environmental Resources* 31:161–92.

Hoffman, Kenneth C. and Dale W. Jorgenson (1977). "Economic and Technological Models for Evaluation of Energy Policy," Bell Journal of Economics, 8(2): 444-466, Autumn.

Horne, M., Jaccard, M. and K. Tiedemann (2005). “Improving Behavioral Realism in Hybrid Energy-Economy Models Using Discrete Choice Studies of Personal Transportation Decisions,” *Energy Economics,* V27, 59-77.

Hourcade, Jean-Charles, Mark Jaccard, Chris Bataille and Frederic Ghersi, editors (2006). Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-Up and Top-Down, *The Energy Journal*, special issue.

Huntington, Hillard, Lee Schipper, Alan H. Sanstad, editors (1994). Markets for Energy Efficiency. *Energy Policy*, 22 (10), October.

Interlaboratory Working Group. 1997. *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond.* Oak Ridge, TN and Berkeley, CA: Oak Ridge National Laboratory and Lawrence Berkeley National Laboratory. ORNL-444 and LBNL-40533. September.

McKinsey & Company (2007). Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost? http://www.mckinsey.com/clientservice/ccsi/greenhousegas.asp

McKinsey & Company (2009). Unlocking Energy Efficiency in the U.S. Economy, http://www.mckinsey.com/clientservice/electricpowernaturalgas/us_energy_efficiency/

Sathaye, Jayant and Amol Phadke (forthcoming). “Energy Efficiency Cost Curves: Empirical Insights for Energy-Climate Modeling,” *Energy Economics*.

Savage, Sam L. (2009). *The Flaw of Averages: Why We Underestimate Risk in the Face of Uncertainty*, Hoboken, NJ: John Wiley & Sons Inc., 2009. 412 pp.

Sorrell, Steve, John Dimitropoulos, and Matt Sommerville (2009). "Empirical estimates of the direct rebound effect: A review," *Energy Policy*, 37(4): 1356-1371, April.

Stavins, Robert, Judson Jaffe, and Todd Schatzki (2007). "Too Good to Be True? An Examination of Three Economic Assessments of California Climate Change Policy," NBER Working Papers 13587, National Bureau of Economic Research, Inc.

