THE ENERGY JOURNAL

IAEE International Association for Energy Economics

WWW.IAEE.ORG

Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective

Volume 32 (Special Issue 1) **October, 2011**

International Association for Energy Economics

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1

The Energy Journal is a publication of the Energy Economics Education Foundation, Inc., 28790 Chagrin Blvd., Suite 350, Cleveland, OH, 44122-4630, USA, a non-profit organization, in association with the International Association for Energy Economics.

Membership dues for the IAEE include subscriptions to *The Energy Journal* and the *IAEE Energy Forum*. Subscriber and Membership matters should be sent to IAEE, 28790 Chagrin Blvd., Suite 350, Cleveland, OH 44122; phone 216-464-5365, fax 216-464-2737.. Non-member subscriptions to *The Energy Journal* are $475 for institutions, libraries, and individuals. Postage and handling are paid by the publisher. Outside the United States and Canada, non-member subscriptions are $500.

Articles appearing in *The Energy Journal* are listed in both *Envir. Per. Bibliography* and *The Journal of Economic Literature* and are indexed/abstracted in *ABI/Inform, EconLit, JEL on CD, ISI Journal Citation Reports, Web of Science, SciSearch, Research Alert, Ei COMPENDEX, Trade and Industry Index, PAIS International, DOE Energy, Energy/ Enviroline,* and *Wilson Business Abstracts,* and the following EBSCO databases: *Academic Search Premier and Business Source Premier.*

AUTHORS: Please see back pages for information on the proper style of submissions.

The Energy Journal (ISSN 0195-6574 / E-ISSN 1944-9089) is published quarterly by the Energy Economics Education Foundation, 28790 Chagrin Blvd., Ste 350, Cleveland, OH, 44122 and additional mailing offices. Subscription price $475, U.S. and Canada; $500 other countries. Application to mail at Periodicals Postage Price is Pending at Cleveland, OH 44101. POSTMASTER: Send address changes to EEEF, 28790 Chagrin Blvd., Ste 350, Cleveland, OH 44122.

STRATEGIES FOR MITIGATING CLIMATE CHANGE THROUGH ENERGY EFFICIENCY: A MULTI-MODEL PERSPECTIVE

A Special Issue of
The Energy Journal

GUEST EDITORS

HILLARD G. HUNTINGTON
Energy Modeling Forum
Stanford University

ERIC SMITH
U.S. Environmental Protection Agency

THE ENERGY JOURNAL

Volume 32 (Special Issue 1)
August, 2011

STRATEGIES FOR MITIGATING CLIMATE CHANGE THROUGH ENERGY EFFICIENCY: A MULTI-MODEL PERSPECTIVE

Table of Contents

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1

Preface

I am delighted to introduce this Special Issue of *The Energy Journal* on the role of energy efficiency in mitigating climate change. Sober and careful analyses of decarbonisation policies and instruments are worth many, many times the resources they consume. The present volume, in my view, falls into this elite category. Poorly designed policies which lead to wasteful expenditures of societal resources are undesirable at any time. In today's world of continuing financial uncertainty, astute policies, informed by sound, dispassionate analyses become all the more essential.

One of the especially appealing features of this volume is that a number of papers consider not only impacts of demand side instruments, but they also compare these to other instruments, notably carbon taxes. Such direct comparisons, founded on common model assumptions and parameters, are of particular value to decision makers who fashion policy portfolios that incorporate a number of different options that may include demand side instruments (such as building standards), supply side instruments (such as feed-in-tariffs and renewable portfolio standards) and market instruments (such as carbon taxes). But some papers contained herein go even further by assessing interactions among market instruments, mandated standards and subsidies for energy-efficient equipment. The physician is ever wary of drug interactions, and so the policy maker must also be vigilant.

This Special Issue was made possible by the U.S. Environmental Protection Agency. Broad-based, independent research requires continued support over extended periods of time. The Forum also wishes to gratefully acknowledge the generous and long-standing support of the following organizations: American Petroleum Institute, Aramco Services, BP America, Central Research Institute of Electric Power Industry in Japan, Chevron, Duke Power, Electric Power Research Institute, Électricité de France, Encana, Environment Canada, Exxon Mobil, General Electric, Lawrence Livermore National Laboratory, The MITRE Corporation, Natural Resources Canada, Southern Company, and U.S. Department of Energy.

Adonis Yatchew
Editor-in-Chief, The Energy Journal

Mitigating Climate Change Through Energy Efficiency: An Introduction and Overview

Hillard Huntington and Eric Smith***

1. BACKGROUND AND THE STUDY

The US economy grew almost six times faster than total delivered energy since 1972, during a period when the standard of living improved dramatically within the United States (Energy Modeling Forum, 2011). These trends are due to many factors, including technological improvement, economic and demographic shifts, higher energy prices, and policies such as building codes, technology standards, environmental regulations and labeling, and utility incentives for end use efficiency. It is likely that economic growth will continue to outpace the growth in energy consumption, both because of continued policy advances and technological changes (e.g. new advances in solid state lighting are cost effective and have yet to be adopted on a wide scale). Nevertheless, increasing energy use has been associated with increased greenhouse gas emissions, and this trend is likely to continue as well.

A central issue in energy policy is the amount by which new policies focused on improving end-use energy efficiency will curtail the economy's greenhouse gas emissions if they are implemented without a strategic carbon-mitigation strategy that includes an effective price on carbon dioxide emissions. To evaluate this possibility, the Energy Modeling Forum (EMF) Working Group 25 focused on cost-effective reductions in energy demand based upon simulations provided by 10 energy-economy models for the United States (of which 8 models are represented in this special issue) and one model each for France, Japan and Switzerland. Whenever possible, the modeling teams have used similar assumptions to represent seven different scenarios.

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Energy Modeling Forum, Stanford University, Stanford, CA 94305-4121; 650-723-1050; hillh@stanford.edu.

** U.S. Environmental Protection Agency, Washington, DC 20460; 202-343-9200; smith.eric@epa.gov.

doi: 10.5547/ISSN0195-6574-EJ-Vol33-SI1-1

The use of consistent assumptions in this study offers the opportunity to understand both broad conclusions about this group of models and to examine the effects of the models' structure on the insights they offer. Economic modeling can illuminate complex issues like energy efficiency, and different models have different strengths. We refer interested readers to the working group report (Energy Modeling Forum 2011) available on the internet for an extensive discussion of the key conclusions from the study. This model-comparison exercise builds upon a previous EMF study (Energy Modeling Forum, 1994; Huntington, Schipper and Sanstad, 1996) on the same topic.

This special journal provides an opportunity for participating modeling teams to discuss the key insights derived from their own model in considering the various cases. The teams have chosen to focus on a subset of issues that they thought required further elaboration for policymakers. Due to space limitations, these articles do not provide comprehensive model documentation nor complete discussion of detailed assumptions in their cases. Instead, they have given priority to showing how their models may help explore a range of issues that will be important to policymakers.

The study considers the effects of several different policies: a carbon tax that rises from $30 to $80 per tonne carbon dioxide emissions over the next two decades, 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 households and by the commercial sector, and a standard applied to new equipment used in all but the industrial sector. Additionally, several cases combined the carbon tax with either the equipment subsidy or the new equipment standards.

All simulations 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 models emphasize the economic relationship between markets (sometimes called "general equilibrium models") with limited technology detail for the end-use sectors, e.g., see the volume edited by Clarke, Böhringer and Rutherford (2009). Although these models are particularly appropriate for incorporating economy-wide effects, they have limited ability to represent end-use standards because they do not explicitly represent energy demand technology.

Many other models in this study represent end-use technologies more explicitly, allowing for representative actors to choose among new technologies based upon their relative costs. Rather than assuming that consumers always purchase the least-cost options as in bottom-up technology models, these systems use adoption rates that are more consistent with people's actual behavior. These models generally don't assume that some *optimal* choice of energy efficiency is selected under *ideal* conditions. Instead, economic choices are generally modeled to represent the *likely* response of actors who confront *non-ideal* barriers and costs and whose preference includes technology attributes besides energy efficiency.

They also incorporate economy-wide effects by representing many different economc sectors. Choices about technologies within one market will also affect decisions in other energy markets and economic sectors. As explained in the volume edited by Hourcade, Jaccard, Bataille and Ghersi (2006), 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. There has been an increasing trend both in this study and more generally for modeling teams to adopt a hybrid approach, particularly when they address energy efficiency issues.

2. FOUR OVERARCHING CONCLUSIONS

General conclusions across a diverse set of models are often difficult. There are some common themes, however, that distinguish the results in the EMF study from other policy analysis.

First, the market penetration of energy-efficiency improvements appears to be much more complicated than assuming that consumers select the least-cost strategy among a set of technology options. Decisions are based upon multiple criteria that include quality, reliability and many other traits that may have little to do with energy efficiency. They are also made in market systems where energy efficiency affects not only choices in other energy markets but also in major economic sectors. As a result, these factors reduce the projected gains in energy efficiency relative to those based upon only the technology performances and costs in isolation from these other conditions.

Second, energy-efficiency mandates and subsidies mitigate greenhouse gas (GHG) emissions by reducing delivered energy use. Relative to a carbon tax, however, they are more limited because they ignore an important channel for making the energy system less GHG intensive. Unlike a carbon tax, mandates and equipment subsidies do not induce the power sector to switch from GHG-intensive to GHG-friendly generation options. This trend appears to be particularly strong in the USA, where coal fires the additional generation units, than for the other countries considered in this study (Canada, Switzerland and France), where hydroelectric and nuclear plants are important.

Third, the mandates have a more limited impact in this study for several institutional reasons that are important to emphasize. Mandates are placed on main end uses like building heating and cooling and major end-use equipment. Energy use in other residential and commercial applications is not affected by the assumed standards. Moreover, industrial and transportation options unrelated to personal vehicles are similarly unaffected by these standards. Finally, the standards are imposed in the beginning of the study’s horizon but they are not continually strengthened over time. As a result, these one-time policies have a milder impact because they cover fewer end uses and are less binding over time, relative to the carbon tax.

And finally, a market distortion in selecting energy-efficient vehicles, heating or cooling equipment or other capital to reduce energy use may require a subsidy for energy-efficient equipment or for mandates for more efficient options. Such a policy might improve societal welfare as long as the distortion existed for energy-efficient equipment rather than a general one for all capital investment. Several authoring teams in this volume (McKibbin, Morris and Wilcoxen; Imhof; and Yuan, Tuladhar, Bernstein and Lane) provide interesting approaches on modeling this distortion. However, they also recognize the need for more research on the causes of the energy-efficiency gap in order to develop correct policy instruments depending upon the existence and size of the distortion in the market for energy-efficient equipment.

3. CONTRIBUTIONS TO THIS SPECIAL ISSUE

The diversity in the following articles is notable, despite the common assumptions used by the teams in the study. In a paper providing a conceptual rather than modeling explanation, Huntington builds separate energy-efficiency cost curves to show how behavioral and policy assumptions influence how much energy efficiency appears cost effective.

Comstock and Boedecker evaluate separate and combined policies with the US Energy Information Administration's modeling system. They find that combining efficiency standards or equipment subsidies with a carbon tax is more likely to be additive rather than redundant; in short, the two policies complement rather than replace each other.

In their hybrid process-economic model, Murphy and Jaccard find that improvements in building shell technology respond less to the carbon tax than to standards. These improvements are costly relative to other ways to reduce GHG emissions when the discount rate reflects revealed and stated preferences.

Energy efficiency can make significant strides in meeting near-term GHG goals, conclude Kyle, Clarke, Smith, Kim, Nathan and Wise. They emphasize, however, that significant advancements in energy-supply technologies need to reinforce these trends to allow a successful transition to a low-emissions future.

Macaluso and White emphasize that carbon taxes raises the relative price of electricity to natural gas more in the USA (where coal-fired generation is important) than in Canada (where hydroelectric power is more widespread). For this reason, interfuel substitution between electricity and natural gas is important when the carbon tax is imposed separately or in combination with other policies, but not when standards alone are imposed.

Applying a general equilibrium model, McKibbin, Morris and Wilcoxen conclude that a carbon tax and a tax credit for household capital have different impacts on real GDP and welfare. If not adopted by other countries, a carbon tax reduces US GDP but improves household welfare through lower prices paid to energy-exporting countries. On the other hand, a revenue-neutral tax credit reduces welfare but initially expands economic growth.

In evaluating the Swiss economy, Imhof shows that both subsidies and standards can reduce emissions and improve welfare if distortions in the fuel-capital choices are known to be significant. Switzerland is an interesting example, because carbon prices do not raise electricity prices much because hydroelectric and nuclear plants dominate the power sector.

It is often difficult to measure the costs of any strategy that includes mandated efficiency improvements because these costs are not explicit, unlike a carbon tax. Yuan, Tuladhar, Bernstein and Lane, however, compare costs of different policies in terms of their reduction in the present value of aggregate consumption (all goods and services). They show that an energy tax is more cost effective at reducing delivered energy use than are mandated efficiency standards. Similarly, they show that a carbon tax is more cost effective at reducing GHG emissions.

Steckley, Meade, Lenox, Hoffman, Reid, and Schoener demonstrate that end-use demand responds to technology improvements, fuel switching and indirect economywide effects by coupling an energy-optimization model (MARKAL) with an inter-industry economic model (University of Maryland's Inforum LIFT). A carbon tax allows emissions to decline in both energy supply and demand. Even larger gains are achieved in a normative case where consumers can replace their market discount rates with a lower 7 percent rate. Although these authors recognize the impediments to reducing rates to this idealized level, they suggest that their results represent an opportunity not only for aggressive standards and regulation but also more informed consumer responses assisted by "smart" end-use devices.

Paul, Woerman and Palmer focus on the US electricity market, a critical sector in climate change policy analysis. They note that whether or not electricity is provided competitively and priced at marginal cost is important for evaluating the welfare effects of a carbon tax. When cost-of-service prevails, the imposition of a tax could raise average prices closer to marginal costs and thereby increase welfare.

In evaluating the French residential sector with a hybrid technology-economic model, Giraudet, Guivarch, and Quirion conclude that stand-alone policies improve the energy efficiency of the building stock, but that unless energy prices are increased, they also produce a rebound effect that increases energy demand. They also find that combining policies causes their impacts to be additive rather than redundant or replacements for each other.

And finally, standards have much stronger impacts on energy use in the Japanese commercial sector evaluated by Takahashi and Asano. With substantially higher energy taxes and prices than in the USA, an additional carbon tax increase has very little impact on the Japanese commercial sector energy use.

REFERENCES

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 (2011). *Energy Efficiency and Climate Change Mitigation*, Stanford University, Stanford, CA.

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

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.

The Policy Implications of Energy-Efficiency Cost Curves

*Hillard G. Huntington**

Energy-efficiency cost curves show the required expenditures for achieving any specific reductions in energy use from the baseline level. When they are applied in a policy setting, the assumptions underlying these schedules need to be carefully evaluated if one is to derive useful conclusions. This paper begins by adopting the cost curve and underlying assumptions used in a previous and highly visible study of the economic potential for energy-efficiency improvements. Adjustments are made to the cost curve to incorporate demographic, economic and market effects that are often included in many energy-economy models. Energy efficiency tends to be more costly with the adjusted than with the original cost curves, due primarily to limits on adoption and to policy program costs. It is hoped that the exposition will allow policymakers more insight into why different results are obtained with alternative behavioral assumptions, even if the technology costs and performances are the same with both approaches.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-2

1. EFFICIENCY IN THE POLICY LIMELIGHT

Major policy interest today is riveted on end-use energy-efficiency improvements as an effective approach for reducing greenhouse gas emissions and other pollutants. In pursuing these goals, governments have imposed energy-use standards on new equipment and have required utilities to provide rebates and subsidies to stimulate the adoption of new equipment.

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Executive Director, Energy Modeling Forum, Huang Engineering Center 261, Stanford University, 475 Via Ortega, Stanford, CA 94305-4121, E-mail: hillh@stanford.edu.

The author acknowledges the significant contributions of the EMF 25 working group members and particularly appreciates detailed comments on earlier drafts provided by Erin Boedecker, Kenneth Gillingham, Louis-Gaetan Giraudet, Mark Jaccard, Henry Jacoby, Page Kyle, Karen Palmer, Rose Murphy, Frances Wood, and Mei Yuan. Sole responsibility for any interpretations, conclusions and other contents, however, lies with the author.
doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-2

Technology-based studies frequently document a compelling case for comprehensive reductions in energy use spread across a range of diversified products and activities (e.g., see Interlaboratory Working Group, 1997). A recent example has been the study conducted by McKinsey and Company (2009), which concluded that an integrated, concerted and balanced strategy to improve energy efficiency could reduce the economy's energy intensity outside of the transportation sector by 23 percent by 2020. The McKinsey team identified a set of applications that would yield net savings of $680 billion (2005 prices) for an initial investment of only $520 billion. These estimates far exceed the returns achievable on other investments in the economy. Their message is very popular among policymakers, because it suggests that they can undertake bold action towards improving energy efficiency without imposing costs on society.

Accompanying papers in this special issue paint a more modest view of the opportunities for achieving greater end-use energy efficiency unless energy costs are increased significantly. The estimates in many of these papers are based upon energy-economy models that incorporate a more comprehensive set of energy market relationships that are often excluded from potential energy studies. These other modeling systems include not only the general equilibrium approach used for global climate change policy[1] but also the linked or hybrid approach combining energy processes and economic responses.[2] Processes are represented only implicitly in the general equilibrium models but explicitly in the hybrid set.

The most salient differences between estimates of potential energy savings and results from energy-economy models appear to be the behavior of market participants rather than the performance and costs of different technologies. We demonstrate how these behavioral factors can lead to very different results, even though they might be based on similar technology characterizations. The discussion will make a few general observations about the various approaches that should help the policymaker understand why the two approaches develop very different results. No claim will be made here about which is the right approach. But if policymakers do not understand the very different worldviews embraced in each approach, they will fail to understand what each group is saying.

This article will describe several major differences between the approach of estimating potential energy savings and the systems that have been used previously for understanding energy markets and global climate change policy. The value of any modeling approach, whether a potential energy analysis or any system it is hoping to replace, relies very much on its assumptions about technologies, economic conditions and particularly the behavior of market participants.[3]

1. See many of the articles contained in the special issue on the Energy Modeling Forum study edited by Clarke, Böhringer and Rutherford (2009).

2. 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).

3. Energy Modeling Forum (1996) and many of the articles contained in Huntington, Schipper and Sanstad (1994) provide good discussions of many differences in approach nearly 15 years ago.

Once all the precise numerical results are peeled away from a model's story, users of the system must decide whether one set of assumptions fits their own beliefs better than another. Policymakers must understand the most critical assumptions if they plan to base their policy decisions on any set of analytical estimates.

The next section places the aggregate US energy demand reductions from large energy-economy models in the context of the potential energy savings in the McKinsey study. Section 3 explains that the out-of-pocket expenses featured in potential energy studies may not incorporate fully the opportunity costs emphasized in the energy-economy models. After describing the concept of potential energy savings in Section 4, the paper discusses several important ways to revise these cost curves in Section 5. Section 6 explains the methodology in greater depth, Section 7 summarizes the resulting decomposition of the energy-efficiency costs curves, and Section 8 highlights the major policy implications.

2. IMPACTS ON DELIVERED ENERGY

The models included in the Energy Modeling Forum (2011) study show considerably smaller cost-effective reductions in U.S. energy demand than do estimates of the economic potential for energy-efficient improvements. This smaller effect is attributable primarily to behavioral responses that shape energy consumers' adoption rates rather than in the costs and technical performances of different processes.

The EMF study considers two different scenarios for estimating cost-effective reductions in energy use.[4] 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 are allowed in this scenario after 2009. For the most part, the modeling groups were able to standardize reasonably closely to these trends, even in situations where they derive them internally within their systems.

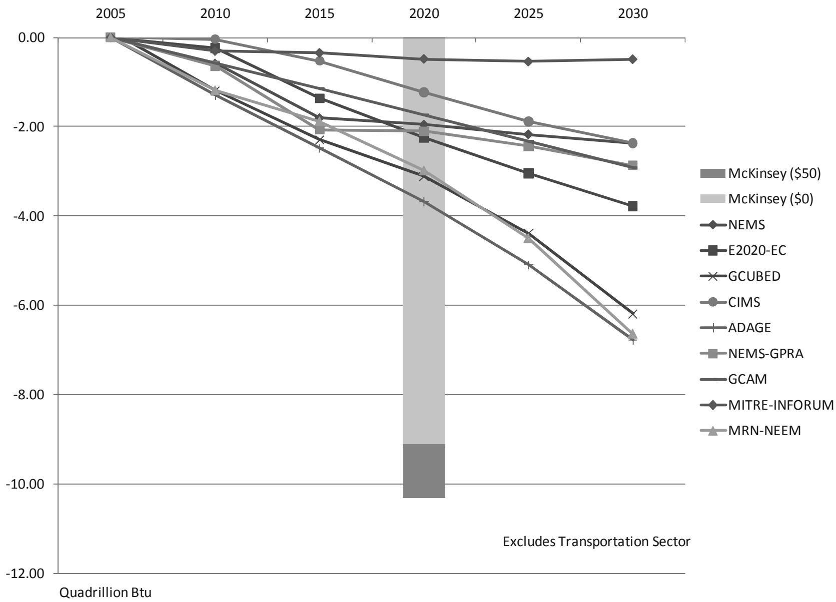
A second case imposes a tax of $30 (2008 dollars) per tonne of carbon dioxide in 2010. After 2010, the inflation-adjusted level of the tax increases by 5 percent each year, reaching a level of about $80 per tonne by 2030. Revenues from the tax are collected by the government but are immediately returned 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.

Figure 1 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 (2009)

A good, more recent paper, critical of the energy-efficiency cost curve approach, can be found in Stavins *et al.* (2007).

4. Energy Modeling Forum (2011) describes the assumptions for each scenario in Appendix B.

Figure 1: Energy Demand Reductions Achievable for Similar Carbon Prices



study on energy-efficiency improvements in the residential, commercial and industrial sectors are strikingly greater for similar carbon costs.[5] The latter study applies a "bottom-up" technology approach for estimating the economic *potential* for energy efficiency for stationary energy use but excluding the mobility uses of energy within the transportation sector. 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 (sum of dark and light bars) 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 quite striking.

All projections in the EMF 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

5. Estimates are based upon their later study on energy efficiency rather than their earlier one on greenhouse gas emissions (McKinsey 2007).

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.

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 savings 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.

3. OUT-OF-POCKET EXPENSES UNDERSTATE OPPORTUNITY COSTS

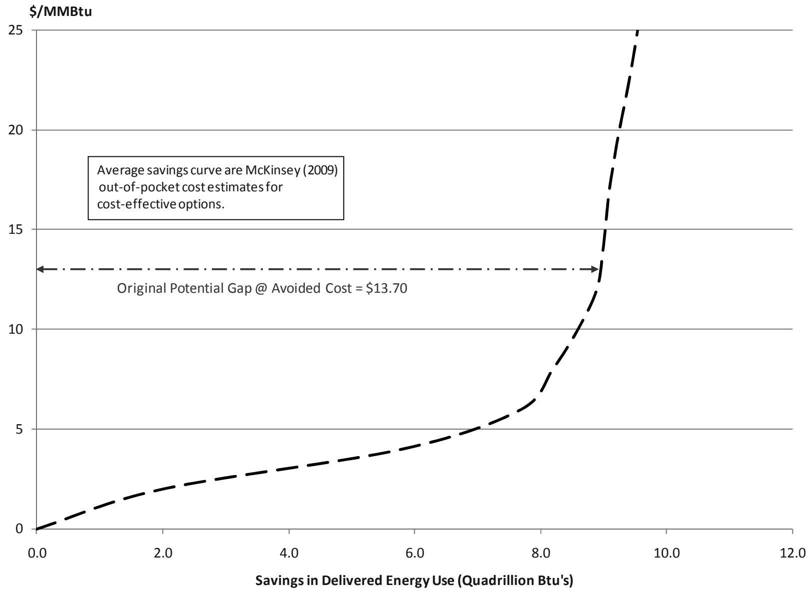
The principal difference between the energy-economy models and potential energy studies lies in how they represent the behavior of individual investors and adopters of new technologies. The potential energy approach focuses on the *optimal* energy efficiency achievable under *ideal* conditions given 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 and realism of removing these barriers.

A useful perspective 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 before and after these adjustments to understand their relative importance.

4. POTENTIAL ENERGY SAVINGS

Figure 2 represents the essential shape and position of the potential energy-efficiency cost curve developed by McKinsey and Company (2009), displaying total costs per million Btu of energy on the vertical axis and the level of quadrillion Btu of energy savings on the horizontal axis. Many options are cost

Figure 2: Energy Efficiency Cost Curve (Based Upon McKinsey)



effective using their estimate of avoided costs equal to $13.70 per million Btu in their reference case (based upon the 2008 Annual Energy Outlook). Although they may require greater equipment costs, they produce more net energy savings that reduce total costs below the reference level.

This cost curve shows the economic potential for energy-efficiency improvement. 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 cost curve also ignores the likely rate of adoption across a diverse group of energy consumers. The chart shows that fully employing all these potential options could save 9.1 quadrillion Btu annually by 2020. These net savings are labeled as the "original potential gap" in the figure.

While the potential energy curve focuses on out-of-pocket direct expenditures by consumers, general economic equilibrium frameworks or hybrid process-economic models of the energy market adopt a very different approach. They view costs much more broadly as the total opportunity cost associated with reducing energy use. Opportunity costs refer to what the consumer foregoes when he invests in improving his energy efficiency. If the consumer needs to change the quality of lighting or other dimensions of the service activity to reduce his energy use, he may suffer an intangible or nonmonetary loss. If society needs to implement new policies and monitor their operation, someone in the society needs to pay for these increased costs. Analysts often term these expenses as hidden or intangible costs, because the consumer and his fellow citizens experience these losses even though they do not pay these costs directly out of their pockets when they buy the equipment.

5. FIVE IMPORTANT REVISIONS FOR BEHAVIOR

The original potential energy cost curve for energy efficiency improvements are adjusted to represent improvements that would be achievable rather than simply optimal under ideal conditions. Rather than selecting any specific model, this approach will select parameters based upon the available literature from energy economics. Although there is clearly some uncertainty about the exact values of these adjustments, this approach provides guidance on why potential energy studies and energy-economy models produce very big differences in their estimates.

The analysis makes the following five sequential revisions:

- excluding consumers with higher than average costs within any given end-user category;
- upper limits on how far a new technology could penetrate the market within a specified time horizon;
- rebound effects encouraging more energy use as operating costs decline;
- fuel and power market responses to large reductions in aggregate energy use;
- costs for developing new institutions or implementing policy changes.

These changes represent modifications that can be easily incorporated into the cost curves as reported in the McKinsey study. Other changes that could have been incorporated might include intangible benefits or costs in the quality of the service, higher discount rates in the range of those consumers pay on their credit cards, and risks in future energy prices and the performance of new technologies that may experience reliability problems. Including these factors would most likely make the energy efficiency cost curves appear more similar to the results from engineering-economic models, but these concepts are more difficult to incorporate without better information about the details behind the technology cost estimates.

The Flaw of Averages.[6] The original technology cost curves may overstate the adoption rate at different cost levels because consumers face very *heterogeneous* demographic, economic and technical conditions. For any technology class, all consumers in an economic potential study adopt under the same uniform

6. Savage (2009) provides an insightful discussion of the problems with representing an uncertain outcome with its average value.

conditions. In the real world, only about half of the consumers will find it economic to switch when the analysis uses the median economic costs. Consumers with costs that exceed the representative value for the group will not adopt under these conditions.

This situation creates a "flaw of averages" problem because potential energy-efficiency studies assume that everybody adopts 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. Optimal evaluations assume that everyone buys when costs per unit of energy saved reach the average rather than when they reach the level paid by the high-cost adopter (the San Francisco home owner).

New Technology Diffuses Slowly. Adoption of even the best new technologies is seldom universal. Furthermore, the diffusion often takes many decades, certainly more than the next ten years shown in Figure 2 above. Within a 20 or 30 year period, even the most aggressive new technologies (cell phones, VCRs, microwave ovens) do not reach much beyond 80 percent of the total market. Reliability is an important concern with many new energy-efficient equipment, just as they are with any new consumer appliance.

Rebound/Income Effect. Households may use their furnaces or vehicles more intensively because the equipment is cheaper to operate when they are more energy efficient (often referred to as the "direct rebound" effect). More importantly, they will use their energy savings on these activities to buy other goods that will use energy (often referred to as the "indirect rebound" effect). Energy savings are likely to be permanent changes in consumers' net income because they continue every year. Permanent changes in income are likely to be allocated to the purchase of durable goods (e.g., televisions) that are often relatively energy using. Unless households and firms convert all their energy savings into bank accounts, this additional income will expand energy use through the income effect and will offset to some extent the initial energy demand reduction. If the income elasticity for all energy or electricity approaches unity, this effect due to additional income could be substantial.

Although economic potential studies calculate energy savings in considerable detail, they often fail to allow consumers to respend these savings on other goods and services. When these other activities also require some energy usage, the original energy savings will be offset as consumers change their spending patterns.

The "rebound/income" effect combines both direct and indirect rebound responses by assuming that part of the initial energy savings is lost. More energy-efficient vehicles, furnaces and other equipment have two competing effects. While they reduce the fuel-intensity in that activity, they may also encourage greater activity levels by reducing operating costs or in some cases improving the quality of that service. Even if the demand for that energy service does not increase directly from its lower costs, consumers will use their energy savings to purchase other products and activities that do use energy.

Market Interactions or the "Fallacy of Composition". 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. This "markets" 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.

Suppose that the country finds about 23 percent more energy supplies by 2020 than they had expected otherwise. Most energy-economic models would allow these increased supplies to pull energy prices downward, as producers would search for new markets to sell their additional energy supplies.

Similar forces operate when the economy aggressively reduces its energy use by 23 percent by 2020 (as in the potential energy gap depicted in Figure 2). Sharp reductions in energy use would create massive energy surplus conditions that would pressure energy producers to reduce their prices in a search for new markets. Markets would adjust to these new lower price conditions in two ways. First, producers would decide to reduce their higher-cost energy supplies because they would find it more difficult to cover their incremental costs when demand shifts downward. And second, energy consumers would gradually learn that their investment in energy-efficiency improvements was not as attractive as they had originally thought. Lower future energy prices would translate directly into lower energy savings and hence reduced investment profits.

This problem represents the "fallacy of composition" inherent when there are many consumers. Each individual consumer expects large profits, provided that all other consumers do not act. But if each consumer acts, their aggregate effect from many individual decisions erodes the potential profits. Gradually, consumers will begin to realize that energy prices with the new market conditions are lower than they had expected and decide to defer some of their energy-efficiency investments. Market interactions are difficult to include without a comprehensive model that merges technology performance and energy market dynamics, but they are a very real phenomenon that need to be incorporated.

Policy Costs. Many government programs for setting standards and monitoring efficiency investments are costly to implement. The previous revisions adjust the private costs for the potential investor in energy efficiency. Even with these changes, it may be that consumers will not invest in all profitable options because myopic behavior or poorly developed institutions prevent this investment. New institutions, rules and programs would be needed to unleash new investment activity and monitor their success through utility-sponsored review. These policy and program changes, however, involve costs that must be borne by taxpayers or utility customers. Society should implement these policies and programs only when they cost less than the derived societal benefits that they provide to all citizens.

It is unknown which policy instruments the government would use. The policy costs will probably vary greatly by instrument and within an instrument like utility demand-side programs or DSM by how it is applied (Nadel & Geller, 1996). Gillingham *et al.* (2006, 2009) provide useful reviews of the costs of energy efficiency programs. As they explain, the most reliable estimates refer to the demand-side-management (DSM) programs operated by individual electric utilities, because these programs must be filed with state regulators. Even with these programs, however, estimating the costs of these programs can be quite contentious and imprecise as the data is often poor.

6. COMPUTING THE REVISED COST CURVES

These cost adjustments are computed in the following way. A general cost curve for improving energy efficiency relates the additional out-of-pocket expenditures for each level of energy use reductions

$$C = A[f(q)] \qquad f_q > 0$$

where C represents the incremental cost, A is a constant parameter, and $f(q)$ is a non-linear function of energy-efficiency improvements, q. Incremental costs for initial equipment expenditures, operation and maintenance of the equipment, and energy expenses rise as consumers adopt increasingly more expensive energy-efficiency improvements. Based upon technology studies, certain values A* and q* can be substituted into this cost function to yield the out-of-pocket costs for each level of energy-efficiency improvement along the energy-efficiency frontier curve

$$C^* = A^*[f(q^*)]$$

where C^*, A^* and q^* are cost and quantity indicators for the potential energy savings curve.

Incorporating the relevant opportunity costs into this relationship involves a series of algebraic manipulations that need to be organized in a logical order. The fully specified, adjusted cost curve is a variant of the potential-energy cost curve and can be represented as:

$$C = [(1+\delta)A^* + \pi\ ] \quad f[\alpha(1-\beta)(q^* - \Delta)]$$

Beginning at the far right side of the equation, the potential level of energy-efficiency improvements (q^*) must be adjusted downward by an amount (Δ) to exclude those applications that are more costly than the average or representative application within each end-use energy consumer cohort. In these calculations, consumers are aggregated into broad blocks of users making similar technology choices. Fifty (50) percent of each block’s energy consumption has been excluded, before adding the remaining 50 percent of the block's consumption to the previous block's potential consumption. Thus, once the curve moves to a new higher-cost block, all consumers in the previous block are considered to be cost effective.

These achieved improvements must be further adjusted for two other effects: (1) the percentage of adopters (α) in the total population and (2) any additional energy use generated by the rebound effect (β). The analysis 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. Over time, the adopters group expands but it is likely to remain below 80 percent even for the most attractive options.

Although measured rebound effects appear to vary greatly by service activity, estimates suggest that the direct rebound effect ranges between a lower bound of 10 percent and a higher bound of 30 percent of the improved efficiency across a range of different OECD countries (Sorrell *et al.* 2009).[7] We have calibrated the rebound/income effect to a mid-range estimate of this range, indicating that the economy overall loses 20 percent of the initial efficiency improvements represented by more energy-efficient equipment. Some analysts will consider this effect to be too large, while others will find it too small.

The final two effects operate through the constant term that influences costs. If all consumers rush to buy options that improve their energy use, energy prices in the system will change. Greater energy conservation will reduce energy prices and the value of future energy savings, making some of the original opportunities uncompetitive. This effect will proportionately raise the net costs of these options by a given percent, δ, times the percentage reduction in energy consumption achieved through energy efficiency improvements shown on the horizontal axis.

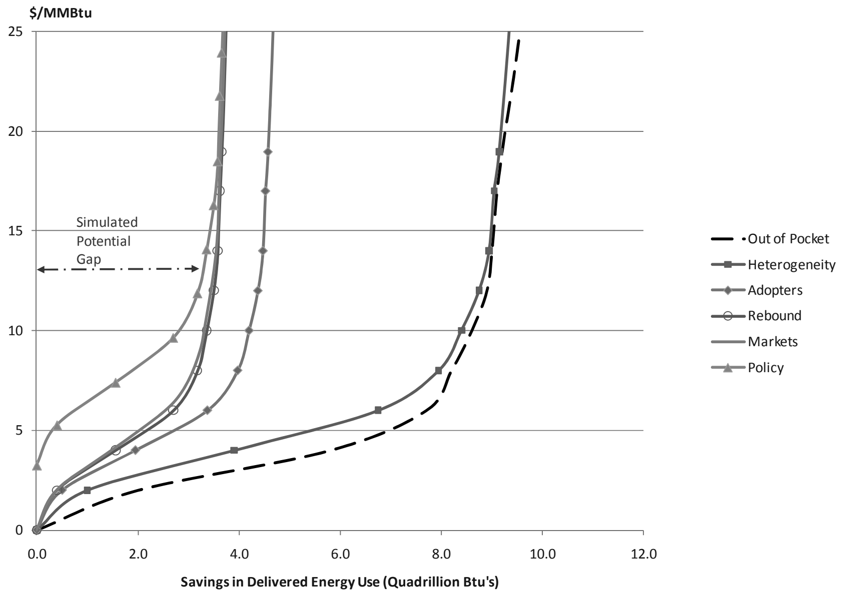
A simple rule for market interactions or feedbacks can be based upon the response of energy supply and demand to price changes. If these two responses each are moderate but still price inelastic, fuel and power prices would decline by 1 percent for every 1 percent reduction in energy use initially achieved through energy-efficient investments. This market adjustment is a long-run adjustment that occurs gradually between now and the year 2020. Allowing them to have lower responses to price would quickly escalate the size of the price response.[8]

The final adjustment includes the additional costs (π) of designing, implementing and monitoring energy-efficiency programs. Policy costs for all en-

7. These estimates are the most recent and comprehensive. The higher estimates in their range are higher than those derived by Greening *et al.* (2000).

8. The 1 percent price response is based upon long-run price elasticities of supply and demand each equal to 0.5. Thus, an initial 23 percent reduction in aggregate energy consumption would reduce fuel and power prices by 23 percent ($= 23\%/(0.5 + 0.5)$). Reducing both elasticities to equal 0.3, the corresponding price rule escalates to about 38 percent. Allowing both elasticities to increase to 0.9 results in a price rule of 13 percent.

Figure 3: Energy Efficiency Cost Curve After Adjustments (for 2020)



ergy-efficiency improvements are set at 1.1 cents per kilowatt-hour (kWh), based upon California utility DSM programs for 2006-2008 (Sathaye and Phadke, 2010). This estimate covers the direct administrative costs incurred by the utilities and excludes the rebates given to program participants. Treating rebates as a pure transfer, however, may not be warranted if the rebates impose additional costs through higher electricity rates for program participants and nonparticipants. This relatively conservative estimate of policy costs equals 11 percent of the average U.S. retail electricity price for all sectors in 2008. Including the distortions created by rebates and using different data for the nation rather than for California alone, Gillingham *et al.* (2006, 2009) suggest higher program costs of 3.4 cents per kilowatt-hours (kWh).

Although there are undoubtedly some upfront costs in designing these programs, many costs are ongoing each year. Regulators need to adjust rules and monitor the resulting investments to ensure that they do reduce energy use according to some pre-defined specifications. In this sense, many policy implementation costs appear to be continuous rather than only an upfront initial expense.

7. RESULTS FOR REVISED COST CURVES

The cost curves in Figure 3 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 should be included. For example, many new technologies are riskier with a greater failure rate than existing options. Adopting these capital-intensive options will become more expensive when they fail, because energy savings will stop once the equipment has failed unless additional investments are made. 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, reducing the energy-efficiency gap (the horizontal distance left of the adjusted cost curve). 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 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. On the other hand, if research and government agencies could identify those programs that imposed less costs, these opportunities would expand relative to those shown in Figure 3. 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 in the purchase of energy-efficient options—could prevent the gap in potential energy efficiency from closing completely. These factors have been discussed extensively by other researchers.[9] 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 additional 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.

After all five effects are incorporated, the size of the energy-efficiency gap is reduced to about one fourth of its original size. The full-cost efficiency improvement curve has shifted significantly higher from its original, out-of-pocket position, even though the 7% discount rate and the out-of-pocket costs and performances of the underlying technologies have not changed as the curve shifts inward.

Although the cost adjustments have been linked to other empirical evidence to the extent possible, it is readily acknowledged that analysts and deci-

9. For example, see the references in footnote 3.

sionmakers may disagree on the appropriate adjustments for each effect. The main value of Figure 3 is to convey to the policymaker that alternative assumptions about behavior and institutions can lead to strikingly different results, even though one applies the same assumptions about technology costs and performances.[10]

8. POLICY IMPLICATIONS

There are two broad implications for policymaking from this analysis. First, policy decision makers cannot escape their responsibility for basing their policy options on how they expect the real world to operate. If decisions about energy use are simply a comparison of initial equipment and future energy savings, policymakers may prefer simple out-of-pocket expense analyses. These estimates are definitely simpler to understand, although all too often they are constructed in a manner that hides what is done under the disguise of pleas for "proprietary data or information" that cannot be released to those whom they are trying to convince.

More frequently in our complex society, decisions are much more complicated. Consumers do not simply tabulate their direct gains and losses and choose the option that allows them to spend the least amount of money. They are often motivated by a number of other factors, some of which are not always as easily measured or represented. It is important to acknowledge these factors explicitly and that they have important influences on people's final decisions. Encouraging more energy efficiency shares many important challenges with other problems where policymakers want to modify behavior. It is probably no easier, for example, than trying to convince an overweight population to reduce their food caloric intake.

The second important implication is that policymakers need more sustained research on how consumers behave and which policies are the lower-cost options. Policies for improving energy efficiency are surprisingly expensive to implement on average, partly due to the diversity of applications.

Improving both energy-economy 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.[11]

This research will not only allow a more realistic assessment of different policy options but will also improve how research teams represent these opportunities in their energy-economy models.

10. A separate spreadsheet is available from the author that shows the effect of different parameter values on the adjusted cost curve.

11. 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., D. Mountain, 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 (2011). *Energy Efficiency and Climate Change Mitigation*, Stanford University, Stanford, CA.

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.

Greening, L.A., D.L. Greene and C. Difiglio (2000). “Energy efficiency and consumption—the rebound effect—a survey.” *Energy Policy* 28(6–7): 389–401.

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., M. Jaccard, and K. Tiedemann (2005). “Improving Behavioral Realism in Hybrid Energy-Economy Models Using Discrete Choice Studies of Personal Transportation Decisions,” *Energy Economics*, 27: 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.

Nadel, Stephen and Howard Geller (1996). “Utility DSM: What Have We Learned? Where Are We Going?” *Energy Policy* 24(4): 289–302.

Sathaye, Jayant and Amol Phadke (2010). “Energy Efficiency Cost Curves: Empirical Insights for Energy-Climate Modeling,” in *Modeling the Economics of Greenhouse Gas Mitigation: Summary of a Workshop,* National Research Council, Washington, D.C.

Savage, Sam L. (2009). *The Flaw of Averages: Why We Underestimate Risk in the Face of Uncertainty*, Hoboken, N.J.: 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.

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.

Energy and Emissions in the Building Sector: A Comparison of Three Policies and Their Combinations

Owen Comstock and Erin Boedecker***

Standards, subsidies, and carbon taxes are among the measures often considered to reduce energy consumption and carbon dioxide (CO_2) emissions in the buildings sector. Using a modeling system developed by the U.S. Energy Information Administration, residential and commercial sector standards and subsidies were each modeled with and without a carbon tax to determine if a multi-policy approach would be redundant. A separate case examining a carbon tax was also completed for comparison. Between the two equipment-based policies, subsidies achieved more energy and CO_2 emissions reductions at less cost to consumers, as incremental investment costs were shifted to the government. When either of the equipment-based policies was combined with a carbon tax, their energy- and carbon-reducing effects were more additive than redundant.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-3

INTRODUCTION

The U.S. Energy Information Administration (EIA) participated in Stanford University's Energy Modeling Forum-25, "Efficiency and the Shape of Future Energy Demand" (EMF-25). A primary focus of EMF-25 was how energy efficiency[1] opportunities influence trends in energy demand. This included anal-

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Corresponding author. U.S. Energy Information Administration, U.S. Department of Energy, Forrestal Building, EI-32, 1000 Independence Avenue SW, Washington, DC 20585.

** U.S. Energy Information Administration, Office of Energy Consumption and Efficiency Analysis.

The analysis presented here is based on policy assumptions provided by participants in Stanford University's Energy Modeling Forum and individual analysts of the U.S. Energy Information Administration (EIA). The views in this report therefore should not be construed as representing those of EIA, the Department of Energy or other Federal agencies.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-3

1. Throughout this paper, the term 'efficiency' is discussed as the ratio of output to input, or a service provided relative to the energy fuel required. In this way, technology efficiency does not affect

ysis of the relative effectiveness of multiple approaches to reducing energy consumption and carbon dioxide (CO_2) emissions. The two policies investigated by EIA were the use of residential and commercial standards (appliance standards, building codes) and subsidies for energy-efficient residential and commercial equipment. A carbon tax case was also developed for comparison with these policies. Furthermore, two additional cases were created: one that combines the Standards case with a carbon tax and another that combines the Subsidies case with a carbon tax. These additional cases provided insight into the extent to which efficiency and tax policies were substitutes or complements.

The analysis was completed using the National Energy Modeling System (NEMS), which is maintained by EIA. The NEMS is an integrated, energy-economy model of U.S. energy markets that projects energy production, imports, conversion, consumption, and energy prices. When the modeling work for EMF-25 was undertaken, NEMS produced projections through 2030. The inputs to NEMS were revised to reflect a combination of assumptions adopted by all EMF modelers and some specific to EIA.

CASE DESCRIPTION

The Reference case used for this analysis is based on the *Updated Annual Energy Outlook 2009* (*AEO2009*) Reference case[2] completed in March 2009, which includes provisions from the American Recovery and Reinvestment Act (ARRA) and reflects the drastic changes in the macroeconomic environment that occurred during 2008.

The residential and commercial appliance standards in the Standards case follow the Congressionally-legislated schedule for implementation, but since the future efficiency levels of the standards are ultimately set by the Department of Energy prior to the rulemakings—and thus not currently known—anticipated efficiency levels were determined by EIA analysts' judgment. Expected levels of future standards are not included in the Reference case, as future standard levels are difficult to anticipate. The schedule and assumed efficiency levels for equipment in the Standards case are provided in Appendix A.

Equipment not currently covered by standards (e.g. televisions, set-top boxes, hot tubs) is not considered in the Standards case. Furthermore, subsequent standards after 2018 were not considered. The rulemaking for standard levels involves detailed market assessment, making appropriate post-2018 standard efficiency levels difficult to predict. Equipment costs were not reduced in the Standards case, even though increased market penetration would likely result in cost declines for newly-standardized advanced equipment.

the quality of service, while other reduction measures might result in reduced service. For example, energy reductions such as conservation would not be considered efficiency, as conservation lowers both output and input.

2. U.S. Energy Information Administration, "Updated Annual Energy Outlook 2009 Reference Case Service Report" April 2009. http://www.eia.doe.gov/oiaf/archive/aeo09/index.html

Building codes in the Standards case were adopted from legislation proposed by Representatives Henry Waxman and Edward Markey in the American Clean Energy and Security Act (ACESA).[3] In ACESA, the national building code efficiency target improves 30 percent upon bill enactment and 50 percent by 2015. Subsequently, 5-percent improvements are implemented every 3 years. States are assumed able to comply with codes within 5 years of code adoption. State-level compliance scores[4] are aggregated to the Census division level by population so that each Census division complies consistent with the historical level of code compliance. Commercial building code improvement is measured relative to the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) code 90.1-2004; residential building code improvement is measured relative to the International Energy Conservation Code (IECC) 2006.

In the Subsidies case, residential and commercial purchasers of energy-efficient equipment received subsidies equal to one-half of the incremental cost between base-level equipment and advanced equipment. These subsidies were calculated for each equipment class. For instance, this means that only the more efficient ground-source heat pumps receive subsidies, even though base-level ground-source heat pumps are more efficient than equipment in other equipment classes, such as natural gas furnaces or electric radiators. While fuel switching might lead to energy and emissions reductions in some cases, no subsidies were provided for fuel switching so that program funds would be applied to equipment costs, not installation costs. Additionally, subsidies for building shell improvements were set to offset half of the incremental cost between advanced residential building shell levels and minimum-level codes.

The EMF working group established assumptions for the carbon tax case. The price of carbon for all energy sources was set at $30 per ton of CO_2 in 2010, increasing at 4.7 percent real escalation annually through the projection.[5] Revenues from this tax were recycled back to the economy, not by funding energy-efficiency programs, but with rebates to each household.

The carbon tax assumption was added to three cases: the Reference case, the Standards case, and the Subsidies case. Policy makers often consider a portfolio of approaches to reduce energy consumption and CO_2 emissions. By combining the carbon tax with each of the energy-efficiency program cases, the additive or substitutive effects of the carbon tax can be examined.

3. U.S. Energy Information Administration, "Energy Market and Economic Impacts of H.R. 2454, the American Clean Energy and Security Act of 2009, Appendix B: Representing H.R. 2454 in the National Energy Modeling System" August 2009. http://www.eia.doe.gov/oiaf/servicerpt/hr2454/appb.html

4. American Council for an Energy-Efficient Economy, "2009 State Energy Efficiency Scorecard" October 2009. http://www.aceee.org/sector/state-policy/scorecard

5. All monetary figures in this document are expressed in year 2007 dollars. Cumulative amounts are in year 2007 dollars discounted back to 2010 at a 7 percent real discount rate.

MODELING APPROACH

The technology menu for residential energy consuming equipment and building shells in the NEMS includes 87 different equipment types within nine different end uses (space heating, water heating, dishwashing, lighting, etc) and five levels of building shell integrity for new construction for each Census division and housing type (single-family, multi-family, and mobile homes).[6] The commercial sector technology menu includes 63 equipment types in ten end uses (cooking, ventilation, office equipment, etc).[7] Unlike the residential module, the commercial module does not have explicit building shell options. Instead, defined annual improvements in new and existing building shells affect heating and cooling requirements for eleven commercial building types (large office, education, assembly, health care, mercantile, etc.).

The technology-rich modeling approach allows for the straightforward implementation of the Standards and Subsidies case assumptions. In the Standards case, any substandard equipment or building shell level is made unavailable in the year the standard is implemented and all years thereafter. Subsidies were modeled by reducing incremental purchaser costs between base-level equipment and more efficient alternatives by 50 percent. For instance, if a base-level refrigerator costs $600 and a more efficient refrigerator costs $700, the value of the subsidy is $50, making the advanced refrigerator's new purchase cost $650. Similarly, advanced building shell levels were subsidized at half of the incremental costs above the base shell level.

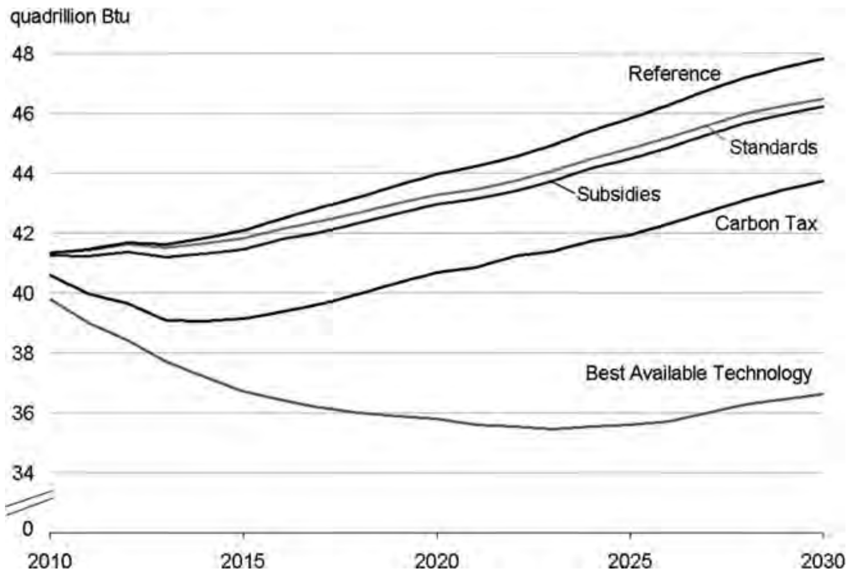
The carbon tax was modeled as a $30 per metric ton tax on CO_2 across all sectors. The $30 per ton tax starts in 2010 and increases by 4.7 percent annually until 2030. The carbon tax revenue—a present value calculated at over $2.6 trillion—was mostly returned to consumers by lump-sum reductions in personal taxes. Before providing these reductions, the macroeconomic module used a portion of the funds to keep the Federal deficit at Reference case levels, thus ensuring deficit neutrality. Due to the deficit-neutrality constraint, the amount returned to consumers in reduced personal taxes does not equal the total amount of carbon tax revenue collected.

The two multi-policy cases involved combining the assumptions for the carbon tax with either the Standards or Subsidies case assumptions. Since the assumptions affected different aspects of the model, there were no conflicting or redundant assumptions when policies were combined.

6. U.S. Energy Information Administration, "The National Energy Modeling System: An Overview: Residential Demand Module" October 2009. http://www.eia.doe.gov/oiaf/aeo/overview/residential.html

7. U.S. Energy Information Administration, "The National Energy Modeling System: An Overview: Commercial Demand Module" October 2009. http://www.eia.doe.gov/oiaf/aeo/overview/commercial.html

Figure 1: Buildings Sector Total Energy Consumption in Five Cases, 2010–2030



ANALYSIS OF RESULTS

The stated goal of these policies is to reduce energy use and CO_2 emissions. Standards and subsidies focus on buildings sector efficiency to reduce energy use, with CO_2 reductions as a secondary effect. A carbon tax works by raising the cost of using carbon-intensive energy sources, resulting in higher energy prices that lead to reduced energy use and CO_2 emissions.

The equipment-related policies were analyzed to determine if the equipment investments were justified by lower fuel bills. The cost impacts of the Carbon Tax case as it relates to the buildings sector are more difficult to discern, as the focus is on U.S. energy markets as a whole where macroeconomic effects are significant enough to affect any direct comparison to the other policies analyzed. Since most of the tax revenue is returned to consumers in the form of personal tax rebates, consumers receive the benefits of a tax levied on all sectors, not just buildings.

Total Energy Consumption

Figure 1 compares the total energy consumption in the three single-policy cases to consumption in the Reference case and the *AEO2009* Best Available Technology case. The Best Available Technology case is one of several alternate cases with different technology assumptions to determine the impacts of technology improvements on end-use energy consumption. It assumes that consumers always purchase the most efficient equipment (without switching fuels) and building shells for new and replacement purchases. Maximum efficiency, not cost-effectiveness, is the priority in the selection process, meaning consumer welfare is disregarded. This case does not include significant retrofitting, however, as the rate of stock turnover is consistent with that of the Reference case. In the absence of aggressive retrofitting, fuel switching, or a price on carbon emissions, the Best Available Technology case represents the maximum energy reduction possible through application of technology alone.

Although consumer choices for end uses or building shells are not limited in the Carbon Tax case, total energy consumption is about 18 percent below the Reference case in 2030 in response to higher energy prices. The smallest reduction in energy consumption, 5.8 percent below the Reference case in 2030, is in the Standards case where higher appliance standards are limited to one additional round of standards for certain end uses between 2012–2018 and improved building codes only affect new construction as they are phased in over time. The Subsidies case, which affects more end uses, has a greater impact on energy consumption: 7.3 percent below Reference case levels in 2030. The Best Available Technology case shows the maximum potential of technology on energy consumption in the buildings sector. By forcing purchase of only the most efficient equipment in each equipment class without regard to cost-effectiveness in reducing energy use and/or CO_2 emissions, energy consumption in the buildings sector is reduced by almost 49 percent by 2030.

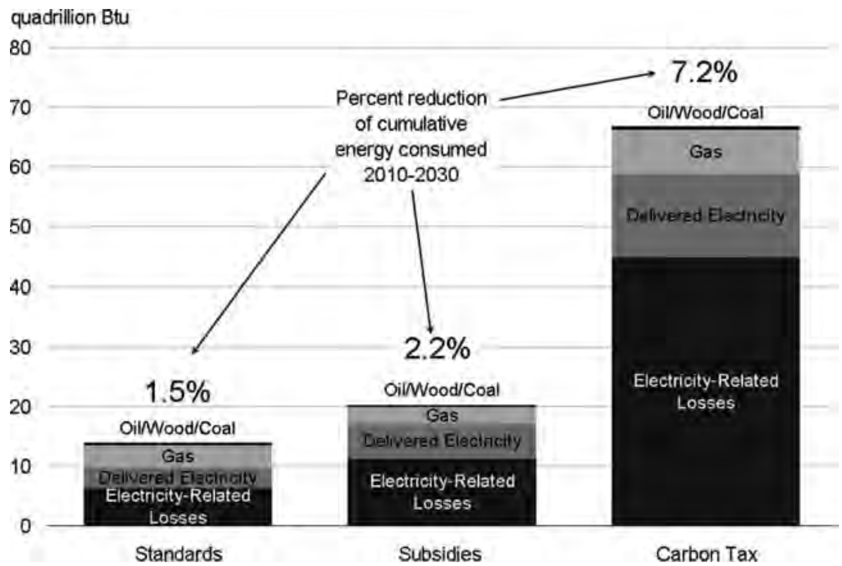
Energy Savings by Fuel

Although the policy assumptions are not intended to favor any particular fuel, the results show that the fuels are impacted in different ways. In the Reference case, cumulative total energy consumption in the buildings sectors from 2010 to 2030 is distributed as follows: electricity, 24 percent; natural gas, 19 percent; and other fuels, 5 percent. Losses in the generation, transmission, and distribution of electricity account for the remaining 52 percent of total energy consumption.

Figure 2 shows the reduction in cumulative total energy consumption in total and by fuel from 2010 to 2030. Cumulative total energy consumption in the buildings sector is 1.5 percent lower in the Standards case and 2.2 percent lower in the Subsidies case than in the Reference case. Cumulative total energy consumption in the buildings sector is reduced by a greater 7.2 percent in the Carbon Tax case with over two thirds of the savings in the form of reduced electricity-related losses.

In the Standards case, the reduction in total energy consumption is more evenly distributed across the fuels: delivered electricity and natural gas each account for about a quarter of overall decline in total energy consumption, and about three percent of the reduction is in oil, wood, or coal consumption. This

Figure 2: Buildings Sector Energy Reductions by Fuel, Cumulative Savings 2010–2030

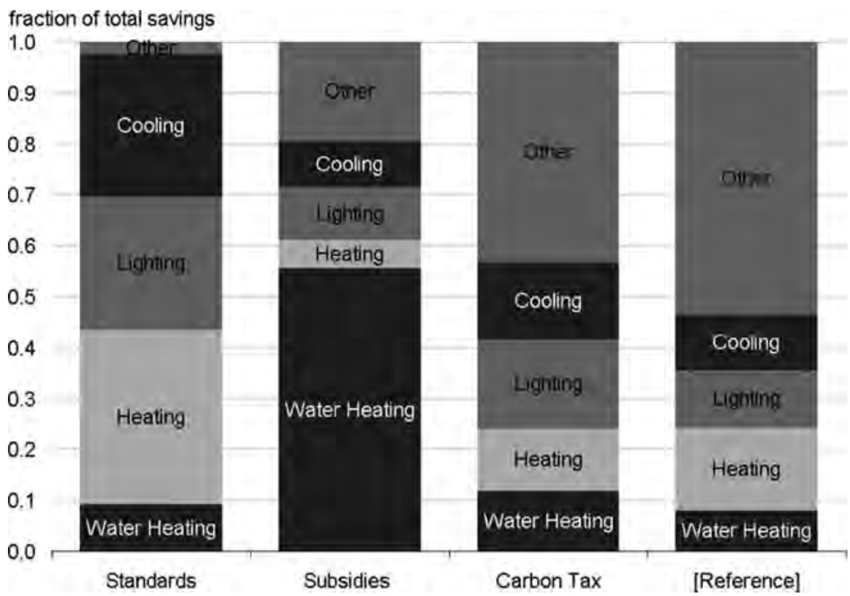


reflects the fact that most of the major gas-powered end uses are covered by standards (heating, water heating, cooking), while several electric-powered end uses are not covered by standards. Stricter building codes and the resulting increase in building shell efficiency also contribute to the reduction in gas use for space heating. Still, the bulk of the savings (45 percent) are in electricity-related losses.

As a percentage of reduction in total energy consumption, there are more savings in electricity-related losses (55 percent) in the Subsidies case than in the Standards case. Further, the decline in delivered electricity consumption is about twice the reduction in gas consumption (29 to 14 percent, respectively). Oil, wood, and coal account for the remaining two percent. Proportionately, these percentages largely mirror the fuel shares in the Reference case, reflecting the assumption that subsidies are applied to all advanced equipment, regardless of end use or fuel.

The Carbon Tax case is dominated by reductions in electricity-related losses (67 percent). Delivered electricity accounts for another 21 percent of the reduction in total energy consumption, while natural gas, oil, wood, and coal combined account for 12 percent of the reduction. This result demonstrates the impact of the carbon tax on the electric power sector, driving not only the need for less generation but also de-carbonization by switching to less carbon-intensive generators.

Figure 3: Buildings Sector Energy Reductions by End Use, Fraction of Cumulative Savings 2010–2030



Energy Savings by End Use

Figure 3 shows each end use's contribution to the cumulative reduction in buildings sector total energy consumption in the Standards, Subsidies, and Carbon Tax cases as compared to the Reference case. In the Reference case, cumulative energy consumption in the buildings sector from 2010 to 2030 is distributed among the end-use services as follows: 16 percent for heating, 11 percent for cooling, 11 percent for lighting, 8 percent for water heating, and 54 percent in other end uses.

The cumulative reduction in energy consumption in the Standards case is spread over the four largest end uses, while the reduction in the Subsidies case is dominated by water heating. The difference between the two is largely explained by the assumptions adopted in each case. In the Standards case, relatively modest increases in electric and natural gas water heater standards are assumed to go into effect in 2013 and those standards are not revised over the projection. Meanwhile, in the Subsidies case the incentives to encourage the use of more efficient water heaters continue to increase throughout the projection. Another difference between the cases results from the purchase of residential solar water heaters. While the Standards case's adoption of solar water heaters is similar to that of the Reference case, the Subsidies case shows a nearly thirty-fold increase in the use of solar water heaters due entirely to the effect of the subsidy.

Beyond the four main end uses, the ‘Other’ category differs greatly across the cases due to differences in how the assumptions are adopted in the cases. In the Standards case, relatively few ‘Other’ end uses are covered by standards, so the energy reduction is limited primarily to the main end uses. Reductions in the Subsidies and Carbon Tax cases are more evenly distributed among the end uses, as subsidies affect all advanced equipment and the carbon tax affects all energy use. Energy reductions in the Standards case exceed those in the Subsidies case in residential freezers and commercial refrigerators, which are included in the ‘Other’ category in Figure 3, but considerably more energy is saved in residential clothes washers and commercial ventilation in the Subsidies case, which are also included in the ‘Other’ category.

The carbon tax is applied to all end uses in the Carbon Tax case; however, its impact will vary depending on the fuel mix in each end use. While lighting is only 11 percent of consumption in the Reference case, it is 18 percent of the savings in the Carbon Tax case. The reduction in water heating energy consumption is also larger than its share of consumption in Reference case, accounting for 12 percent of energy savings compared to only an 8 percent share of consumption in the Reference case.

Since the price effects in the Carbon Tax case are likely to influence consumer behavior as well as efficiency levels, the savings in this case include a significant conservation component. Lighting and water heating are two of the most common end uses cited when discussing conservation, as it is relatively simple to turn off lights, take shorter showers, and lower the water heater thermostat. Similarly, the ‘Other’ category includes small electric loads (e.g. small kitchen appliances, digital alarm clocks, battery chargers) that do not have much opportunity for energy reductions through either conservation or efficiency, so they contribute less to the overall savings in the Carbon Tax case.

Carbon Reduction

If the primary policy goal is to reduce CO_2 emissions, then a carbon tax will be more efficient than policies that focus exclusively on end-use technologies in the buildings sector. Figure 4 shows buildings-sector energy-related CO_2 emissions in five cases. The Standards and Subsidies cases have about the same effect on CO_2 emissions, which is less than what is possible with adoption of the most-efficient technologies, as shown by the Best Available Technology case. With price signals experienced throughout U.S. energy markets, the Carbon Tax case shows a greater reduction in CO_2 emissions.

A benefit of the Standards and Subsidies cases compared to the Carbon Tax case is that the changes in the buildings sector are long-lasting. As Figure 5 shows, the equipment changes in these cases will still save energy and emissions long after the policy has ended. Although the NEMS modules were only run to 2030, a simple estimate of future avoided CO_2 emissions from 2030 to 2040 was made by multiplying avoided emissions in the year 2030 by ten. This calculation

Figure 4: Buildings Sector CO_2 Equivalent Emissions, 2010–2030

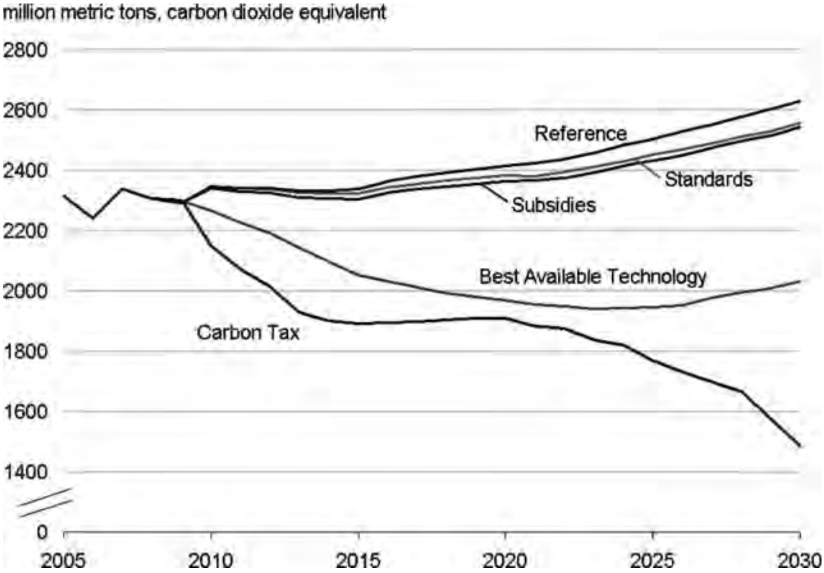
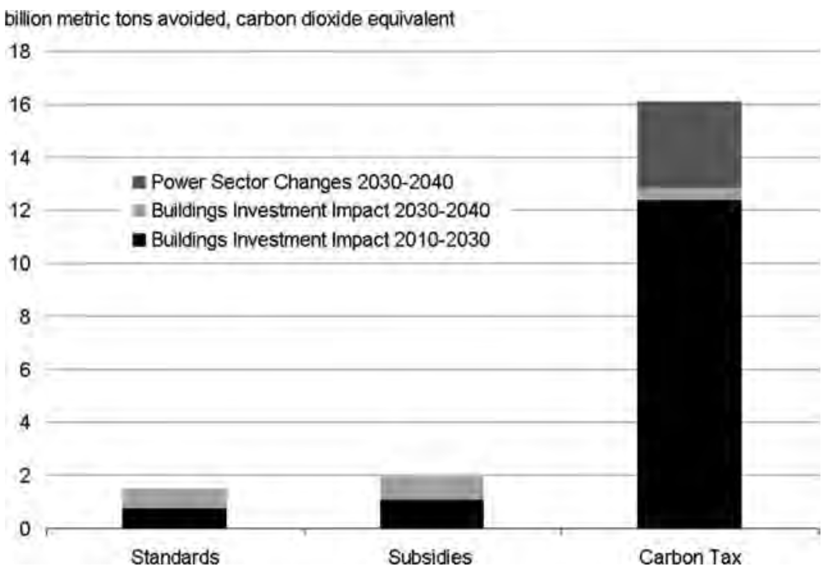


Figure 5: Cumulative CO_2 Equivalent Emissions Avoided, 2010–2030, and Estimates of Future Benefits, 2030–2040



likely underestimates the actual savings in these years, as energy savings grow over time. The estimates show that the CO_2 emissions reductions in the Standards and Subsidies cases for those ten years provides almost as many reductions as the previous twenty years. In the Standards case, equipment investment reduces 744 million metric tons from 2010–2030 relative to the Reference case and an estimated 742 million metric tons in the ten years after 2030. The Subsidies case reduces 1,082 million metric tons from 2010–2030 and 866 million metric tons afterwards.

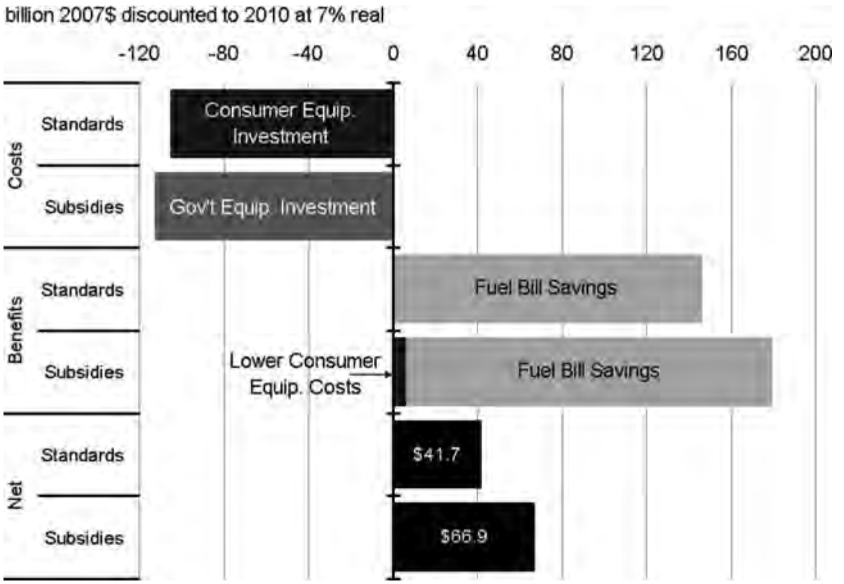
The CO_2 emissions reductions in the Carbon Tax case reflect an increase in delivered fuel prices. If the carbon tax is discontinued, fuel prices will decline, and energy usage will move back toward pre-tax patterns. However, energy consumption will not move completely back to pre-tax patterns since consumers are unlikely to replace the investments made in energy-saving equipment in buildings from 2010 to 2030, while carbon taxes were in effect. It is difficult to discern how much of the reduction in CO_2 emissions from 2010 to 2030 is attributable to equipment changes, as opposed to price-related factors. The Standards and Subsidies cases save, on average, 8.63 cumulative metric tons of CO_2 for each dollar (present value) of equipment investment. Using that average rate, the investment in the Carbon Tax case from 2010 to 2030 would result in an additional 450 million metric ton reduction in CO_2 emissions from 2030 to 2040 in the building sectors, much less than the reduction in the Standards and Subsidies cases.

The greater long-term impact in the Carbon Tax case is in CO_2 emissions from the changes in the electric power sector. Although all of the cases result in less energy demand, the Carbon Tax case is the only policy that encourages decarbonization of the electricity supply mix. The post-2030 impacts in the electric power sector are estimated by multiplying the reduction in non-buildings-related CO_2 emissions in 2030 by ten to arrive at 3,281 million metric tons. This calculation may overestimate future CO_2 emissions reductions, due to unknown changes in the dispatch order of electricity generation plants in the absence of a carbon tax. The impact of standards and subsides on the electric power sector emissions are relatively negligible: estimated at 63 and 80 million avoided metric tons over ten years in Standards and Subsidies cases, respectively.

Energy Price Impacts

Energy prices in the Standards and Subsidies cases were barely impacted by policies. The average residential prices in 2030 were down by 1.2 and 0.6 percent in the Standards and Subsidies cases, respectively, while the average commercial prices were down 0.4 and 1.4 percent compared to the 2030 Reference Case value. In the commercial sector, prices were affected nearly equally across fuels. However, in the residential sector, the average price across fuels hides that natural gas prices rose (1.3 and 0.3 percent) while electricity prices fell (2.8 and 0.7 percent in the Standards and Subsidies cases, respectively). Still,

Figure 6: Net Present Value of Cumulative Savings in Two Cases, Difference from the Reference Case, 2010–2040



these impacts are not large enough to trigger a discernible rebound effect of increased consumption. The Carbon Tax case raised 2030 prices by 23.2 percent in the residential sector and 27.1 percent in the commercial sector resulting in the energy and emissions impacts discussed above.

Buildings Sector Cost Impacts

Cost impacts to consumers are a key consideration in any policy analysis. When standards are considered, the expected fuel bill savings are weighed against incremental equipment investment cost to determine the net present value. Subsidies share the incremental investment cost between the consumer and government in order to incentivize the purchase of efficient equipment. A carbon tax influences prices and thereby influences equipment purchase decisions and electricity generation decisions. Policy-makers must also determine how tax revenues will be used.

Figure 6 and Table 1 show the cost impacts to consumers and the government for the two equipment-focused cases. Administrative program costs are assumed to be similar in cases and are not included in this comparison. Note that all cost impacts are presented as relative to the Reference case, implying that any purchase of advanced equipment present in the Reference case are subtracted from the results of the alternate cases. In this way, the impacts of those who act even in the absence of policy are eliminated.

Table 1: Net Present Value of Cumulative Savings in Two Cases, Difference from the Reference Case, Billion 2007$ Discounted to 2010 at 7 Percent Real, 2010–2040

	Standards	Subsidies
Fuel Bill Savings	147	173
Consumer Equip. Investment	(105)	6
Government Equip. Investment	—	(113)
Total Net Benefit	**41.7**	**66.9**

Furthermore, this analysis focuses on the easily-quantified impacts that consumers and governments realize in the form of investment and fuel cost changes. Additional effects such as the societal benefit of the long-term impacts of avoided carbon emissions or the societal cost of reduced consumer choice in the Standards case are not presented here.

Costs realized from 2010 to 2040 were used in this net present value calculation, as the equipment-related policies will still have benefits in the form of lower energy bills for several years after the policies expire in 2030. Benefits in the decade post-2030 were estimated by extending the 2030 value for ten years.

For the $105 billion that consumers invest in the Standards case, they receive $147 billion in fuel bill savings, resulting in a net benefit of $41.7 billion. Again, equipment costs were not reduced in this case, even though cost declines would be expected due to increased market penetration of newly-standardized equipment.

Investment in the Subsidies case was quite different. Since the costs for advanced equipment were reduced (e.g. a $700 refrigerator now costs the consumer $650 due to the $50 government subsidy), consumers spent $6 billion less on equipment than in the Reference case. Consumers' equipment purchases required government subsidies of $113 billion. Note that the total incremental equipment investment amount from consumers and the government—$106 billion—is almost equal to the equipment investment in the Standards case. This investment in advanced equipment reduces fuel bills by $173 billion, resulting in a net benefit of $66.9 billion.

Consumer impacts in the Carbon Tax cases are much more significant and more difficult to quantify due to macroeconomic impacts. Consumers face higher building-related energy costs in the form of increased equipment investment and increased fuel bills. However, since the carbon tax applies to all sectors of the economy, consumers are also affected by higher costs in other sectors, as virtually all goods and services would be affected by a carbon tax.

Generally, increasing energy prices lead to higher prices in the economy and thus lower economic activity. However, the rebate of carbon tax revenues to consumers can ameliorate the adverse economic impacts on consumers. As this analysis is focused on buildings-sector impacts and efficiency options, overall cost impacts to the economy are not presented.

Buildings Sector Cost-effectiveness

The total net energy expense savings presented in Table 1 can be divided by either the cumulative total energy savings or cumulative CO_2 reductions from 2010 to 2040 to determine cost-effectiveness. Again, post-2030 results were estimated by multiplying the 2030 value of energy savings or CO_2 reductions by ten.

When considering the cost per unit of energy from 2010 to 2040, the Standards case has a benefit of $1.52 billion per quad of total energy saved, while the Subsidies case has a benefit of $1.85 billion per quad saved. With regard to avoided CO_2 emissions from 2010–2040, the Standards case has a benefit of $28.04 per metric ton of CO_2 emissions, while the Subsidies case has a benefit of $34.35 per metric ton of CO_2 emissions.

Additive Effects of Policy Combinations

Standards and subsidies target end-use equipment choices, while a carbon tax affects end-use equipment choices, the utilization of existing and new end-use equipment, and the electricity generation mix. Given these basic differences, it is important to determine if a policy that combined a carbon tax with either standards or subsidies would have overlapping, additive, or superadditive effects, or if one policy would diminish or cancel the other. Two dual-policy cases, Standards + Carbon Tax and Subsidies + Carbon Tax were modeled.

Figure 7 shows how the combined policies impact the reduction in energy consumption. In both situations, combining a carbon tax with an equipment-focused policy, standards or subsidies, results in more energy savings than the sum of the two stand-alone policies would suggest. Combining standards with a tax on carbon decreases energy use by an additional one percent, whereas combining subsidies with a carbon tax decreases energy use by an additional three percent. The additive effects are due to the combined changes made as a result of the policies: consumers are using more efficient equipment while also changing how they use that equipment due to increased prices.

Figure 8 shows the same 'greater than the sum of its parts' effect for the reduction in CO_2 emissions from 2010 to 2030 with the combined policies showing greater reductions in CO_2 emissions in both cases. Combining standards with a carbon tax decreases CO_2 emissions by an additional one-half percent. Combining subsidies with a carbon tax reduces CO_2 emissions by nearly two percent. The additional CO_2 reductions are a by-product of the energy savings in the combined cases: better equipment and changes in consumer usage behavior.

Regarding equipment investment, Figure 9 shows that impacts are subadditive in the combined Standards + Carbon Tax case, as some equipment purchased in response to standards overlaps with equipment purchased in response to a carbon tax, making the policy combination redundant by about 3 percent. In the combined Subsidies + Carbon Tax case, equipment investment

Figure 7: Cumulative Effects of Policy Combinations: Buildings Sector Total Energy Reductions, 2010–2030

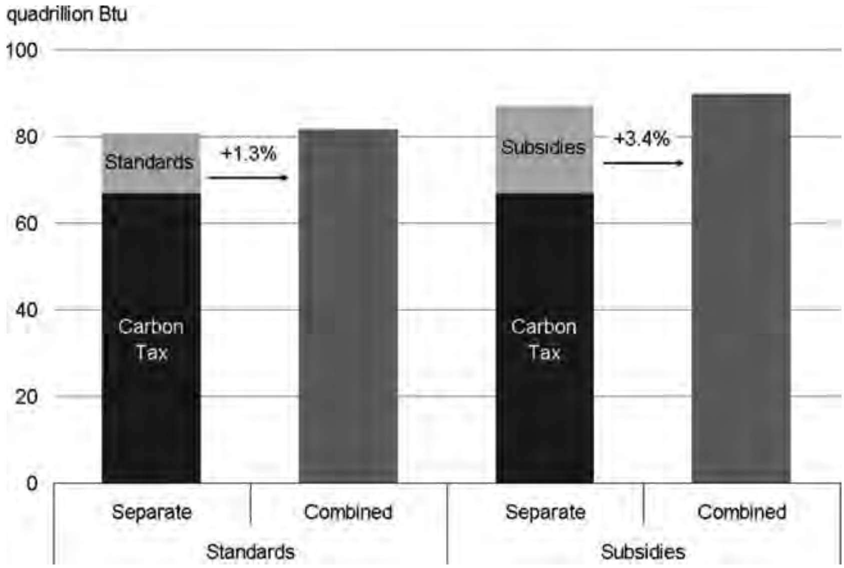


Figure 8: Cumulative Effects of Policy Combinations: CO_2 Reductions, 2010–2030

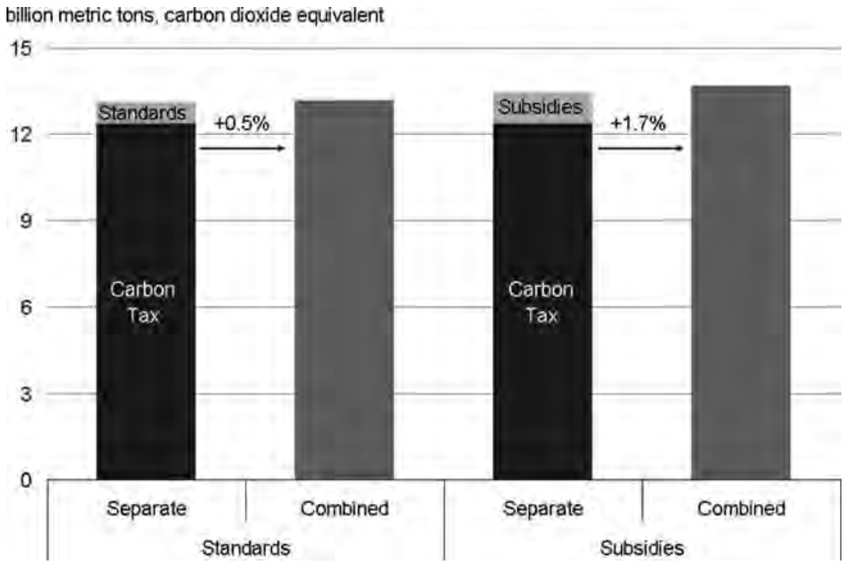
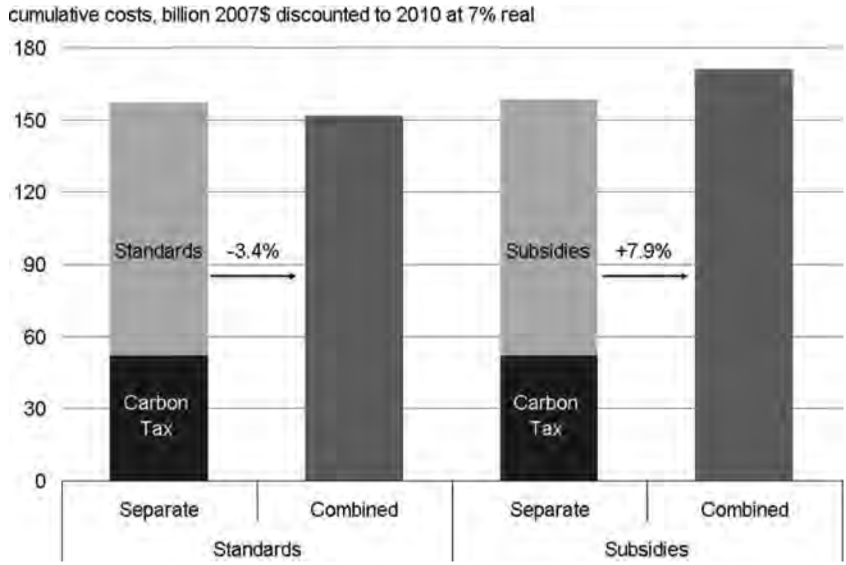


Figure 9: Cumulative Effects of Policy Combinations: Equipment Investment Costs, 2010–2030



impacts are superadditive by almost 8 percent, as increased prices encourage consumers to take advantage of government subsidies on advanced equipment. In this combined case, consumers' incremental investment above the Reference case makes up 24 percent of the overall incremental investment, while the government provides the remaining 76 percent.

CONCLUDING REMARKS

The primary purpose of this analysis was to compare alternative equipment-focused policy approaches to achieve energy and CO_2 reductions in the buildings sector. Between the two equipment-focused policies, standards impose a slight cost to consumers during the projection, but ultimately lead to a net benefit as fuel bill savings continue after 2030. The impact of this policy is limited since not all equipment is covered by standards. Although standards guarantee improved efficiency, they do so by reducing consumer choice. In situations where the utilization of equipment varies widely across consumers due to differences in climate or individual behavior, or consumers located in different regions face a wide range of energy prices, the setting of standards based on average utilization and average energy prices may impose net economic losses on some consumers even if the standards result in a net gain for the average consumer.

Subsidies, when applied to all advanced equipment, have a slightly larger impact than standards. Subsidies may appear more attractive to consumers since the fuel bill savings outweigh their incremental equipment investment, and some of the investment cost is shifted to the government.

Both standards and subsidies policies have significant limitations and are incapable of producing immediate results due to the slow rate of stock turnover. Investments are required up front while the benefits in the form of decreased fuel bills accrue over the span of years or even decades. Unlike a carbon tax, these policies do not encourage either reduced utilization of both existing and new end-use equipment or movement towards a less carbon-intensive electricity generation mix. In this sense, equipment-based policies do not operate on all of the relevant margins for reducing energy use and CO_2 emissions.

APPENDIX A

Table A1: Assumed Residential Standards

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

Installed costs represent total capital costs plus installation costs in real 2007 dollars.

Table A2: Assumed Commercial Standards

Commercial Products	Date	Level	Typical Capacity	Installed Cost
Gas-fired Furnace	2012	82% Thermal Efficiency	400,000 Btu/hr	$3150
Halogen Reflector Lighting	2012	Halogen infrared (IR)	1172 system lumens	$70.60*
Oil-fired Furnace	2012	83% Thermal Efficiency	400,000 Btu/hr	$3900
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
Vending Machines	2012	2400 kWh/yr	700 Btu/hr	$1639
Gas-fired Boiler	2013	85% Combustion Efficiency	440,000 Btu/hr	$9000
Linear Fluorescent Lighting ≤ 4 foot	2014	High efficiency lamps w/ High Efficiency fixture	3500 system lumens	$84.30*
Automatic Ice Makers	2015	3750 kWh/yr	500 lbs/day	$2647
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*
Centrifugal Chillers	2016	6.1 COP	350 tons	$425/ton
Reach-in Refrigerator	2016	2400 kWh/yr	3,000 Btu/hr	$2650
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

*Commercial lighting costs represent lighting system – including lamps/ballast/fixture + installation
Installed costs represent total capital costs plus installation costs in real 2007 dollars.

REFERENCES

American Council for an Energy-Efficient Economy, (2009). *2009 State Energy Efficiency Scorecard*. Document available online at: http://www.aceee.org/sector/state-policy/scorecard.

U.S. Energy Information Administration, (2009). *Energy Market and Economic Impacts of H.R. 2454, the American Clean Energy and Security Act of 2009, Appendix B: Representing H.R. 2454 in the National Energy Modeling System*. Document available online at: http://www.eia.doe.gov/oiaf/servicerpt/hr2454/appb.html.

U.S. Energy Information Administration, (2009). *The National Energy Modeling System: An Overview: Residential Demand Module*. Document available online at: http://www.eia.doe.gov/oiaf/aeo/overview/residential.html.

U.S. Energy Information Administration, (2009). *The National Energy Modeling System: An Overview: Commercial Demand Module*. Document available online at: http://www.eia.doe.gov/oiaf/aeo/overview/commercial.html.

U.S. Energy Information Administration, (2009). *Updated Annual Energy Outlook 2009 Reference Case Service Report*. Document available online at: http://www.eia.doe.gov/oiaf/archive/aeo09/index.html.

Modeling Efficiency Standards and a Carbon Tax: Simulations for the U.S. using a Hybrid Approach

Rose Murphy and Mark Jaccard***

Analysts using a bottom-up approach have argued that a large potential exists for improving energy efficiency profitably or at a low cost, while top-down modelers tend to find that it is more expensive to meet energy conservation and greenhouse gas (GHG) reduction goals. Hybrid energy-economy models have been developed that combine characteristics of these divergent approaches in order to help resolve disputes about costs, and test a range of policy approaches. Ideally, such models are technologically explicit, take into account the behavior of businesses and consumers, and incorporate macroeconomic feedbacks. In this study, we use a hybrid model to simulate the impact of end-use energy efficiency standards and an economy-wide carbon tax on GHG emissions and energy consumption in the U.S. to the year 2050. Our results indicate that policies must target abatement opportunities beyond end-use energy efficiency in order to achieve deep GHG emissions reductions in a cost-effective manner.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-4

1. INTRODUCTION

For more than three decades, it has been argued that opportunities for profitable energy efficiency exist throughout the economy. In the wake of the first

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* School of Resource and Environmental Management, Simon Fraser University, Vancouver, British Columbia, V5A 1S6.

** Corresponding author. School of Resource and Environmental Management, Simon Fraser University, Vancouver, British Columbia, V5A 1S6. Phone: (778) 782-4219; Fax: (778) 782-4968; E-mail: jaccard@sfu.ca; Web: www.emrg.sfu.ca.