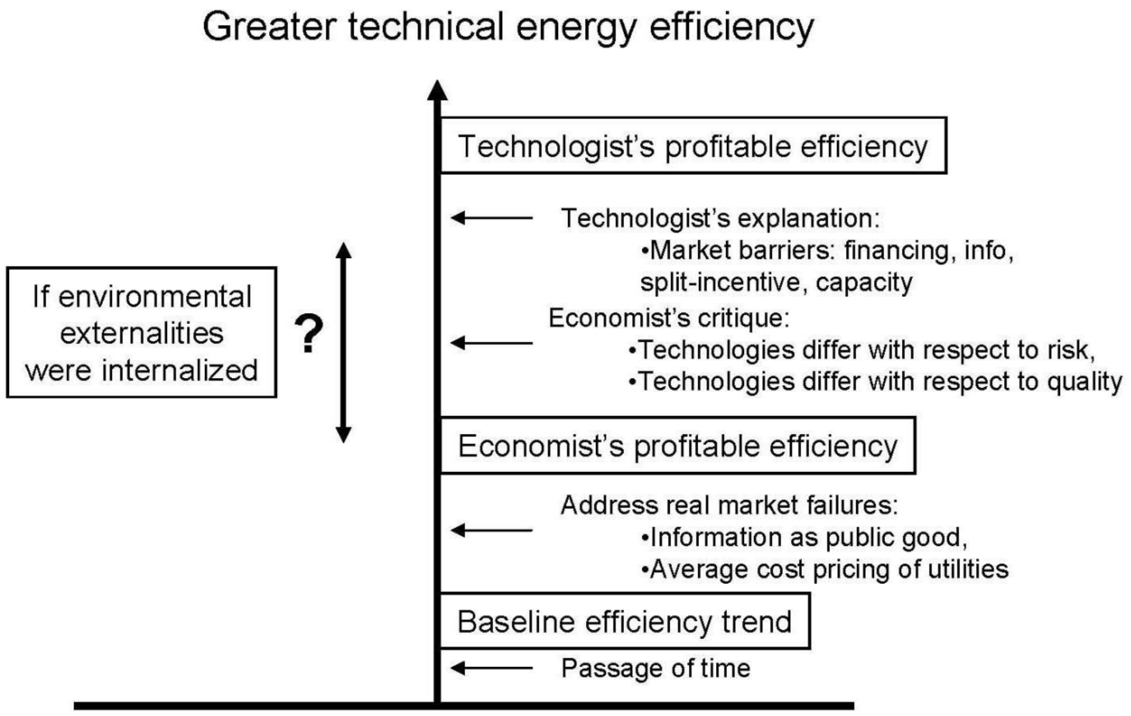
Appendix A: Additional Discussion

Energy Efficiency and Energy Intensity

This study focuses on *cost-effective* reductions in the energy used to support a level of energy services. The full costs of adopting new energy-saving technologies include both monetary and non-monetary costs. When these decisions are aggregated to a sectoral or economy level, these very different energy services must be combined. The common practice has been to measure these trends with energy intensities, frequently represented as energy per square foot of commercial floor space (for the commercial sector) or energy per dollar of GDP (for the economy).

Although there are some important problems in measuring energy intensities (discussed in the next section), their use avoids some of these complications caused by different definitions. Energy efficiency is frequently an engineering concept that refers to the designed energy use in physical heat units (e.g., British thermal units or Btu) associated with a particular piece of equipment. Increased energy efficiency may or may not be cost effective and differs from economic efficiency. In contrast, economic efficiency refers to the best use of all inputs in improving society's well-being.

Figure A-1. Technical and Profitable Energy Efficiency



Source: Mark Jaccard.

Figure A-1 provides a conceptual framework for discussing energy intensity trends. Technical change, structural economic shifts and recent energy price shocks (e.g., 1973 or 2008) will all contribute to a declining baseline energy intensity trend. Consumers will eventually adopt these improvements, but only gradually as they replace older equipment.

If these declines are not rapid enough, policy makers may initiate new policies for reducing energy intensity faster. The energy-efficiency debate has centered upon whether consumers and investors are purchasing all of the new energy-saving equipment that is cost effective. Everyone agrees that better public information about the availability and performances of new equipment might encourage more adoption of these options. Government programs providing this information could be less costly than asking each individual to discover this information on the own. This policy represents the removal of a market failure that would improve everyone's situation, provided that the information program was less costly than the derived benefits from the program.

Arguments begin to emerge when energy intensity is pushed beyond this level. New technologies may be riskier because they may break down more quickly. They may also change the quality of the service, requiring consumers to buy a different product than what they want. The technologist will push forward with these new options to his profitable intensity level because he believes that these problems are market barriers that need to be overcome. The economist will stop here at his profitable intensity level because he believes that these barriers are costs that the seller or buyer of the equipment should resolve themselves. For example, the buyer could purchase a warranty that protected him against possible equipment failure.

Problems with the market for energy-using equipment, however, are not the only concern. There may be market failures in other markets that cause consumers to use too much energy. The price of electric power in many countries is set based up on average cost for all electricity rather than the incremental cost of the last unit sold in the market. Additionally, carbon emissions may create external damages on everyone. If no price exists for these emissions, each consumer will have less incentive to reduce energy use. The economist will want to remove these problems because markets, as they currently exist, have failed to provide the correct incentives. By removing these environmental and other market failures, the economist will end up with a reduction in energy intensity that is closer to the technologist's targeted amount.

Finally, both the economist's and technologist's preferred position for profitability lie inside the society's potentially available technical efficiency, based upon detailed engineering data and ignoring any costs.

Measuring Energy Consumption

This study will measure energy consumption at the delivered rather than the primary level because the discussion focuses on decisions made by final consumers. This measure will be appropriate when consumers trade off one source for another on heat content (Btu). This section compares various measures for aggregate U.S. energy consumption.