Funding support for this research was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Pacific Institute for Climate Solutions (PICS), the Canadian Association for Energy Economics (CAEE Graduate Scholarship), Simon Fraser University, Natural Resources Canada, and Environment Canada. We wish to thank Bill Tubbs, Suzanne Goldberg, and Adam Baylin-Stern for assistance with the research. An anonymous referee offered very helpful suggestions and comments on an earlier draft.
doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-4

oil price shock, Amory Lovins (1977) published *Soft Energy Paths* in which he proposes energy efficiency as the first step in any energy policy directed at environmental protection and energy security. He suggests that a 75% reduction in energy use for a given level of services is profitable over about a 30 year time-frame via the full adoption of commercially available technologies (Lovins et al., 1981). In the 1980s, utilities and governments developed ambitious programs to foster energy efficiency, especially but not only in the electricity sector. Interest in energy efficiency declined in the 1990s, but re-emerged over the last decade as this is an appealing option for policy makers to reduce energy-related greenhouse gas (GHG) emissions. Using an approach very similar to that of Lovins, the McKinsey consulting firm has produced estimates of energy efficiency profitability for the U.S. and other countries, estimates which imply that substantial reductions of GHG emissions could be realized at little or no cost (for the U.S., see McKinsey, 2007; 2009).

The approach pioneered by Lovins and adopted more recently by McKinsey is often referred to as bottom-up analysis. In this type of analysis, technologies that provide the same energy service are generally assumed to be perfect substitutes except for differences in their anticipated financial costs and emissions. When their financial costs in different time periods are converted into present value using a social discount rate, many emerging technologies available for abating emissions appear to be profitable or just slightly more expensive relative to conventional technologies. This is especially the case for energy-efficient substitutes for more conventional technologies, because the higher capital cost of an efficient technology can be offset by lower energy costs over its lifetime. Many economists criticize the bottom-up approach, however, for its assumption that a single, anticipated estimate of financial cost indicates the full social cost of technological change (Sutherland, 1991; Jaffe and Stavins, 1994; Jaffe et al., 1999). New technologies present greater risks, as do the longer paybacks associated with investments such as energy efficiency. Some low-cost, low-emission technologies are not perfect substitutes in the eyes of the businesses or consumers expected to adopt them. To the extent that they ignore some of these costs, bottom-up models may inadvertently suggest the wrong technological and policy options for policy makers.

The fact that some elements of the full social cost are not taken into account by bottom-up models helps explain why investments in energy efficiency that appear profitable according to this approach are not necessarily realized. Proponents of the bottom-up methodology tend to attribute this "energy paradox" to a variety of institutional, information, and financing barriers, which they argue should be addressed through government intervention. Mainstream economists, on the other hand, recommend government intervention only to address a smaller subset of market failures that reduce economic efficiency. Market failure explanations for the energy paradox generally relate to a lack of information on energy-efficient and low-emission technologies due to the public good and positive externality qualities of information. Where such failures are identified, government intervention may be appropriate, but only if the benefits outweigh the costs to society, including the costs of policy implementation (Jaffe and Stavins, 1994; Jaffe et al., 1999).

The contrasting top-down approach, usually applied by economists, estimates aggregate relationships between the relative costs and market shares of energy and other inputs to the economy, and links these to sectoral and total economic output in a broader equilibrium framework. At their most basic level, conventional top-down models represent the economy through a series of simultaneous equations linking economic outputs and inputs (especially energy), whose parameters are estimated econometrically from time-series data. Models that link all of the major macroeconomic feedbacks in a full equilibrium framework are referred to as computable general equilibrium (CGE) models. Top-down models are used to simulate the economy's response to a financial signal (an emissions tax, an emissions permit price) that increases the relative cost of emissions-intensive technologies and energy forms. The magnitude of the financial signal necessary to achieve a given emissions reduction target indicates its implicit cost. Because they incorporate to some extent the transitional costs and risks of technological change, top-down cost estimates for achieving GHG reduction targets are almost always higher than bottom-up cost estimates.

A considerable challenge for top-down models is the estimation of statistically significant parameters from real-world experience. Often there is insufficient variability in the historical record for confident parameter estimation, and therefore most CGE modelers set the key elasticity of substitution (ESUB) parameters in their models judgmentally (Loschel, 2002). Furthermore, if the critical top-down parameters for portraying technological change—ESUB and the autonomous energy efficiency index (AEEI)—are estimated from aggregate, historical data, there is no guarantee that these parameter values will remain valid into a future under substantially different policies, different energy prices, and with different technological options for environmental improvement (Grubb et al., 2002; DeCanio, 2003; Laitner et al., 2003). For example, the parameters of a top-down model may incorporate market failures that could be addressed in future to the overall benefit of society. As conditions change, the estimated cost of GHG abatement may decrease, but conventional top-down models are unable to help policy makers assess this dynamic.

Another difficulty with the top-down approach is that policy makers often prefer, for political acceptability, policies that focus on individual technologies in the form of technology- and building-specific tax credits, subsidies, penalties, regulations, and information programs. This is especially the case where emissions charges would need to be high in order to overcome significant costs of environmental improvement. Because conventional top-down models represent technological change as an abstract, aggregate phenomenon, this approach helps policy makers assess only economy-wide policy instruments such as taxes and tradable permits. A model would be more useful if it could assess the combined effect of these economy-wide, price-based policies along with technology-focused policies.

The past decade has seen significant advances in the development of hybrid modeling approaches that can help resolve disputes about the cost of improving energy efficiency and reducing GHG emissions, and are also capable of performing a more useful range of policy simulations. Ideally, such models combine critical elements of the conventional bottom-up and top-down approaches in order to satisfy at least three criteria: explicit representation of the potential for technological change, microeconomic realism in accounting for how businesses and firms will decide among future technology options as policies and other conditions evolve, and macroeconomic feedbacks in reflecting how changes in production costs and preferences will change the structure of the economy and the growth rate of total output.

In this paper, we use a hybrid energy-economy model to simulate two policy options for reducing GHG emissions and energy consumption in the U.S. to the year 2050: energy efficiency standards in the buildings and personal transportation sectors, and an economy-wide carbon price with escalating stringency over time. The former would traditionally have been associated with bottom-up modeling, while the latter would traditionally have been associated with top-down modeling. Using a hybrid modeling framework, we are able to simulate both policies and compare their impacts on GHG emissions and energy use. Our results shed light on the cost of improving energy efficiency and its appropriate role in mitigating GHG emissions relative to other responses when parameters estimated from behavioral research are taken into account. We also use the hybrid methodological approach to test simultaneous implementation of the efficiency standards and the carbon tax, considering whether the policies might cause the same actions or complement each other by causing different actions.

Our study is one of a number presented in this special issue by modeling teams who participated in EMF-25, a project organized by the Energy Modeling Forum to investigate the potential for energy efficiency policies to mitigate climate change and reduce energy demand. Key assumptions about reference case economic activity and energy prices, as well as the design of the policies tested were established by the EMF and standardized across the different models.

We provide a description of the hybrid model used in this study and how some of its key parameters are estimated in the following section. In section 3, we discuss our methodology for representing the policy options. The presentation and analysis of our simulation results begins in section 4, which compares the effects of the efficiency standards and the carbon tax on GHG emissions and energy consumption in the buildings and personal transportation sectors. In section 5, we disaggregate the estimated emissions reductions by action to improve our understanding of the results from section 4. We also include a brief discussion of the impact of reduced equipment costs (subsidies) in this section. The effect on GHG emissions of combining the standards with the carbon tax is examined in section 6. Section 7 considers GHG emissions and energy consumption not just in the buildings and personal transportation sectors, but across the entire economy, and section 8 provides some insights on the cost-effectiveness of the efficiency standards. We conclude in section 9 with a summary of the insights gained from this analysis.

2. THE CIMS HYBRID ENERGY-ECONOMY MODEL

The hybrid model used for this study, called CIMS, is an integrated, energy-economy equilibrium model that simulates the interaction of energy supply-demand and the macroeconomic performance of key sectors of the economy, including trade effects. It is technologically explicit and incorporates microeconomic behavior in portraying the selection of technologies by businesses and consumers. Although it incorporates substantial feedbacks, the version of CIMS used in this analysis does not equilibrate government budgets and the markets for employment and investment as most CGE models do. Also, its representation of the economy's inputs and outputs is skewed toward energy supply activities, energy-intensive industries, and key energy end uses in the residential, commercial/institutional, and transportation sectors.

CIMS simulates the evolution of capital stocks over time through retirements, retrofits, and new purchases, in which consumers and businesses make sequential acquisitions with limited foresight. The model calculates energy costs (and emissions) at each energy service demand node in the economy, such as heated commercial floor space or person-kilometers traveled. In each time period, capital stocks are retired according to an age-dependent function (although retrofit of unretired stocks is possible if warranted by changing economic conditions), and demand for new stocks grows or declines depending on the initial exogenous forecast of economic output, and then the subsequent interplay of energy supply-demand with the macroeconomic module. A model simulation iterates between energy supply-demand and the macroeconomic module until energy price changes fall below a threshold value, and repeats this convergence procedure in each subsequent five-year period of a complete run, which usually extends for 30–50 years but could continue indefinitely.

Technologies compete for market share at energy service nodes based on a comparison of their life-cycle costs (LCCs) mediated by some technology-specific controls, such as a maximum market share limit in the cases where a technology is constrained by physical, technical, or regulatory means from capturing all of a market. Instead of basing its simulation of technology choices only on anticipated financial costs and a social discount rate, CIMS applies a formula for LCC that allows for divergence from that of conventional bottom-up analysis by including behavioral parameters that reflect revealed and stated consumer and business preferences with respect to specific technologies and time. Equation (1) presents how CIMS simulates technology market shares for new capital stocks

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}} \qquad (1)$$

where MS_j is the market share of technology j, CC_j is its capital cost, MC_j is its maintenance and operation cost, n_j is the average lifespan of the technology, and EC_j is its energy cost, which depends on energy prices and energy consumption per unit of energy service output—producing a tonne of steel, heating one square meter of a residence, transporting a person or tonne of cargo one kilometer. Equipment manufacturers, trade journals, marketers, government ministries, and international agencies provide information on the capital costs and operating characteristics of many energy-using and energy-producing technologies.

The r parameter represents the weighted average time preference of decision makers for a given energy service demand; it is the same for all technologies competing to provide a given energy service, but can differ between different energy services according to empirical evidence. The i_j parameter represents all intangible costs and benefits that consumers and businesses perceive, additional to the simple financial cost values used in most bottom-up analyses, for technology j as compared to all other technologies k at a given energy service node. For example, public transit and light-duty vehicles compete to provide the service of personal transportation. Empirical evidence suggests that some consumers implicitly put an intangible, non-financial cost on public transportation to reflect their perceptions of its lower convenience, status, and comfort relative to the personal vehicle. Theoretically, the r parameter represents risk relating to long payback periods, while the i_j parameter represents risk relating to the newness of a technology.[1]

The v parameter represents the heterogeneity in the market, whereby individual consumers and businesses experience different LCCs, perhaps as a result of divergent preferences, perhaps as a result of differences in real financial costs. It determines the shape of the inverse power function that allocates market share to technology j. A high value for v means that the technology with the lowest LCC captures almost the entire new market share. A low value for v means that the market shares of new equipment are distributed fairly evenly, even if their LCCs differ significantly.

In previous applications of CIMS, the three key behavioral parameters in equation (1) (i, r, and v) were estimated through a combination of literature review, judgment, and meta-analysis. However, the available literature usually provides only separate estimates for the three parameters, often using the discount rate to account for several factors, such as time preference and risk aversion to new technologies. This creates problems for predicting the costs and effects of policies that attempt to influence only one of these factors. More recent efforts to estimate these three behavioral parameters involve the use of discrete choice methods for estimating models whose parameters can be transposed into the i, r, and v parameters in CIMS (Jaccard, 2009). The data for a discrete choice model

1. Whether it is actually possible to distinguish between these two aspects of risk depends on the method of parameter estimation (see discussion below).

can be acquired from the revealed preferences in actual market transactions or from the stated preferences in a discrete choice survey.[2]

CIMS includes two functions for simulating endogenous change in the characteristics of the new and emerging technologies that are represented in the model: a declining capital cost function and a declining intangible cost function. The declining capital cost function links a technology's cost in future periods to its cumulative production, reflecting economies of scale and economies of learning. The declining intangible cost function links the intangible costs of a technology in a given period with its market share in the previous period, reflecting the 'neighbor effect'—improved availability of information and decreased perceptions of risk as new technologies penetrate the market.

3. MODELING THE CARBON TAX AND EFFICIENCY STANDARDS

For this study, the U.S. version of CIMS was standardized to the Energy Information Administration's Annual Energy Outlook (AEO) for 2009. We used the updated version of the AEO 2009 reference case, which takes into account the energy-related stimulus provisions of the American Recovery and Reinvestment Act (ARRA) of 2009, and also reflects changes in the macroeconomic outlook since the published version. We standardized to the updated AEO 2009 by revising the exogenous forecasts of energy prices and sectoral and sub-sectoral driving variables in CIMS (these can be subsequently adjusted, however, by energy supply-demand and macroeconomic feedbacks during a model simulation). We did not explicitly include in our reference case the numerous examples of federal and state legislation and regulations that affect energy consumption, and which are incorporated into AEO 2009. However, these would be implicit, to some extent at least, in historical data used to calibrate CIMS, as well as the forecasts of energy prices and driving variables informed by AEO 2009.

3.1 Economy-wide Carbon Tax

The carbon tax rates that were applied in this analysis are shown in Table 1. The tax is established in 2010 at $30/tonne CO_2 equivalent (CO_2e), and grows by 5% per year to the end of the simulation period in 2050. The revenue recycling function in CIMS returns carbon tax revenues collected from each sector of the economy to the sector on a lump sum basis, rather than returning all of the revenues to households.

2. The behavioral parameters of CIMS may capture some legitimate market failures. This is more likely in cases where the parameter values are estimated using revealed preference data, because stated preference surveys often provide information to participants—the lack of which, in the real world, could result in a market failure. Where a model user believes that market failures exist, they may adjust the behavioral parameters in CIMS accordingly when conducting simulations.

Table 1: Economy-wide Carbon Tax Rates ($2007 US/tonne CO_2e)

2010	2015	2020	2025	2030	2035	2040	2045	2050
30	38	49	62	80	102	130	165	211

3.2 End-use Energy Efficiency Standards

We based our efficiency standards on the EMF-25 policy design documentation (Energy Modeling Forum, 2010), which includes energy efficiency standards on end-use equipment in the residential and commercial sectors, building codes in these sectors, and light-duty vehicle fuel economy standards. All of the standards were implemented by 2020 and remain the same after that. In some cases, we chose not to incorporate the level of technological detail that would have been required to model particular standards on residential and commercial products as described by the EMF, because additional detail comes at a price in terms of increasing model complexity. To simulate the building codes proposed by the EMF, we identified the shell technologies in the residential and commercial sector models of the current version of CIMS that come closest to achieving 30% and 50% reductions in heating, ventilation, and air conditioning requirements (HVAC) relative to the existing standards in those models. The shell technologies with a 30% reduction were designated as the new standard from 2011 on, and the technologies with a 50% reduction were the standard from 2016 on. The light-duty vehicle fuel economy standards described by the EMF were approximated by standards on vehicle size and engine efficiency in the CIMS personal transportation model.[3]

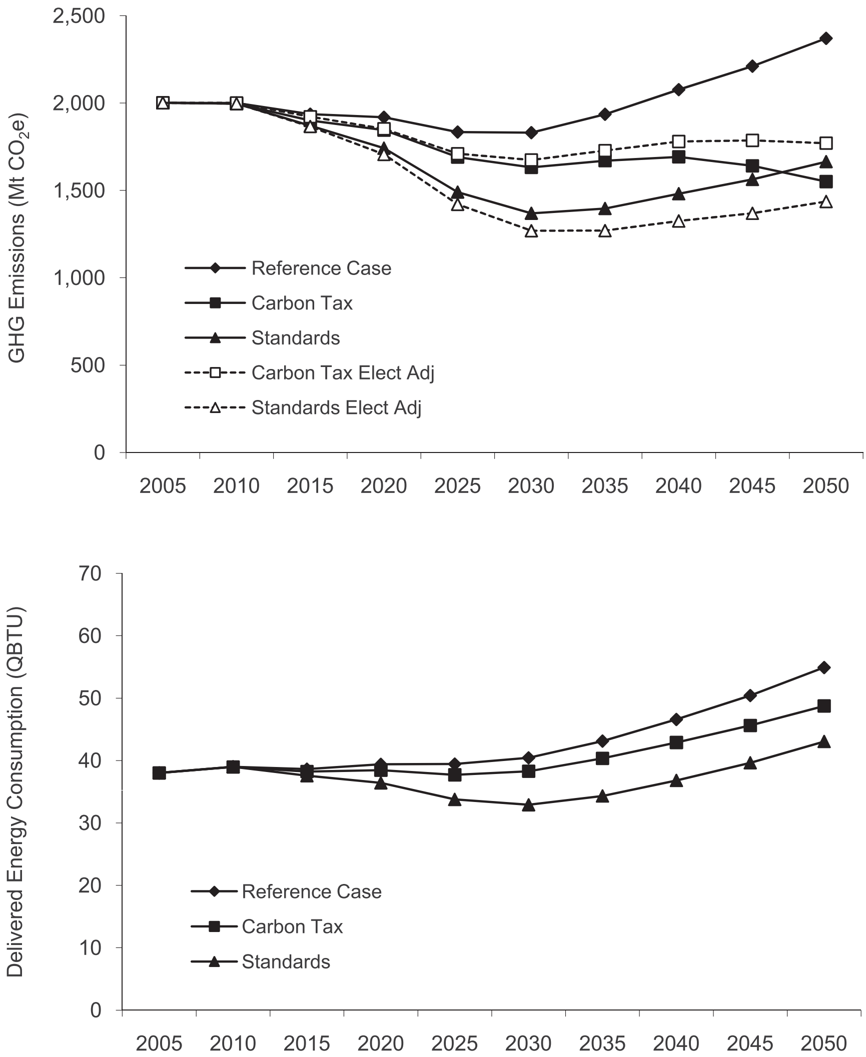
4. IMPACTS ON THE TARGETED END-USE SECTORS

The energy efficiency standards described in the previous sub-section are forecast to reduce annual GHG emissions from the buildings and personal transportation sectors by 25% from reference case levels in 2030 and by 30% in 2050 (Figure 1). Emissions are also reduced from 2005 levels, with the maximum percentage reduction occurring in 2030 at about 30%. The GHG emissions trajectory for the carbon tax is initially much higher than the trajectory for the standards, with only about a 10% reduction from the reference case in 2030. From this point on, however, emissions under the carbon tax stabilize and then begin to decline, while emissions under the efficiency standards begin to increase, and by 2050 emissions are slightly lower under the carbon tax. The simulation results suggest that the efficiency standards would need to increase in stringency over time—as the carbon tax does—in order to maintain greater emissions reductions.[4]

3. Our approximation resulted in somewhat more aggressive vehicle standards than those specified by the EMF.

4. While we expect that increasingly stringent energy efficiency standards would reduce energy consumption and GHG emissions further, greater demands for energy services could also result from

Figure 1: Direct GHG Emissions and Energy Consumption Summed over the Residential, Commercial, and Personal Transportation Sectors



the efficiency improvements, leading to rebound effects on energy consumption. CIMS accounts for some but not all of the potential rebound effects in the economy.

The GHG emissions trajectories described above (the solid lines in Figure 1) represent emissions at the point of end-use. Adjusting these direct emissions for the efficiency standards and the carbon tax policies to account for the increase or decrease in emissions associated with changes in the output of the electricity generation sector (for each policy simulation relative to the reference case) produces the dashed lines shown in Figure 1. The efficiency standards reduce electricity consumption from the buildings and personal transportation sectors, resulting in indirect emissions abatement due to reduced output from the electricity sector. Conversely, under the carbon tax, much of the emissions reductions at the point of end-use are due to fuel switching from fossil fuels to electricity. Accounting for the increase in emissions from greater electricity generation partially offsets direct GHG abatement in the case of the carbon tax (the adjustment would have been larger if the emissions intensity of electricity generation were not significantly reduced over time in this simulation).

The efficiency standards reduce annual energy consumption by about 20% from the reference case in each simulation year from 2030 on, and it is 2045 before energy consumption surpasses 2005 levels. The carbon tax has less of an effect, reducing energy consumption by only 5% from the reference case in 2030, rising to about 10% by 2050. The performance of the carbon tax relative to the standards is much lower in terms of delivered energy consumption than for GHG emissions because fuel switching under the carbon tax can reduce emissions without reducing energy consumption.

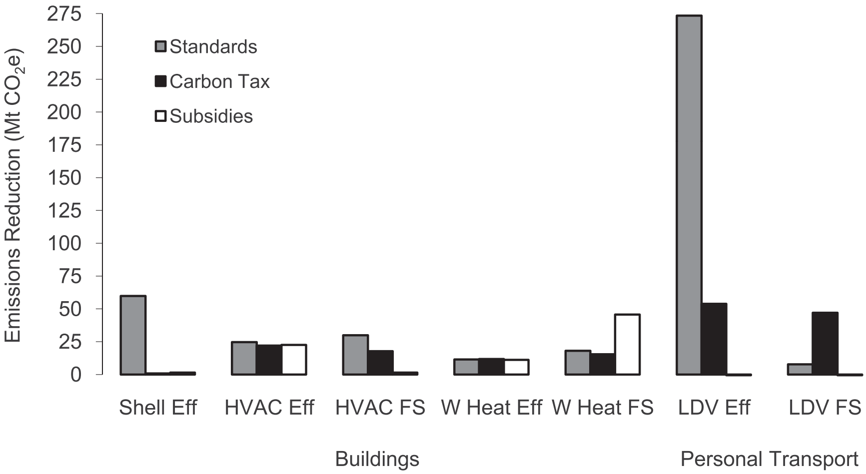
5. EMISSIONS REDUCTIONS BY ACTION

In order to explain the relative effect on direct GHG emissions of the efficiency standards and the carbon tax, we disaggregated the estimated emissions reductions described in the previous section across a number of different actions. This analysis also helps to illustrate the role of energy efficiency relative to other responses under the carbon tax. Figure 2 shows the results for key actions in the year 2030, when the standards reduce more than twice as many emissions as the carbon tax from the targeted end-use sectors. Under the carbon tax, emissions reductions from energy efficiency are similar in magnitude to emissions reductions from fuel switching based on the actions included in the figure.

In our simulations, improved light-duty vehicle (LDV) fuel efficiency under the standards has a much larger impact than any other action (although LDV efficiency improvements do occur under the carbon tax as well). The reduction in emissions from fuel switching in LDVs, on the other hand, is much larger under the carbon tax. Based on our behavioral parameter estimates, when larger vehicles and lower efficiency engines (which may be higher performance) are no longer available under the standards, consumers continue to prefer vehicles that use conventional fuels over alternatives with lower emissions. A price on carbon is necessary to make fuel switching attractive in this case.

A significant reduction in emissions is achieved through improvements in building shell technology under the standards, but this action is not taken up

Figure 2: Direct GHG Emissions Reductions by Action under the Carbon Tax, Standards, and Subsidies Policies in 2030



Note: Shell Eff = Building Shell Efficiency; HVAC Eff = Heating, Ventilation, and Air Conditioning Efficiency; HVAC FS = HVAC Fuel Switch; W Heat Eff = Water Heating Efficiency; W Heat FS = Water Heating Fuel Switch; LDV Eff = Light-Duty Vehicle Efficiency; LDV FS = LDV Fuel Switch.

under the carbon tax. Building shell efficiency improvements are costly relative to other methods of reducing emissions when evaluated using a discount rate that reflects revealed and stated preferences. Also, in our modeling, decisions regarding heating, ventilation, and air conditioning (HVAC) technologies occur prior to decisions regarding shell technologies. Because emissions reductions occur due to efficiency improvements and fuel switching in HVAC equipment under the carbon tax (see discussion below), the incentive for building shell improvements is not as strong.

Under both the standards and the carbon tax policies, moderate emissions reductions are associated with improvements in energy efficiency for HVAC and water heating services, as well as fuel switching for these services. Fuel switching to electricity occurs under the standards for HVAC because the efficiency standards are applied to space heating that uses fossil fuels, but not to electric space heating. There is also fuel switching from oil to natural gas for space heating. For water heating, electric heat pumps gain market share from natural gas applications, resulting in emissions reductions through both improved energy efficiency and fuel switching.

According to our simulations, by 2050 the carbon tax surpasses the standards in terms of reducing direct GHG emissions from buildings and personal transportation. The most important action contributing to this shift is a dramatic increase in fuel switching for LDVs, as the escalating carbon price stimulates demand for plug-in hybrid and ethanol vehicles.[5] Other changes that reduce the gap between the two policies include increases in emissions reductions from LDV efficiency, HVAC efficiency, and HVAC fuel switching under the carbon tax relative to the standards.

We also simulated reduced equipment costs (subsidies) corresponding to the energy efficiency standards for the residential and commercial sectors, as described in the EMF-25 policy design documentation (subsidies were not implemented in the transportation sector). In our forecasts, the subsidies are found to have less of an impact relative to the standards on direct GHG emissions and energy consumption in the buildings sectors. As illustrated in Figure 2, the overall discrepancy in terms of GHG emissions is in large part due to the fact that there are virtually no emissions reductions from building shell efficiency improvements under the subsidies. The same factors that limit the penetration of this action under the carbon tax are at play here.

6. COMBINED EFFECT OF THE POLICIES

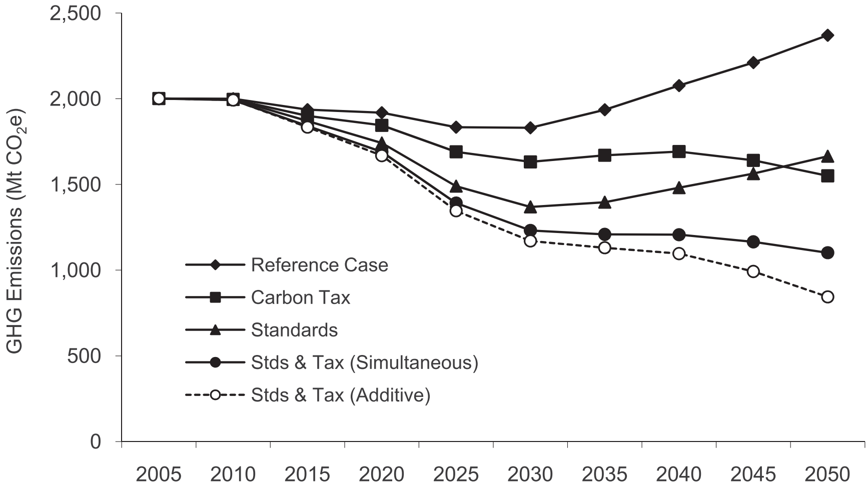
When the efficiency standards and the carbon tax are run simultaneously, as shown in Figure 3, annual direct emissions from the buildings and personal transportation sectors are reduced by about 35% from reference case levels in 2030 and by about 55% in 2050. These emissions reductions are substantially greater than those achieved under the efficiency standards, which in turn reduce emissions by more than the carbon tax (in all years except 2050). To assist in analyzing these results, we constructed an additive emissions trajectory by summing the emissions reductions from when each policy was simulated by itself. The GHG emissions trajectory for the run where the policies are implemented simultaneously is closer to this additive trajectory than to the trajectory for the efficiency standards, suggesting that the standards and the carbon tax tend to complement each other by causing different actions. This finding could be expected given our observations about emissions reductions from key actions under the two policies in the previous section. The policies may complement each other somewhat less over time as more energy efficiency actions are encouraged by the increasing carbon tax.

7. IMPACTS ACROSS THE ENTIRE ECONOMY

According to our simulations, when GHG emissions reductions across the entire economy are taken into account, the carbon tax has much more of an

5. In our simulation of the carbon tax, plug-in hybrid and ethanol vehicles are key to achieving significant reductions in GHG emissions. While there is great uncertainty about future technological change, especially as the time horizon extends to 2050, these technologies can be considered as a proxy for a wide array of low- and zero-emission vehicles including full electric and hydrogen fuel cell vehicles.

Figure 3: Combined Effect of the Efficiency Standards and the Carbon Tax on Direct GHG Emissions

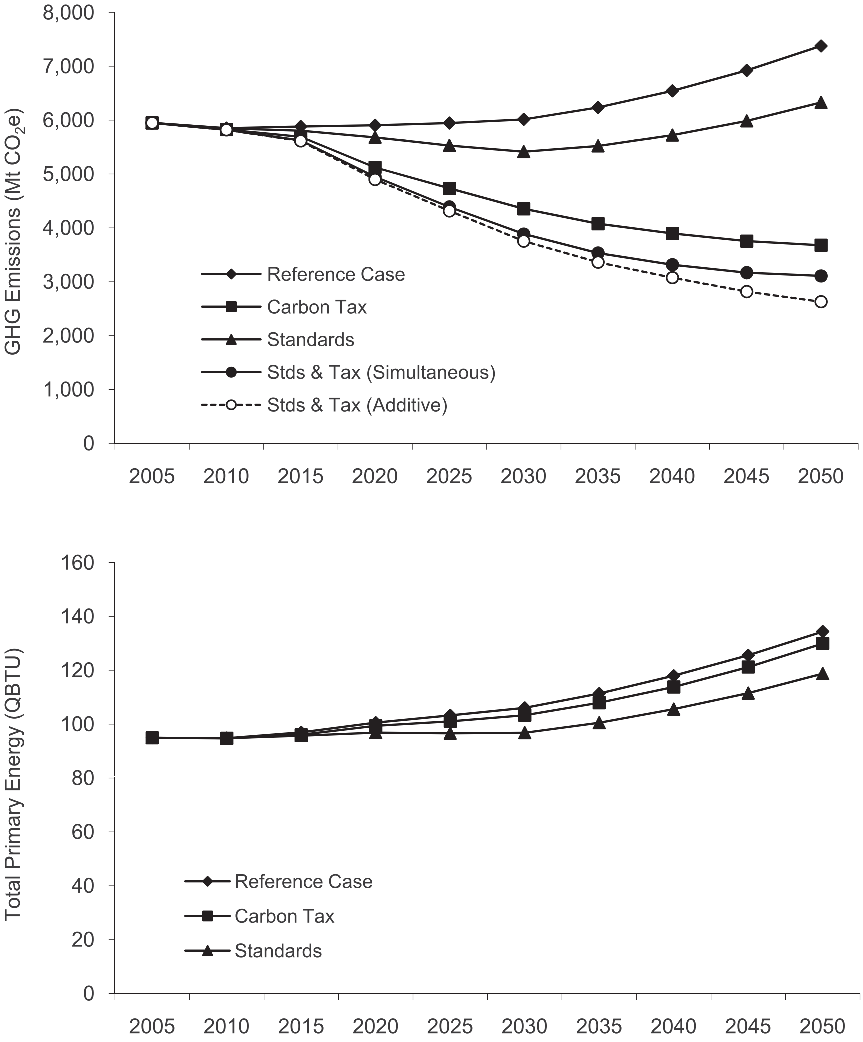


effect than the efficiency-based standards (Figure 4).[6] Indirect emissions are associated with an increase in electricity generation due to fuel switching under the carbon tax; however, the increase in output is accompanied by a dramatic reduction in the emissions intensity of generation. Carbon capture and storage (implemented in both coal- and natural-gas fired baseload generation plants), a shift to renewable energy sources, fuel switching from coal to natural gas, and energy efficiency improvements contribute to this reduction. Carbon pricing also stimulates emissions reductions from freight transportation, other energy supply (partly from reduced demand for fossil fuels), and the industrial sub-sectors. Under the standards, on the other hand, emissions reductions outside the targeted end-use sectors are limited to the energy supply sectors whose output is diminished as a result of the improvements in energy efficiency. This economy-wide comparison underscores the importance of policy comprehensiveness, across sectors and categories of abatement action, in the design of standards for GHG abatement.

When the efficiency standards and the carbon tax are run simultaneously and the results examined across the entire economy, it appears that the policies complement each other in terms of GHG emissions reductions, as was the case

6. Our simulations include GHG emissions from the combustion of fossil fuels, as well as process emissions linked to production levels (e.g. the carbon dioxide released when limestone is calcined in cement and lime production, or the methane released through venting, flaring, and fugitive emissions in natural gas fields, processing plants, and pipelines). However, we have removed process emissions from our results for this paper in order to be more consistent with the Annual Energy Outlook.

Figure 4: Economy-wide GHG Emissions (Combustion Only) and Energy Consumption



in the previous section (where only the results from the buildings and personal transportation sectors were considered). However, there may be more overlap between actions at the economy-wide level because both policies cause emissions abatement through a reduction in the demand for fossil fuels.

As discussed previously, the efficiency standards have more of an effect than the carbon tax on energy consumption from the buildings and personal transportation sectors in our forecasts. The gap between the two policies grows larger when comparing total primary energy consumption, as in Figure 4.[7] The reduction in energy demand from the targeted end-use sectors under the standards reduces the output of the energy supply sectors, leading to lower energy consumption by these sectors as well. Under the carbon tax, reductions in energy consumption from efficiency actions outside the buildings and personal transportation sectors are more than offset by higher electricity related losses (losses converting primary forms of energy to electricity, as well as transmission and distribution losses) as the demand for electricity increases.

8. OBSERVATIONS ON COST-EFFECTIVENESS

The CIMS model that is the basis for our policy simulations can be used to estimate detailed microeconomic costs ranging from anticipated financial costs evaluated at a social discount rate to costs that take into account market heterogeneity and the revealed and stated preferences of decision makers. Although the model does not incorporate feedbacks to the full extent of a CGE model, a methodology has been developed to estimate impacts on gross domestic product based on its partial equilibrium representation. CIMS has also been used to estimate key elasticity of substitution values for simulating the technological response to price changes by consumers and firms in a CGE framework (Bataille et al., 2006). Such exercises were not undertaken for this particular study; however, it is possible to make some general observations regarding the cost-effectiveness of the energy efficiency standards based on the extent to which marginal costs are equalized across sectors and actions in our simulation.

If we consider a single policy objective of addressing the environmental externality associated with GHG emissions, economic theory indicates that, in the absence of other market failures, cost-effectiveness will be maximized when marginal abatement costs are made equal across actions, economic agents, and sectors. This can be accomplished through an economy-wide carbon tax or tradable permit program. We simulated a series of constant, economy-wide GHG prices at increments of \$25/tonne CO_2e to allow us to investigate the distribution of marginal abatement costs under the energy efficiency standards tested for this study.

As a means to achieve GHG emissions reductions across the entire economy, the standards would have an unnecessarily high cost per unit of emissions

7. We used a partial substitution method to calculate the primary energy equivalent of electricity generated from solar, hydro, and wind in this analysis. The coefficients used to calculate the primary energy equivalent for these sources are therefore related to the amount of energy required to generate electricity in conventional thermal power plants. If we had instead used a physical energy content method and assumed 100% efficiency for solar, hydro, and wind, we would have observed a smaller gap between the carbon tax and the efficiency standards, as switching to renewables under the carbon tax would have reduced electricity related losses. We used the partial substitution method so that an increase in the share of electricity generation from renewables would come across as a fuel switching action rather than as an energy efficiency action.

reduction because they apply only to the buildings and personal transportation sectors, and would therefore fail to take advantage of low-cost opportunities to reduce emissions outside these sectors. Assuming the efficiency standards would be implemented along with policies to address other economic sectors, however, we can move on to consider the cost-effectiveness of the allocation of emissions reductions within the targeted end-use sectors.

In our simulations, to achieve the same overall reduction in emissions from the end-use sectors in question as under the efficiency standards in 2030, a constant, economy-wide GHG price approximately mid-way between $125 and $150/tonne CO_2e is required. To match the emissions reductions from the residential, commercial, and personal transportation sectors separately, GHG prices of $175, $100–125, and $125–150/tonne CO_2e respectively are necessary. Based on these results, the standards appear to induce greater emissions reductions from the residential sector and less emissions reductions from the commercial sector than would be cost-effective, although the allocation of emissions reductions across the end-use sectors is not far from the cost-effective solution.

For most of the end-use categories targeted by the standards, energy efficiency improvements are much greater in 2030 than under a constant GHG price of $125–150/tonne CO_2e (the price that achieves the same overall emissions reduction as the standards from the buildings and personal transportation sectors), indicating that the allocation of emissions reductions across actions is not cost-effective according to our simulations, due to the lack of fuel switching actions. Exceptions are space heating and water heating end-uses in the buildings sectors, where efficiency levels are matched at a GHG price of approximately $100/tonne CO_2.

9. CONCLUSION

Policy makers are understandably interested in the potential for energy efficiency to mitigate climate change and reduce energy demand. For more than three decades, bottom-up analyses conducted by researchers such as Lovins and (more recently) the McKinsey consulting firm have indicated that abundant opportunities exist for improving energy efficiency profitably or at a low cost. Top-down modelers criticize these findings for taking into account neither the risks of new technologies and long payback investments in energy efficiency, nor the intangible preferences of consumers and businesses. However, the top-down approach has its own methodological challenges. In particular, because conventional top-down models do not represent technologies explicitly, they cannot assess policies that focus on individual technologies, such as energy efficiency standards.

As part of an effort organized by the Energy Modeling Forum (EMF-25), we simulated two policy options for reducing GHG emissions and energy consumption in the U.S. to the year 2050: energy efficiency standards in the buildings and personal transportation sectors, and an economy-wide carbon price with escalating stringency over time. We used a hybrid energy-economy model that combines critical elements of the conventional bottom-up and top-down approaches. This allowed us to simulate both the technology-specific efficiency standards and the economy-wide carbon tax.

In our forecasts, the efficiency standards initially perform much better than the escalating carbon tax at reducing direct GHG emissions from the targeted end-use sectors. However, the gap between the emissions trajectories for the two policies becomes smaller during the latter part of the simulation period, and by 2050 the carbon tax achieves greater reductions. This result suggests that the efficiency standards would need to be updated over time. Our policy simulations indicate that the efficiency standards produce greater reductions in energy consumption than the carbon tax for the end-use sectors in question. The hybrid modeling framework we used for this analysis includes parameters estimated from behavioral research, making it less likely than a bottom-up approach to show significant penetration of energy efficiency as a result of pricing GHG emissions. Fuel switching occurs under the carbon tax in our modeling, which reduces GHG emissions but not necessarily energy use.

We disaggregated the estimated emissions reductions from our simulations across a number of different actions. In 2030, the roles of energy efficiency and fuel switching are roughly equal under the carbon tax for the buildings and personal transportation sectors. As expected, energy efficiency dominates under the standards. The major differences we observed between the two policies in terms of the contribution of key actions are also reflected in our assessment of the combined effect of the efficiency standards and the carbon tax, which found that these policies tend to complement each other by causing different actions.

According to our simulations, when the analysis is extended from the buildings and personal transportation sectors to the entire economy, the carbon tax reduces GHG emissions by much more than the efficiency-based standards. Results at the economy-wide level emphasize the need for standards to be designed in a comprehensive way in order to capture abatement opportunities across different sectors, particularly electricity generation, and categories of abatement action—i.e. fuel switching and carbon capture and storage in addition to energy efficiency—if the goal is to reduce GHG emissions.

We simulated constant, economy-wide GHG prices to provide some insight regarding the cost-effectiveness of the standards, and found that the cost per unit of emissions reduction would be unnecessarily high because only energy efficiency actions in the buildings and personal transportation sectors are targeted. This is consistent with our earlier observations that a carbon tax harnesses substantial abatement opportunities in other sectors and from other actions. However, there are still reasons why policy makers might want to implement energy efficiency standards.

Where market failures are identified that limit the adoption of technologies that appear profitable, government intervention in the form of efficiency standards and/or subsidies may be appropriate if the benefits outweigh the costs to society, including the costs of policy implementation. More research is needed to rigorously evaluate potential market failures and the policies designed to address them. Another reason why policy makers might want to consider energy efficiency standards is if a price on GHG emissions is not sufficient to address other environmental, social, and security externalities associated with energy consumption. Our simulation results suggest that if efficiency standards were used to supplement a carbon tax in order to address additional externalities or market failures that limit the penetration of energy-efficient technologies, the policies would tend to complement each other.

REFERENCES

Bataille, C., M. Jaccard, J. Nyboer and N. Rivers (2006). "Towards General Equilibrium in a Technology-rich Model with Empirically Estimated Behavioral Parameters." *The Energy Journal* 27(Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down): 93–112.

DeCanio, S.J. (2003). *Economic Models of Climate Change: A Critique.* New York: Palgrave Macmillan.

Energy Information Administration (2009). "An Updated Annual Energy Outlook 2009 Reference Case Reflecting Provisions of the American Recovery and Reinvestment Act and Recent Changes in the Economic Outlook." April. Accessed at http://www.eia.doe.gov/oiaf/servicerpt/stimulus/index.html.

Energy Modeling Forum (EMF) (2010). "EMF 25 Scenario Design." Stanford University, Stanford, CA. Document available online at http://emf.stanford.edu/files/res/2372/25design2.pdf.

Grubb, M., J. Kohler and D. Anderson (2002). "Induced Technical Change in Energy and Environmental Modeling: Analytic Approaches and Policy Implications." *Annual Review of Energy and the Environment* 27: 271–308.

Jaccard, M. (2009). "Combining Top Down and Bottom Up in Energy Economy Models." In J. Evans and L.C. Hunt, eds., *International Handbook on the Economics of Energy.* Cheltenham, UK and Northampton, MA, USA: Edward Elgar. pp. 311–331.

Jaffe, A.B., R.G. Newell and R.N. Stavins (1999). "Energy-efficient Technologies and Climate Change Policies: Issues and Evidence." Resources for the Future, Climate Issue Brief no. 19, December.

Jaffe, A.B. and R.N. Stavins (1994). "The Energy-efficiency Gap: What Does It Mean?" *Energy Policy* 22: 804–810.

Laitner, J.A., S.J. DeCanio, J.G. Koomey and A.H. Sanstad (2003). "Room for Improvement: Increasing the Value of Energy Modeling for Policy Analysis." *Utilities Policy* 11: 87–94.

Loschel, A. (2002). "Technological Change in Economic Models of Environmental Policy: A Survey." *Ecological Economics* 43: 105–126.

Lovins, A., L. Lovins, F. Krause and W. Bach (1981). *Least-Cost Energy: Solving the CO_2 Problem.* Andover, Mass.: Brick House Publishing.

Lovins, A.B. (1977). *Soft Energy Paths: Toward a Durable Peace.* San Francisco: Friends of the Earth International; Cambridge, Mass.: Ballinger Publishing.

McKinsey (2009). "Unlocking Energy Efficiency in the U.S. Economy." July. Accessed at http://www.mckinsey.com/clientservice/electricpowernaturalgas/us_energy_efficiency/.

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

Sutherland, R.J. (1991). "Market Barriers to Energy-efficiency Investments." *The Energy Journal* 12(3): 15–34.

The Value of Advanced End-Use Energy Technologies in Meeting U.S. Climate Policy Goals

Page Kyle†, Leon Clarke*, Steven J. Smith*, Son Kim*, Mayda Nathan*, and Marshall Wise**

This study, a contribution to the EMF 25 scenarios on the role of energy efficiency in climate change mitigation, explores the value of technological improvement in the buildings, industry, and transportation sectors in meeting 2050 CO_2 emissions mitigation targets in the United States. Six scenarios of future end-use technology evolution are analyzed without any future emissions mitigation policy, and with two linear emissions constraints that begin in 2012 and achieve 50% and 80% reductions from 1990 CO_2 emissions levels in 2050.The scenarios show that end-use technologies are important for reducing near-term energy demand and CO_2 emissions, and advanced transportation technologies in particular are important for allowing the energy system as a whole to achieve deep emissions reductions in a cost-effective manner. Total discounted economic costs of meeting the emissions constraints are reduced by up to 53% by advanced end-use technologies, and similar cost reductions are observed when the policies allow inter-temporal shifting in the emissions pathways (i.e., banking and borrowing). The scenarios highlight the importance of end-use technologies that facilitate electrification and decrease the direct use of hydrocarbon fuels through efficiency improvement, but we stress that end-use technology advancement should be complementary to technology advancement in energy supply.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-5

1. INTRODUCTION

Energy efficiency is often considered to be a low-cost source of CO_2 emissions mitigation in the United States, particularly in the next couple of de-

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Joint Global Change Research Institute, Pacific Northwest National Laboratory, 5825 University Research Court, College Park, MD 20740.