The heat content of U.S. energy consumption in 2008, prior to the financial collapse, reached almost 100 quadrillion Btu (quads) when measured at the primary level but only about 74 quads at the stage of delivered energy used by households and firms. Most of the "missing" 26 quads were losses incurred by generating, transmitting and delivering electricity. Whether one wants to include or exclude these transformations depends critically upon the question being addressed.

Table A-1. Alternative Measures of Total U.S. Energy Consumption (Quadrillion Btu)

	Primary Excluding Electricity	Electricity Sales	Primary Electricity	Delivered	Primary	Productivity-Adjusted
2008	61.3	12.7	38.0	74.0	99.3	98.0
% p.a.:						
1972-2008	0.23%	2.38%	2.38%	0.50%	0.87%	0.85%

Table A-1 describes the relationship between these concepts. The top row shows energy consumption for different measures in 2008, just prior to the financial collapse. The "Primary Excluding Electricity" column reports total primary non-electric quadrillion Btus. The next column reports electricity consumption (sales) at the end-use level based upon the heat rate (3412 Btu per Kwh) at the delivered stage. The third column shows electricity consumption at the generation level by using the heat rate for generating power from fossil fuels before any transmission and distribution (10200 Btu per Kwh). When electricity sales (in the second column) are added to the first column, the sum equals about 74 quadrillion Btus for total delivered energy (in the fourth column). When primary electricity consumption (in the third column) is added to the first column, the sum equals about 99 quadrillion Btus for total primary energy (in the fifth column).

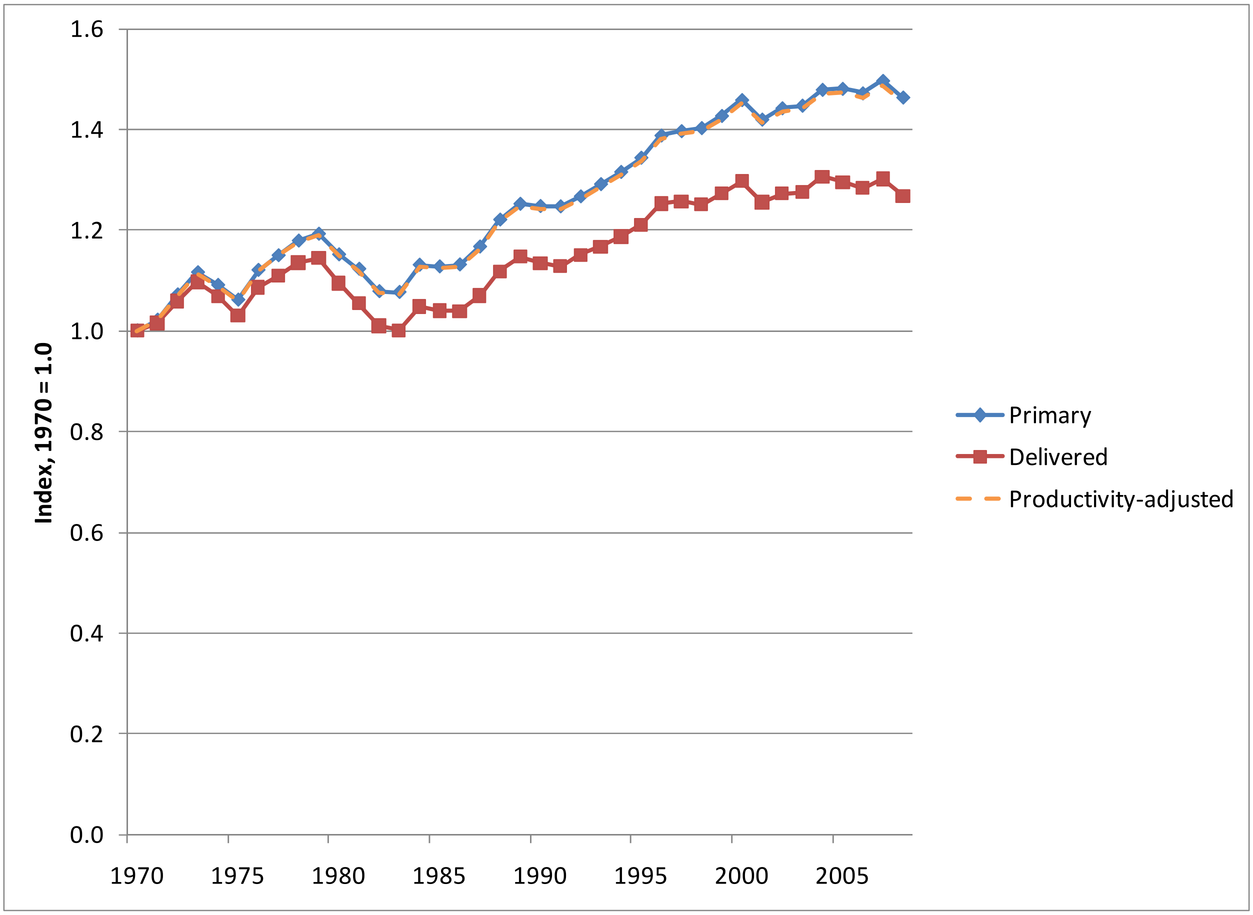
When these adjustments are done for every year since 1972, the trends between primary and delivered energy are quite different. As indicated in the fourth and fifth columns, primary energy grows by almost 0.9 percent per year over this period, while delivered energy grows more slowly at 0.5 percent per year. As noted in the main text, the U.S. economy grew almost six times faster than delivered energy, at an annual rate of 2.9 percent per year. Primary energy may be more relevant for studies evaluating the impact of energy use on global climate change because future greenhouse gas emissions will be influenced by both delivered energy and total energy losses in the transformation of fuels into electric power. Delivered energy may be more relevant for studies evaluating the opportunities for households and firms to improve their heat-content efficiency in the activities that they control.