† Corresponding author. E-mail: pkyle@pnl.gov. Tel: 301-314-6758.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-5

cades. A number of studies over the last few decades have attempted to quantify the magnitude of potential reductions in energy use and greenhouse gas emissions from enhanced end-use energy efficiency, with a wide range of findings, from significant reductions in energy demand at near zero net cost (Interlaboratory Working Group, 2000; McKinsey Global Institute, 2007), to studies finding that energy efficiency is a limited and very costly strategy for reducing energy consumption and emissions (Joskow and Marron, 1992; Sutherland, 2003). In part, these differences can be explained by different assumptions of consumer behavior, such as discount rates (Jaffe and Stavins, 1994a) or the magnitude of the "rebound effect" (Greening et al., 2000); potential efficiency improvements of individual technologies at present and in the future; and how to assess the costs of development and deployment of energy-saving technologies (Sathaye and Murtishaw, 2004; Clarke et al., 2008a).

Although costs, mitigation potentials, and barriers to energy efficiency have been debated for two decades (for review see Sorrell et al., 2004), a more recent topic of interest is the system-wide role of end-use energy technology advancement in climate change mitigation (Kyle et al., 2007; Clarke et al., 2008b; Kyle et al., 2009). The levels and types of energy demanded for end-use purposes will have implications for the future development of the energy supply infrastructure, and its ability to reduce CO_2 emissions. A number of studies have found that electrification of end-use energy demands, combined with removal of emissions from electricity generation, can serve as a cost-effective foundation for system-wide emissions mitigation (Clarke et al., 2006; Edmonds et al., 2006, Richels and Blanford, 2008). In this context, end-use energy technology improvement is important not only for improving energy efficiency—that is, reducing the amount of fuel required to provide any given level of service demand—but also for facilitating transitions towards low-carbon pathways of final energy production, as they become available.

Enhanced end-use technologies are an appealing strategy for meeting climate policy goals, due to the perception of low costs, which some researchers have argued to be negative (Levine et al., 1995; Brown, 2001; Geller et al., 2001). That is, these researchers have argued that some level of reductions in CO_2 emissions from enhanced end-use technologies is available at a net benefit to consumers, due to a range of market failures that, together, tend to keep energy consumption at greater-than-optimal levels. These market failures include the principal-agent problem (Murtishaw and Sathaye, 2006; IEA, 2007a), imperfect information (Jaffe and Stavins, 1994b), and consumer myopia (Jansen and Denis, 1999). Their existence implies that some level of end-use improvement can be forced into the market through standards or other policies, and consumers will be better off as a consequence. Irrespective of the net effects on consumer welfare, energy efficiency standards have been implemented in the U.S. for decades, and have been quite effective at reducing energy consumption (Geller and Attali, 2005; Gillingham et al., 2006). A second benefit of energy efficiency improvement is that because it reduces final energy demands, it also reduces the scale and costs of transitions in energy supply systems that will be required both to meet growing energy demands, and to reduce emissions for climate change mitigation purposes. Advanced end-use energy technologies can therefore reduce consumers' energy expenditures both by reducing energy consumption, and by reducing energy prices (Hirst et al., 1996; Laitner, 2000). Finally, because end-use technologies tend to have short lifetimes as compared with energy supply technologies (e.g., electric power plants, refineries), end-use energy efficiency allows near-term reductions in primary energy demand and CO_2 emissions to be achieved without early retirement of existing energy sector capital. In fact, technology improvement in the end-use sectors is thought to be key in reducing emissions in the next couple of decades (e.g., Levine et al., 2007; Schafer et al., 2009).

The net value of end-use energy technology advancement in future emissions mitigation in the U.S. will depend on a variety of unknown factors, including (1) the costs of research, development, and deployment of advanced end-use technologies, (2) the levels of energy savings that will be realized through deployment of these technologies, (3) how the technologies will interact with the energy supply systems and the consequent effects on system-wide emissions, and (4) the nature and attributes of future climate policies. The EMF-25 study addresses the latter three, and this study is primarily focused on the latter two. We present scenarios of reference and advanced end-use technology development and deployment in U.S. buildings, industry, and transportation, as a starting point from which to assess the consequent system interactions. Advanced technology scenarios generally assume deployment of already-existing best-available-practice technologies in the next couple of decades, with continued improvement thereafter. These scenarios are analyzed with two national emissions constraints designed to achieve 50% and 80% reductions from 1990 CO_2 emissions levels in 2050, emissions targets that roughly bracket the range of a number of proposed U.S. mitigation policies (Paltsev et al., 2007). Because end-use technology improvement tends to be considered as a strategy for near-term emissions reductions, we also assess the value of advanced end-use technologies when the policies allow banking and borrowing, or inter-temporal shifting in annual emissions rates.

The scenarios in this paper demonstrate that even high levels of energy efficiency alone do not meet future climate policy goals—that is, an end-use technology strategy is not sufficient to meet the sorts of climate goals currently being debated—but that end-use technology improvements in all three end-use sectors are important for reducing energy consumption, CO_2 emissions, and costs of meeting emissions mitigation targets. These economic cost savings are substantial regardless of whether a national mitigation policy is based on annual CO_2 emissions constraints or the corresponding long-term cumulative CO_2 emissions target. This is because advanced end-use technologies are important both in the near term for energy demand reduction, and in the long term for facilitating a shift in final energy demands, away from fuels with high fuel-cycle CO_2 emissions and low mitigation potentials, towards low-carbon fuels as they become available. Electric light-duty passenger vehicles are especially important in this context.

More broadly, advanced end-use technologies can enable the energy system to evolve in a way that freely emitting fossil fuels are replaced with low- or zero-emissions supply sources such as fossil energy with carbon capture and storage, nuclear energy, biomass, and non-biomass renewable energy.

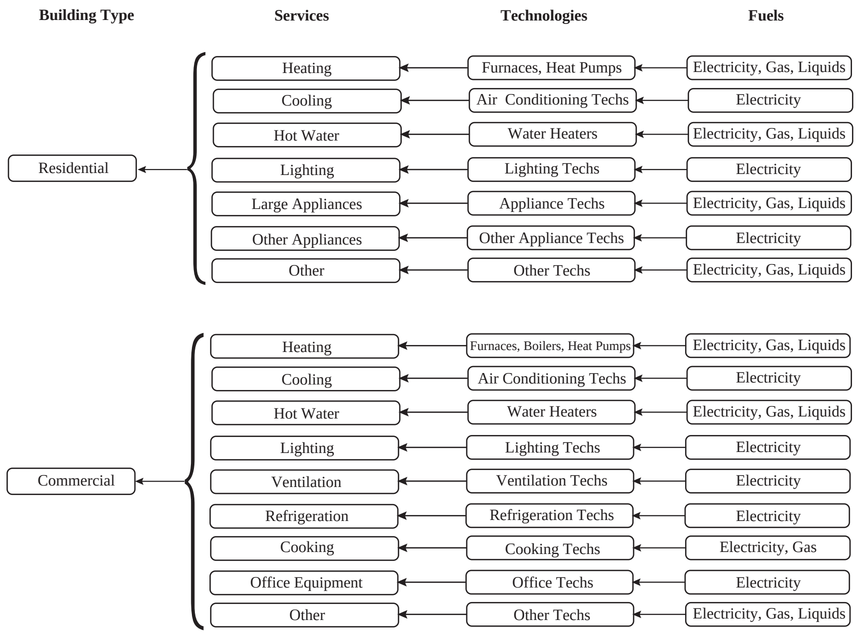
2. GCAM

This study is conducted using the GCAM integrated assessment model (formerly MiniCAM; Brenkert et al. 2003; Kim et al. 2006). GCAM is a long-term, technologically detailed, partial-equilibrium model that links representations of global energy, agriculture, land-use, and climate systems. GCAM runs in 15-year time steps from 1990 through 2095, and has 14 regions, one of which is the U.S. The model calculates equilibria in each time period in regional and global markets for energy goods and services, agricultural goods, land, and (where applicable) greenhouse gas emissions. Therefore, while the present study focuses on the buildings, industry, and transportation sectors of the U.S., all interactions with other sectors of the U.S. energy and agricultural systems are tracked, as are the interactions with other regions.

Each of the end-use sectors in this study is modeled as demanding a range of services, which are supplied by competing representative technologies. This competition is based on each technology's relative cost of service provision, using a logit-based formulation (Clarke and Edmonds, 1993). The logit approach assumes that model-derived technology costs in any period represent the median of a distribution of costs to consumers. This assumed heterogeneity in costs ensures that technologies with comparatively high average costs nevertheless gain market share. The cost of each technology is calculated in each period as the sum of non-fuel costs, fuel costs, and any CO_2 emissions cost penalties, when emissions are priced. Non-fuel costs are exogenous and include discounted capital and equipment installation costs, and all operations and maintenance costs, represented per unit of service output produced by the technology. Fuel costs are calculated as the endogenous market price each fuel consumed, divided by the efficiency, an exogenous, unitless measure of the amount of service output per unit of fuel consumed. Efficiencies and non-fuel costs of technologies are exogenous, specified for each technology in each model period, and account for much of the differentiation between technology scenarios in this analysis.

Most services in this study are represented with a two-level nested logit structure, where technologies (e.g., typical gas furnace, high-efficiency gas furnace) compete within subsectors (e.g., gas, electricity, liquid fuels) to supply a specific service (e.g., heating, cooling). In addition to the model-derived costs, market shares of each subsector and technology in each period are also influenced by calibration parameters, calculated from base year (2005) market shares. As such, any market failures or non-price-related consumer preferences for particular technologies and fuels are passed forward to future periods. Base-year decisions can further influence future energy consumption when equipment is assumed to

Figure 1: Schematic of the U.S. Buildings Sector in GCAM



be long-lived, in which case some portion of the existing stock in 2005 continues operating in subsequent periods.

2.1. The U.S. Buildings Sector

The U.S. buildings sector, documented in Kyle et al. (2010), consists of a residential and commercial sector, each represented in terms of floorspace, as shown in Figure 1. Per-capita floorspace demand increases with per-capita income, modified by changes in the future price of floorspace. Each unit of floorspace demands a range of services, such as heating, cooling, and water heating, which are supplied by technologies that consume energy. These services are represented in terms of useful energy; base-year (2005) demands of each service are calculated as energy consumption multiplied by the stock average efficiency of all technologies supplying the service. In future periods, service demands scale with floorspace, modified by exogenous income-related demand saturation, and the price of each service. Heating and cooling demands are further modified by future average building shell efficiency, and the effects of internal gain energy produced by all other equipment operating within the building envelope.

Residential and commercial buildings each have space heating, space cooling, water heating, and lighting services. "Large appliances" in residential buildings consist of refrigerators, freezers, clothes washers, clothes dryers, stoves, and dishwashers. Residential “other appliances” consist of furnace fans, set-top boxes, personal computers, and televisions. The remaining residential “other” category includes many smaller energy-consuming services, detailed in TIAX (2006); the largest of these remaining demands are ceiling fans, VCRs and DVD players, microwaves, and audio equipment. In the commercial sector, the largest “other” services are distribution transformers, water filtration, treatment, and pumping, and vertical transport equipment (TIAX 2006).

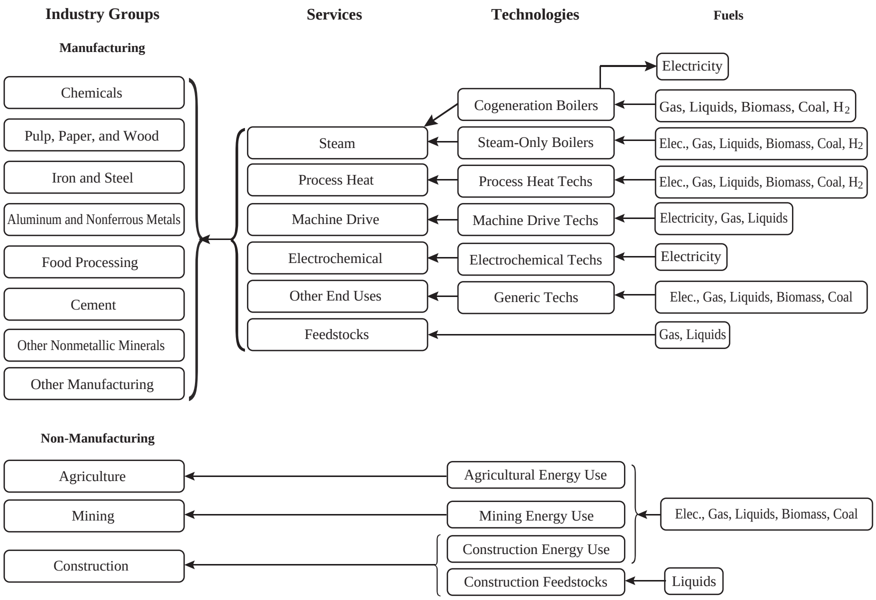
Base year model calibration of energy by fuel and end-use, and stock average efficiency by technology, is based on EIA (2009). For many services—heating, cooling, water heating, residential appliances, and commercial refrigeration—energy consumption by fuel is further disaggregated to representative “typical” and “high-efficiency” technologies, with costs and efficiencies from technology isoquants defined by Rosenquist et al. (2006). Electricity used for lighting is disaggregated into representative incandescent and fluorescent technologies using NCI (2002). Non-fuel costs of most technologies are calculated from capital costs in Rosenquist et al. (2006), amortized over the average equipment lifetime using a 10% discount rate, with operations and maintenance costs added (NCI, 2004). For technologies supplying heating, cooling, water heating, and residential large appliance services, a portion of the 2005 stock of equipment in buildings is assumed to operate through the 2020 time period; this portion is calculated from Residential Energy Consumption Survey data (EIA 2005).

2.2. The U.S. Industrial Sector

The U.S. industrial sector is documented in Wise et al. (2006), and consists of eight manufacturing industry groups and three non-manufacturing industry groups. Each manufacturing industry group is modeled as a producer of output (represented as value of shipments; EIA, 2008) and a consumer of a range of services that are provided ultimately by energy (see Figure 2). As in the buildings sector, services are defined in terms of useful energy, calculated as energy consumption times stock average efficiency of technologies supplying the service. In each manufacturing industry group, base-year (2005) levels of demand of each service are derived from energy consumption by fuel and end-use from the Manufacturing Energy Consumption Survey (EIA, 2002), and assumed technology efficiencies. Energy consumption by non-manufacturing industries is from EIA (2008), with all industrial fuel demands scaled to match IEA (2007b). In future periods, each industry group’s production of industrial output is modeled as a Leontief production function: different service inputs are non-substitutable, and the levels of each input are exogenous, specified for all future time periods. For example, industrial production functions do not allow for price-driven substitution of machine drive for steam or process heat. However, less steam-intensive manufacturing practices may be assumed in advanced technology scenarios.

Services are provided by technologies that consume any of several competing fuels, typically gas, coal, liquid fuels, electricity, biomass, and (in future

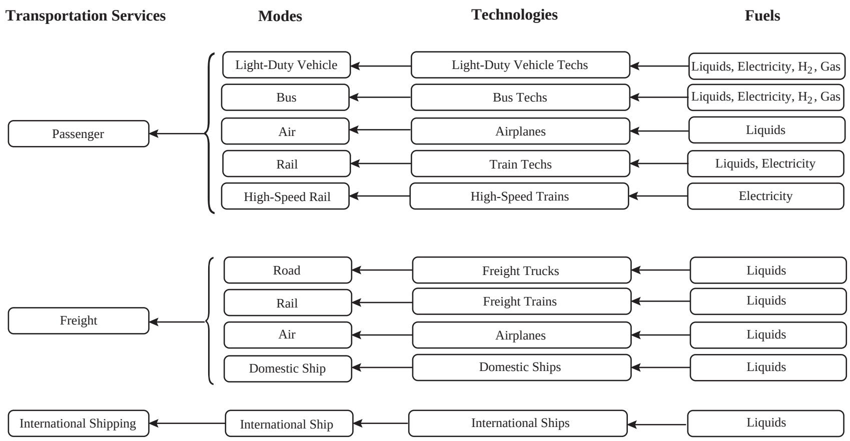
Figure 2: Schematic of the U.S. Industrial Sector in GCAM



periods) hydrogen. With several exceptions, industrial services are modeled as generic to all industries; that is, steam used by the chemicals industry is not differentiated in the model from steam used by the food processing industry. Exceptions include steam in the pulp, paper, and wood industries, where biomass by-products supply most of the boiler fuel (Ozalp and Hyman, 2006); process heat in the primary metals industries, where coke is used in blast furnaces and electricity is used in electric arc furnaces (EIA 2002); and process heat in the cement industry, which is mostly supplied by coal and waste-derived fuels (IEA, 2007c). Cogeneration technologies are included as options for producing steam and heat in all industries; as compared with steam- or heat-only systems, cogeneration systems are generally characterized as having lower fuel efficiencies in producing the primary service (steam or heat) and higher capital costs, but gain additional revenue from the electricity produced. Cogeneration typically requires about 25% less primary energy than separate heat and power systems (IEA, 2007c).

Future technological improvement in industrial manufacturing can be represented in GCAM both by increasing the efficiency of specific energy-consuming technologies—e.g., boilers producing steam, or kilns producing process heat—and in the coefficients of the production functions that prescribe the service inputs required per unit of output. The latter encompasses changes to manufacturing systems that reduce the needs for energy-intensive services, and is generally thought to be the source of much of the industrial sector's future energy and CO_2

Figure 3: Schematic of the U.S. Transportation Sector in GCAM



emissions reduction potential (Worrell et al., 2004; IEA, 2007c; Masanet et al., 2009). In any individual scenario in this analysis, the principal means for reducing the future CO_2 emissions intensity of industrial manufacturing include switching to fuels with lower carbon intensity, the use of cogeneration systems, and the use of CCS systems in the cement industry.

2.3. The U.S. Transportation Sector

The U.S. transportation sector in GCAM (Kim et al., 2006) is disaggregated into passenger transport, freight transport, and international shipping. Service output is represented in passenger-km and tonne-km, respectively, and future demands are driven by population and GDP, modified by average service prices. The passenger and freight sectors are disaggregated into several modes (e.g., air, rail, light-duty vehicle; see Figure 3), and different technologies may compete within each mode. Transportation service costs for most modes are from U.S. Department of Transportation (2008), with light-duty vehicle costs from Davis et al. (2008). In the passenger sector, modal costs include time value costs, determined from each mode's average transit speed, and regional per-capita GDP. Consistent with historical data, increasing incomes increase passenger service demands, but cause a greater share of passenger service to be supplied by faster modes, such as light-duty vehicles and aviation (Schafer et al., 2009). This modal shifting allows per-capita passenger-km to increase, while per-capita total time in transit remains relatively stable (Schafer et al., 2009).

Base year energy consumption, service output, and fuel efficiency of all passenger and freight technologies are from Davis et al. (2008), with international shipping energy from IEA (2007b) and service from UNCTAD (2006). Future technological change in the transportation sector is modeled as efficiency improvement of individual technologies (i.e., increased vehicle fuel economy), and by allowing alternative-fuel vehicles to compete for service share within any mode. At present, petroleum-derived liquid fuels supply about 99% of passenger and freight fuel demands in the U.S. (IEA, 2007b). While this is unlikely to change substantially in the near future, a number of alternative-fuel light-duty vehicle technologies are in development (Schafer et al., 2009). In any scenario in this analysis, the options for reducing the emissions intensity of transportation service provision include modal shifting, fuel-switching, and technology change in the refining sector (or other sectors supplying energy used for transportation).

2.4. Energy Supply

While the energy supply system is not the focus of this paper, it is nevertheless important to future emissions mitigation from all three end-use sectors, as technology change in the energy supply system will determine the upstream CO_2 emissions from end-use fuel consumption. These upstream emissions, in turn, determine the level of whole-system emissions mitigation that is possible from fuel-switching at the end-use level. Upstream CO_2 emissions are especially important in this study from electricity generation and liquid fuel refining.

Electricity in GCAM may be produced from nine primary fuels: coal, gas, oil, biomass, hydroelectricity, nuclear power, solar, wind, and geothermal energy. Each of these fuel types may have multiple competing technologies (e.g., coal IGCC, pulverized coal), and fossil fuel and biomass power generation technologies have the option to use CO_2 capture and storage (CCS). CCS systems remove about 90% of CO_2 emissions from power generation, but increase non-fuel costs and reduce fuel efficiencies. As with end-use technologies, the total costs of any electric generation technology include fuel costs, exogenous non-fuel costs, and where applicable, any cost penalties for CO_2 emissions. Electric sector technologies are assumed to be long-lived (between 30 and 60 years), so even through 2050, some portion of electricity generation may produced by currently existing plants. However, these plants may be retired as the variable costs increase relative to the value of the electricity produced (e.g., due to emissions cost penalties, or fuel price increases).

Refined liquid fuels in GCAM include all petroleum- and biomass-derived fuels (e.g., gasoline, diesel, ethanol), and in the future these fuels may be produced from any of the following primary energy sources: crude oil, unconventional oil, coal, gas, and biomass. Unconventional oil is differentiated from crude oil in that its production and upgrading requires additional energy, causing higher upstream emissions. Coal and biomass liquids each have the option to use CCS systems, but note that CCS only captures CO_2 that would otherwise be emitted at the refinery; due to the carbon content of the fuels produced, full mitigation of the liquid fuel cycle requires the use of biomass.

Table 1: Scenarios of End-use Technology Advance Investigated in this Study

Name	Description
Ref	Reference technology
Adv-bld	Advanced building technologies only
Adv-ind	Advanced industrial technologies only
Adv-trn-ICE	Advanced transportation technologies; internal combustion engine vehicles only
Adv-trn-EV	Advanced transportation technologies; internal combustion engine and electric vehicles
Adv-all	Advanced buildings, industry, and transportation technologies

Note that both electricity and refined liquid fuels can be produced with negative fuel-cycle CO_2 emissions, through the use of biomass with CCS. However, the deployment of these technologies will be limited by the supply of biomass. Both residue biomass (Gregg and Smith, 2010) and biomass crops are included, the latter determined by an endogenous land-use model (Wise et al., 2009). While no constraint is imposed on the supply of biomass, the use of cropland for biomass production competes with other uses of cropland. In this study, all climate policies assume that CO_2 emissions from land-use change are priced at the same rate as fossil and industrial CO_2 emissions. Because croplands tend to have low above- and below-ground carbon content as compared with most other land uses (IPCC, 2001), expansion of cropland for bioenergy production is somewhat limited by the economic value of the carbon in non-cropland (Wise et al., 2009).

3. SCENARIO DESIGN

3.1. Technology Scenarios

This study begins by developing six scenarios differentiated by future end-use technology levels, as outlined in Table 1. The "advanced" assumptions specific to each sector are detailed below, and may be representative of standards that promote the deployment of already-existing energy-saving technologies, or successful research, development, and deployment of new technologies over the next four decades. These technology scenarios generally start with the specifications for each end-use sector in the EMF 25 Standards Case (Energy Modeling Forum, 2010), and include additional improvements. Note that this study does not estimate the costs of achieving the technological outcomes assumed, and as such, these scenarios should not be used to assess the presence or magnitude of zero-net-cost opportunities for technological advancement in the end-use sectors.

A number of researchers have argued that, among all sectors of the economy, the buildings sector presents the greatest opportunities for near-term technological advance to reduce emissions (Levine et al., 2007). In buildings, both energy-efficient technologies and consumer behavior are important for future energy use (e.g., Lutzenhiser 1993; Kyle et al, 2010); this study focuses on technology only. The reference building technology scenario includes incremental energy efficiency improvement in all technologies through 2050; the advanced technology scenario is based on the Standards Case of the EMF 25 scenarios (Energy Modeling Forum, 2010; see Tables A1 and A2). This scenario includes a set of standards implemented between 2014 and 2020 that increase the minimum allowed efficiency of technologies providing space heating, space cooling, water heating, residential appliances, and commercial refrigeration and ventilation (see Energy Modeling Forum, 2010). The advanced building technologies in this study expand upon the EMF 25 Standards Case in also assuming accelerated building shell improvements, low-cost solid-state lighting, and technology changes that reduce miscellaneous electric loads in the residential and commercial sectors. Reference and advanced building shell improvements are estimated based on off-line stock models informed by potential energy-saving shell improvements using the BEopt program (Christensen et al., 2005). Office equipment energy efficiency potential is based on Kawamoto et al. (2001), and all other miscellaneous electric technology efficiency improvements are from TIAX (2006).

The future deployment of advanced industrial production technologies in the U.S. will depend on the evolution of the U.S. industrial sector broadly, and in particular, on the level of investment both in building new industrial facilities and in retrofitting existing ones. The reference scenario assumes 0.1% per year improvement in all industrial energy-consuming technologies, with a 0.35% annual reduction in service requirements per unit of output produced, not differentiated between industries (Tables 2 and 3). The advanced industrial scenario posits that energy-saving investments are made both to increase the efficiency of specific energy-consuming technologies (e.g., boilers, motors), and to reduce the energy service intensity of specific manufacturing processes, as specified in IEA (2007c) and Masanet et al. (2009). This scenario assumes that by 2035, efficiencies of gas boilers and all machine drive systems improve by 20%; other boilers improve by 10% (IEA, 2007c; Table 2). Specific changes to industrial production technologies are implemented, reducing service input requirements per unit of output; these changes, detailed in Table 3, reflect the adoption of present-day “best available practices” by 2035 (IEA, 2007c; Masanet et al., 2009).

In the transportation sector, the future emissions mitigation potential will be influenced heavily by which fuels are supplying the services. Several studies have shown that if the sector remains reliant on liquid hydrocarbon fuels, the potential for emissions mitigation will either be limited in scope, or costly, relative to other sectors of the economy (Richels and Blanford, 2008; Schafer et al., 2009; Kyle et al, 2009). However, with present-day technology, vehicles powered by electricity, natural gas, or hydrogen would be very unlikely to displace vehicles powered by liquid fuels in the next few decades, due to a range of issues such as consumer preferences, cost, refueling infrastructure, and safety (Schafer et al.,

Table 2: Assumed Efficiency Improvements of Cross-cutting Industrial Technologies, 2005 to 2035, Reference and Advanced Technology Levels

Service	Industry	Fuel	Reference	Advanced
Steam	Pulp, Paper and Wood	Gas	3%	15%
		Electricity	0%	0%
		Biomass, coal, liquids	3%	10%
	All Other Industries	Gas	3%	19%
		Electricity	0%	0%
		Biomass, coal, liquids	3%	10%
Process Heat	Primary Metals Industries	Gas	3%	29%
		Electricity	3%	3%
		Biomass, coal, liquids	3%	3%
	All Other Industries	Gas	3%	30%
		Electricity	3%	18%
		Biomass, coal, liquids	3%	18%
Machine Drive	All Industries	Electricity	3%	19%
		Gas, liquids	3%	3%
Electrochemical	All Industries	Electricity	3%	3%
Other End Uses	All Industries	Gas	3%	26%
		Electricity	3%	7%
		Biomass, coal, liquids	3%	3%

2009). Still, it is unclear how the technologies will evolve over the next few decades. For this reason, this study considers two advanced transportation scenarios: one (Adv-trn-ICE) in which the sector continues to rely primarily on liquid hydrocarbon fuels through 2050, but with light-duty vehicle fuel economy standards implemented in the next decade, as specified in the EMF-25 study (Energy Modeling Forum, 2010; see Table 4). Additional improvements are also assumed in freight trucking. The Adv-trn-ICE scenario includes light-duty vehicles powered by electricity, natural gas, and hydrogen, but with higher costs and limited availability. The second scenario (Adv-trn-EV) has the same advanced fuel economy standards for ICE vehicles, but includes technological advances allowing electric light-duty vehicles to compete with the same levelized non-fuel cost as ICE vehicles by 2035. These two scenarios allow assessment of the value of fuel-switching, as opposed to within-fuel efficiency improvement.

3.2. Emissions Mitigation Policies

A wide range of future U.S. greenhouse gas mitigation policies have been discussed in recent years, differing in features such as (1) the stringency of the future emissions mitigation targets, (2) how the different sectors of the economy are covered, (3) which emissions sources and greenhouse gases are included,

Table 3: Assumed Service Intensity Reductions in Specific U.S. Industries, 2005 to 2035, Reference and Advanced Technology Levels

Industry	Service	Reference	Advanced
Chemicals	Steam	10%	20%
	Process Heat	10%	11%
	All Other End Uses	10%	25%
Pulp, Paper, and Wood	Steam	10%	27%
	Process Heat	10%	16%
	Machine Drive	10%	17%
	All Other End Uses	10%	16%
Iron and Steel	Process Heat	10%	11%
	All Other End Uses	10%	10%
Aluminum and Non-Ferrous Metals	All End Uses	10%	13%
Food Processing	Steam	10%	22%
	All Other End Uses	10%	10%
Cement	Process Heat	7%	60%
	All Electricity Uses	7%	59%
Other Nonmetallic Minerals	Steam	10%	14%
	All Other End Uses	10%	10%
Other Manufacturing	Steam	10%	13%
	All Other End Uses	10%	15%

Table 4: Reference and Advanced Technology Levels in the U.S. Transportation Sector

Technology	unit	2005	2020	2035	2050	2020	2035	2050
Vehicle fuel economy								
Light-duty vehicle - ICE	mpg*	19.8	23.9	26.2	28.7	27.7	33.8	40.9
Light-duty vehicle - Electric	mpg*	59.8	62.1	64.4	66.9	62.1	64.4	66.9
Freight truck	mpg**	6.7	7.2	7.6	8.1	7.7	8.8	10.1
Non-fuel cost								
Light-duty vehicle - ICE	$/veh-mi	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Light-duty vehicle - Electric	$/veh-mi	0.68	0.68	0.68	0.68	0.65	0.62	0.62

* Light-duty vehicle fuel economy expressed in miles per gallon of gasoline equivalent.
** Freight truck vehicle fuel economy expressed in miles per gallon of diesel equivalent.

(4) what levels of international offsets are allowed, and (5) whether inter-temporal shifting, also known as banking and borrowing, will be allowed (Paltsev et al., 2007; Fawcett et al., 2009). This study addresses policies differing in stringency, and in whether they allow banking and borrowing. Policies include all sectors in the economy, including land-use-change emissions. Policies in this study do not

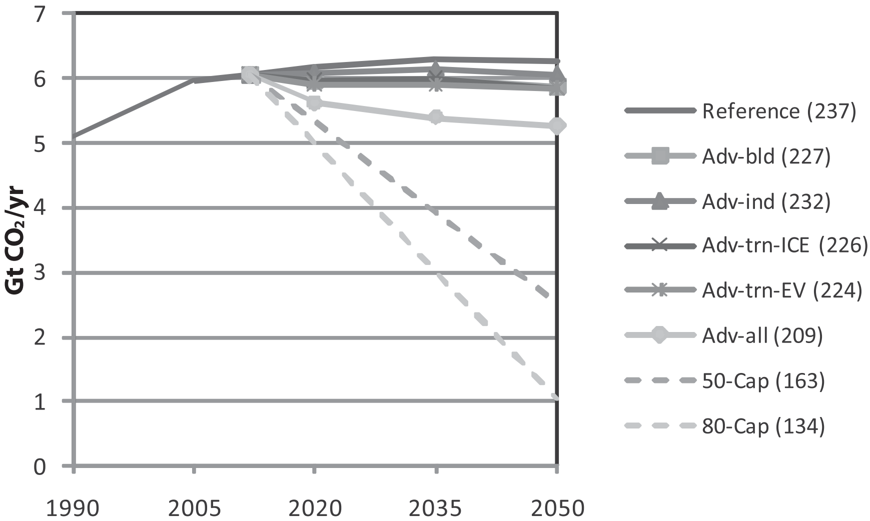
address non-CO_2 greenhouse gas emissions or international offsets, each of which could modify the level of CO_2 emissions abatement required to meet any policy target. Note that a high level of purchased offsets with the more stringent policy could be roughly equivalent to the less stringent policy with no offsets (Fawcett et al., 2009), in terms of domestic energy-system impacts.

The first two policies analyzed, 50-Cap and 80-Cap, have emissions pathways starting at 2012 Reference scenario emissions, and decreasing linearly thereafter, reaching a target annual CO_2 emissions level in 2050 that amounts to either a 50% or 80% reduction from the 1990 level. These annual emissions caps are met by a price on CO_2 emissions, implicit or explicit, such that emissions reductions take place across the whole economy with equal marginal abatement costs in all sectors, which maximizes the economic efficiency of abatement. The CO_2 price in each period in these scenarios is endogenous to the model, calculated as the market-clearing price necessary to achieve the specified abatement level. Total policy costs are calculated as the area under the marginal abatement cost curve; that is, the sum that results by raising the price of CO_2 from zero to the equilibrium price and multiplying along the way by the total mitigation at each price. This cost metric represents the total cost of mitigation including reductions in both consumer and producer surplus.

The two cap policies are characterized by limits on the ability to shift emissions mitigation over time, if such shifts would prove valuable. To allow for such intertemporal banking and borrowing of emissions, two additional policies, 50-Cumulative and 80-Cumulative are also explored. These policies are implemented such that the cumulative emissions between 2012 and 2050 are the same as those in the linear constraint policies described above—163 Gt CO_2 for the 50-Cap policy, and 134 Gt CO_2 for the 80-Cap policy. These cumulative emissions targets are met with a CO_2 price that increases at the long-term discount rate (assumed to be 5% in this study), in order to maximize the economic efficiency of the time path of future emissions allowances (Peck and Wan, 1996). Intertemporal flexibility of the emissions path could potentially allow for higher emissions in the next decade, offset by deeper reductions at a later time period, after the energy supply system has had adequate time to implement low-carbon technologies. These additional policies allow assessment of the extent to which the value of end-use technology advances depend on their role in reducing emissions in the near term, as opposed to more long-term interactions with the energy supply system.

In all policies in this study, it is assumed that the rest of the world also acts to limit emissions, but with delayed participation by developing regions, as in Fawcett et al. (2009). The less aggressive climate policies abroad could create an incentive for the U.S. to import bioenergy, effectively exporting the indirect land-use change emissions from bioenergy production. For this reason, importation of biomass and biomass-derived fuels into the U.S. is not allowed in any of the policies investigated.

Figure 4: Annual CO_2 Emissions by Technology Scenario, Compared with Policy Emissions Pathways. Cumulative 2012–2050 emissions shown in parentheses



4. RESULTS AND DISCUSSION

4.1. End-Use Technology without a Constraint on CO_2

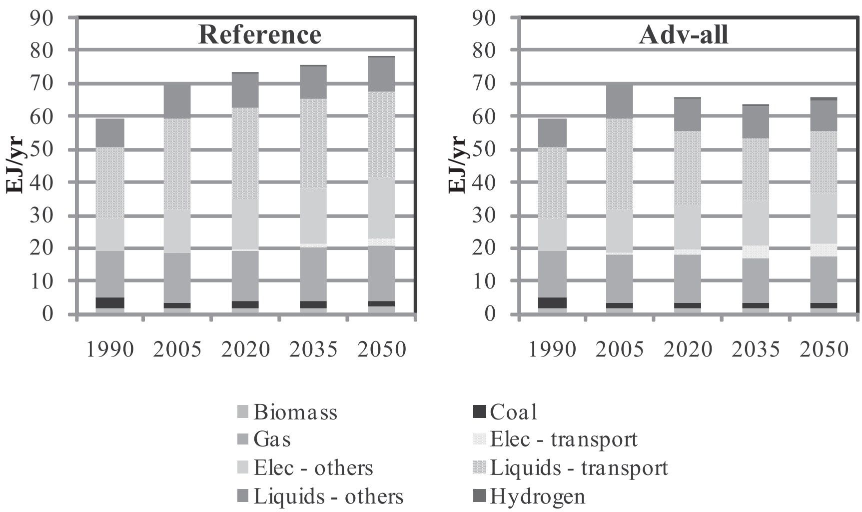
The underlying scenario for the U.S. that serves as the basis for this study is one of modest CO_2 emissions growth. Under the least optimistic end use technology assumptions (the Reference technology scenario), CO_2 emissions increase by about 5% from 2005 levels over the next four decades. This is a consequence of the full suite of assumptions that define the reference scenarios, including not only end use technology assumptions, but those regarding population, economic growth, the demand for end use services associated with this growth, and energy supply and conversion technologies. This moderate growth is roughly consistent with recent U.S. government projections (EIA, 2009).

Independent of CO_2 emissions constraints or pricing, all advanced technology scenarios in this study reduce economy-wide CO_2 emissions as compared with the Reference scenario, with cumulative 2012–2050 emissions reduced by between 2% (Adv-ind) and 12% (Adv-all; see Figure 4, Table 5). For comparison, the GCAM Standards Case of the EMF 25 study reduced cumulative emissions from the Reference Scenario by 4% over this same time horizon (Energy Modeling Forum, 2010). Note that in no future time period are advanced end-use technologies alone sufficient to meet the emissions caps specified by even the less stringent policy (Figure 4). This result confirms two key elements of climate

Table 5: Reduction in Cumulative Discounted Policy Costs by Technology Scenario, as Compared with Reference Technology Scenario, with Four Climate Policies

	50-Cap	50-Cumulative	80-Cap	80-Cumulative
Adv-bld	18%	19%	11%	13%
Adv-ind	10%	12%	7%	8%
Adv-trn-ICE	23%	23%	20%	18%
Adv-trn-EV	31%	33%	30%	27%
Adv-all	53%	57%	45%	43%

Figure 5: Total Final Energy by Fuel, Ref and Adv-all Scenarios with No Climate Policy



technology research: (1) that a portfolio of technologies will be required to address climate change, and (2) that advanced technology alone is not sufficient to address climate change (Edmonds et al., 2007).

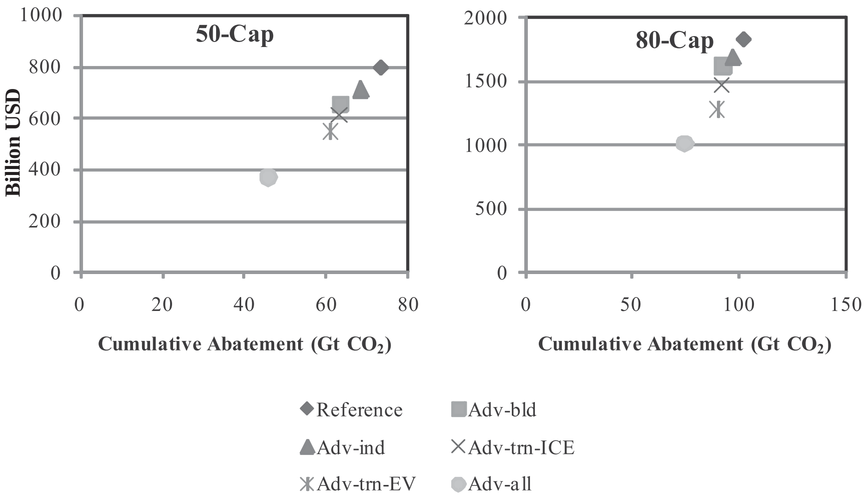
These baseline (i.e., without any CO_2 mitigation policy) reductions in CO_2 emissions from advanced end-use technologies are largely due to reduced liquid fuel demand in transportation, and reduced electricity demand in buildings and industry (Figure 5). Total final energy consumption in the Adv-all scenario is reduced by 15% relative to the Reference scenario, in both 2035 and 2050. Advanced buildings technologies reduce the demand for electricity more so than for other fuels because the standards assumed in this study force the greatest departure from the reference in services fueled by electricity: cooling, lighting, residential appliances, commercial refrigeration, and commercial office equipment (see Tables A1 and A2). While the standards include gas and oil furnaces and water heaters, new furnaces are already quite efficient, and the water heater standards are not especially stringent. In total, the standards result in a 20% decrease in building sector electricity demands in both 2035 and 2050, as compared with a 9% reduction in direct use of gas and oil. Advanced industrial technologies also drive a 15% reduction in electricity, due mostly to assumed improvements in machine drive, a cross-cutting service that is generally supplied by electricity and accounts for about 60% of electricity use in manufacturing (EIA, 2002; IEA, 2007c). Unlike the buildings sector, the industrial sector also sees a reduction in fossil fuel demand of about 15% in 2035 and 2050, mostly due to reduced demands for heat and steam in manufacturing processes, and implementation of technologies to reduce losses and recycle heat in steam systems, kilns, and blast furnaces (see Tables 2 and 3). In the transportation sector, fuel economy standards alone (Adv-trn-ICE) reduce total final energy demand by about 15% in 2050, and in this scenario, electricity supplies 15% of light-duty vehicle kilometers traveled in 2035, and 20% in 2050. Advanced electric vehicles (Adv-trn-EV; Adv-all) allow electricity to supply nearly 50% of light-duty vehicle kilometers traveled in 2035 and 2050, reducing transportation total final energy by 20% compared with the Reference scenario.

Despite the fact that the advanced end-use technologies are not sufficient to meet the emissions constraints by themselves, the reductions in CO_2 emissions due to technology alone, or baseline emissions reductions, do achieve a substantial portion of the abatement requirements of the climate policies (Figure 4), particularly in the near-term. In 2020, advanced technology achieves up to 65% of the abatement requirements of the Reference technology scenario in the 50-Cap policy. However, note that this "head start" decreases to 30% in 2050, as the policy becomes increasingly stringent over time. This observation is consistent with the hypothesis that end-use technology improvement is most important for meeting emissions targets in the short term. The following sections further explore the role of end-use technology advances in reducing economy-wide mitigation costs.

4.2. End-Use Technology under Economy-Wide CO_2 Caps

The value of advanced end-use technologies in CO_2 emissions mitigation is not limited to their direct effects on energy use and baseline CO_2 emissions; end-use technologies play an integral role in the future evolution of the energy system, particularly under a CO_2 emissions constraint. The six final energy forms available to the end-use sectors in this study—biomass, coal, gas, liquid fuels, electricity, and hydrogen—all have different capacities for fuel-cycle CO_2 emissions mitigation. Whole-system costs of emissions mitigation can be reduced if final energy demands are shifted away from fuels with relatively high-cost fuel-cycle CO_2 mitigation potential, towards those with low-cost mitigation potential. End-use technologies play a key role in determining the capacity of final energy consumers to shift the composition of final energy demands towards fuels with

Figure 6: Cumulative Discounted Policy Costs (2012 to 2050) for All Technology Scenarios with 50-Cap and 80-Cap CO_2 Mitigation Policies, as Compared with Cumulative Abatement Requirements

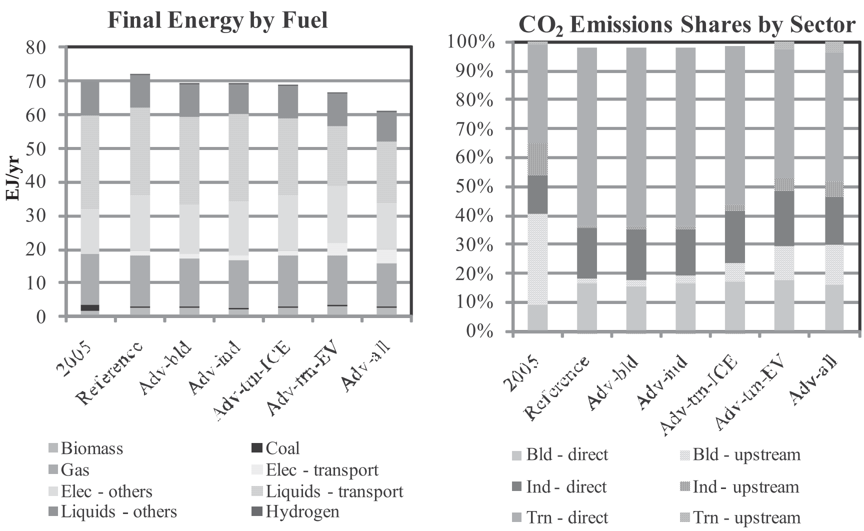


low-cost mitigation potential, whether through service demand reduction, energy efficiency improvement, or fuel substitution. In this way, advanced end-use technologies may reduce costs of emissions mitigation, independent of their effects on baseline emissions.

Both of these mechanisms contribute to the observed value of the end-use technology advances in the scenarios in this study, shown in Figure 6. In general, the scenarios with the greatest levels of baseline CO_2 emissions abatement have the highest economic value in the context of reducing policy costs. However, Figure 6 also highlights the non-linear nature between baseline emissions reduction and the economic value of advanced technologies in reducing abatement costs from an evolving energy system. Note that advanced building (Adv-bld) and transportation (Adv-trn-ICE; Adv-trn-EV) technologies all achieve reasonably similar levels of cumulative baseline abatement—between 10 and 12 Gt CO_2—and as such have similar abatement requirements in both the 50-Cap and 80-Cap policies. However, scenarios with advanced transportation technologies, electric vehicles in particular, are able to achieve the required levels of abatement at lower costs than those with advanced buildings technologies. This relatively high value of advanced transportation technologies is especially pronounced with the more stringent climate policy.

The effects of advanced technologies on the composition of total final energy demand allows insight into how these different technology areas interact with the energy system as a whole to reduce emissions mitigation costs (Figure

Figure 7: Total Final Energy by Fuel, and CO_2 Emissions by Each End-use Sector, for All Technology Scenarios in 2035 with 80-Cap Policy.

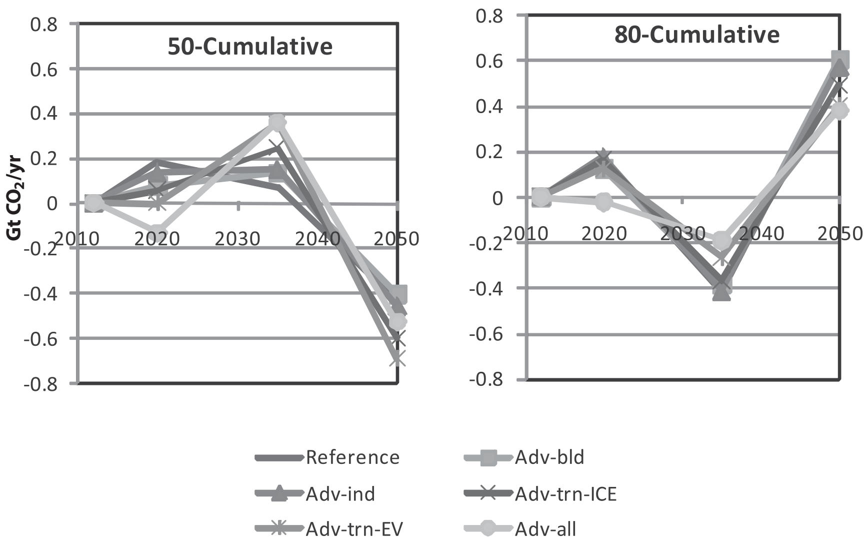


Upstream emissions from the use of electricity and refined liquid fuels are calculated using average national CO_2 emissions intensities.

7). The scenario with advanced building technologies (Adv-bld) is characterized by relatively low electricity demands, as compared with the Reference scenario. However, this doesn't translate to a shift in the sectoral composition of CO_2 emissions from the Reference scenario (Figure 7), as fuel-cycle emissions from electricity are low in 2035 in the 80-Cap scenario. In contrast, the scenario with advanced ICE vehicles (Adv-trn-ICE) has relatively low liquid fuel demands compared with the Reference, which translates to a relatively low portion of CO_2 emissions from transportation. Advanced electric vehicles (Adv-trn-EV) further decrease liquid fuel demands, substituting an increase in electricity, further reducing the transportation sector's share of CO_2 emissions (even considering the additional upstream emissions from electricity generation). This reduction in emissions from the transportation sector reduces the abatement requirements on all other sectors of the economy, important for reducing whole-system mitigation costs.

These scenarios demonstrate especially high value for technology advances that allow the composition of final energy demands to shift away from liquid fuels, which have high fuel-cycle abatement costs, towards electricity, which has low fuel-cycle abatement costs (Figure 6). This shift could take place as a result of reducing liquid fuel demands through energy efficiency (Adv-trn-ICE), but is greatest where advanced end-use technologies facilitate the substi-

Figure 8: Net Emissions Borrowing by Technology Scenarios with 50-Cumulative and 80-Cumulative Policies, as Compared to Straight-line Emissions Pathways of 50-Cap and 80-Cap Policies



tution of electricity for liquid fuels (Adv-trn-EV). As a general rule, advanced end-use technologies will have the greatest economic value when they facilitate system-wide transitions from emission-intensive fuels to low-emissions fuels.

4.3. End Use Technology under Cumulative Economy-Wide CO_2 Caps with Banking and Borrowing

The final sensitivity explored in this study is the effect of banking and borrowing on the time path of emissions, and on the value of end-use technological advance. Because of the long lifetimes of energy supply technologies, it may be that an effective mitigation strategy would be to delay emissions mitigation for several decades, avoiding premature retirement of existing, emissions-intensive energy supply capital, and also avoiding the consumer welfare losses associated with service demand reductions in the end-use sectors. Such a scenario could have a lesser role for end-use technologies, which are often considered most important for near-term emissions reductions.

As shown in Figure 8, most scenarios in the study do show near-term borrowing of emissions. However, the amount of emissions borrowing depends on the end-use technology level, and in fact, the Adv-all scenario shows net banking in 2020 in both the 50-Cumulative and 80-Cumulative policies. Note also that all scenarios with the 80-Cumulative policy are borrowing in 2050 due to the stringency of this target, but the amount of borrowing—which has implications for post-2050 climate policy—is lowest in scenarios with the most advanced end-use technology levels. This latter point highlights that the role of advanced end-use technologies is not limited to near-term emissions reductions.

Importantly, the cumulative discounted economic value of advanced end-use technologies in emissions mitigation is not reduced by allowing banking and borrowing (Table 5). Even in scenarios where near-term emissions borrowing reduces economy-wide abatement requirements in the near term, this shift does not reduce the value of end-use technological advances over the next four decades. This is because end-use technology advances are important not only for providing near-term emissions reductions, but for contributing to the long-term capacity of the system to achieve deep emissions reductions at low economic cost. In contrast to the hypothesis that inter-temporal flexibility would reduce the importance of advanced end-use technologies, these scenarios find that end-use technologies are important for determining the intertemporal allocation of emissions, and for achieving long-term emissions goals.

5. CONCLUSIONS

This study presents detailed, technology-oriented representations of the U.S. buildings, industry, and transportation sectors, embedded within the GCAM integrated assessment model, allowing consideration of the role of specific end-use technology futures on total final energy demands and greenhouse gas mitigation over the next four decades. It uses a series of scenarios of potential efficiency improvements in each of the end-use sectors, and analyzes the implications of these improvements on the future evolution of final energy demands and CO_2 emissions from the energy system in the U.S. It then analyzes how these technologies contribute to reducing future costs of greenhouse gas mitigation, and offers several insights into the role of end-use technology.

First, enhanced energy efficiency reduces energy consumption and CO_2 emissions even without a climate policy, and these "baseline" reductions can go a long way towards meeting climate policy targets, particularly in the near term. However, the magnitude of these reductions is insufficient to meet even the least stringent emissions target considered in this study, a 50% reduction in 2050 from 1990 levels (50-Cap). We also note that this study does not consider the costs of achieving the technological outcomes assumed in the "advanced" scenarios, so this study should not be used to assess the presence or magnitude of cost-free energy demand reductions.

Second, the actual economic value of end-use technologies in meeting long-term emissions targets can not be deduced from baseline reductions in final energy demand and CO_2 emissions. The economic value of advanced end-use technologies will depend on how they interact with the evolving energy supply system. This study finds that the technologies that reduce liquid fuel demand have greater economic value than those that reduce electricity demand, as fuel-cycle mitigation costs are higher for refined liquid fuels than electricity. In this context, electric-powered light-duty vehicles can contribute significantly to reducing emissions mitigation costs.

Finally, the study demonstrates that the value of advanced end-use technologies is not limited to meeting emissions targets in the next couple of decades, before the energy supply system has time to adopt low-carbon technologies. End-use technologies are an integral part of the energy system, important for shaping the future composition of final energy demands. Because each final energy form will have different costs of fuel-cycle mitigation, end-use technologies will be important for allowing transitions to low-emissions fuels as they become available. It also follows that advanced end-use technology deployment should be seen as complementary to advances in energy supply technologies that allow for mitigation of upstream emissions from the fuels consumed by end-use sectors.

ACKNOWLEDGMENTS

The authors would like to thank the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy for support of end-use sector model development. The authors are also indebted to the U.S. Department of Energy's Office of Science, the Electric Power Research Institute, and other sponsors of the Global Energy Technology Strategy Program (GTSP; http://www.globalchange.umd.edu/gtsp/) for their support of the GCAM model development. Finally, the authors thank Eric Masanet, Jayant Sathaye, and Michael McNeil of Lawrence Berkeley National Laboratory for providing detailed technology data on the U.S. buildings and industrial sectors.

REFERENCES

Brenkert, A., Smith, S., Kim, S., Pitcher, H. (2003). *Model Documentation for the MiniCAM*. PNNL-14337. Pacific Northwest National Laboratory, Richland, WA.

Brown, M. (2001). *Market Failures and Barriers as a Basis for Clean Energy Policy*. DOE/019-0335, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Christensen, C., Horowitz, S., Givley, T., Courtney, A., Barker, G. (2005). *BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy*. NREL/CP-550-37733. Golden, CO: National Renewable Energy Laboratory.

Clarke, J.F., Edmonds, J.A. (1993). "Modeling Energy Technologies in a Competitive Market." *Energy Economics* 15 (2): 123–129.

Clarke, L., Weyant, J., Edmonds, J. (2008a). "On Sources of Technological Change: What do the Models Assume?" *Energy Economics* 30, 409–424.

Clarke, L., Wise, M., Edmonds, J., Placet, M., Kyle, P., Calvin, K., Kim, S., Smith, S. (2008b). *CO_2 Emissions Mitigation and Technological Advance: An Updated Analysis of Advanced Technology Scenarios*. PNNL-18075. Richland, WA: Pacific Northwest National Laboratory. Available at http://www.pnl.gov/science/pdf/PNNL18075.pdf (Accessed June 2010).

Clarke L., M. Wise, S. Kim, A. Thomson, R. Izaurralde, J. Lurz, M. Placet, S. Smith (2006). *Climate Change Mitigation: An Analysis of Advanced Technology Scenarios*, Technical Report PNNL-16078, Pacific Northwest National Laboratory.

Davis, S.C., Diegel, S.W., Boundy, R.G. (2008). *Transportation Energy Data Book*. ORNL-6981, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Edmonds J., T. Wilson, M. Wise, and J. Weyant (2006). "Electrification of the economy and CO_2 emissions mitigation." *Environmental Economics and Policy Studies* 7(3):175–203.

Edmonds, J.A., Wise, M.A., Dooley, J.J., Kim, S.H., Smith, S.J., Runci, P.J., Clarke, L.E., Malone, E.L., Stokes, G.M. (2007). *Global Energy Technology Strategy Addressing Climate Change: Phase 2 Findings from and International Public-Private Sponsored Research Program.* Available at http://www.globalchange.umd.edu/data/gtsp/docs/gtsp_2007_final.pdf (Accessed June 2010).

EIA (2002). *Manufacturing Energy Consumption Survey*. Energy Information Administration, Washington, DC. Available at http://www.eia.doe.gov/emeu/mecs/contents.html (Accessed June 2010).

EIA (2005). *Residential Energy Consumption Survey*. Energy Information Administration, Washington, DC. Available at http://www.eia.doe.gov/emeu/recs/ (Accessed June 2010).

EIA (2008). *Annual Energy Outlook 2008*. Energy Information Administration, Washington, DC. Available at http://www.eia.doe.gov/oiaf/archive/aeo08/index.html (Accessed June 2010).

EIA (2009). *An Updated Annual Energy Outlook 2009 Reference Case Reflecting Provisions of the American Recovery and Reinvestment Act and Recent Changes in the Economic Outlook*. SR-OIAF/2009-03, Energy Information Administration, Washington, DC. Available at http://www.eia.doe.gov/oiaf/servicerpt/stimulus/index.html (Accessed June 2010).

Energy Modeling Forum (EMF) (2010). “EMF 25 Scenario Design.” Stanford University, Stanford, CA. Document available online at http://emf.stanford.edu/files/res/2372/25design2.pdf.

Fawcett, A.A., Calvin, K.V., de la Chesnaye, F.C., Reilly, J.M., Weyant, J.P. (2009) Overview of the EMF 22 U.S. transition scenarios. *Energy Economics* 31: S198-S211.

Geller, H., Kubo, T., Nadel, S. (2001). *Overall Savings from Federal Appliance and Equipment Efficiency Standards*. Americal Council for an Energy-Efficient Economy, Washington, DC.

Geller, H., Attali, S. (2005). *The Experience with Energy Efficiency Policies and Programmes in IEA Countries – Learning from the Critics*. IEA Information Paper, International Energy Agency, Paris, France.

Gillingham, K., Newell, R., Palmer, K. (2006). Energy Efficiency Policies: A Retrospective Examination. *Annual Review of Environment and Resources* 31: 161–192.

Gregg, J.S., Smith, S.J. (2010). Global and regional potential for bioenergy from agricultural and forestry residue biomass. *Mitigation and Adaptation Strategies for Global Change* 15: 241–262.

Greening, L.A., Greene, D.L., Difiglio, C. (2000). Energy efficiency and consumption – the rebound effect – a survey. *Energy Policy* 28: 389–401.

Hirst, E., Cavanagh, R., Miller, P. (1996). The future of DSM in a restructured U.S. electricity industry. *Energy Policy* 24: 303–315.

IEA (2007a). *Mind the Gap – Quantifying Principal-Agent Problems in Energy Efficiency*. International Energy Agency, Paris, France.

IEA (2007b). *Energy Balances of OECD Countries, 1960 to 2005*. Paris, France: International Energy Agency.

IEA (2007c). *Tracking Industrial Energy Efficiency and CO2 Emissions*. International Energy Agency, Paris, France.

Interlaboratory Working Group (2000). *Scenarios for a Clean Energy Future*. ORNL/CON-476 and LBNL-44029, Oak Ridge National Laboratory and Lawrence Berkeley National Laboratory, Oak Ridge, Tennessee, and Berkeley, California.

IPCC (2001). *Climate Change 2001: the Scientific Basis*. Intergovernmental Panel on Climate Change. Available at http://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/wg1/index.htm (Accessed June 2010).

Jaffe, A.B. and R.N. Stavins (1994a). Energy-efficiency investments and public policy. *Energy Journal* 15: 43–65.

Jaffe, A.B. and R.N. Stavins (1994b). The energy-efficiency gap – what does it mean. *Energy Policy* 22: 804–810.

Jansen, H. and C. Denis (1999). A welfare cost assessment of various policy measures to reduce pollutant emissions from passenger road vehicles. *Transportation Research Part D: Transport and Environment*: 4: 379–396.

Joskow, P. and D. Marron (1992). What does a negawatt really cost? Evidence from utility conservation programs. *Energy Journal* 13: 41–74.

Kawamoto, K., J.G. Koomey, B. Nordman, R.E. Brown, M.A. Piette, M. Ting, and A.K. Meier (2001). *Electricity Used by Office Equipment and Network Equipment in the U.S.: Detailed Report and Appendices*. LBNL-45917. Berkeley, CA: Lawrence Berkeley National Laboratory.

Kim, S.H., J.A. Edmonds, J. Lurz, S.J. Smith, and M. Wise (2006). "The ObjECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation." *Energy Journal* 27: 63–91.

Kyle, G.P., S.J. Smith, L.E. Clarke, S.H. Kim, and M.A. Wise, (2007) *The Value of End-Use Energy Efficiency in Mitigation of U.S. Carbon Emissions*. PNNL-17039, Pacific Northwest National Laboratory, Richland, WA.

Kyle, P., L. Clarke, G. Pugh, M. Wise, K. Calvin, J. Edmonds, and S. Kim (2009). The value of advanced technology in meeting 2050 greenhouse gas emissions targets in the United States. *Energy Economics* 31: S254-S267.

Kyle, P., L. Clarke, F. Rong, and S. Smith (2010). Climate policy and the long-term evolution of the U.S. buildings sector. *Energy Journal* 31: 145–172.

Laitner, J.A. (2000). Energy efficiency: rebounding to a sound analytical perspective. *Energy Policy* 28: 471–475.

Levine, M.D., J.G. Koomey, J.E. McMahon, A.H. Sanstad, and E. Hirst (1995) Energy efficiency policy and market failures. *Annual Review of Energy and the Environment* 20: 535–555.

Levine, M., D. Ürge-Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli Mehlwana, S. Mirasgedis, A. Novikova, J. Rilling, and H. Yoshino (2007). "Residential and commercial buildings." In Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., eds., *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Lovins, A. and H. Lovins 1997. *Climate: Making Sense and Making Money*. Rocky Mountain Institute, Old Snowmass, Colorado.

Lutzenhiser, L. (1993). Social and behavioral aspects of energy use. *Annual Review of Energy and the Environment* 18: 247–289.

Masanet, E., M. Ting, E. Worrell, A. Sanstad, A. Novikova, R. Bharvirkar, M. Marsidi, A. North, and M. Rufo (2009). *Estimation of Long-Term Energy-Efficiency Potentials for California Buildings and Industry*. Sacramento, CA: California Energy Commission, PIER Energy-Related Environmental Research, CEC-500-06-005.

McKinsey Global Institute (2007). *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?* San Francisco, California: McKinsey & Company, Inc., 2006.

Murtishaw, S. and J. Sathaye (2006). Quantifying *the Effect of the Principal-Agent Problem on US Residential Energy Use*. LBNL-59773, Lawrence Berkeley National Laboratory, Berkeley, California. Available at http://ies.lbl.gov/iespubs/59773Rev.pdf (Accessed June 2010).

NCI (2002). *U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate*. Washington, D.C.: Navigant Consulting, Inc. Available at http://www.cee1.org/eval/db_pdf_es/275es.pdf (accessed June 2010).

NCI (2004). *EIA – Technology Forecast Updates – Residential and Commercial Building Technologies*. Washington, D.C.: Navigant Consulting, Inc. Reference No. 117943.

Ozalp, N. and B. Hyman (2006). Energy end-use model of paper manufacturing in the US. *Applied Thermal Engineering* 26: 540–548.

Paltsev, S., J. Reilly, H. Jacoby, A. Gurgel, G. Metcalf, A. Sokolov, and J. Holak (2007). *Assessment of U.S. Cap-and-Trade Proposals*. MIT Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Peck, S.C. and Y.H. Wan. Analytical solutions of simple greenhouse gas models. In: E.C. Van Ierland and K. Gorka, eds. *Economics of Atmospheric Pollution*, Springer, New York.

Richels, R. and G. Blanford (2008). "The Value of Technological Advance in Decarbonizing the U.S. Economy." *Energy Economics* 30 (6): 2930–2946.

Rosenquist, G., M. McNeil, M. Iyer, S. Meyers, and J. McMahon (2006). Energy efficiency standards and codes for residential/commercial equipment and buildings: additional opportunities. *Energy Policy* 34: 3257–3267.

Sathaye, J. and S. Murtishaw (2004). *Market Failures, Consumer Preferences, and Transaction Costs in Energy Efficiency Purchase Decisions*. Lawrence Berkeley National Laboratory for the California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2005-020.

Schafer, A., J.B. Heywood, H.D. Jacoby, and I.A. Waitz (2009) *Transportation in a Climate-Constrained World*. The MIT Press, Cambridge, MA, USA.

Sorrell, S., E. O'Malley, J. Schleich, and S. Scott (2004). *The Economics of Energy Efficiency*. Edward Elgar Publishing, Inc., Northampton, Massachusetts.

Sutherland, R. (2003). *The High Costs of Federal Energy Efficiency Standards for Residential Appliances*. Policy Analysis No. 504. The Cato Institute, Washington, DC.

TIAX LLC (2006). *Commercial and Residential Sector Miscellaneous Electricity Consumption: Y2005 and Projections to 2030*. Reference No. D0366.

UNCTAD (2006. *Review of Maritime Transport*, United Nations Conference on Trade and Development, UNCTAD/RMT/2006.

U.S. Department of Transportation (2008). *Transportation Statistics Annual* Report. Research and Innovative Technology Administration, Bureau of Transportation Statistics, Washington, DC.

Wise, M.A., P. Sinha, S.J. Smith, and J.P. Lurz (2007). *Long-Term US Industrial Energy Use and CO2 Emissions*. PNNL-17149, Pacific Northwest National Laboratory, Richland, WA.

Wise, M.A., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, A. Janetos, and J. Edmonds (2009). Implications of limiting CO2 concentrations for land use and energy. *Science* 5931: 1183–1186.

Worrell, E., L. Price, and C. Galitsky (2004). *Emerging Energy-Efficient Technologies in Industry: Case Studies of Selected Technologies*. LBNL 54828, Lawrence Berkeley National Laboratory, Berkeley, California.

APPENDIX

Table A1: Residential Sector Efficiencies Used in Reference and Advanced Buildings Scenarios

Service	Technology	unit	2005	Reference 2020	Reference 2050	Advanced 2020	Advanced 2050
	Building shell	W/m2	0.219	0.202	0.170	0.199	0.159
Heating	Wood furnace	out/in	0.40	0.41	0.42	Same as Ref	
	Gas furnace (typical)	AFUE	0.78	0.78	0.80	0.90	0.93
	Gas furnace (hi-eff)	AFUE	0.90	0.96	0.99	Same as Ref	
	Electric furnace	out/in	1	1	1	1	1
	Electric heat pump	HSPF	7.15	8.20	8.60	9.74	10.04
	Fuel furnace (typical)	AFUE	0.78	0.78	0.80	0.85	0.88
	Fuel furnace (hi-eff)	AFUE	0.85	0.85	0.88	Same as Ref	
Cooling	Air conditioning (typical)	SEER	10.0	10.2	10.5	16.0	16.5
	Air conditioning (hi-eff)	SEER	15.0	15.2	15.7	16.0	16.5
Water Heating	Gas water heater (typical)	EF	0.54	0.59	0.61	0.64	0.66
	Gas water heater (hi-eff)	EF	0.75	0.77	0.79	0.77	0.79
	Electric water heater (typical)	EF	0.84	0.90	0.93	0.95	0.98
	Electric water heater (hi-eff)	EF	0.90	0.95	0.98	Same as Ref	
	Heat pump water heater	EF	n/a	2.20	2.27	Same as Ref	
	Fuel water heater (typical)	EF	0.53	0.53	0.55	Same as Ref	
	Fuel water heater (hi-eff)	EF	0.68	0.68	0.70	Same as Ref	
Lighting	Incandescent lighting	lumens/W	14	15	15	Same as Ref	
	Fluorescent lighting	lumens/W	82	83	86	Same as Ref	
	Solidstate lighting	lumens/W	n/a	105	113	160	186
Large Appliances	Gas appliances	index	1	1.01	1.03	2.47	2.55
	Electric appliances (typical)	index	1	1.02	1.05	1.39	1.43
	Electric appliances (hi-eff)	index	n/a	1.68	1.73	Same as Ref	
	Fuel appliances	index	1	1.00	1.00	1.00	1.00
Other Appl.	Other electric appliances	index	1	0.91	0.98	1.02	1.05
Other	Other gas	index	1	1.00	1.00	Same as Ref	
	Other electric	index	1	1.09	1.18	1.12	1.40
	Other oil	index	1	1.00	1.00	Same as Ref	

Table A2: Commercial Sector Efficiencies Used in Reference and Advanced Buildings Scenarios

Service	Technology	unit	2005	Reference 2020	Reference 2050	Advanced 2020	Advanced 2050
Heating	Building shell	W/m2	0.219	0.201	0.170	0.201	0.168
	Wood boiler	out/in	0.65	0.6598	0.68	Same as Ref	
	Gas furnace/boiler (typical)	out/in	0.70	0.78	0.80	0.82	0.84
	Gas furnace/boiler (hi-eff)	out/in	0.86	0.87	0.89	Same as Ref	
	Electric furnace	out/in	1	1	1	Same as Ref	
	Electric heat pump	out/in	3.10	3.30	3.56	3.40	3.50
	Fuel furnace (typical)	out/in	0.70	0.81	0.83	0.83	0.86
	Fuel furnace (hi-eff)	out/in	0.85	0.85	0.88	Same as Ref	
Cooling	Air conditioning (typical)	SEER	9.1	10.5	10.9	13.0	13.4
	Air conditioning (hi-eff)	SEER	13.9	13.3	13.7	Same as Ref	
Water Heating	Gas water heater (typical)	out/in	0.78	0.79	0.82	0.85	0.88
	Gas water heater (hi-eff)	out/in	0.94	0.95	0.98	Same as Ref	
	Electric water heater	out/in	0.98	0.99	0.99	Same as Ref	
	Heat pump water heater	out/in	n/a	2.20	2.44	2.20	2.49
	Fuel water heater	out/in	0.77	0.80	0.82	Same as Ref	
Lighting	Incandescent lighting	lumens/W	14	15	15	Same as Ref	
	Fluorescent lighting	lumens/W	82	83	86	Same as Ref	
	Solidstate lighting	lumens/W	n/a	105	113	160	186
Ventilation	Ventilation (typical)	out/in	0.71	0.72	0.74	0.82	0.87
	Ventilation (hi-eff)	out/in	0.85	0.87	0.89	Same as Ref	
Cooking	Gas cooking equipment	out/in	0.51	0.53	0.54	Same as Ref	
	Electric cooking equipment	out/in	0.71	0.75	0.77	0.80	0.86
Refrigeration	Refrigeration (typical)	out/in	1.96	1.99	2.05	2.78	2.87
	Refrigeration (hi-eff)	out/in	3.09	3.14	3.24	Same as Ref	
Office	Office equipment	index	1.00	1.04	1.12	1.24	1.60
Other	Other gas	index	1.00	1.04	1.12	Same as Ref	
	Other electric	index	1.00	0.97	1.05	1.00	1.25
	Other oil	index	1.00	1.04	1.12	Same as Ref	

Impact of Relative Fuel Prices on CO_2 Emission Policies

Nick Macaluso† and Robin White**

The multi-sector end-use energy model E3MC was used to analyze the energy and greenhouse gas emissions impact of adding a carbon tax to efficiency improvement standards for the residential sector in Canada and the USA. Compared to standards alone, the addition of the tax led to further residential emission reductions in Canada, but attenuated the residential emission reductions in the USA. Examination of the relative residential electricity:natural gas prices demonstrated that the different country impacts were due to an increase in relative prices in the USA, but a decrease in relative prices in Canada that led to opposite shifts in preference for electricity over natural gas in the residential sector. Markedly different impacts of the carbon tax on electricity prices was due to the predominance of hydroelectric power in Canada and coal-fired electric generation in the USA. doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-6

1. INTRODUCTION

Energy efficiency standards and carbon taxes are key instruments that will likely play important roles in any future greenhouse gas (GHG) emission mitigation policy. In determining the best use of these instruments, policy-makers need to consider not only the relative advantages and disadvantages of various approaches, but also potential interactions.

Energy efficiency standards are not ideal as stand-alone policy instruments for mitigating overall energy use and GHGs because standards may only reduce energy intensity rather than total energy consumption. Furthermore, standards target only a subset of end-use applications and do not provide an incentive to go beyond mandated requirements or encourage the use of less emission intensive energy sources (Gillingham et al., 2009; Parry and Williams, 1999).

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Environment Canada, Economic Analysis Directorate, 25th Floor, 10 Wellington Street, Gatineau, QC, K1A 0H3, Canada. Tel: 1-819-953-1772.

† Corresponding author. E-mail: nick.macaluso@ec.gc.ca.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-6

Standards may also lead to less-than-expected emission reductions through the rebound effect, whereby efficiency increases reduce marginal operating costs and hence increase demand. In addition, standards may cause economic efficiency losses by forcing investments in applications lacking a payoff from efficiency gains. In setting standards, governments may lack sufficient information to choose the best channel for energy reductions (Goulder and Parry, 2008). Compared to market-based instruments, standards are also associated with higher enforcement costs to ensure compliance to desired emission levels (Proost and Rousseau, 2009). Nevertheless, standards can be valuable for reducing energy use in applications, such as non-space heating related residential appliances, in which fuel consumption is nearly price inelastic (Haupt and Stadejek, 2010).

By internalizing environmental externalities into energy prices, carbon taxes avoid many of the problems inherent in standards. In particular, carbon taxes provide incentives across a broad spectrum of end-use applications for reductions in energy intensity, total energy consumption and GHG emissions. Carbon taxes also provide the necessary price signals for the development of better technology (Newell et al., 2006). Any labour market distortions and reductions in near- to mid-term GDP caused by a carbon tax can be reversed through recycling carbon revenues back to the economy (Gerlagh and van der Zwaan, 2006). Nevertheless, there may be concerns about carbon taxes putting disproportionate burdens on low-income families, particularly if it is doubtful that the government will recycle revenues back to households (Wissema et al., 2007). More importantly, the political acceptability of a carbon tax may be lacking given persistent broad support for low energy prices as a means of stimulating economic growth (Pizer et al., 2006). Carbon taxes may be particularly unpopular in heavy manufacturing or energy producing regions due to their relatively large impact on energy intensive industries (Labandeira et al., 2009).

Given the increasing need to reduce GHGs, but ambiguous political support for such action, future emission mitigation regimes may emerge that combine market and regulatory-based approaches. Consequently, it is very important for decision-makers to consider interactions between policy instruments. While it may be expected that policy instruments would interact positively, further reducing emissions, policy overlap may lead to less than anticipated reductions. Furthermore, in some cases, certain policies may actually undermine the efficacy of already existing policies (Oikonomou et al., 2010).

Recently, the Stanford Energy Modeling Forum (EMF) established a modeling study group, EMF 25, to evaluate opportunities for reducing electricity, fuel demand and GHG emissions through energy conservation programs and various policy instruments. One particular objective is to advance understanding of the additionality of multiple policy instruments for reducing energy use and GHG emissions. For example, are the total GHG emission impacts of a policy package including both carbon taxes and efficiency standards less than, greater than or equal to the sum of the individual policies in isolation?

In an attempt to shed light on these questions, this paper examines a subset of modelled scenarios initially produced for EMF 25. The analysis explores how the addition of a carbon tax to standards affects delivered energy use and CO_2 emissions in the residential sectors in both Canada and the USA. A cross-country comparison is used to analyze the underlying price dynamics influencing the additionality of multiple policies on energy use and CO_2 emissions. For the purposes of this paper, all references to energy use refer to delivered energy unless otherwise specified.

2. MODEL DESCRIPTION

The results in this paper were generated using the Energy, Emissions and Economy Model for Canada (E3MC), which is Environment Canada's key analytical tool for examining the energy, emissions and macroeconomic impacts of various climate change policies. E3MC combines two models—Energy2020 (E2020) and The Informetrica Model (TIM) (Figure 1).

E2020 is a multi-sector end-use energy model that simulates supply, price, demand and emissions for all fuels (Systematic Solutions, 1996). E2020 captures feedback dynamics between an electric utility supply sector and four demand sectors (residential, commercial, transportation and industry).

The electric utility supply sector simulates forecasting of capacity needs, construction, operation costs and retirement of utility generation and transmission components. Electric generation plants are dispatched based on costs and specified constraints, such as emission regulations and power purchasing agreements. The Canadian portion of the model contains plant-by-plant detail, while the USA electric utility sector is modeled by five regions. Utilities in both countries are characterized by plant type (peaking, combined cycle, steam, advanced coal, hydro, etc.) and energy source (coal, natural gas, oil, hydro, biomass, wind, solar, etc.). Nuclear and non-hydro renewable electric capacity additions are exogenously specified.

In the demand sectors, energy demand is derived and based on historical trends rather than the use of price elasticities. E2020 simulates consumer energy demand causally by explicitly identifying the multiple ways price changes influence behavior and technology use (Figure 2). The model accounts for variable price responses over time due to changes in the rate of investment, age and efficiency of capital stock, and relative prices of alternative technologies. The model captures how the impact of price on energy demand depends on utilization of capital stocks, device and process efficiencies, fuel market share and growth of the economy.

In the short-term, higher fuel prices cause behavioral responses (lowering the thermostat, turning off lights, car-pooling etc.) to reduce utilization of existing capital stocks and hence energy use as consumers seek to stay within their budget constraints. In the longer term, higher fuel prices put downward pressure on energy demand as consumers purchase costlier higher efficiency appliances (thereby increasing device efficiency) or shift to less energy intensive methods of production (thereby increasing process efficiency). In the buildings sector, process efficiency improvements also include increased insulation that reduces heat loss and interior design changes that reduce lighting requirements. Changes in relative fuel prices may also lead to fuel-switching. However, the extent of fuel-switching is constrained by fuel market shares established largely by prevailing relative energy prices at the time of production capacity (residential housing, commercial establishments or industrial complexes) additions. Investments in production capacity are influenced by both energy prices and economic growth.

TIM is a macroeconomic model that uses econometrically based demand and price formation with a closed I-O centre. The model has extensive current-period and dynamic linkages between and within economic segments (Informetrica, 2010). Using an embedded 285 sector input-output module that models direct, indirect, and induced effects, TIM captures the interaction between industries and changes in producer prices, relative final prices and income. TIM factors in government fiscal balances, monetary flows, interest and exchange rates, imports and exports. TIM can be used to project the direct impacts of policies on final demand, output, employment, prices and sectoral income.

Run in tandem with E2020 as part of E3MC, TIM facilitates the integration of macroeconomic policy impacts into the modeling of energy and emissions. E3MC models both the behavior of individual sectors and the interaction between sectors. E220 provides TIM with changes in energy investments, intensities and prices, while TIM provides E220 with inflation, tax rates, exchange rates, gross outputs and personal income (Figure 1).

The integrated nature of E3MC enables it to capture all secondary and tertiary policy impacts, thus explicitly capturing the rebound effect, incrementality (the extent to which the impact of policy packages is less than the sum of the individual policies) and free-ridership. E3MC captures direct price effects, the income effect, product substitution, factor (capital, labor, materials) substitution and economy transformational effects (consumer preferences, social institutions, etc.).

While the Canadian component of E3MC is fully integrated, thus enabling two-way interactions between the E2020 and TIM models, the USA component has only a limited static TIM model that feeds one-way into the E2020 model. As such, the USA component is unsuitable for determining the outcome of an equilibrated micro-macro economy or for accounting for recycling of carbon tax revenues. Nevertheless, previous experience with the Canadian model demonstrates that the differences between the unintegrated and integrated recycled modeling results are usually relatively small ($<5\%$). Moreover, the USA model output can still be analyzed for important trends.

3. SCENARIO DESCRIPTION

3.1 Overview

The model was calibrated using historic (1985 to 2007) energy and price data from the Energy Information Administration (EIA) and Statistics Canada for the USA and Canada, respectively (EIA, 2009; Statistics Canada, 2009). Crude oil and wholesale natural gas price projections were provided exogenously as per the 2009 National Energy Board (NEB) (for the period up to 2020) and EIA 2005 (for the period post-2020) forecasts (NEB, 2009; EIA, 2005). Crude oil and natural gas production projections were provided exogenously as per forecasts from the EIA and the NEB for the USA and Canada, respectively (EIA, 2005; NEB, 2009).

The USA and Canada were modeled independently to 2025 for base cases and policy scenarios. Unlike the Canadian scenarios, the USA scenarios did not have full integration with the macroeconomic TIM model. The scenarios modelled for this analysis were an economy-wide carbon tax, efficiency improvement standards (for the residential, commercial and transportation sectors) and a combination carbon-tax standards package.

Carbon Tax

Beginning in 2010, a $33 per tonne ($30 per US short ton) CO_2 tax was applied to all sectors. The tax, which was expressed in 2007$US, was increased 5% per annum in real terms. For Canada, carbon tax revenues were recycled to households on a lump-sum basis. Due to model limitations, the USA had no revenue recycling.

Standards

The standards scenario included building codes and equipment improvements in the residential and commercial sectors. The standards also included vehicle fuel efficiency requirements.

Residential and commercial building codes were increased to be consistent with specifications in the Waxman-Markey Bill (H.R. 2454, 2009). Specifically, beginning in 2010, residential and commercial codes for new buildings were increased linearly to be 30% more efficient in 2012 and 50% more efficient in 2016, relative to the baseline code (The baseline code was set as 2004 and 2006 values for commercial and residential buildings, respectively). In 2017 and every three years thereafter through 2023 an additional 5% efficiency improvement relative to the baseline code was added to residential buildings. In 2018 and every three years thereafter through 2024 an additional 5% efficiency improvement relative to the baseline code was added to commercial buildings.

Due to model limitations, residential and commercial equipment standards were not modelled as per the detailed technology-specific schedule provided in EMF 25. As an alternative the standards were modelled as a 25% smooth increase in energy efficiency standards by 2016 (with respect to 2007) for all new devices (appliances) in the commercial and residential sectors.

Up to and including 2011, passenger car and light-duty truck fuel economy standards were increased to achieve the US 2009 Reference Case estimated fuel economies for lab-tested vehicles (EIA, 2009). From 2012 to 2016, passenger car fuel economy standards were increased linearly from 7.19 l/100 km (32.7 mpg) to 6.03 l/100 km (39 mpg), while light truck fuel economy standards were increased linearly from 8.91 l/100 km (26.4 mpg) to 7.84 l/100 km (30.0 mpg). Passenger car and light-duty truck fuel economy standards were held constant post-2016.

Carbon-Tax Standards Package

The carbon-tax standards package modeled the combination of the aforementioned economy-wide carbon tax and standards (residential, commercial and transportation).

4. RESULTS & DISCUSSION

4.1 Policy Impacts on Overall Emissions and Energy Use

At an economy-wide level in both Canada and the USA, primary energy use and CO_2 emissions were most reduced by the carbon tax + standard combination, followed by standards and then the carbon tax (Figure 3 to Figure 6). In both countries, the greater impact of the standards on primary energy use and emissions compared to the carbon tax was mirrored in delivered energy in the residential sector (Figure 7 to Figure 10).[1] However, unlike in Canada, compared to the standards-only case, the carbon-tax standards package in the USA actually exhibited lower reductions in delivered energy use and CO_2 emissions in the residential sector.

In the Canadian residential sector, addition of the carbon tax to the standards had no impact on energy reductions (Figure 7), but further reduced CO_2 emissions (Figure 8). Compared to the standards-only case, the carbon tax + standard case further reduced natural gas consumption while attenuating the electricity reduction (Figure 11 and Figure 12).[2]

At a fuel-specific level, the addition of the carbon tax to the standards in the USA residential sector had the opposite effect to that in Canada. Indeed, the combination of a carbon tax with standards did not reduce energy or CO_2 emissions as much as standards alone (Figure 9 and Figure 10). While electricity use was lowest with the carbon tax + standards combination, the incremental drop in electricity induced by the carbon tax was more than compensated for by a carbon tax-mediated attenuation of the reduction in natural gas use (Figure 13 and Figure 14).[3] A comparison of relative residential fuel prices and relative fuel consumption in Canada and the USA for the two dominant residential fuel types

1. Impacts are measured with respect to business-as-usual (BAU).
2. Ibid.
3. Ibid.

(electricity and natural gas) was performed to explain the counter-intuitive finding in the USA.

4.2 Relative Fuel Prices as Determinants of Policy Impacts

The discrepancy between Canada and the USA in the emissions impact of adding a carbon tax to standards in the residential sector may be explained on the basis of relative prices, which determine relative energy use of different fuel types. Changes in relative energy use may arise due to fuel switching (in applications, such as space heating or cooking, where alternative technologies that use different fuels can be substituted) or the sector's preference to reducing one energy form more than another (due to divergent returns on capital investments of energy-saving measures, etc.) in order to achieve the required energy and/or emission reductions of a given policy set. Shifts from non-polluting end-use forms of energy (such as electricity) to polluting end-use forms (such as natural gas) would show up as attenuated reductions in CO_2 emissions.

In the current analysis, Canada and the USA exhibited opposite movements in relative prices and hence consumption of electricity and natural gas in the residential sector. The addition of a carbon tax to the standards resulted in a decrease in the relative residential price of electricity in Canada, but an increase in relative prices in the USA (Figure 15 to Figure 16). Conversely, the addition of a carbon tax to the standards resulted in an increase in the relative use of electricity in Canada's residential sector, but a decrease in relative use of electricity in the USA residential sector (Figure 17 to Figure 18).

The opposite movement in relative residential electricity prices between the USA and Canada may be explained by differences in electricity mix in the two countries. Compared to the USA, Canada has a much smaller fraction of the electricity mix provided by high CO_2-emitting coal plants and a much larger fraction provided by non-emitting hydroelectric plants. (In 2007, coal generation provided 16% of electricity in Canada versus 57% in the USA, while hydro made up 60% of electricity in Canada and 5% in the USA.) In contrast to the USA, Canada also has excess electric production (In 2007, Canada exported 27 TW · h to the USA) that shifts from international to domestic markets to moderate any electric price impacts arising from carbon-tax induced increases in electric demand (results not shown). In addition, regulation of the majority of provincial electric utilities in Canada may have modified any price increases. Consequently, the carbon tax had a much smaller impact on residential electricity prices in Canada compared to the USA (respectively 11% and 43% above business-as-usual (BAU) in 2025). Conversely, by 2025 residential natural gas prices increased 48% and 28% for Canada and the USA, respectively. Compared to the USA, the higher percentage increase in residential natural gas prices in Canada can be explained by much lower BAU prices. Indeed, at an absolute level residential natural gas price increases in both countries were approximately equal.

In Canada, the decrease in the relative price of electricity led to the residential sector favouring reductions in natural gas rather than electricity. This preference showed up as attenuated reductions in electricity use (Figure 11), increased reductions in natural gas use (Figure 12), and consequently a reduction in the relative energy use of natural gas (Figure 17). When compared to the standards case alone, the shifting of energy reductions from a polluting form of energy (natural gas) to a non-polluting form (electricity) resulted in the carbon tax + standards case exhibiting decreased residential CO_2 emissions, despite the absence of change in total delivered energy (Figure 7 and Figure 8).

The impact of adding the carbon tax to the standards was very different in the USA compared to Canada. In the USA, the impact of adding a carbon tax to the standards was to greatly increase the relative residential price of electricity (Figure 16). Consequently, there was a preference to favouring reductions in electricity rather than natural gas use. This preference showed up as attenuated reductions in natural gas use (Figure 14), increased reductions in electricity use (Figure 13), and consequently a reduction in the relative energy use of electricity (Figure 18). When compared to the standards case alone, the shifting of energy use from a non-polluting form of energy at the end-use (electricity) to a polluting form (natural gas) resulted in the carbon tax + standards case exhibiting increased CO_2 emissions (Figure 10).

The lack of an integrated model for the USA cannot explain the opposite shift in relative energy use in the USA compared to Canada upon addition of the carbon tax to standards. As explained in *Model Description*, the differences between scenario impacts with and without macroeconomic feedbacks are small. Computable General Equilibrium (CGE) modelling at Environment Canada confirms that for the consumer sector (includes E2020 residential and transportation sectors), carbon taxes lead to a shift in relative fuel use from natural gas to electricity in Canada, but from electricity to natural gas in the USA (Table 1). CGE model results also indicate that the presence or absence of recycling does not affect overall country trends in shifts in energy use.