Productivity and Energy Use

"Delivered" energy makes the strong assumption that each consumer is indifferent to whether he uses another Btu of fossil fuels or electricity. In fact, total energy becomes more productive as more versatile and useful electricity replaces fossil fuel. One might want to give a greater weight to electricity to reflect its greater productivity, particularly when investigating energy's role in economic growth.

Under the "Productivity-Adjusted" column of Table A-1, total energy consumption is measured by non-electric sources (in quadrillion Btus), plus "value-adjusted" electric sales. The value adjustment involves weighting electricity sales by the price ratio between electricity and all other fuels over the 1970-2008 period. (This approach could have further disaggregated fossil fuels but did not, because their Btu prices did not vary nearly as much as the relative fuel and electricity prices.) Since the yearly price ratio fluctuates with the oil price and over time, the average value (about 2.9) used in this calculation has been adjusted for the oil price and a time trend through a linear-least-squares regression analysis. This average provides a better indicator of the long-run relationship between these energy sources than do the yearly movements in electricity and fuel prices. In a market economy, consumers should choose to use electricity where it is most valuable to reflect its higher price. When regulators rather than markets determine electricity prices, this adjustment shows how consumers rather than society value the different energy forms. Energy consumption, under this adjustment, appears to grow very closely with primary energy since 1972. Figure A-2 shows the trend for the productivity-adjusted variable is nearly identical to that for primary energy since 1970.

Figure A-2. Measures of Total U.S. Energy Consumption, 1970-2008



Combined Policy Cases

The modeling groups used different approaches in simulating the combined policy cases that require more elaboration.

Some modeling teams like Energy 2020 believe that they impose much stricter end-use efficiency standards than the other groups. As a result, one cannot simply compare the size of the bars to determine whether governments should adopt standards or a carbon tax.

Other modeling groups like IMACLIM note that standards have a somewhat smaller effect on delivered energy than the carbon tax because these mandates reduce home-heating costs while taxes increase these costs. Often called the rebound effect, lower home-heating costs encourage occupants to use more energy to keep their homes slightly warmer.