4.3 Policy Implications

The current study indicates that decisions concerning combinations of regulatory and market-based instruments should consider sector-specific impacts. While the carbon tax + standards combination provided more CO_2 emission economy-wide reductions than either of the policies in isolation in Canada and the USA, the policy combination did not always have the largest impact at a sector-specific level. Specifically, in the residential sector, the addition of the carbon tax to the standards increased CO_2 emission reductions achieved by standards alone in Canada, but attenuated CO_2 emission reductions in the USA.

The contrasting impacts of a carbon tax on standards at an economy-wide versus residential sector level in the USA indicate that the carbon tax shifted emission reductions from the residential sector to the electric utility sector in the form of reduced generation, shifts from coal-fired electric generation to natural gas-fired electric generation, and increases in hydroelectric generation (results not

Table 1: CGE Generated Policy Impacts in 2020 on Delivered Energy Use (PJ) in the Consumer Sector for a $54 USD/tonne CO_2 Tax

Country	Scenario	Consumption (PJ)	
		Electricity	Natural Gas
Canada	CO_2 tax + recycling	−52	−151
	CO_2 tax	−85	−191
USA	CO_2 tax + recycling	−792	−592
	CO_2 tax	−969	−794

A $54 USD per tonne CO_2 tax corresponds to the value in 2020 of a $33 USD per tonne CO_2 tax implemented in 2010 and increased 5% annually.

Table 2: Policy Impacts on USA CO_2 Emissions (Mt) in 2025

	Standards	Standards + Carbon Tax	Difference
Residential	−70	−60	11
Other Sectors	−180	−375	−195
Electric Generation	−431	−900	−469
Economy-wide	−681	−1334	−653

shown). In the USA, while the addition of the carbon tax to the standards lowered emission reductions in the residential sector by 11 Mt, emission reductions in the electric generation sector increased by 469 Mt (Table 2). These changes are consistent with other studies indicating that a carbon tax in the USA would simultaneously reduce electric generation and substantially shift the electricity mix away from coal to less polluting and renewable energy sources (Palmer et al., 2009; Wing, 2006).

For political acceptability, emerging carbon tax regimes may be restricted to traditional targets of environmental regulations, such as power generators, industry and transportation. Excluding a limited number of diffuse emission sources, such as the buildings sector would incur only a small societal cost (Pizer et al., 2006). However, the study results in this paper suggest that a residential sector subject to higher building standards may still exhibit attenuated emission reductions in the event a carbon tax is applied to non-residential sectors. In jurisdictions with substantial coal-fired electric generation, such a carbon tax would increase the relative electricity to natural gas prices and further favour residential natural gas use. Under such a regime, additional policy levers would need to be used to discourage any undesired changes in relative preferences for natural gas over electricity.

The findings of this study indicate that policy-induced changes in relative prices of substitutable fuel types are major factors determining the impact of multiple emissions policies at a sector level. Moreover, changes in these relative prices influence the relative emission reduction burden of different sectors. Shifts in the distribution of emission reduction burdens may be important considerations for decision-makers who may be concerned with equity and welfare aspects of various policies. In addition, the differing results between Canada and the USA suggest that there may be important distributional issues concerning emission reduction burdens between various jurisdictions, which may differ in composition (size and fuel-source) of installed electric generation capacity.

5. FURTHER WORK AND CONCLUSIONS

The present paper's analysis revealed that while a combination standard-tax package in Canada yielded the most CO_2 emission reductions in the residential sector, a combination standard-tax package in the USA actually lowered residential emission reductions relative to the standards alone case due to shifts of energy use from electricity to natural gas. The contrasting results in the residential sector between Canada and the USA highlight the need to consider relative fuel prices in anticipating the impacts of any policy package and underscore the possibility that additions of supplemental policies may inadvertently shift emission reduction burdens to other sectors.

The current study is an important contribution to the policy debate on optimal instrument combinations for reducing energy use and GHGs. Concerning the USA residential sector, further work needs to be done to better understand the magnitude of the attenuating impact of the carbon tax on standards. In the current study, the dampening impact of the carbon tax on standards in the USA residential sector was likely affected by the exogenous nature of natural gas prices in the model. Unlike Canada, the USA is not a strict price-taker for natural gas. Consequently, it would be expected that any increase in price caused by the carbon tax would be modified by net demand-side price pressures arising from conservation and fuel-switching. Conservation and shifts to renewable energy would be expected to cause downward price pressures, while shifts from coal and other carbon-intensive fuels to natural gas would be expected to cause upward natural gas price pressures. For example, modeling results from some researchers have indeed demonstrated that deployment of renewable energy lead to reduced natural gas prices (Wiser et al., 2005).

Robustness of the residential results would also be improved by endogenizing nuclear and non-hydro renewable electricity generation capacity additions, particularly in the USA given its heavy reliance on fossil fuels for electric generation and its position as a net electricity importer. Carbon tax impacts on electricity prices could be moderated in the USA if capital costs of zero-emission electricity generation capacity additions were competitive with capital costs of natural gas or hydro electricity generation capacity additions.

Further work also needs to be conducted to better understand the underlying end-use changes producing the shift from electricity to natural gas. For example, using a hybrid energy-financial accounting model, Atkinson et al. (2009) found that differentiation between the escalation of electricity and natural gas prices in pre-existing multi-residential buildings in the UK was a leading factor influencing investments in energy efficiency refurbishments. Analyses could also be performed to determine the sensitivity of fuel switching to relative fuel costs and relative costs of competing advanced technologies. Sensitivity analysis would also be useful in better characterizing residential retrofit decisions, which are highly dependent on fuel prices and expected return on investments (Amstalden et al., 2006). Sensitivity analysis may be of particular interest given the trend to increasing electrification of the USA buildings sector (Kyle et al., 2010).

While this paper's analysis examined the simultaneous introduction of standards and a carbon tax, additional work may be merited to compare outcomes when the policies are introduced sequentially, given that sequencing may affect the impact of each policy and the final outcome (Murphy et al., 2006).

In recent years various approaches, such as technology efficiency standards, carbon taxes or combination standard-tax packages, have been proposed to achieve required GHG reductions. Modeling of policy combinations in particular will play an increasingly important role in the determination of optimal policy frameworks as new alternative fuel technologies are developed. It is hoped that this paper's results and related on-going work will be useful to decision-makers as they struggle to find technologically feasible and politically tenable policy solutions to reach emission reduction goals.

ACKNOWLEDGMENTS

The authors would like to thank Jeff Amlin (Systematic Solutions Inc., Xenia, Ohio) and Charles Saunders (Informetrica Ltd., Ottawa) for assistance with modeling scenarios, in addition to Environment Canada colleagues Yunfa Zhu, Muhammad Shahid Siddiqui, and Deming Luo for providing CGE modelling results for the USA and Canada. The authors also recognize the contribution of Environment Canada colleagues Katherine Monahan, Milica Boskovic, Mark Radley and Andrew Nelson for proofreading the text and providing material for a literature review.

REFERENCES

Amstalden, R. W., M. Kost, C. Nathani and D. M. Imboden (2006). "Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and energy price expectations." *Energy Policy* 35(3):1819–1829.

Atkinson, J., T. Jackson and E. Mullings-Smith (2009). "Market influence on the low carbon energy refurbishment of existing multi-residential buildings." Energy Policy 37(7): 2582–2593.

Energy Information Administration (EIA) (2009). Annual Energy Outlook 2009 with Projections to 2030, DOE/EIA-0383(2009). Energy Information Administration, U.S. Dept. of Energy, Washington D.C. Available from: http://www.eia.doe.gov/oiaf/archive/aeo09/pdf/0383(2009).pdf

Energy Information Administration (EIA) (2005). Annual Energy Outlook 2005 with Projections to 2025, DOE/EIA-0383(2005). Energy Information Administration, U.S. Dept. of Energy, Washington D.C. Available from: http://www.eia.doe.gov/oiaf/archive/aeo05/download.html

Gerlagh, R. and B. van der Zwaan (2006). “Options and Instruments for a Deep Cut in CO2 Emissions: Carbon Dioxide Capture or Renewables, Taxes or Subsidies.” The Energy Journal 27(3):25:48.

Gillingham, K., R. G. Newell and K. Palmer (2009). Energy Efficiency Economics and Policy, Discussion Paper 09-13, Resources for the Future, Washington D.C.

Goulder, Lawrence H. and Ian W.H. Parry (2008). “Instrument Choice in Environmental Policy.” Review of Environmental Economics and Policy 2(2): 152–174.

Haupt, A. and M. Stadejek (2010). The Choice of Environmental Policy Instruments: Energy Efficiency and Redistribution, CESIFO Working Paper No. 2986. Presented at CESIFO Conference on Energy and Climate Economics, October 2009.

H.R. 2454 (2009). “American Clean Energy and Security Act of 2009.” 111th Congress, 1st Session. Washington, D.C.

Informetrica Ltd. (2010) Personal communications with Charles Saunders (Informetrica Ltd.).

Kyle, P., L. Clarke, F. Rong and S. J. Smith (2010). “Climate Policy and the Long-Term Evolution of the U.S. Buildings Sector.” The Energy Journal 31(2): 145–172.

Lambandeira, X., J. M. Labeaga and M. Rodríguez (2009). “An integrated economic and distributional analysis of energy policies.” Energy Policy 37(12): 5776:5786.

Murphy, F. H. and E. C. Rosenthal (2006). “Allocating the Added Value of Energy Policies.” Energy Policy 27(2): 143–156.

National Energy Board (NEB) (2009). 2009 Reference Case Scenario: Canadian Energy and Supply to 2020. National Energy Board, Calgary, Canada. Available from: http://www.neb.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyftr/2009/rfrnccsscnr2009-eng.pdf

Newell, R. G., A. B. Jaffe and R. N. Stavins (2006). “The effects of economic and policy incentives on carbon mitigation technologies.” Energy Economics 28(5–6): 563–578.

Oikonomou V., A. Flamos and S. Grafakos (2010). “Is blending of energy and climate policy instruments always desirable?” Energy Policy 38(8): 4186–4195.

Parry, Ian W.H. and Roberton C. Williams (1999). “A Second-Best Evaluation of Eight Policy Instruments to Reduce Carbon Emissions.” Resource and Energy Economics 21(3–4): 347–373.

Pizer, W., D. Burtraw, W. Harrington, R. Newell and J. Sanchirico (2006). “Modeling Economy-wide vs Sectoral Climate Policies Using Combined Aggregate-Sectoral Models.” Energy Journal 27(3):135–168.

Proost, Stef and Sandra Rousseau (2009). “The Relative Efficiency of Market-Based Environmental Policy Instruments with Imperfect Compliance.” International Tax and Pubilc Finance 16(1): 25–42.

Statistics Canada (2009). Report on Energy Supply and Demand in Canada. Ministry of Industy, Ottawa, Canada. Available from: http://www.statcan.gc.ca/pub/57-003-x/57-003-x2007000-eng.pdf

Systematic Solutions (1996). ENERGY 2020 Documentation 1: 1–14. Fairborn, Ohio.

Wing, I. S. (2006) “The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO2 emissions.” Energy Policy 34(18): 3847:3869.

Wissema, W. and R. Dellink (2007). “AGE analysis of the impact of a carbon tax on the Irish economy.” Ecological Economics 61(4): 671–683.

Wiser, R. and M. Bolinger (2007). “Can deployment of renewable energy put downward pressure on natural gas prices?” Energy Policy 35(1): 295–306.

APPENDIX

Figure 1: Canadian E3MC Modeling Framework

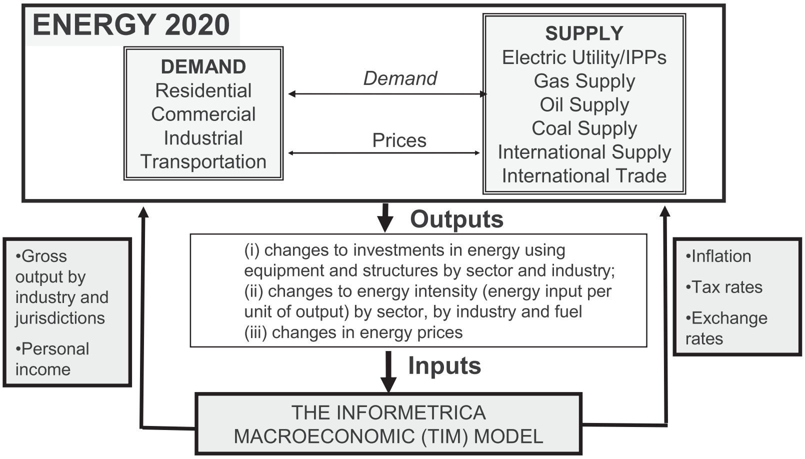


Figure 2: Energy Price Effects on Energy Demand in E2020

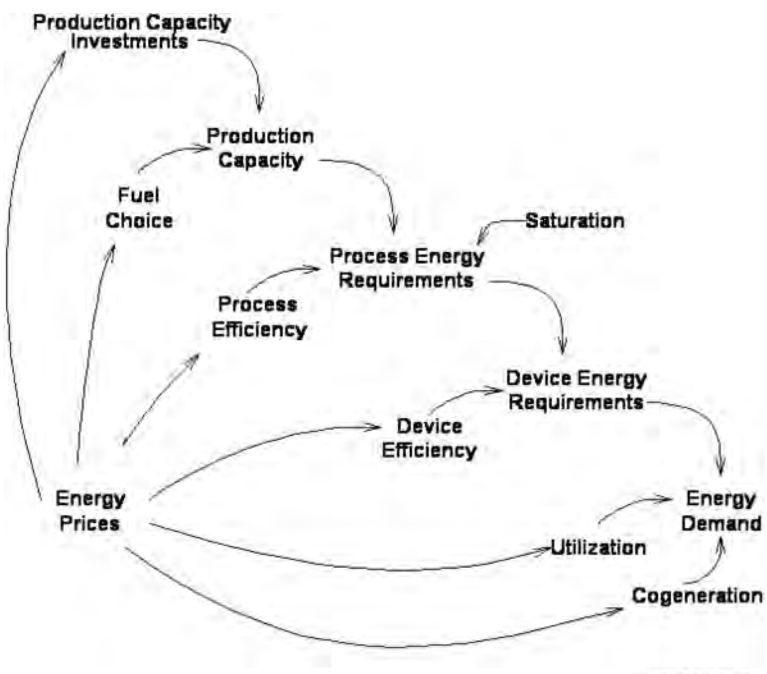


Figure 3: Canadian Economy-wide Primary Energy Use (EJ) under Various Scenarios

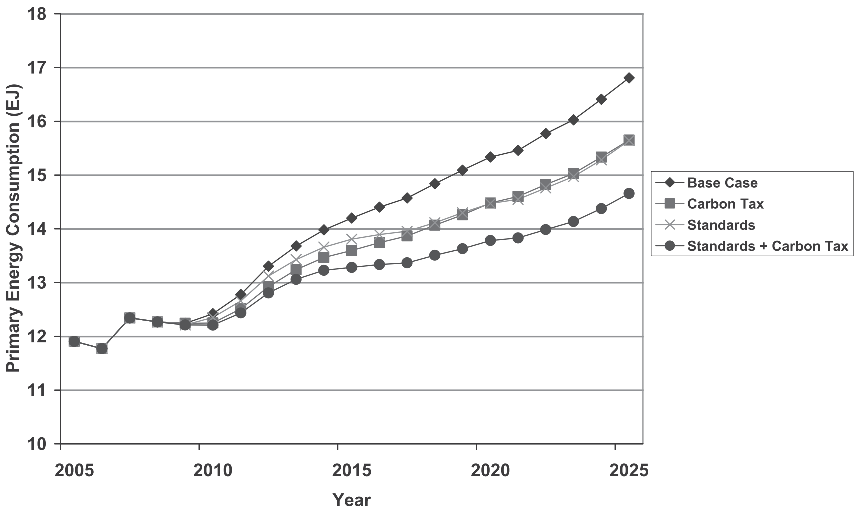


Figure 4: Canadian Economy-wide CO_2 Emissions (Mt) under Various Scenarios

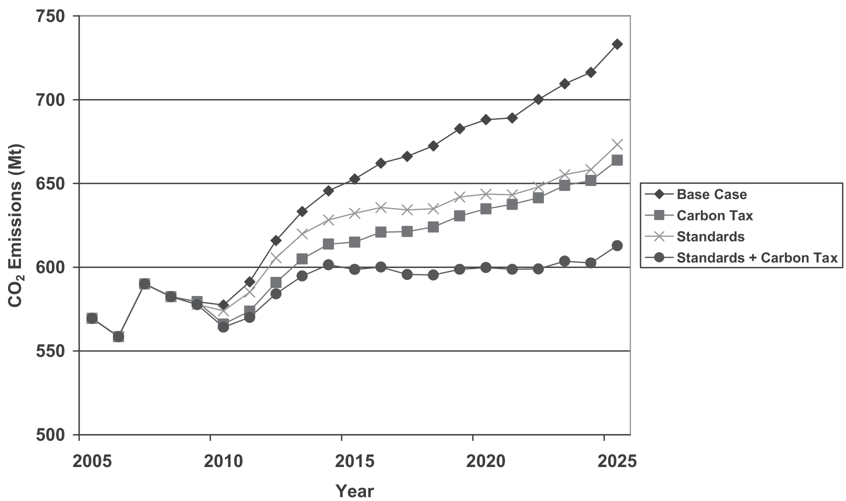


Figure 5: USA Economy-wide Primary Energy Use (EJ) under Various Scenarios

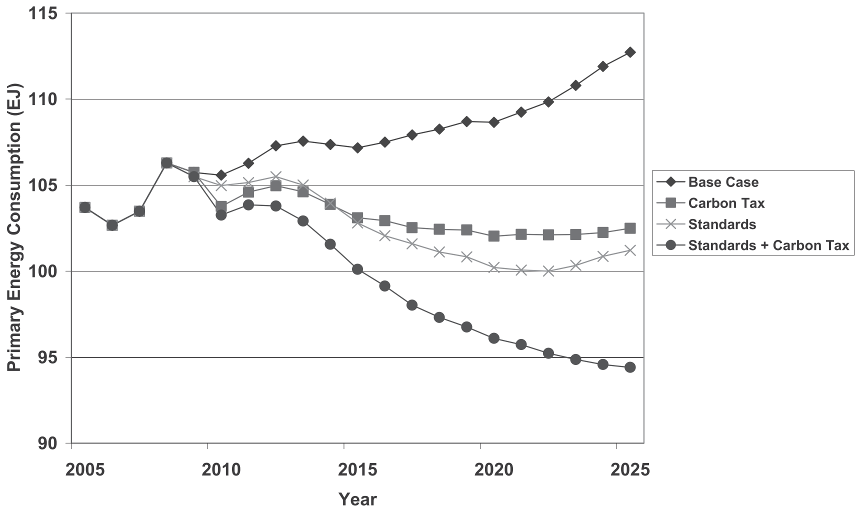


Figure 6: USA Economy-wide CO_2 Emissions (Mt) under Various Scenarios

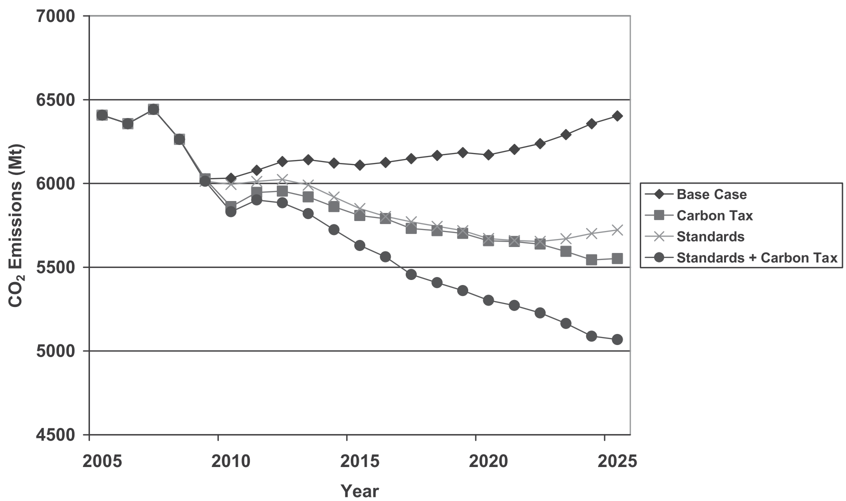


Figure 7: % Policy Impacts on Canadian Residential Delivered Energy Use

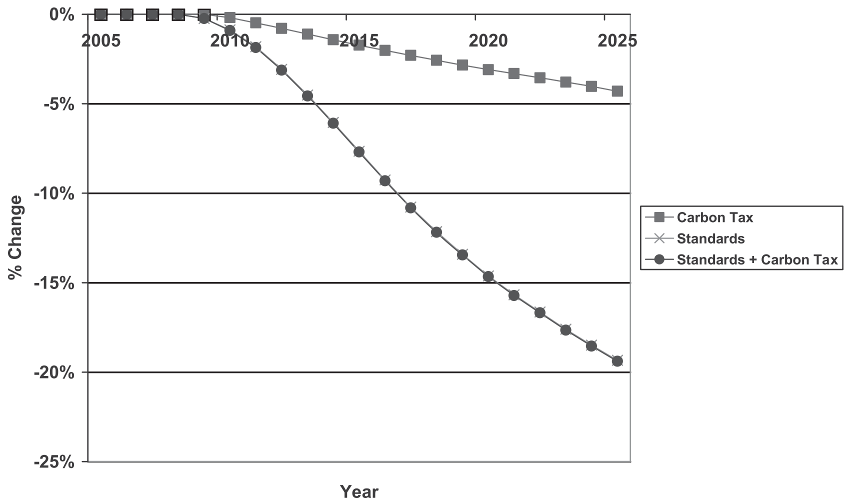


Figure 8: % Policy Impacts on Canadian Residential CO_2 Emissions

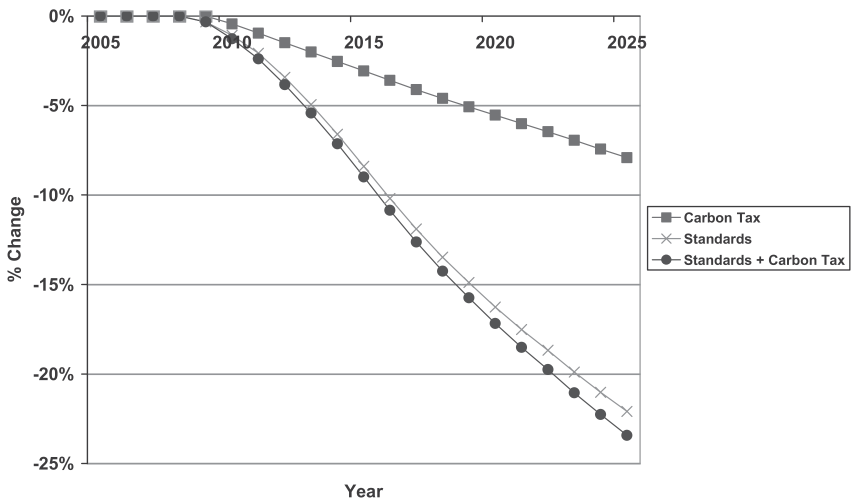


Figure 9: % Policy Impacts on USA Residential Delivered Energy Use

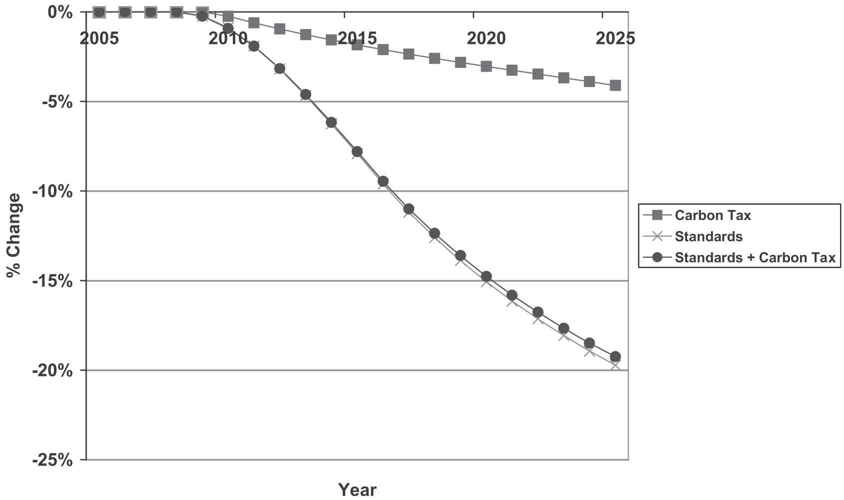


Figure 10: % Policy Impacts on USA Residential CO_2 Emissions

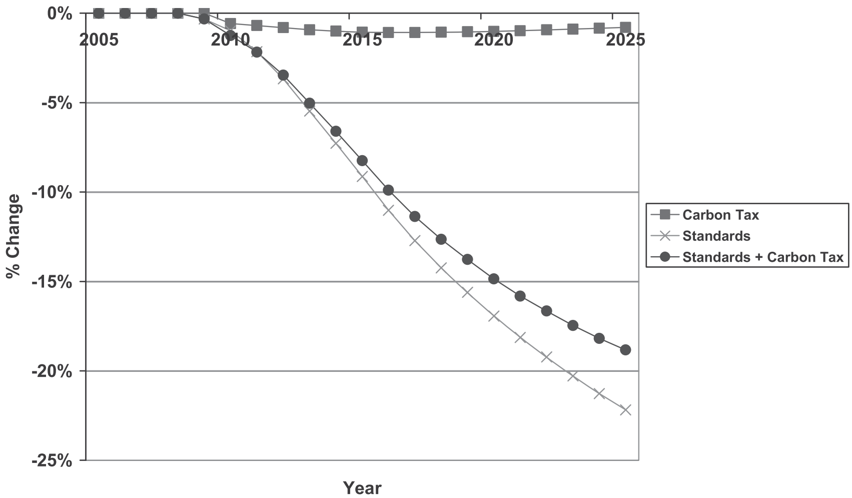


Figure 11: Policy Impacts on Canadian Residential Electricity Use (PJ)

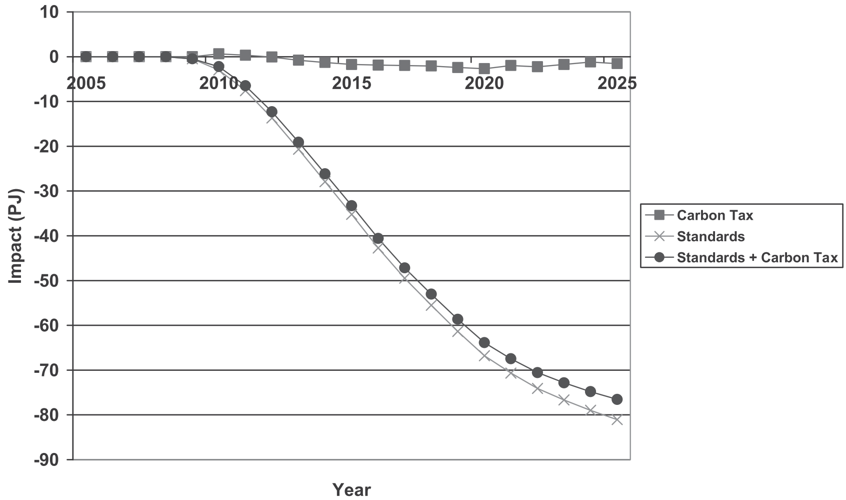


Figure 12: Policy Impacts on Canadian Residential Natural Gas Use (PJ)

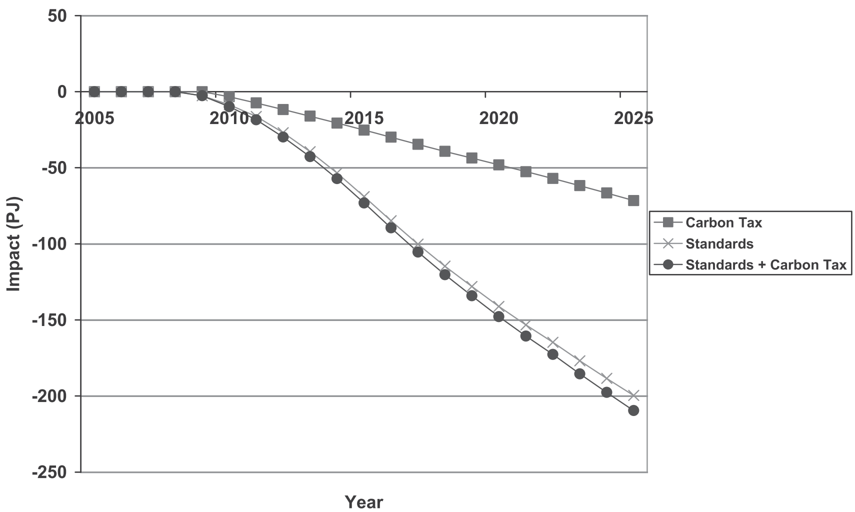


Figure 13: Policy Impacts on USA Residential Electricity Use (PJ)

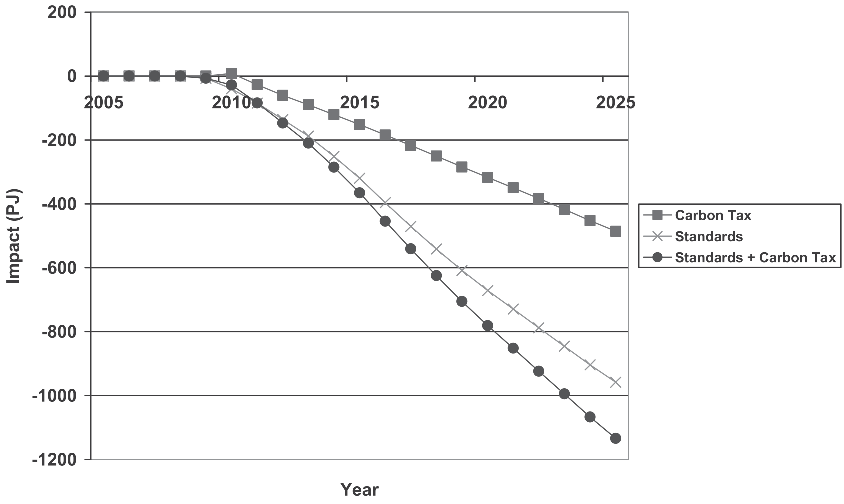


Figure 14: Policy Impacts on USA Residential Natural Gas Use (PJ)

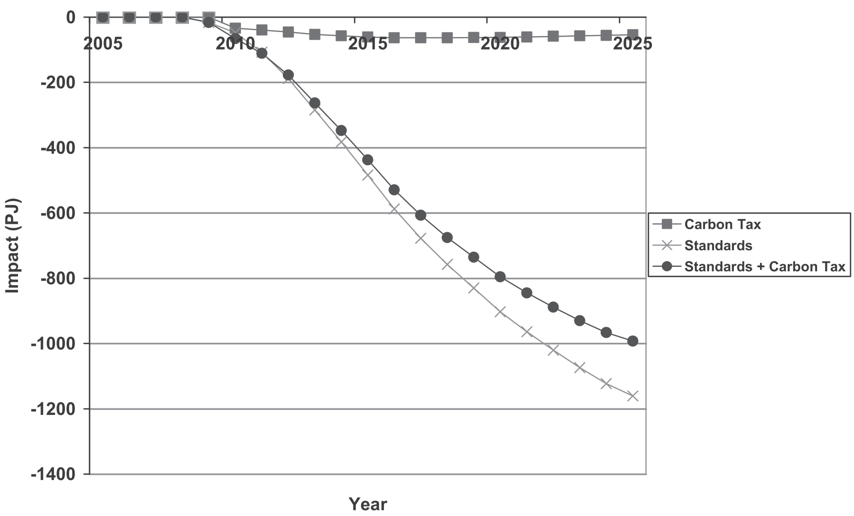


Figure 15: Relative Canadian Residential Fuel Prices (Electricity:Natural Gas) by Policy

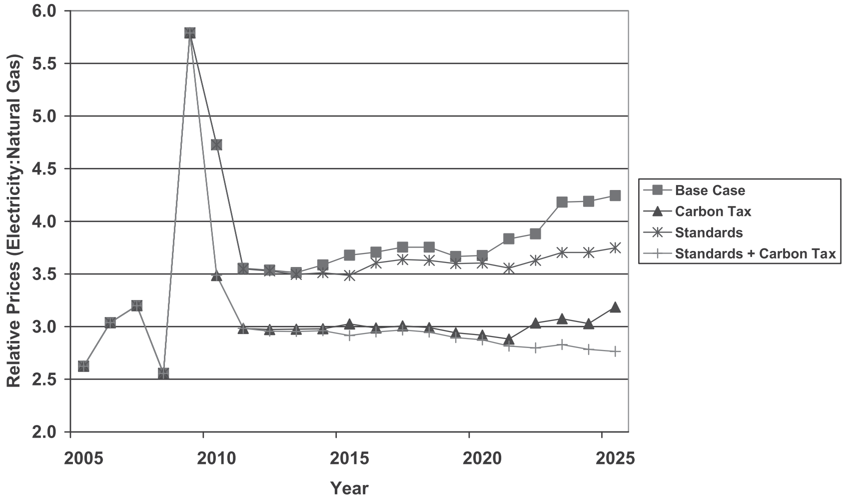


Figure 16: Relative USA Residential Fuel Prices (Electricity:Natural Gas) by Policy

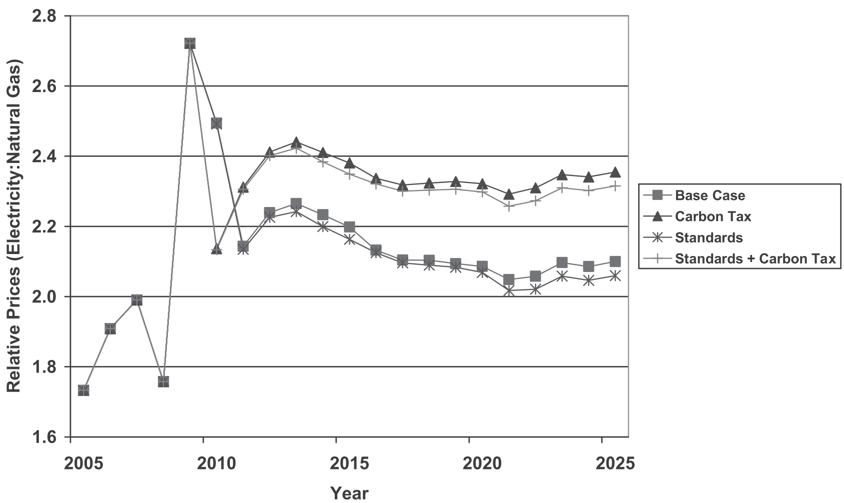


Figure 17: Relative Canadian Residential Delivered Energy Use (Electricity:Natural Gas) by Policy

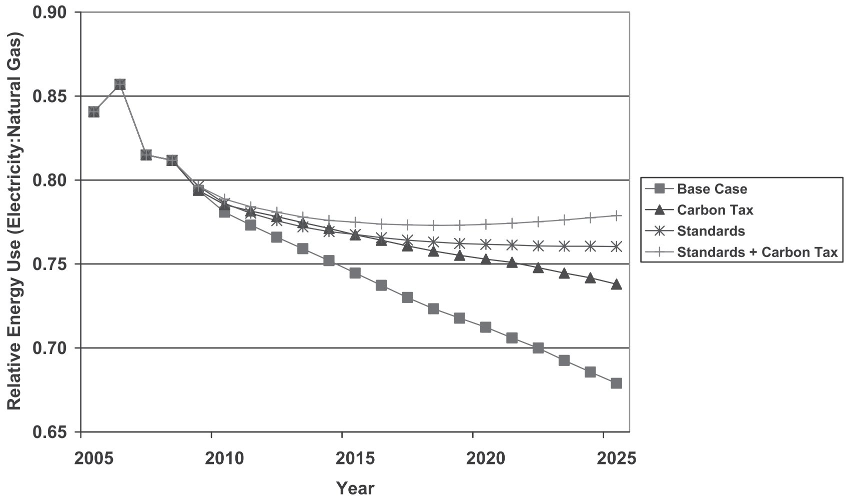
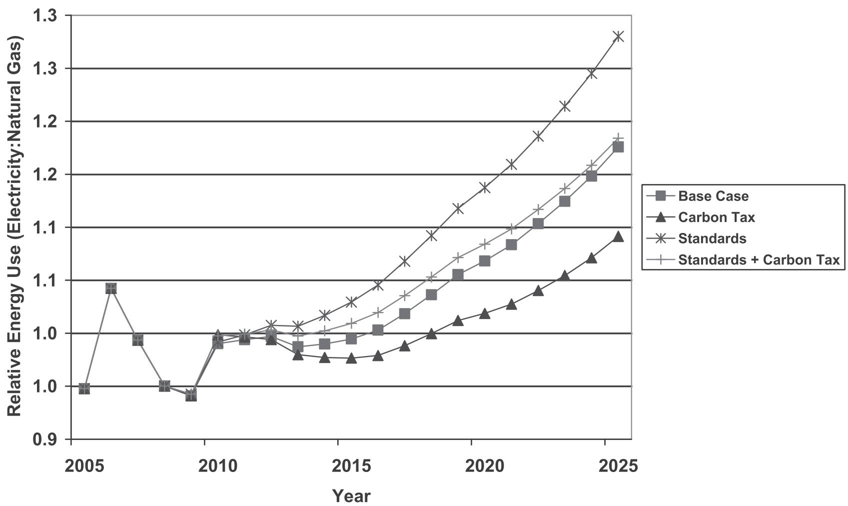


Figure 18: Relative USA Residential Delivered Energy Use (Electricity:Natural Gas) by Policy



Subsidizing Household Capital: How Does Energy Efficiency Policy Compare to a Carbon Tax?

Warwick J. McKibbin, Adele C. Morris**, and Peter J. Wilcoxen****

This study uses a general equilibrium model to compare environmental and economic outcomes of two policies: (1) a tax credit of 10 percent of the price of household capital that is 20 percent more energy efficient than its unsubsidized counterpart, assuming half of new household investment qualifies for the credit; and (2) a tax starting at $30 ($2007) per metric ton of CO_2 rising five percent annually. By 2040, the carbon tax and tax credit reduce emissions by about 60 1.5 percent, respectively. Assuming other countries impose no carbon price, we find that although the carbon tax reduces U.S. GDP, it improves U.S. household welfare because it reduces world fuel prices, strengthens U.S. terms of trade, and makes imports cheaper. The revenue neutral tax credit reduces welfare but boosts U.S. GDP growth slightly at first. Both policies have similar impacts on the federal budget, but of opposite signs. doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-7

1. INTRODUCTION

Proponents of ambitious climate policy often support imposing both a price on carbon and "complementary policies" to provide incentives for the de-

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Australian National University, The Brookings Institution.
** Corresponding author. The Brookings Institution, 1775 Massachusetts Ave, NW, Washington, DC 20036. E-mail: amorris@brookings.edu.
*** Syracuse University. The Brookings Institution.

We gratefully acknowledge assistance from the U.S. Department of Energy. McKibbin acknowledges support from ARC Discovery Grant DP0988281. We thank Alison Stegman for technical support and Yiyong Cai and Hyejin Park for excellent research assistance. We also thank an anonymous referee who provided a number of suggestions that improved the paper. The views expressed in the paper are those of the authors and should not be interpreted as reflecting the views of any of the above collaborators or of the institutions with which the authors are affiliated including the trustees, officers or other staff of the Australian National University, Syracuse University, the U.S. Department of Energy, or Brookings.
doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-7

ployment of energy-efficient and low carbon technologies. Current U.S. law offers an extensive variety of tax benefits for certain kinds of energy production and conservation, including incentives for renewable electricity production, energy efficient household investments, and bio-fuel production.[1] The U.S. Congress expressed its continued enthusiasm for these measures in the American Recovery and Reinvestment Act of 2009 (Recovery Act), which extended many consumer energy-related tax incentives as part of the fiscal stimulus package.

In particular, the Recovery Act expanded two energy-related tax credits for households: the non-business energy property credit and the residential energy efficient property credit.[2] The non-business energy property credit equals 30 percent of homeowner expenditure on eligible investments, up to a maximum tax credit of $1,500 over 2009 and 2010. The capital and labor costs of certain high-efficiency heating and air conditioning systems, water heaters and stoves that burn biomass qualify, as does the capital (but not labor) cost of certain energy-efficient windows, doors, insulation and roofs. The residential energy efficient property credit equals 30 percent of the installed costs of solar electric systems, solar hot water heaters, geothermal heat pumps, wind turbines, and fuel cell systems.

Another potential expansion of subsidies for energy efficiency appears in HOME STAR, a bill designed to strengthen short-term incentives for energy efficiency improvements in residential buildings.[3] This proposal would establish a $6 billion rebate program for energy-efficient appliances, building mechanical systems and insulation, and whole-home energy efficiency retrofits. The program targets energy efficiency measures that would achieve an energy efficiency gain of 20 percent.

One key goal of subsidies for energy efficiency investments is to reduce electricity generation and thereby reduce carbon dioxide emissions and other air pollutants. Some analyses suggest that increasing energy efficiency is a relatively low, possibly negative, cost way to abate greenhouse gas emissions and other air pollutants as well. However, adoption rates for energy efficient technologies fall short of levels that many believe are justified by the potential return on such investments. For example, the rates of return households apparently require for investments in energy efficiency are considerably higher than the rates of return used by electric utilities when investing in new generation. That difference in rates of return has spurred the development of utility-based demand side management (DSM) programs which often include subsidies for household energy efficiency. A growing economic literature explores this “energy-efficiency gap.”[4]

1. Joint Committee on Taxation (2010).

2. U.S. Internal Revenue Service Newswire article IR-2009-98, Oct. 29, 2009, “Expanded Recovery Act Tax Credits Help Homeowners Winterize their Homes, Save Energy; Check Tax Credit Certification Before You Buy, IRS Advises.” http://www.irs.gov/newsroom/article/0,,id=214873,00.html.

3. We accessed the bill, S. 3434, on June 18, 2010 from the Senate Energy Committee website: http://energy.senate.gov/public/index.cfm?FuseAction=IssueItems.View&IssueItem_ID=24dea252-01ef-4d6a-a17d-03ac78eb0dfd.

4. Jaffe and Stavins (1994) explain the energy-efficiency gap in more detail.

Regardless of the net benefits from investments in energy efficient capital, recent expansions in policies to promote those investments raise the question of how much they reduce carbon emissions and how they compare to policies that target carbon more directly. This paper uses an intertemporal general equilibrium model called G-Cubed to compare and contrast the environmental and economic performance in the United States of a tax credit for energy efficient household capital and an economy-wide price signal on carbon from fossil fuels used in the energy sector. We choose the tax credit and carbon tax rates of those policies so that they have roughly comparable fiscal impact on the US government; that is, if the policies were implemented together, the revenue from the carbon tax would offset most of the reduction in revenue associated with the tax credit. When examining the policies individually, we use a lump sum tax or rebate in order to hold federal spending and the budget deficit constant.

A tax credit for energy-efficient household capital reduces its relative price to homeowners and induces them to invest more. As household capital turns over, the energy saving properties of the policy accrue along with the aggregate tax expenditure up to the point where households have adopted all the energy efficient capital that is cost-effective at the subsidized rate. Unless market conditions evolve to the contrary, the government must sustain the subsidy to prevent households from reverting to purchasing relatively lower-efficiency capital. As a result, it will have permanent effects throughout the economy. By raising the rate of return on household capital relative to capital in other sectors, the subsidy permanently shifts the economy's overall portfolio of physical capital.