The policy package combining standards and the carbon tax in the residential sector appears to have a negligibly larger effect than the two separate policies in the IMACLIM model. As discussed in their modeling paper, this over-additive effect is not a systematic outcome of the model's general results regarding policy combinations.

Another important qualification on the policy combination results is the method for integrating these two policies. Many models applied the same assumptions in the joint policy case as they did in each of the two separate policy cases. This approach was not used by MRN-NEEM, which instead allowed policymakers the opportunity to observe the energy-efficiency opportunities with a carbon tax before they established the standards. In the joint policy case, the standards were layered on top of the carbon tax in places where the carbon tax did not achieve enough efficiency improvement. As a result, some of the improvements observed in the stand-alone standards case were not implemented in the combined policy case. This assumption pushes their combined policy case results more inside the stacked bars, relative to many of the other model results. This approach tends to reduce the stringency, and the costs, of the combined policy.

Appendix B: Study Design

EMF Scenario Design (Second-Round) Highlights

Baseline case:

- Please use 2009 AEO Stimulus reference case, focusing on oil prices and real GDP.
- Link for variables reported in Annual Energy Outlook 2009 AEO stimulus reference case: http://www.eia.doe.gov/oiaf/servicerpt/stimulus/index.html
- Extensions beyond 2030 (end of AEO projections) will require modeler assumptions. They might be calibrated to be consistent extensions of (but necessarily equal to) the AEO trends over the last 5 or 10 years of their projection. Please discuss with EMF headquarters if you need further guidance.
- Standardize on your model's exogenous variables (maybe GDP) with this reference case.
- If oil prices are endogenous and you usually consider a range of price paths, please try to select one that is closer to AEO 2009 stimulus results.
- Please report as many fuel prices shown in the EMF model output worksheet as you can. This effort will be helpful for comparing results across models.
- EIA has included the following programs from The American Recovery and Reinvestment Act (ARRA) in its Stimulus reference case: Weatherization and assisted housing, Energy efficiency and conservation block grant programs, State energy programs, energy efficiency funding for Federal buildings, Plug-in hybrid vehicle tax credit, Electric vehicle tax credit, Updated tax credits for renewables, Loan guarantees for renewables and biofuels, Support for carbon capture and storage (CCS), and Smart grid expenditures.

Carbon tax case:

- All taxes are adjusted for inflation and are expressed in 2007$.
- All energy sources are taxed at $30 per ton of carbon dioxide equivalent in 2010.
- Tax rate is increased by 5%, inflation adjusted, each year.
- Please assume that all tax revenues are recycled back to the economy in as neutral a manner as possible. In computable general equilibrium models, this assumption means that revenues are returned to households as a lump-sum, equal dividend to each household. In models with aggregate demand macroeconomic relationships, this procedure may require that the federal deficit will not change. No specific government energy-efficiency or other targeted program should be financed with these revenues. Please discuss with EMF staff if you still have a question.

General energy sales tax case:

- All energy sources are taxed at the same 15% excise tax rate (approximately, $2.50 per million BTU in 2010). New price = reference price x (1.15) in 2010.
- All percent taxes (15%) are applied to delivered not primary energy.
- Please see attached Table B-1 for derivation of this tax.
- BTU tax level is increased by 5%, inflation adjusted, each year. Tax level ($/MMBTU) in 2011 = tax level ($/MMBTU) in 2010 x (1.05), etc.
- Please use the same revenue recycling assumptions as in the carbon tax case.

Residential, Commercial and Transportation Sector Standards:

- There appears to be some merit in considering standards and equipment cost subsidies separately rather than as one "all-in" policy package. This revision is the major change between the cases discussed at the meeting.
- Building Codes increase as specified in the Waxman-Markey Bill. See attached Table B-2.
- Energy-efficiency standards are improved for selected new building and equipment in the residential and commercial sectors.
- Light vehicle fuel economy standards are increased to President Obama's proposed standards that require a minimum passenger car fuel economy of 39 miles per gallon and a light truck fuel economy of 30 miles per gallon by model year 2016. The standards are ramped up linearly for model years 2012 through 2016 and held constant after 2016.
- Table B-3 provides the CAFE standards in the form of minimum fuel economy requirements and as parameter values for NHTSA's continuous function formula that is used to determine minimum fuel economy by vehicle footprint.
- New equipment with energy efficiencies below these standards are not allowed to enter the market.
- Please contact EMF headquarters if you need additional guidance on implementing this case.

Reduced Costs for New Equipment (Subsidy):

- Case can be considered as either a subsidy for new capital costs or the benefits of successful RD&D.
- Reduce the capital costs of new energy-efficiency units in the residential and commercial sectors.
- For each new unit with energy efficiency that exceeds the least efficient unit available (i.e., the current standard), please reduce its cost by 50% of the difference between its cost relative to the least efficient unit available (i.e. the current standard).
- Please contact EMF headquarters if you need additional guidance on implementing this case.

Standards with Carbon Fee: Combine assumptions for carbon fee and standards.

Reduced Equipment Costs with Carbon Fee: Combine assumptions for carbon fee and reduced costs for new equipment.

7% Solution or "Magic Bullet":

- "Magic Bullet" is a diagnostic rather than a policy scenario. Since it ignores possible cost implications of reducing the discount rate, there will be no efforts to see if society's welfare improves.
- Consumers select energy equipment based solely upon costs using a 7% discount rate.
- Please do not adjust other constraints for market barriers, consumer heterogeneity and intangible costs in addition to direct equipment and energy costs. Please do not adjust other assumptions, such as payback periods, diffusion rates, etc.

Removed Scenarios:

- The addition of several new second-round scenarios has required the elimination of two first-round cases: oil taxes and non-price energy conservation programs where consumers selected the most energy-efficient units available during that year.

- Two other cases discussed at the meeting have also not been included: the flat price and frozen technology cases for evaluating the role of prices and other factors in energy intensity trends.

Table B-1. Comparable CO2, BTU and Oil Taxes

	2010			
Tax				
Carbon	**$30.00**	$ per metric ton		
BTU	$1.76	$ per million BTU		
BTU-delivered	$2.46	$ per million BTU		
Expenditures	$1,217.94	$ billion		
Average Price	$16.96	$ per million BTU		
BTU-delivered %	**14.48%**			
BTU x Renew	$1.85	$ per million BTU		
Oil	**$26.85**	$ per barrel		
Levels				
CO2	5880.08	million metric tons		
BTU	99946.39	trillion BTU	99.95	quad (10^15) BTU
BTU-delivered	71820.14	trillion BTU	71.82	quad (10^15) BTU
BTU x Renew	95215.52	million barrels	95.22	quad (10^15) BTU
Barrels	6569.19	million barrels	6.57	billion barrels
Revenues				
CO2	$176,402	million dollars		
BTU	$176,402	million dollars		
BTU-delivered	$176,402	million dollars		
BTU x Renew	$176,402	million dollars		
Oil	$176,402	million dollars		
Oil				
conversion	5.80		AEO 2009 (Dec) Reference	
Qd BTU	38.10		estimates in yellow.	
B Barrels	6.57			
MMBD	18.00			

Oil converted to million barrels and energy to trillion BTU under “Levels”.
Entries under “Tax” show BTU and oil fees needed to equate “Revenues.”

Table B-2. Buildings Sector Standards for EMF25 Standards Case

Residential and Commercial – adopt updated building codes as described in the Waxman-Markey proposed legislation

Residential Products	Date	Level	Installed Cost ($2007)
Central AC and Heat Pumps	2016	16 SEER	$3500
Furnaces (fossil)	2018	90 AFUE	$2200
Boilers	2018	85 AFUE	$3400
Refrigerators	2014	460 kWh/yr	$650
Freezers	2014	350 kWh/yr	$450
Clothes Dryers (electric)	2014	3.48 EF	$450
Electric Water Heater	2013	.95 EF	$470
Gas Water Heater	2013	.64 EF	$475
Gas Cooktop	2012	.42 EF	$500
Dishwashers	2018	.65 EF	$750
Room AC	2014	10.8 EER	$370
Clothes Washers	2015	1.72 MEF	$750
Linear Fluorescent Lamps	2012	28 watts	$7.00
Torchiere Lamps	2016	154 watts	$2.22
Reflector Lamps	2012	50 watts	$4.10