The empirical evidence on the effects of investment tax credits is limited and pertains primarily to the effect of tax credits on investment levels and energy savings. Gillingham et al. (2006) summarize the literature on tax credits to promote energy efficiency. Hassett and Metcalf (1995) show that a ten percentage point change in the tax price for energy investment would lead to a 24 percent increase in the probability of energy conservation investment.

The degree to which households and firms anticipate policies can significantly affect the results, particularly in the early years of the policy. For example, if households anticipate a subsidy to capital then they will delay acquiring capital they would otherwise purchase in order to take advantage of the subsidy later. Similarly, Hassett and Metcalf (1995) and others point out that tax credits are unlikely to be efficient tools for reducing carbon emissions. Consumers who would have purchased energy efficient capital in the absence of the subsidy receive a windfall, and unless the subsidy is perceived to be permanent, the effect could be to induce an intertemporal substitution in investments more than a net increase. This intertemporal substitution can be an important real-world policy effect, and it is captured in the G-Cubed model via forward-looking behavior on the part of households and other investors.

The paper proceeds as follows. A brief summary of the modeling framework and a description of the specific scenarios appear in Section 2. Section 3 presents and discusses the results, and Section 4 concludes. We find that although

Table 1: Regions in the G-Cubed Model (Country Aggregation E)

Region Code	Region Description
USA	United States
Japan	Japan
Australia	Australia
Europe	Western Europe
ROECD	Rest of the OECD, i.e. Canada and New Zealand
China	China
EEFSU	Eastern Europe and the former Soviet Union
LDC	Other Developing Countries
OPEC	Oil Exporting Developing Countries

both the carbon tax and the energy efficiency subsidy are formulated to produce the same fiscal implications (when combined they are revenue neutral), the carbon tax reduces carbon emissions by 40 times the reduction achieved by the energy efficiency policy. We also find that the carbon tax produces a substantial rise in the US terms of trade through global oil market changes which is beneficial to US consumers.

2. MODELING APPROACH

The G-Cubed model is an intertemporal computable general equilibrium (CGE) model of the world economy.[5] A brief technical discussion of G-Cubed appears in McKibbin et al. (2009) and a more detailed description of the theory behind the model can be found in McKibbin and Wilcoxen (1999).

This study uses a version of the model that includes the nine geographical regions listed in Table 1. The United States, Japan, Australia, and China are each represented by a separately modeled region. The model aggregates the rest of the world into five composite regions: Western Europe, the rest of the OECD (not including Mexico and Korea); Eastern Europe and the former Soviet Union; OPEC oil exporting economies; and all other developing countries.

The Baseline Scenario

A model's assumptions (or in the case of G-Cubed, its endogenous projections) about future emissions and economic activity in the absence of climate

5. The type of CGE model represented by G-Cubed, with macroeconomic dynamics and various nominal rigidities, is closely related to the dynamic stochastic general equilibrium models that appear in the macroeconomic and central banking literatures.

policy is called the baseline scenario. A detailed discussion of the baseline in G-Cubed appears in McKibbin, Pearce and Stegman (2009). The baseline in this study is calibrated to the Department of Energy's Updated *Annual Energy Outlook* Reference Case Service Report from April 2009.[6] It sets G-Cubed's projected productivity growth rates so that the model's baseline results approximate the report's forecasts for oil prices and real gross domestic product (GDP) as well as other key factors.

Along with the baseline for the U.S., we construct a baseline scenario for the entire world that reflects our best estimate of the likely evolution of each region's economy without concerted climate policy measures. To generate this scenario, we begin by calibrating the model to reproduce approximately the relationship between economic growth and emissions growth in the U.S. and other regions over the past decade. In the baseline, neither the U.S. nor other countries adopt an economy-wide price on carbon through 2050.[7]

The Policy Scenarios

In this study we use the model to explore two potential ways to address greenhouse gas emissions: a tax credit for energy efficient household capital and a carbon tax. The key innovation of this paper is its analysis of a subsidy to energy-efficient household capital, but to better illustrate the subsidy's effects relative to standard alternatives we compare this with a straightforward carbon tax.

We model a household investment tax credit for energy-efficient household capital as follows. Household capital in G-Cubed includes housing and durable goods such as appliances and vehicles.[8] The policy scenario requires assumptions about the share of total capital covered by the credit, the relative energy efficiency of subsidized capital vs. non-subsidized capital, and the process by which new capital replaces old capital. To keep the analysis simple, we assume that the rate of credit offered by the government for qualifying capital is ten percent. We assume that only half of the capital acquired by households after the policy takes effect qualifies for the subsidy. This means that the subsidy lowers the average price of all household investment by five percent. We assume that all capital that is eligible for the subsidy is 20 percent more efficient than its unsubsidized counterpart. Thus new investment after the policy takes effect is half high-efficiency and half conventional, and it is ten percent more energy efficient overall than the capital households acquire in the baseline.

6. The report appears at the DOE's Energy Information Administration website: http://www.eia.doe.gov/oiaf/servicerpt/stimulus/index.html.

7. The model is solved to 2100 to ensure that expectations have converged but because the model is most suitable for medium run analysis we only report results to 2040.

8. See the model's technical details in McKibbin and Wilcoxen (1999).

This investment tax credit scenario differs from actual policies that have been proposed or implemented in two respects: it applies a lower credit rate to a broader investment base, and it is permanent rather than temporary. Along with simplifying the modeling, the scenario is intended to reflect a policy meant to reduce emissions over the long run. In contrast, some of the actual policies were designed as much to produce short-run fiscal stimulus as they were to produce energy savings. For example, the Recovery Act's non-business energy property tax credit equals 30 percent of household spending on specific energy-saving investments, but only up to a maximum total credit per household of $1,500 and only for 2009 and 2010. Our scenario models a permanent tax credit and does not impose limits on the total credit per household or the overall tax expenditure, but it applies a lower subsidy rate (ten percent) than the Recovery Act.

In practice, the economic and environmental effects of a tax credit depend on which goods qualify, how many people take advantage of the credit, and how many would not have otherwise purchased the eligible goods. For example, the Recovery Act's non-business energy property credit and residential energy efficient property credit target very specific and distinctly different types of capital. In this study, we assume half of all new investment qualifies and that of that half, all of it is more energy efficient than it would otherwise be.

Some policies, such as the Home Star program, include point-of-sale rebates rather than (or in addition to) tax credits. We implicitly treat rebates and tax credits as equivalent from the household's point of view and assume that our subsidy rate roughly captures the effective benefit to households from choosing optimally among their options.

We assume that household capital depreciates at ten percent per year, regardless of its energy efficiency. Thus the energy efficiency of capital in any year is a share-weighted sum of the capital left over from the previous year and the efficiency of the new capital investment. Both the tax and subsidy policies begin in 2010. We run the model from 2008, rewriting history a bit to see how households would have behaved had they known the new policies were to be implemented.

Next we model a carbon tax. The tax begins at $30 ($2007) per metric ton of carbon dioxide equivalent in 2010 and increases by five percent (inflation adjusted) each year thereafter. We assume the tax applies only to CO_2 from fossil fuel consumption from the energy sector, including combustion of coal, natural gas, and oil. CO_2 from energy-related fossil fuel consumption includes a large majority of total U.S. greenhouse gas emissions and the vast majority of emissions growth since 2000. For example, according to the U.S. Environmental Protection Agency, fossil fuel combustion comprised 94 percent of all U.S. CO_2 emissions in 2008, and over 80 percent of gross U.S. greenhouse gas emissions on a CO_2–equivalent basis.[9]

9. U.S. Environmental Protection Agency (2010), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008*, p. ES-4, Table ES-2. Accessed on July 8, 2010: http://epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_ExecutiveSummary.pdf.

We run three scenarios with these policies: (1) the tax credit for more energy-efficient household capital alone; (2) the carbon tax alone; and (3) a combination the two policies. All three policies potentially affect government revenue. In the absence of compensating changes elsewhere in the tax system, they would affect government spending or the fiscal deficit. However, to focus our analysis on the key variables of interest and avoid introducing confounding macroeconomic effects, we hold government revenue constant by introducing a lump sum tax or rebate as necessary. Accordingly, the first scenario funds the household capital subsidy with lump sum taxes on households. The second scenario returns all revenues from the carbon tax to households on a lump-sum basis. The combination scenario uses revenues from the carbon tax to fund part of the household capital subsidy and any remaining revenue required is raised from households on a lump-sum basis.

The overall federal cost of the subsidy depends on the level of household investment and the subsidy rate. Suppose I is household investment in capital, s is the share of new investment eligible for the subsidy, p is the price of all goods, and p_I is the price of household capital without the subsidy. Then, the federal cost in foregone revenue, E, of the tax credit is equal to:

$$E_t = sI_t \times \frac{p_I}{p} \qquad (1)$$

For the parameters in the model, this means that E is approximately 4.5 percent of household investment spending. In practice, we iterate to calculate consistent equilibrium values of E, I and the prices of new capital and other goods.

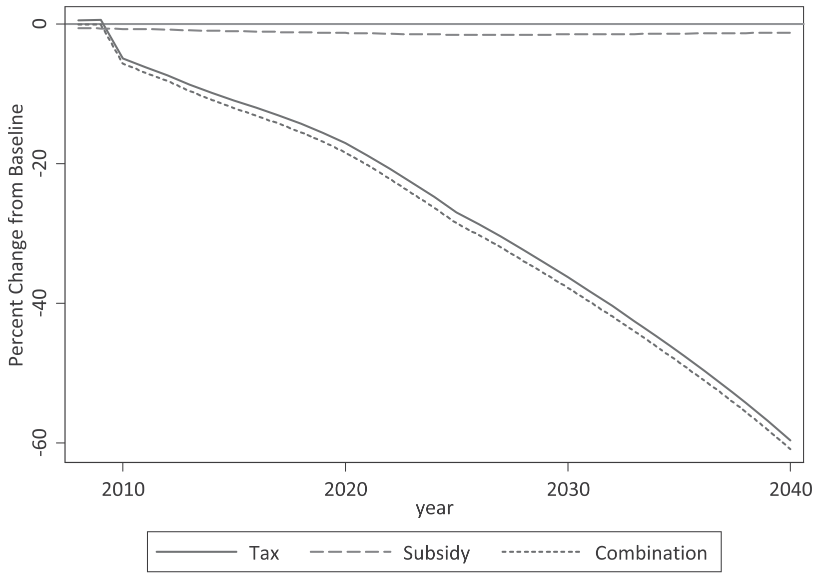
3. RESULTS

In comparing the results of the two policy scenarios it is convenient to start with the carbon tax and then proceed to the results for the energy efficiency policy. Our carbon tax results are consistent with numerous studies of the effect in the United States of an economy-wide price on carbon.[10] Figure 1 shows U.S. CO_2 emissions levels for the policy scenarios from 2008 to the imposition of the carbon price in 2010 and then on through 2040. The carbon tax, which is shown as a solid line, causes emissions to fall immediately when it is implemented in 2010. Anticipation of the carbon tax does not meaningfully change investment or emissions behavior prior to the imposition of the policy. Emissions continue to decline in subsequent years as the real value of the tax rises at five percent per year. By 2040, emissions are about 58 percent below the reference case.

Emissions under the tax credit (shown as a dashed line) fall far less than under the carbon tax: approximately 1.5 percent relative to the baseline in each

10. See for example McKibbin et al (2009).

Figure 1: Effect of Policies on Annual U.S. CO_2 Emissions



year. Although the energy efficiency of household capital increases by ten percent in the long run, the household elasticity of substitution between energy and capital is –0.8, which causes households take part of that gain in the form of increased demand for energy services. For comparison, had the elasticity of substitution been equal to 0, energy consumption would have fallen by close to ten percent; had it been equal to –1, energy consumption would not have fallen at all.

Finally, when the two policies are combined (shown by the dotted curve), emissions fall by about 61 percent.[11] Cumulative results and values for selected years are shown in Table 2.

Table 3 shows the effects of the three policies on industry output in a representative year, 2030. As expected, the industries that are most affected by the carbon tax are the energy sectors. Coal and crude oil and gas production both decline by about 31 percent relative to the reference case. Electricity production declines less, falling by about 10 percent. As shown in Figure 2, the input mix used by electric utilities changes significantly in the long run: fuel consumption drops considerably more than output—by nearly 30 percent in the long run—while capital input drops by less than output. The tax thus causes both an overall

11. The solution algorithm for the G-Cubed model uses mixed linearization, and its output satisfies the superposition principle: the results from running two policies together are equal to the sum of the results of running them separately. As a result, we cannot capture second-order interdependencies between the two policies, such as potentially more elastic response to the subsidy in the presence of a carbon tax.

Table 2: Effect of Policies on Annual and Cumulative Emissions. All values are in billions of metric tons of CO_2.

	Reductions Relative to the Reference Case			
	2020	2030	2040	Cumulative 2008 to 2040
Carbon Tax	0.9 (17%)	1.8 (36%)	3.7 (58%)	48.1 (26%)
Tax Credit	0.1 (1%)	0.1 (1%)	0.1 (1%)	2.2 (1%)
Combined Policy	1.0 (18%)	1.9 (38%)	3.7 (61%)	50.4 (28%)

Table 3: Effect of Policies on Industry Output in 2030. Percentage changes from base case output

No.	Sector	Carbon Tax	Tax Credit	Combination
1	Electric Utilities	–9.9%	–0.9%	–10.8%
2	Gas Utilities	–4.5%	–1.0%	–5.5%
3	Oil Refining	–26.0%	–1.5%	–27.5%
4	Coal	–31.2%	–0.8%	–32.0%
5	Crude Oil and Gas	–31.8%	–1.5%	–33.4%
6	Other Mining	–3.0%	0.5%	–2.5%
7	Agriculture	–0.9%	0.0%	–1.0%
8	Forestry	–2.2%	0.4%	–1.8%
9	Durables	–3.3%	0.7%	–2.6%
10	Nondurables	–0.8%	–0.1%	–0.9%
11	Transportation	–1.1%	0.0%	–1.2%
12	Services	0.6%	–0.2%	0.5%

reduction in the size of the industry and a shift in its input mix away from fossil fuels and toward capital (greater use of renewables and nuclear power).

Among the non-energy sectors, durable goods production is most affected, and output decreases by about 3 percent from the baseline. Output of services, in contrast, increases slightly. The industry effects under the tax credit are sharply different. Output of the energy sectors decline slightly—typically by about one percent—while the output of durable goods (a key component of household investment) rises by 0.7 percent. The effects under the combination policy are the sum of the others: large declines in the energy sectors, small declines in most other industries, and a small increase in services due to its relatively low carbon intensity.

Figure 3 shows the effect of the scenarios on annual GDP growth rates. From 2008 to 2040, the average annual rate of GDP growth in the baseline simu-

Figure 2: Effect of a Carbon Tax on Output and Key Inputs to Electric Utilities

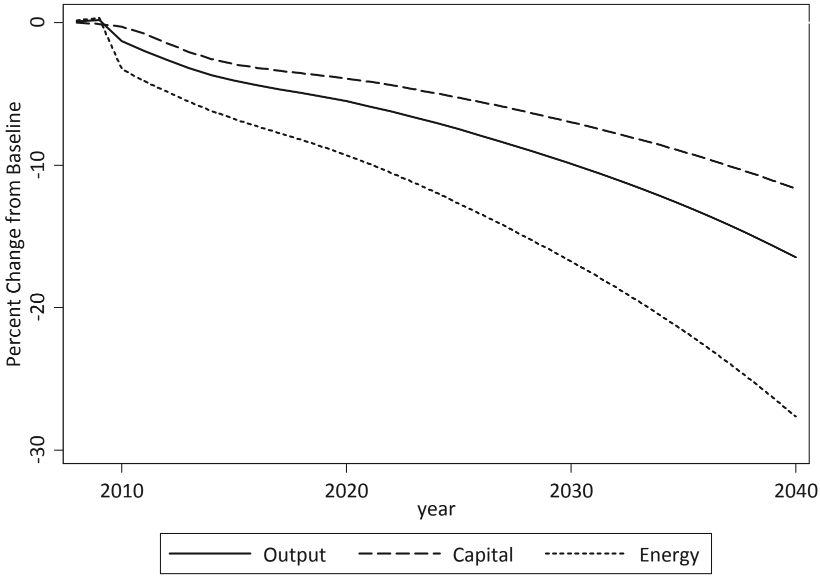


Figure 3: Effect of Policies on the Growth Rate of Real GDP

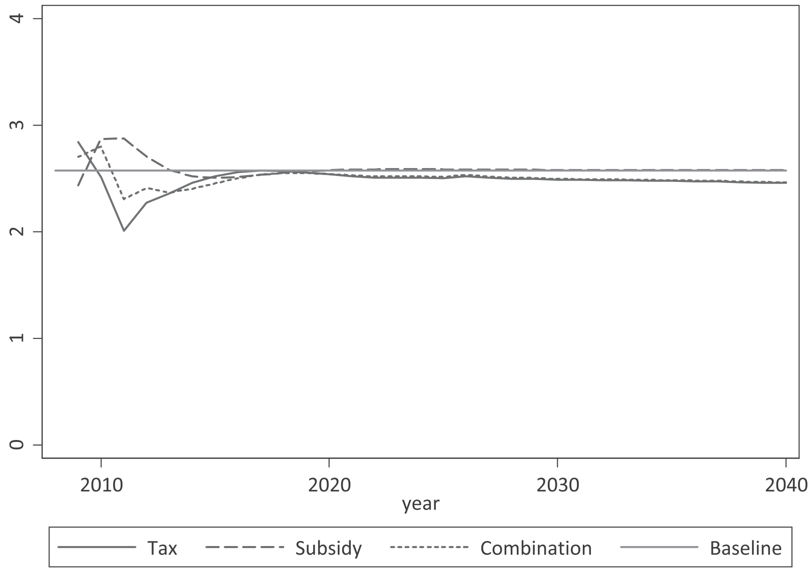
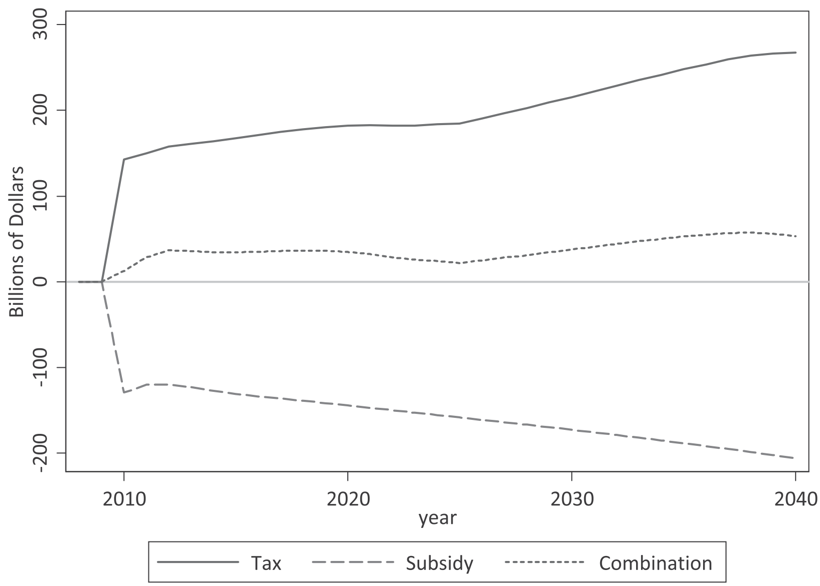


Figure 4: Effect of Policies on the U.S. Fiscal Balance

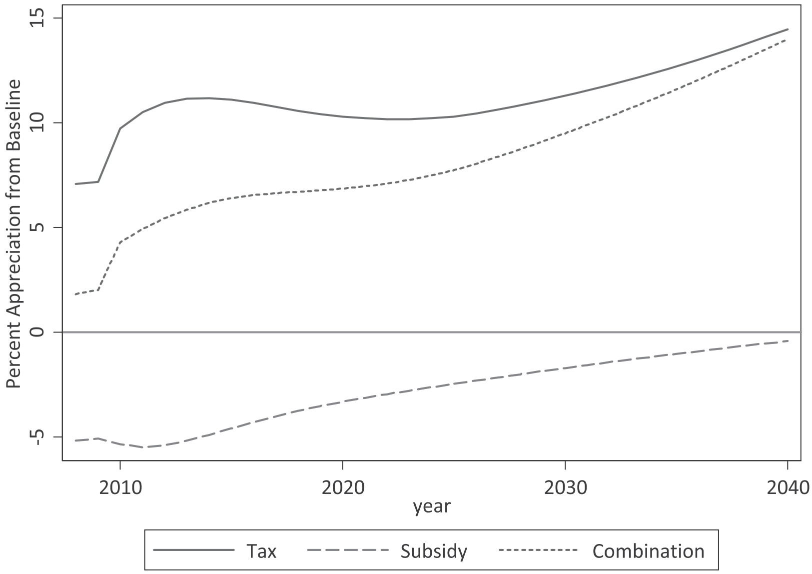


lation is 2.6 percent. Under the carbon tax, the growth rate would drop somewhat in the first few years of the policy, with the peak reduction being about half a percent per year. In contrast, under the tax credit, the growth rate would drop slightly between 2008 and 2010 as households postpone investment in order to take advantage of the tax credit available in the future. After 2010, growth would exceed the baseline rate for several years before eventually falling back. Under the combination policy, the effects largely offset one another and the growth rate would be reduced by less than 0.1 percent.

The fiscal effects of the policies are shown in Figure 4. The carbon tax, shown as a solid line, raises $143 billion of revenue when it is implemented in 2010. The amount of revenue rises gradually: the increase in the tax rate is largely offset by the decline in emissions. All of the revenue is returned to households as a matching lump sum rebate. The tax credit, in contrast, reduces income tax revenue by almost $130 billion in 2010 and by more than $200 billion in 2040. Under the combined policy, the net revenue gain from the carbon tax and tax credit is $12 billion in 2010 and rises to $53 billion by 2040. In both the tax credit and combined scenarios, the government returns the excess each year with a lump sum rebate to households.

Exploring the results in more detail, the carbon tax sharply raises the after-tax price of imported and domestic fossil fuels, reducing demand for both. Imports of crude oil fall substantially, causing the U.S. trade account to move toward surplus and the U.S. dollar to appreciate against other currencies. In ad-

Figure 5: Effect of Policies on the U.S. Real Effective Exchange Rate

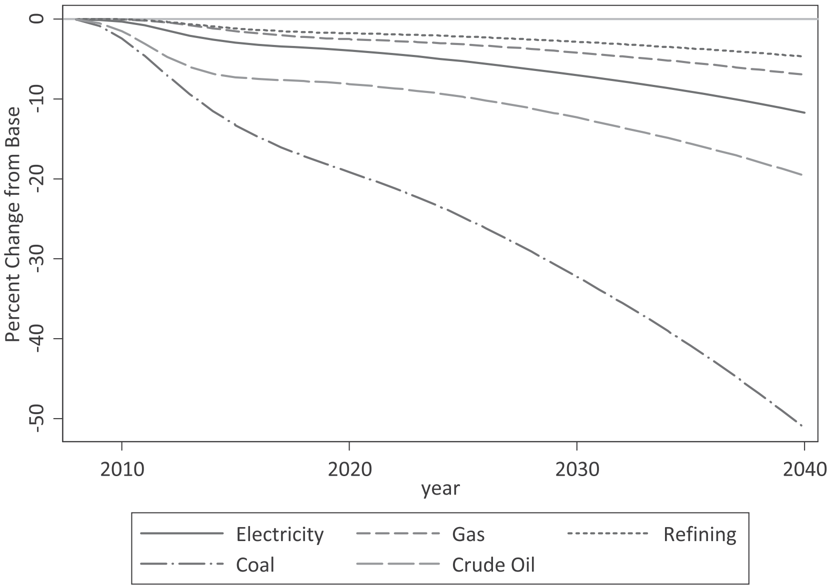


dition, because the U.S. is a large consumer on the world oil market, the world price of oil falls, augmenting the improvement in U.S. terms of trade. In contrast, under the tax credit the dollar initially depreciates and then gradually recovers to its baseline value. Under the combination policy, the short run effects of the carbon tax and the investment subsidy offset one another and there is little change in the exchange rate. In the long term, the carbon tax dominates and the exchange rate appreciates. The real effective trade-weighted exchange rate is shown in Figure 5 for all three policies.

The improvement in U.S. terms of trade under the carbon tax reduces the cost of imported goods other than fuels. Particularly important, it reduces the relative domestic price of imported durables, a significant component of household investment. At the same time, the contraction in demand for energy goods reduces investment in those sectors, lowering the capital stock in the energy sectors as shown in Figure 6.

The magnitude of the terms of trade change is due in part to the model's substitution elasticities between foreign and domestic goods. In the version of the model used in this paper, the elasticity of substitution between domestic and foreign sources of goods for the US varies across sectors between 0.2 (electricity) and 0.9 (durable and non-durable goods). Substitution elasticities between different foreign sources are 2.0. The sensitivity of the model's results for carbon pricing simulations to different assumptions about these elasticities was examined in detail in McKibbin, Ross, Shackleton and Wilcoxen (1999). That study found that higher trade elasticities (in particular between domestic and foreign goods)

Figure 6: Effect of a Carbon Tax on Energy Sector Capital Stocks

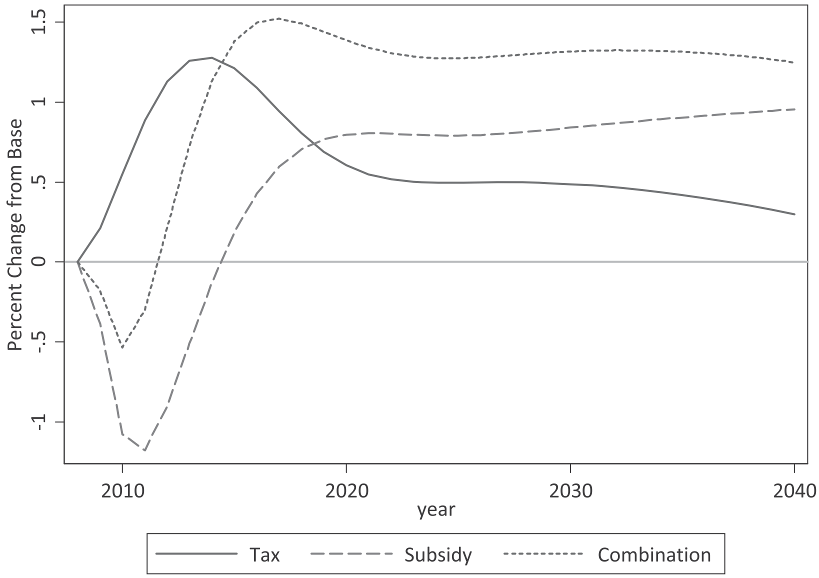


induce larger GDP losses from a carbon price. Also the real exchange rate effect can change sign if the trade elasticities are increased substantially.

The general strengthening of U.S. terms of trade and the decline in the relative price of imported durables together sharply reduce the relative price of household capital, even in the absence of a tax credit. As a result, shown by the solid line in Figure 7, the carbon tax causes the stock of household capital to begin rising immediately, reach a peak about 1.2 percent above baseline around 2014, and remain almost 0.5 percent higher than baseline in the long run. The tax credit, shown by the dashed line, also increases the long-run capital stock but by a somewhat larger magnitude: about one percent. However, the short run effects of the two policies are sharply different. Beginning immediately in 2008, household capital falls under the tax credit policy as households postpone investment until the credit comes into effect in 2010. Household capital is more than one percent lower than baseline by 2011.[12] After that, household investment rises sharply and the capital stock rapidly approaches its long term value. The combination policy has short run effects between the others: a milder investment drop from 2008 to 2010 as the effect of the carbon tax partially offsets the decline due to anticipation of the tax credit. After the credit takes effect in 2010, the

12. Note that these are beginning of period capital stocks so although investment is already rising in 2011, the beginning of period capital stock for 2011 is unaffected.

Figure 7: Effect of Policies on Household Capital Stock

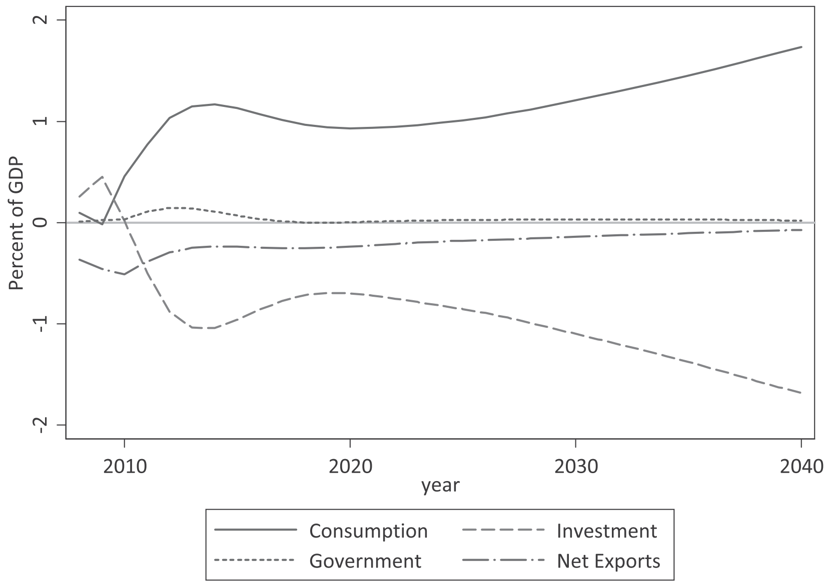


capital stock rises rapidly to a long run value almost 1.5 percent higher than the reference case.

The relative price faced by households for non-energy goods falls as well. As a result, the composition of U.S. GDP shifts toward household consumption and away from investment and net exports. Changes in GDP shares over time appear in Figure 8. The share of consumption in GDP gradually rises by 1.7 percent relative to baseline while the shares of investment and net exports fall by about 1.6 and 0.1 percent, respectively. Consumption is able to rise because fewer goods are exported to achieve the same level of imports for consumption (the positive terms of trade effect) and investment is reduced because of the reduction in scale of the very capital intensive electric utilities sector. In other words foreign goods become cheaper and consumers are able to consume more of domestic production that would otherwise have gone into investment. The decline in investment is most obvious in the coal sector (figure 6) but is found in all of the energy sectors.

Although important, GDP effects don't directly capture how the policies affect the economic well-being of households. One way to measure the overall welfare effect of each policy is to compute its equivalent variation (EV). Because household behavior in G-Cubed derives from an intertemporal optimization problem (where consumption but not leisure appears in the utility function), the EV for a given policy is the change in lifetime wealth that would be needed to achieve the utility obtained under the policy at the prices that prevailed under the base

Figure 8: Effect of a Carbon Tax on the Composition of GDP



case. A positive EV means the policy makes people better off, and a negative EV means that the policy makes people worse off, not counting environmental or other non-monetized benefits the policy accrues. A convenient way to express an intertemporal EV, or the welfare effect of the policy over its duration, is as a percentage of baseline wealth. Measured that way, we find that the EV of the carbon tax is 0.6 percent: that is, the policy creates a gain for U.S. households from 2008 to 2040 equivalent to receiving about half a percent of additional wealth in 2008. As noted above, the gain is due largely to the improvement in U.S. terms of trade. In contrast, the EV of the subsidy is –0.3 percent; households would be slightly worse off than under the base case. The combination policy lies between the two with an EV of 0.3; across the duration of the policy, households gain slightly.

4. CONCLUSION

Our results have several clear implications. First, a carbon tax would be far more effective at reducing U.S. emissions than an investment tax credit for energy efficient household capital. By 2040, a carbon tax reduces emissions by 60 percent while the reduction due to an investment tax credit for energy-efficient capital would be about 1.5 percent. U.S. emissions do fall under the tax credit scenario, but the total reduction is very small compared to the baseline. Second, combining the policies potentially offsets short run GDP effects that would occur under either of the policies in isolation. The carbon tax alone reduces the rate of GDP growth in the short to medium run while the energy efficiency tax credit increases GDP. Adopting both policies simultaneously leaves overall GDP growth very close to its baseline rate. However, direct measures of household welfare (not counting the environmental benefits) suggest that a carbon tax alone would consistently make households better off than either the combination policy or the tax credit alone. This is because the tax strengthens U.S. terms of trade and makes imported goods cheaper, which more than offsets the burdens to households of the tax. In contrast, the tax credit lowers welfare by reducing consumption and increasing saving and investment.

Our findings are subject to several important caveats. The first is that our tax credit results are sensitive to the elasticity of substitution between energy and capital. A smaller substitution elasticity would cause the credit to be more effective in reducing energy consumption. Our elasticity is based on the historical record, but it might be possible to design the tax credit in a way that limits substitution possibilities by households.

A second caveat is that the welfare benefits of a carbon tax for U.S. households hinge critically on the policy's effects on U.S. terms of trade, particularly as a result of a fall in world oil prices. Strategic or monopolistic behavior by major oil exporting countries may dampen the terms of trade benefits and make the carbon tax more costly for U.S. households than the results here suggest. In addition, our results are likely to be specific to policies implemented by the U.S. because it is such a large consumer in the world oil market. Actions taken by smaller countries would have much smaller effects on world oil prices.

Finally, our terms of trade results could change if other countries adopt more stringent climate policies than are implied by our baseline. The magnitude and direction of the change is an empirical question and would be a fruitful topic for future research. On one hand, action by other countries would push world oil prices down further, enhancing the terms of trade effect. On the other hand, carbon policies implemented abroad would raise the U.S. price of imported goods other than fuels, offsetting part of the terms of trade gain.

REFERENCES

Gillingham, Kenneth, Richard Newell, and Karen Palmer (2006). "Energy Efficiency Policies: A Retrospective Examination." *Annual Review of Environment and Resources* 31: 161–192.

Hassett, Kevin A. and Gilbert E. Metcalf (1995). "Energy Tax Credits and Residential Conservation Investment: Evidence from Panel Data." *Journal of Public Economics* 57: 201–17.

Hassett, Kevin A. and Gilbert E. Metcalf (1995). "Energy Tax Credits and Residential Conservation Investment: Evidence from Panel Data." *Journal of Public Economics* 57(2): 201–217.

Jaffe, Adam B. and Robert N. Stavins (1994). "The Energy-Efficiency Gap: What Does it Mean?" *Energy Policy* 22(10): 804–810.

Joint Committee on Taxation (2010). *Present Law Energy-Related Tax Provisions and Proposed Modifications Contained in the President's Fiscal Year 2011 Budget* (JCX-23-10), April 12.

McKibbin W., D. Pearce and A. Stegman (2009). "Climate Change Scenarios and Long Term Projections." *Climate Change* 97(1–2): 23–47.

McKibbin, W., A. Morris, P. Wilcoxen, and Y. Cai (2009). "Consequences of Alternative U.S. Cap-and-Trade Policies: Controlling Both Emissions and Costs." The Brookings Institution, June.
McKibbin W., M. Ross, R. Shackleton and P. Wilcoxen (1999). "Emissions Trading, Capital Flows and the Kyoto Protocol." *The Energy Journal* Special Issue "The Costs of the Kyoto Protocol: A Multi-model Evaluation" 287–333.
McKibbin, W J. and P J. Wilcoxen (1999). "The Theoretical and Empirical Structure of the G-Cubed Model." *Economic Modelling* 16: 123–148.

Subsidies, Standards and Energy Efficiency

*Jan Imhof**

Carbon taxes have been shown to be the most cost-effective instrument for carbon abatement in a second-best world characterized by non-energy-related market failures such as pre-existing taxes. We show, however, that both subsidies for energy efficiency improvements and fuel standards can be good policy instruments in a third-best world in which consumers underinvest in energy service capital. In this framework, subsidies and standards can both reduce emissions and increase welfare. We show additionally that still further emission reductions are attainable by combining these instruments with a CO_2 tax. Two versions of a CGE model for Switzerland are used to compare five policy proposals. First, we examine the transitional impacts of the different policies using the dynamic CEPE model. The same policies are then implemented within a static representation of the model, which includes a bottom-up representation of light-duty vehicles and allows a more detailed examination of the role of fuel standards and subsidies for energy-efficient vehicles. doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-8

1. INTRODUCTION

While most modeling teams in the current EMF exercise focus on the US economy, our contribution to the study implements the EMF scenarios in a model of the Swiss economy. This change in perspective can yield new insights concerning the role of electrification in carbon abatement and energy efficiency improvements. The case of Switzerland is interesting in that its electricity is

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Department of Management, Technology and Economics, ETH Zurich, Zürichbergstr. 18, CH-8032 Zurich, Switzerland. Tel. +41-44-632 04 19, Fax. +41-44-632 10 50. E-mail: imhofj@ethz.ch.

The author wishes to thank Thomas Rutherford, Olga Kiuila, David Goldblatt and an anonymous reviewer for their very helpful comments and suggestions. All remaining errors are the author's responsibility.
doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-8

Table 1: 2008 Electricity Production Shares, Selected OECD Countries [%]

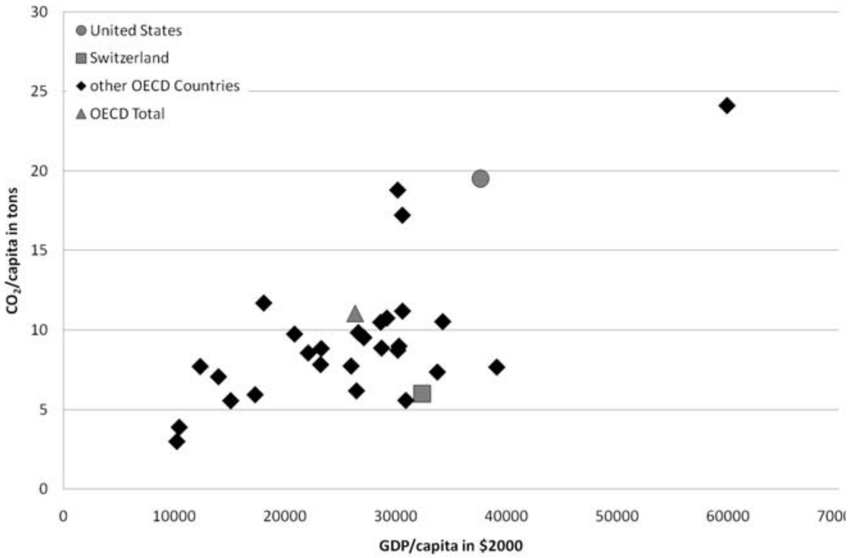
	Coal	Oil	Gas	Other CO_2	Nuclear	Hydro	Other non-CO_2	Gross Production [TWh]
Australia	77	1	15	—	—	5	2	257
Canada	17	2	6	0	14	59	2	651
France	5	1	4	1	76	12	1	575
Germany	46	1	14	1	23	4	10	637
Italy	15	10	54	1	—	15	5	319
Japan	27	13	26	1	24	8	2	1,082
Norway	0	0	0	0	—	98	1	143
Sweden	1	1	0	1	43	46	7	150
Switzerland	—	0	1	3	40	55	1	69
United Kingdom	33	2	45	1	13	2	4	389
USA	49	1	21	1	19	6	3	4,369
OECD Europe	26	3	24	1	25	15	6	3,636
OECD N. America	43	2	21	0	18	13	3	5,279
OECD Total	36	4	22	1	21	13	4	10,745
Non-OECD	46	8	20	0	5	20	1	9,524
World	41	5	21	0	13	16	2	20,269

Source: OECD (2010). “-” indicate that sources are not used for electricity production, while “0” refers to a production share of less than 0.5 percent.

virtually carbon-neutral, making electrification there useful not only in improving energy efficiency but in substantially helping reduce carbon emissions as well.

Swiss climate and energy policy faces major obstacles. In fact, carbon abatement and more highly efficient energy use may be very costly. Switzerland’s situation, common in developed countries, is one of being at the global energy efficiency frontier. It can be very costly for a country that already has highly energy-efficient machinery and buildings to increase efficiency further. Second, whereas most countries have the possibility of reducing emissions by decarbonizing their electricity supply, this option is not open to Switzerland. Table 1 displays the percentage shares of energy sources used for electricity production in selected OECD countries and demonstrates that Swiss electricity, which is primarily produced from hydropower (around 55%) and nuclear power (40%) is virtually carbon neutral. A carbon-free electrification of energy supply is, however, only possible if Switzerland is able to meet considerable increases in electricity demand. Yet the potential for hydroelectric power plants is almost exhausted and building new nuclear plants is politically difficult. Figure 1 shows this as well in its display of per capita emissions and per capita GDP for all OECD countries. Swiss carbon emissions per capita (6 tons of CO_2) are more than 3 times lower than those of the US (about 19.5 tons per capita). While the US only faces the problem of being at the energy efficiency frontier, Switzerland

Figure 1: CO_2 Emissions and GDP Per Capita in 2005



Source: OECD (2009) and IEA (2009).

is also at the "carbon intensity frontier" which may further increase marginal abatement costs.

Switzerland's modern climate and energy efficiency policy started in 1990 with the launch of the "Energy 2000 Program" as a first effort to reduce energy and fossil fuel consumption. The program, which was approved by the Swiss parliament, promoted and subsidized research and improvements in energy efficiency as well as the use of renewable energy sources. While this program ran until the year 2000, the Federal Council tried to pass a CO_2-tax law in 1994 to fulfill the Switzerland's Rio pledge of 1992. The goal was to implement a CO_2-tax by 1996 at 12 CHF[1] per ton of carbon dioxide[2] and to raise it to 36 CHF by 2000. Although energy-intensive sectors would have been exempted, the law was withdrawn following heavy criticism by major political parties and other interest groups. In 1997, the Federal Council successfully implemented a carbon abatement policy through the CO_2 law, which was meant to ensure that Switzerland's Kyoto commitments were met. These commitments oblige Switzerland to reach a mean CO_2-equivalent emission reduction of 10% between 2008 and 2012 as

1. CHF is the currency code for the Swiss Franc. The exchange rate ranged between 0.95 and 1.35 USD per CHF between August 2010 and August 2011.

2. This refers roughly to a price of 12 USD per ton of CO_2.

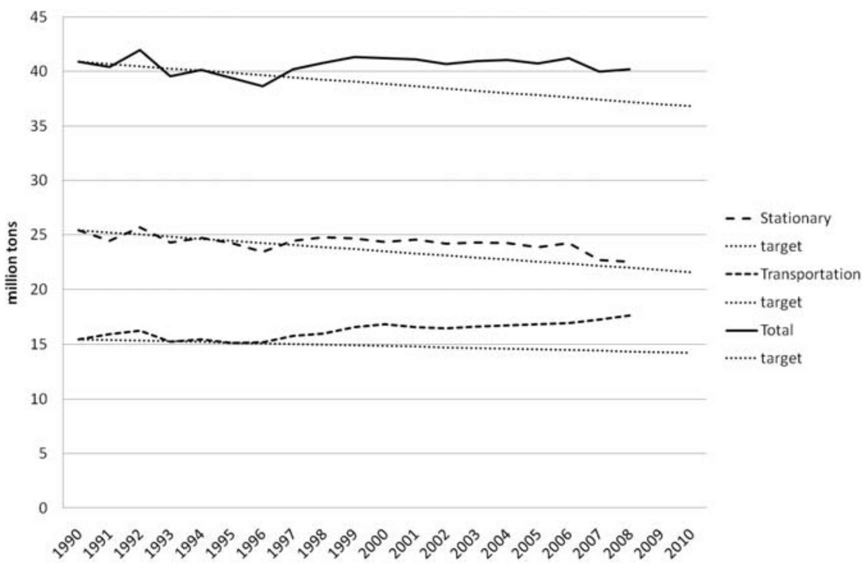
compared to 1990 levels. While the law aimed at abating carbon emissions through voluntary actions, it also gave the government authority to implement a carbon tax if the Kyoto goals seemed likely to be missed. In subsequent years the Federal Council made several target conventions[3] with important emitting sectors such as the car importers, the cement industry and the oil importers. In 2006 the federal council concluded that these agreements were not going to be sufficient and in 2008 introduced a carbon tax on stationary fuels at a level of 12 CHF/tCO_2. In January 2010, the tax was increased to 36 CHF. While stationary fuels are taxed, transport fuels are not. Instead, the oil industry has to charge a "Climate Cent" of 1.5 Swiss cents per liter of gasoline and diesel[4], which corresponds to a price of roughly 6 CHF/tCO_2. The levy has to be used to offset 9 million tons of CO_2 between 2008 and 2012 by subsidizing domestic carbon abatement projects and buying foreign carbon certificates. Nevertheless, the Swiss Carbon Balance has shown that these measures are not likely to fulfill Switzerland's Kyoto commitments: Even though carbon emissions from stationary fuels were reduced by approximately 15% compared to 1990, transport fuel consumption has increased substantially, leaving overall carbon emissions at their 1990 levels (see Figure 2). Since the Kyoto protocol and the CO_2-Law expire after 2012, the Federal Council announced a revision of the law in August 2009 and plans to continue to tax stationary fuels at 36 CHF per ton of carbon dioxide. Most likely the "Climate Cent" agreement will be extended with slightly more aggressive targets. Whereas the tax revenue was previously redistributed partly by lump-sum payments to consumers and partly through a reduction in social security payments on wages, the Swiss parliament has already decided that under the new law, one third of the revenue will be used to subsidize energy efficiency improvements of buildings while building and vehicle fuel standards will be increased in parallel.