Commercial Products	Date	Level	Typical Capacity	Installed Cost ($2007)
Centrifugal Chillers	2016	6.1 COP	350 tons	$425/ton
Reciprocating Chillers	2016	2.8 COP	100-200 tons	$465/ton
Rooftop AC	2016	11.7 EER	90,000 Btu/hr	$7800
Rooftop Heat Pump	2016	11.7 EER/ 3.4COP (heat)	90,000 Btu/hr	$7800
Gas-fired Furnace	2012	82% Thermal Efficiency	400,000 Btu/hr	$3150
Oil-fired Furnace	2012	83% Thermal Efficiency	400,000 Btu/hr	$3900
Gas-fired Boiler	2013	85% Combustion Efficiency	440,000 Btu/hr	$9000
Supermkt Display Case	2012	21 MWh/yr	20,000 Btu/hr	$6078
Supermkt Refrigeration Compressor Rack	2012	1000 MWh/yr	1,050 MBtu/hr	$122,550
Supermkt Refrigeration Condenser	2012	120 MWh/yr	1,520 mBtu/hr	$44,120
Reach-in Refrigerator	2016	2400 kWh/yr	3,000 Btu/hr	$2650
Vending Machines	2012	2400 kWh/yr	700 Btu/hr	$1639
Automatic Ice Makers	2015	3750 kWh/yr	500 lbs/day	$2647
Halogen Reflector Lighting	2012	Halogen infrared (IR)	1172 system lumens	$70.60*
Linear Fluorescent Lighting ≤ 4 foot	2014	High efficiency lamps w/ High Efficiency fixture	3500 system lumens	$84.30*
Metal Halide Lighting	2015	system efficacy	system lumens	
High Bay Application		55.9 lumens/watt	16250	$321.60*
Low Bay Application		49.5 lumens/watt	9600	$352.00*

*Commercial lighting costs represent lighting system – include lamps/ballast/fixture + installation

Table B-3. CAFE Standards for EMF25 Standards Case

	2012	**2013**	**2014**	**2015**	**2016**
Passenger Car	32.7	34.3	35.9	37.5	39.0
Light Truck	26.4	27.1	27.8	28.6	30.0
Parameter Values for Continuous Function Formula					
Passenger Car					
Parameter A	32.8	34.4	36.0	37.6	39.2
Parameter B	24.9	25.8	26.6	27.5	28.4
Parameter C	51.4	51.4	51.4	51.4	51.4
Parameter D	1.9	1.9	1.9	1.9	1.9
Light Truck					
Parameter A	27.9	28.7	29.4	30.2	31.0
Parameter B	21.6	22.1	22.7	23.2	23.7
Parameter C	56.4	56.4	56.4	56.4	56.4
Parameter D	4.3	4.3	4.3	4.3	4.3

Appendix C: Participating Modeling Teams

Model	Representing Institution
NEMS	US Energy Information Administration
E2020-EC	Environment Canada
CEPE-Swiss	Centre for Energy Policy and Economics, ETH Zurich
GCUBED	Brookings Institution
EPPA-MIT	Massachusetts Institute of Technology
CIMS	Simon Fraser University
ADAGE	Research Triangle Institute
GCAM	Joint Global Change Research Institute, Pacific Northwest National Laboratory
IMACLIM	Centre International de Recherche sur l’Environnement et le Développement (CIRED)
MITRE-INFORUM	MITRE with Environmental Protection Agency & INFORUM
NEMS-GPRA	US Department of Energy & Onlocation, Inc.
MRN-NEEM	Charles River Associates
RFF-Haiku	Resources for the Future
CRIEPI-Japan	Central Research Institute of Electric Power Industry, Japan