In general, environmental and energy policy should address two major issues. First, it is widely recognized that CO_2 emissions have likely had and will certainly have future impacts on economies and people worldwide. Therefore the Swiss climate policy should counter the global climate externality. Second, it is argued that a nation's high energy dependency could harm its energy security. Thus, an adequate energy policy should induce energy conservation for example through increased energy efficiency. However, it is important that each goal is pursued with the right instrument. An externality is best internalized by means of a Pigouvian tax. A carbon tax or carbon permits might be appropriate for the climate change issue. But which policy instrument is best suited to enhancing

3. Two forms of freely consented measures exist in the Swiss terminology. Target conventions are promises made to the government before the introduction of the carbon tax, designed to avoid its implementation. Second, formal commitments can still be negotiated for certain facilities to get exemption from the carbon tax.

4. The oil importers managed to avoid a tax on transport fuels via this agreement with the Federal Council.

Figure 2: Official CO_2 Statistics of Switzerland with Target Projections



Source: FOEN (2010, p.4)

energy efficiency? A study by McKinsey (McKinsey 2009) argues that Swiss annual CO_2 emissions, currently at about 41 million tons, could be reduced by around 9 million tons at zero or even negative cost. If this is taken to be true, it must be reconciled with economic theory, using assumptions about why agents are not using these cost saving opportunities. The authors of the study suggest that the reason could be capital market imperfections, as energy efficient equipment comes at a higher incremental cost. If agents require shorter pay-back periods or face barriers in capital markets, their choices could be distorted. If that is the case, subsidies or standards for energy-efficient equipment could be the right response.

We will examine the issues surrounding the Swiss debate using five of the seven EMF25 counterfactuals. The carbon tax case will shed light on the role of electrification for reducing emissions and increasing energy efficiency in an environment in which electricity is produced carbon-neutrally. We will then be able to illustrate the contribution of increased efficiency standards or subsidies for energy efficiency improvements with and without an additional carbon tax. As we will see, analyzing the interaction of these instruments with a carbon tax yields interesting insights. These policies are simulated with a dynamic version of the CEPE model[5] which allows the investigation of their transitional impact.

5. CEPE-D is the Dynamic version of the Climate and Energy Policy Evaluation model of the Swiss economy.

This is of interest because timing plays a major role in climate policy. In a second step, we implement a static version of the model that includes a bottom-up representation of the LDV sector to further examine the role of fuel efficiency standards and subsidies for higher efficiency vehicles. We justify the focus on the LDV sector by the fact that it accounts for almost 30% of Swiss CO_2 emissions.

We find that while standards and subsidies might help reduce carbon emissions, carbon taxes are still more efficient in general. However, with the further assumption that consumers' energy-specific investment decisions are distorted, subsidies and standards can become welfare increasing, as they directly help to reduce the market distortion. Interestingly, we find that combining subsidies or standards with carbon taxes can reduce carbon emissions even further than either instrument can alone, while reducing the welfare burden of the carbon tax. However, this finding relies crucially on the assumption of a distortion in energy specific investment decisions: If we are indeed in a second-best world with non-distorted investment decisions rather than a third-best world, subsidies and standards introduce the distortion, rather than reducing it. While the results of the two models are mostly similar, the dynamic model stresses the importance of timing for climate policy. While high standards may reduce CO_2 emissions early in the period, associated abatement costs may be rather high.

The remainder of the paper is organized as follows: Section 2 describes the specification of the scenarios. Section 3 provides an overview of the CEPE-D model and presents its results. Section 4 takes a closer look at fuel efficiency standards of light-duty vehicles by implementing a static version of the model with an activity analysis submodel. Section 5 concludes.

2. SCENARIOS

Our business-as-usual scenario is based on Switzerland's 2005 input-output table and baseline projections of important economic and energy-related variables. We have implemented five counterfactuals. The first counterfactual introduces a uniform carbon tax on all fossil fuels. The second scenario includes energy efficiency standards for vehicles and buildings. The third examines a subsidy for energy-efficient capital. The last two are combinations of the non-tax scenarios with the carbon tax. All scenarios are constructed such that the implemented policy is revenue neutral: Revenue from the carbon tax is redistributed as a lump-sum payment from the government to the consumers, while a subsidy decreases pre-existing lump-sum payments. These scenarios were chosen to reflect our interest in the role of standards and subsidies in climate policy. In fact, the two combination scenarios resemble the current proposals for Switzerland's post-Kyoto climate policy. Indeed, on top of the current carbon tax, Swiss authorities plan to implement both subsidies for energy efficient building renovations and increased vehicle standards. In particular, we are interested in understanding the interaction of standards and subsidies with the current carbon tax and their impact on emission reductions and abatement costs. The role of the stand-alone policy scenarios is to help isolate the effects of the three instruments and identify their individual advantages and disadvantages. We now define the scenarios in more detail:

Business-as-usual (BAU)

The business-as-usual case is a benchmark projection that is in line with current estimates of growth, technological change and other basic variables. We report the basic parameters and projections of important variables in section 3, as computed by CEPE-D. The BAU scenario of CEPE-S is defined in the same way but for the year 2005 only. It is noteworthy that no environmental policies are implemented in our BAU case.

Carbon Tax Case (CT)

A uniform carbon tax on fossil fuel combustion is implemented starting in 2010 at a level of 30 CHF per ton of carbon dioxide and charged on fossil fuel combustion.[6] The tax subsequently increases by 5% per year, inflation adjusted. In the static model, the tax is implemented at a rate of 30 CHF/tCO_2.

Sectoral Standards (SS)

This scenario examines the role of increased efficiency standards for buildings and motor vehicles. Between 2012 and 2016, the average energy efficiency of buildings and vehicles is to increase by six percent per year. After that, the required minimum fuel efficiency remains constant. Note that due to technical change, efficiency continues to increase beyond 2016. In the static setup, we implement an increase of 30% in fuel efficiency on light-duty vehicles only.

Subsidy Case (SUB)

In the dynamic model we implement a subsidy on capital that is used to provide heating and transportation services. The 20% subsidy aims to encourage consumers to substitute capital for fuel in the provision of energy services. While the subsidy is applied to all energy-specific capital in the dynamic model, in the static model we applied the subsidy to more efficient vehicles only. The rate of the subsidy is set such that half of the cost increase for more highly efficient vehicles is paid for by the government. Subsidizing energy capital regardless of its qualitative properties vis-à-vis energy efficiency may overestimate potential rebound effects in the dynamic model, since inefficient technologies will benefit as well.

6. This corresponds to approximately 30 USD/tCO_2

Standards with Carbon Fee (SST)

This scenario is a combination of the standards case with the carbon tax. Both instruments are introduced in parallel, exactly as they were in the stand-alone cases.

Subsidy Case with Carbon Fee (SUBT)

This scenario couples the subsidy with the carbon tax.

All scenarios, including the business-as-usual case, have been computed with and without a distortion in the representative consumer's investment in energy efficiency. While we designate a second-best world as the case where pre-existing taxes are the only distortions on the economy, we will call third-best the world that suffers from the additional distortion of consumers' investment decisions. Because the representative consumer does not choose the optimal amount of energy efficiency by himself, there will be room for a welfare-increasing policy reform. The investment distortion was implemented such that the representative consumer perceives an energy service capital price that is twice as high as the market rate[7].

3. DYNAMIC TOP-DOWN APPROACH

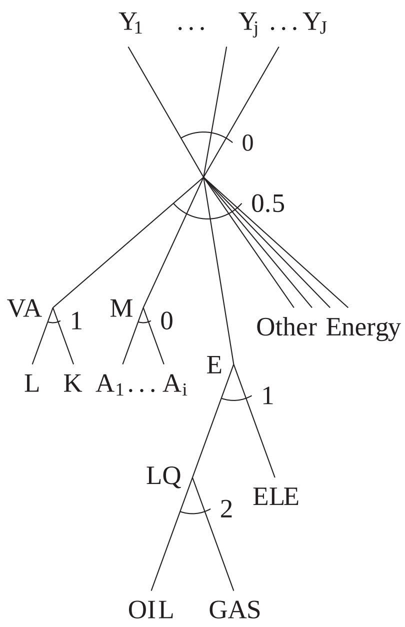
To analyze the above-mentioned issues, we developed an intertemporal computable general equilibrium model of the Swiss economy referred to as CEPE-D.[8] The model is of the classical Ramsey-type with endogenous depreciation and capital adjustment costs.[9] Firms have perfect foresight and maximize their present value profit over the whole model horizon. The model runs until the year 2060 and we control for the finite horizon problem with terminal constraints on investment and capital levels. The current version of the model includes 10 sectors producing 17 goods. The output can be exported or used domestically. Production for domestic use is combined with imports using the Armington assumption (Armington 1969). The Armington composite can be used as an intermediate input in production or in final demand. There are two demand-side agents. The representative consumer, who maximizes his discounted utility over the whole model horizon such that his budget constraint holds with equality, and the government, which buys a fixed bundle of goods and adjusts lump-sum transfers such that its budget is balanced period-by-period in all scenarios.

7. This distortion applies to all energy-related capital in the production of private transportation and heating in the private sector.

8. A detailed technical description of the model is available upon request from the author.

9. The capital adjustment cost feature is well explained by McKibbin and Wilcoxen (1999) and follows the idea of Uzawa (1969). We also explain this feature in our technical description.

Figure 3: Production Function Nesting Applied to All Sectors



3.1 Energy Supply, Demand and Substitution Possibilities

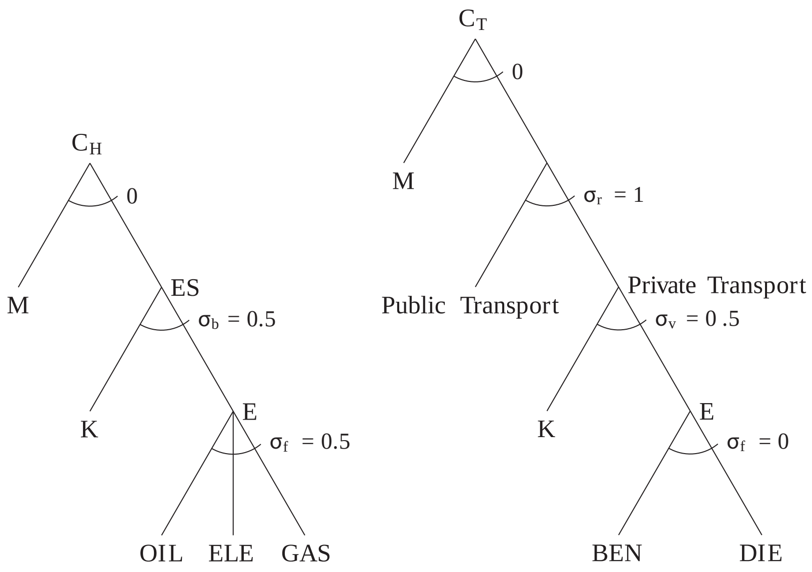
CEPE-D covers 7 intermediate energy goods: Fuel oil, natural gas, coal, electricity, gasoline, diesel and kerosene. Switzerland is not endowed with any primary energy resources and has to import crude oil, coal, natural gas and uranium. While about half of Switzerland's demand for refined oil products is met by imports, the other half is produced from crude in the oil processing sector. The model includes an electricity sector, in which electricity is produced using capital, labor and uranium as its major inputs. Other intermediates and small amounts of other energy inputs enter the production function in the same way as in other sectors.

The nested CES production function, common to all sectors, and associated elasticities of substitution are illustrated in Figure 3. On the top nest less important energy sources such as coal[10] and motor fuels[11] are substituted with a value added composite, intermediate goods and an energy aggregate with an elas-

10. Coal plays a minor role in the Swiss economy. Coal accounts for less than one percent of total primary energy supply.

11. Transport fuels covered are gasoline, diesel and kerosene. Kerosene is only used in the air transport sector and industrial demand for gasoline and diesel is minor.

Figure 4: Production Function for Housing and Transportation Services



ticity of substitution of 0.5. The energy aggregate is produced in a Cobb-Douglas nest from electricity and fossil fuels, which combine fuel oil and natural gas inputs, substitutable with a constant elasticity of 2.

While final government demand for energy is fixed, the representative consumer has additional substitution possibilities. His one-period utility function combines consumption of non-energy activities with housing and transport services in the top nest. He can trade-off different activities with an elasticity of substitution of 0.5. Non-energy-related consumption goods are purchased with fixed budget shares.

Figure 4 demonstrates the substitution possibilities for the energy consuming activities of the consumer. In the lowest nest of the housing activity, fuel oil (OIL), natural gas (GAS) and electricity (ELE) are substituted with a constant elasticity of 0.5. The energy aggregate then trades-off with capital services representing improvements in furnaces, insolation or appliances. To meet his transportation needs, the consumer purchases gasoline (BEN) and diesel (DIE) in fixed proportions. He can invest in higher fuel efficiency by substituting transport fuels with capital at a rate of 0.5. Finally, he spends fixed shares of his budget for public and private transportation.

3.2 Business-as-usual Projections (BAU)

In this basic scenario no environmental measures are implemented, but there are pre-existing taxes on value added, some excise taxes, import tariffs, a

Table 2: Benchmark Parameters

Parameter	Description	Value
gr	Growth rate	2%
r	Interest rate	4%
δ	Depreciation rate	7%
φ	Adjustment cost intensity	0.3
ε	Maintenance cost elasticity	0.5

Table 3: BAU Projections

Variable	Unit	2005	2010	2020	2030	2040	2050
GDP	billion CHF_{2005}	455	503	613	747	910	1109
		(2.0)	(2.0)	(2.0)	(2.0)	(2.0)	(2.0)
Consumption	billion CHF_{2005}	280	309	376	459	559	682
		(2.0)	(2.0)	(2.0)	(2.0)	(2.0)	(2.0)
CO_2 emissions	million metric tons	40.3	43.3	50.0	57.9	67.2	78.2
		(1.4)	(1.4)	(1.5)	(1.5)	(1.5)	(1.5)
Energy	PJ, delivered	780	841	978	1140	1332	1561
		(1.5)	(1.5)	(1.6)	(1.6)	(1.6)	(1.6)
Electricity	PJ	206	225	268	320	382	458
		(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Electricity share	% of delivered energy	26	27	27	28	29	29
		(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
CO_2 intensity of GDP	g/CHF	88.5	86.1	81.6	77.5	73.8	70.5
		(–0.6)	(–0.5)	(–0.5)	(–0.5)	(–0.5)	(–0.5)
Energy intensity of GDP	MJ/CHF	1.71	1.67	1.60	1.53	1.46	1.41
		(–0.5)	(–0.5)	(–0.4)	(–0.4)	(–0.4)	(–0.4)
CO_2 intensity of energy	g/MJ	51.7	51.5	51.1	50.8	50.4	50.1
		(–0.1)	(–0.1)	(–0.1)	(–0.1)	(–0.1)	(–0.1)

Notes: Annual growth rates reported in parenthesis (%)

lump-sum transfer from the government to the consumer, and optionally a distortion in the capital-fuel choice of the consumer. We refer to the scenarios with the additional distortion as a third-best world. There, the consumer perceives a price for energy-efficient capital that is double the market rate. The model is calibrated to the 2005 input-output table of Switzerland (Nathani, Wickart and van Nieuwkoop 2008) and parameters as presented in Table 2. Table 3 presents some basic variables of the business-as-usual projection.

GDP grows at the calibrated rate of 2% through the whole model horizon. Starting at a value of 455 billion Swiss Francs in 2005, it doubles by the year 2040. In the meantime CO_2 emissions and energy consumption grow at smaller rates. In 2005, CO_2 emissions from fossil fuel combustion are 40 million tons and increase by only 60% until 2040. The overall CO_2-intensity of GDP therefore declines from 88.5 grams per CHF to 73.8 grams in 2040. The energy intensity of GDP decreases as well. This decline in energy and CO_2 intensity is due to the exogenous technological change assumed in CEPE-D. Whereas the rates of decline of both energy and carbon intensity decrease over time, it is noteworthy that the carbon content of energy slowly declines as well. The share of electricity in total energy consumption increases from 26% in 2005 to 29% in 2040.

3.3 Subsidies and Standards versus a Carbon Tax

Neoclassical economic theory propounds that a policy maker aiming to reduce carbon emissions does best by implementing a carbon tax. While optimal sectoral standards can enforce the same cost-effective outcome as a tax, they require that the government act under complete information regarding both available technologies and heterogeneity of firms and consumers. Standards not implemented in the optimal way will not be cost-effective, since they will not equalize marginal abatement cost. In some ways subsidies suffer from the same problem. If implemented properly, they adjust relative prices of carbon-abating investments optimally. For that to happen, though, the policy maker has to know exactly which technologies to subsidize and at which rate. On the other hand, a subsidy on energy-efficient capital would decrease the price of energy services and could thus increase their consumption. This rebound effect could have—to some extent—adverse effects on emissions and energy use. This section will address these issues in both a second and a third-best world.

3.3.1 Second-best world

We will first examine the counterfactuals in a second-best world without the energy-specific investment distortion. Figures 5 to 7 display the percentage deviation from BAU levels for selected variables. The results of these counterfactuals emphasize that a uniform carbon tax is the most cost-effective abatement-inducing instrument. Subsidies and standards do not equalize marginal abatement costs between sectors and technologies and thus increase total abatement costs, which negatively impacts consumption.

Figure 5 indicates that all policies are costly in terms of consumption, which is expected, as all policy proposals introduce additional distortions to the economy. While sectoral standards and subsidies only slightly decrease consumption levels, the impact of the combined policies is worse, as they distort the economy twofold. They do in fact distort both energy prices and the representative consumer's energy-specific investment decisions.

As indicated by Figure 6, carbon taxes reduce CO_2 emissions more than all other stand-alone policies and, combined with subsidies or standards, can further decrease emissions. Although emissions are reduced by up to 21% in 2050 compared to the BAU level, this reduction is not sufficient to stabilize emissions in absolute terms.

Figure 5: Real Consumption: Difference from BAU in %

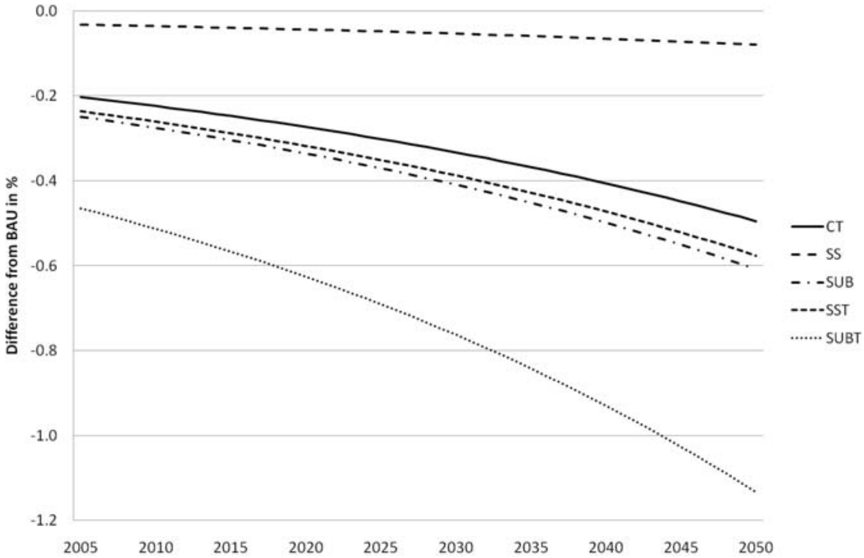


Figure 6: CO_2: Difference from BAU in %

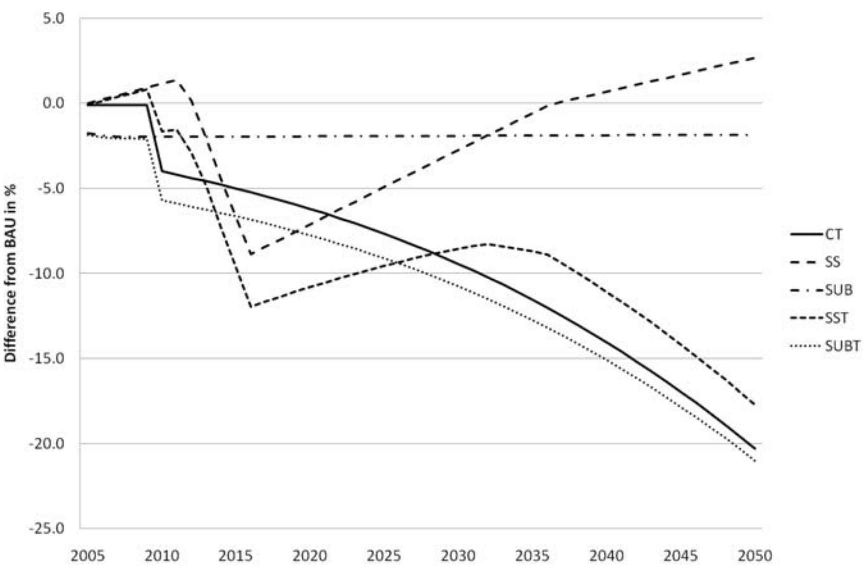
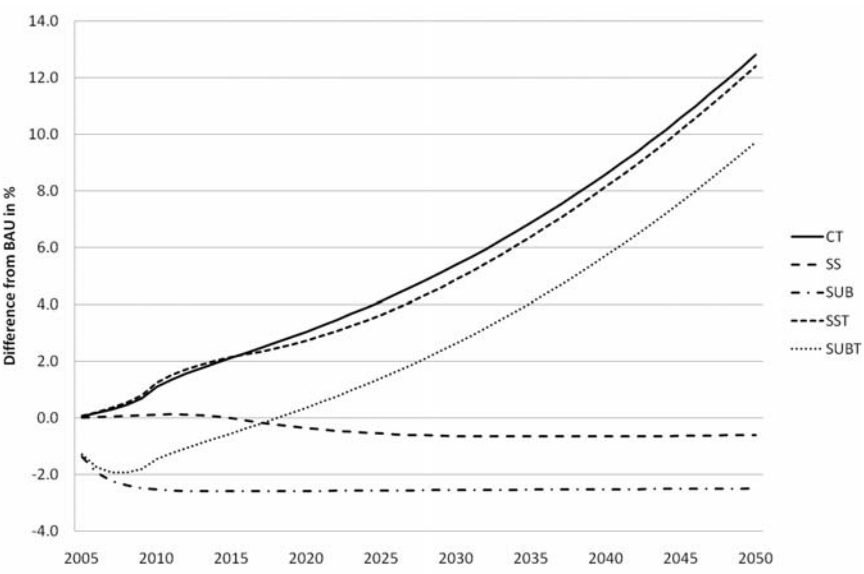


Figure 7: Electricity: Difference from BAU in %



As the standards are not changed after 2016, their impact declines due to technological progress and after 2035 overall emissions even increase relative to BAU levels. This "rebound effect" is due to the larger accumulated energy-specific capital stock. As all proposed policies force substitution from energy to capital inputs, the energy-specific capital stock increases in all scenarios relative to the BAU. But while the other measures persist, the standard becomes less constraining after 2016, and thus the increased capital stock will induce a higher level of energy consumption afterwards. This motivates the need for policy makers to update standards continuously, in order to keep them binding and prevent a rebound in energy use in the regulated sectors.

While total energy demand declines for all binding policy proposals, electricity consumption increases relative to the business-as-usual projections in the three proposals with carbon taxes. In the carbon tax case, as well as in the combined proposals, the share of electricity in total delivered energy increases as the price of electricity relative to other energy inputs declines. This effect is driven by the carbon neutrality of Swiss electricity production: While the price of fossil fuels increases, carbon-neutral energy sources are not directly affected by the tax and thus experience a relative price advantage over fossil fuels.[12] The relative

12. This result crucially relies on the possibility to supply an increased amount of carbon-neutral electricity for example by building new nuclear or hydropower facilities.

price of electricity drops, since the electricity price is not affected by the carbon tax. In the standards and subsidy scenarios, however, energy use in general is affected. Electricity faces no relative price advantage over fossil fuels and its use declines as well.

3.3.2 Third-best world with distorted investment

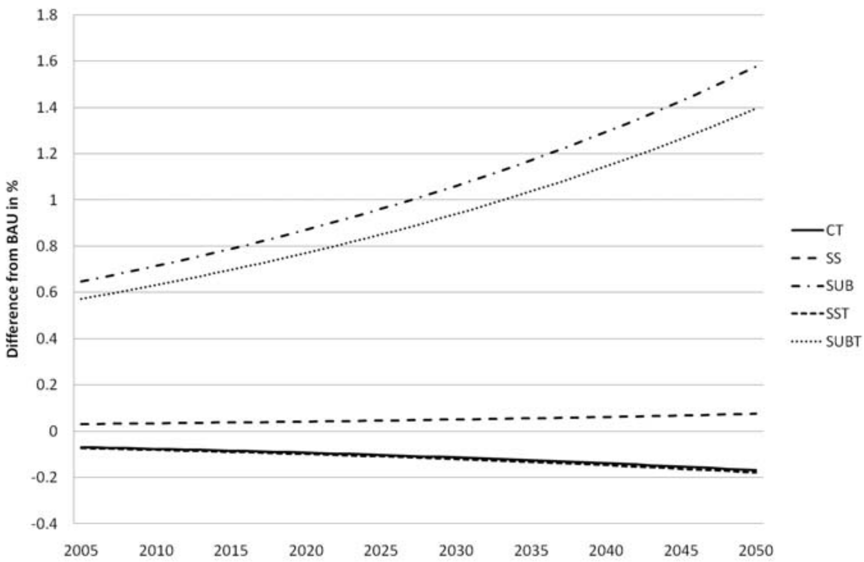
We now additionally assume that the representative consumer's energy-specific investment decisions are distorted, as he overvalues the incremental cost of energy service capital by a factor of two. This distortion would justify the findings of the McKinsey study (McKinsey 2009), which posits the existence of energy efficiency improvements at negative costs. In the absence of the investment distortion, a carbon tax would optimally internalize the environmental damages caused by emissions,[13] while both subsidies and standards could not guarantee equalization of marginal abatement costs.[14] Carbon taxes are thus the most cost-effective and therefore best instrument to control carbon emissions in the second-best world. An assumed distortion in the fuel-capital choices made by consumers can, however, change the set of suitable instruments. A subsidy on energy service capital could indeed reduce the distortion and move the outcome closer to second-best.

Figure 8 displays the gains or losses in consumption associated with the five policy proposals. Both non-tax proposals increase welfare, as they correct the investment distortion. A carbon tax still decreases consumption, but since the CO_2 tax also reduces the investment distortion by increasing the relative price of energy, its negative impact on welfare is smaller than in the second-best world. Combining taxes with standards has a negative impact on consumption. While a standard in itself increases consumption by reducing the capital price distortion, a combined scenario decreases consumption relative to the tax-only case. While each proposal decreases the investment distortion to some extent when implemented by itself, when implemented together they overcorrect it. Additionally the standard causes emissions to decrease dramatically in an early period at rather high costs. The same effect already causes the large difference between the standards and the subsidy case. While the subsidy causes emissions to drop in a smooth manner, the standard is much more demanding in an earlier period. This specific design of the standard induces additional costs, since on the one hand marginal abatement costs increase with the abatement level, and on the other hand earlier abatement is more costly because of technological progress. The timing

13. Note that this is a pure cost-side exercise. We do not have a damage function or another approach to calculate environmental benefits of a climate policy.

14. Additionally a standard could harm the "when"-flexibility of GHG abatement. This could essentially influence total abatement costs. The freedom to choose the timing of GHG abatement has been shown to reduce abatement costs in the EMF21 exercise for example by Böhringer, Löschel and Rutherford (2006).

Figure 8: Real Consumption: Difference from BAU in %



of standards as well as their effectiveness may be crucial to the outcome of such a policy. Conversely, if the tax revenue is used to finance a subsidy, consumption levels are increased while emissions are reduced relative to the tax-only case. However, while the proposals' impacts on welfare rely crucially on the assumption of the investment distortion, associated emission paths are not affected much.[15]

Considering welfare and emissions, we find that a policy proposal which combines a subsidy and a carbon tax would be most apt at countering carbon emissions in the third-best world. Due to the investment failure, marginal abatement costs are not equalized initially, and thus a carbon tax stand-alone policy would not counter this initial distortion. The subsidy reduces the distortion on private investment and thus helps equate marginal abatement costs. The subsidy and tax scenario has the highest emission reduction rates of all scenarios, while also boosting consumption. Thus, if we believe that consumers invest too little in energy efficiency, we may want to implement a carbon tax and use the revenue partly to subsidize energy-saving investments in buildings, vehicles and equipment.

15. Realized emission paths in the scenarios decline a bit. However, emission paths resulting from the policy proposals do not vary more than 1% annually compared to the paths in a second-best world. This corresponds to a difference of less than 0.7 million tons of CO_2 per year.

Table 4: GHG Abatement Technologies for Switzerland's Transportation Sector

Technology	Label	Abatement potential [Mt CO_2e/year]	Marginal costs [EUR/t CO_2e]
LDV Gasoline Bundle 1	g1	0.82	−82
LDV Diesel Bundle 1	d1	0.47	−67
LDV Gasoline Bundle 2	g2	1.12	−52
LDV Diesel Bundle 2	d2	0.60	−32
LDV Gasoline Bundle 3	g3	0.76	−29
LDV Diesel Bundle 3	d3	0.42	−18
LDV Gasoline Bundle 4	g4	0.45	−13
LDV Diesel Bundle 4	d4	0.17	−4

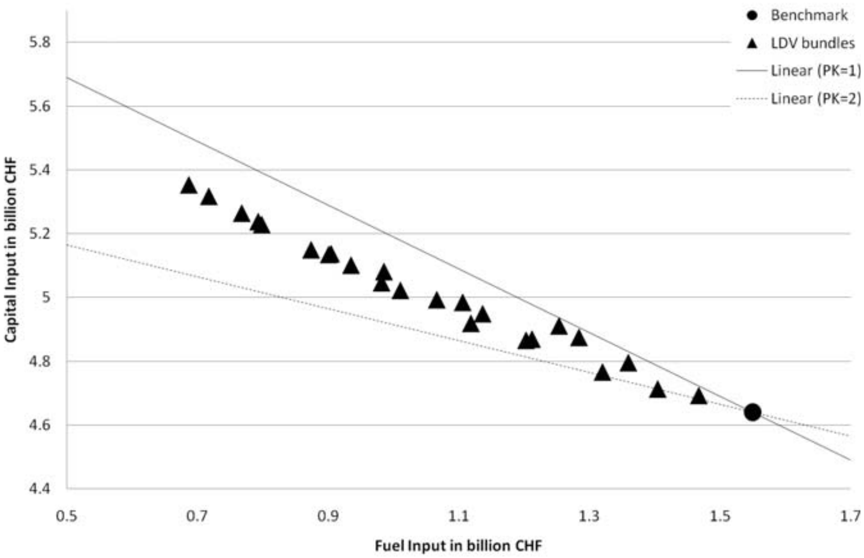
Source: Kiuila and Rutherford (2010) based on McKinsey (2009)

Comparing the cost-effectiveness of our scenarios is not straightforward. Achieved emission reductions vary widely over the different policy proposals. Since marginal abatement costs increase with the level of abatement, simply computing average cost per ton of CO_2 reduced will not do. To deal with this issue we introduced additional scenarios, which are comparable in their impact on emissions. Through analysis of those scenarios, it becomes clear that CO_2 taxes are the most effective instrument to reduce carbon emissions in our second-best baseline. If private and corporate agents base their decisions on non-distorted capital-fuel choices, subsidies or standards will add substantial costs for achieving a given environmental target. Losses in consumer welfare may be 4 times as high when achieved with standards and even more expensive when achieved with subsidies. On the other hand, if consumers' capital-fuel choices are distorted, a subsidy is most suitable for reducing carbon emissions at low costs. We discuss these additional scenarios in greater detail in the appendix.

4. INTEGRATED STATIC APPROACH

A more detailed analysis of the vehicle-fuel choice in the transportation sector is undertaken with an extension of CEPE-S based on Kiuila and Rutherford (2010). Kiuila and Rutherford nest the static CEPE-S model with a bottom-up representation of the LDV sector. This framework allows examination of consumers' vehicle-fuel choices at the technology level. Table 4 lists the available LDV abatement technologies as indicated by McKinsey's Swiss GHG abatement cost curve (McKinsey 2009, p. 11). Close examination of the transportation sector is justified by the fact that it is responsible for a growing share of around 40% of Swiss carbon emissions, corresponding to almost 17 million tons of carbon dioxide, of which around 13 million tons stem from light-duty vehicles. LDVs thus account for almost 30% of Switzerland's CO_2 emissions in 2005.

Figure 9: Relative Price Adjustment of McKinsey's LDV Technologies



Source: Kiuila and Rutherford (2010)

The McKinsey study indicates there is potential for abatement at negative costs. In an attempt to justify this finding in an economically relevant manner, Kiuila and Rutherford adjust the technologies' capital cost such that the technologies not currently in use lie outside the budget set (see Figure 9).

As the plain line portrays relative benchmark prices given by the input-output table, the LDV technologies lie within the budget set. In order to rationalize observed consumer choices, we assume a private capital price that is about twice as high as the market rate and excludes the non-chosen technologies from the representative consumer's budget set, represented by the dashed line.[16] This assumption is identical to the private investment distortion we had introduced in the dynamic model.[17] This distortion leaves room for economically profitable investments, which can subsequently increase welfare.

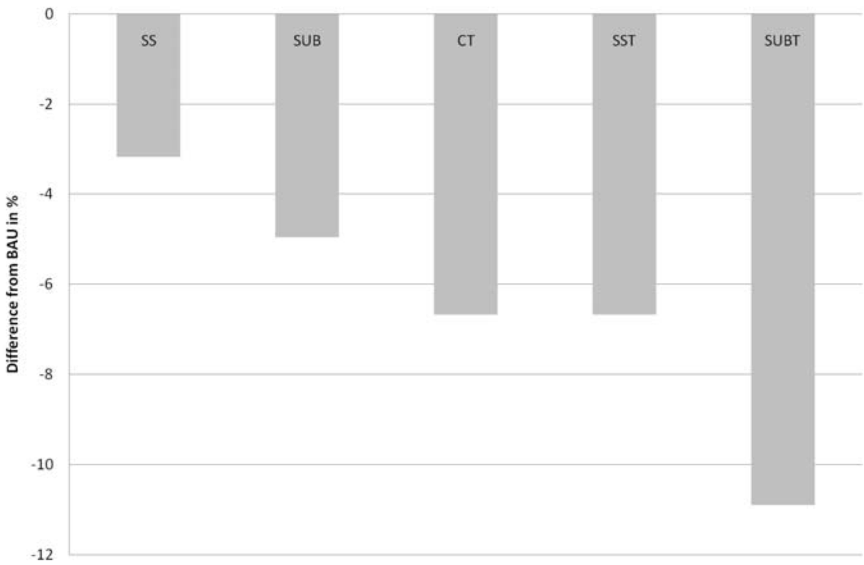
4.1 Subsidies and Standards versus a Carbon Tax in the LDV Sector

We calibrated the static BAU case to the 2005 input-output table and we do comparative-static analysis using the scenarios from section 2, focusing on the

16. Where the relative price of capital *PK* equals two.

17. The data can be thus interpreted. However, if we subscribe to the notion of a distortion of energy-saving investments, we would expect this failure to apply to other investment decisions as well.

Figure 10: CO_2 Emission Reduction

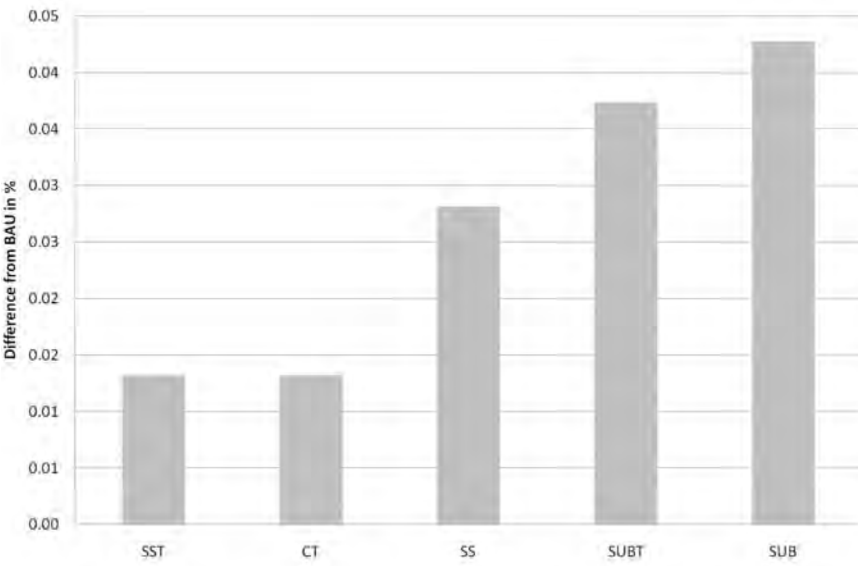


third-best world with the investment distortion. The scenarios are comparable to those implemented in the dynamic analysis. But in the dynamic model we implemented a subsidy on all energy-specific capital, while the subsidy in the static model applies to more highly efficient technologies only. The effect of this difference is straightforward. A subsidy on highly efficient technologies will have a larger effect on the market penetration of new technologies. Similarly, a subsidy on all energy service capital decreases the relative price of capital and forces the consumers to substitute fuel with capital, but with less pressure for improved technologies. Thus CO_2 emissions are reduced by less, but welfare increases, since the market barriers on the capital market apply to all energy service capital.

Figure 10 displays total CO_2 reduction as a percentage of BAU emission levels. The carbon tax policy reduces CO_2 emissions by almost 7%. In the standard-only case, CO_2 emissions decrease by little more than 3%, while an emission reduction of almost 5% is achieved by the subsidy on fuel-efficient vehicles. The combined policy of standards and the carbon tax has an exactly identical impact on emissions as the tax itself. The carbon tax makes highly efficient technologies profitable, and since fuel efficiency already increases by more than 30% the standard is no longer binding. A policy combining a subsidy with the carbon tax reduces CO_2 emissions the most.

Since we assume vehicle-fuel choices are distorted, all policies are welfare-increasing as they help reduce a large pre-existing distortion (see Figure 11).

Figure 11: Hicksian Equivalent Variation in Percent of BAU Consumption



Standards and subsidies are better in terms of welfare than a carbon tax stand-alone policy, since they address the investment distortion directly. It seems that by comparison subsidies are a better instrument than standards, since they reduce emissions more and increase welfare even further. In fact, the implemented subsidy just refers to a more restrictive standard.[18] It should be noted, however, that differences in welfare are rather small.

Table 5 reveals which of the LDV technologies are active under each policy and presents the expenditures on LDV transportation and associated CO_2 emissions. The proposed policies do not have a huge impact on the set of implemented technologies. However, in all scenarios at least the first technology upgrade for gasoline driven cars (g1) becomes profitable. For all counterfactuals except the standards case, the first diesel upgrade (d1) is also cost-effective. The most restrictive policy is the subsidy and tax proposal, which enforces even the use of the second gasoline bundle (g2). Table 5 indicates that the standards are

18. If there are no additional market imperfections, subsidies and standards differ in only one important respect. While a standard forces economic agents to pay for improved equipment by themselves, a subsidy takes over the expenses. In CEPE-S the subsidy is financed by lump-sum transfers and is thus equivalent to a standard. While a standard is a quantity instrument, the subsidy is the corresponding price instrument.

Table 5: LDV technologies used, associated expenditures and CO_2 emissions

Scenario	Technology in use	LDV transportation expenditures [billion CHF_{2005}]	LDV CO_2 emissions [million tons]
BAU	Reference technology	6.19	13.5
SS	g1	6.12	12.2
SUB	g1 and d1	6.08	11.5
CT	g1 and d1	6.00	11.4
SST	g1 and d1	6.00	11.4
SUBT	g2 and d1	5.87	9.7

not binding in the combined policy, as the carbon tax is already sufficient to make diesel bundle 1 profitable.

5. CONCLUSION

We introduced a dynamic and a static general equilibrium model for Switzerland with and without a distortion of energy-specific investment decisions. In a world with investment distortions, we find that subsidies and standards are good measures to reduce both carbon emissions and the distortion in investment. Since carbon taxes are more directly targeted at CO_2 abatement, combined policies may further improve the outcome: A CO_2 tax may efficiently reduce emissions and raise money, while a subsidy may counter the investment distortion. However, if we drop the assumption that consumers are underinvesting in energy-efficient capital, subsidies and standards are revealed to be sub-optimal. Although, in theory, standards and subsidies may be set to reach the same outcome as a uniform tax on carbon emissions, in reality, defining the optimal level of standards or subsidies may be almost impossible. Heterogeneity of consumers and lack of knowledge about technologies and production processes may prevent equalization of marginal abatement costs. Therefore, a carbon tax is the cost-effective instrument to reduce CO_2 emissions in this second-best world.

The dynamic model illustrates the importance of timing in climate policy. Restrictive standards that are introduced early and standards that are not updated subsequently to keep up with technological progress can increase the costs of GHG abatement substantially. Of course our model does not take into account learning-by-doing. Early standards could push technologies up the learning curve and help innovation, which could reduce the negative cost effect.

The static model indicates that subsidies for more highly efficient vehicles and standards are actually similar instruments if we correct a pre-existing market failure in vehicle-fuel choices. Combined with carbon taxes, their impact may be different since standards could become non-binding and therefore negligible. However, the static as well as the dynamic model show that in a world with distorted investment, subsidies and carbon taxes may be good complements.

The EMF scenarios fit the currently discussed policy proposals in Switzerland quite well. While the parliament plans to continue to tax stationary fuels at 36 CHF per ton of CO_2, it is likely to implement subsidies and standards as well. The case of Switzerland and its carbon-neutral electricity is interesting; As carbon taxes are increased, the demand for electricity increases too, since the electricity price falls relative to other energy sources. At the same time, keeping the carbon intensity of electricity at a low level is very important, and thus, increased production from renewables or other low-carbon sources will become essential.

Finally, we conclude that carbon taxes are still the best policy for reducing carbon emissions at low costs. As long as we are not sure about the existence and the nature of energy-specific distortions, finding the right instrument is a troublesome and almost impossible task. Researchers should study the efficiency gap and its causes carefully in order to formulate the efficient policy response.

REFERENCES

Armington, P. S. (1969). "A Theory of Demand for Products Distinguished by Place of Production." *IMF Staff Papers* 16: 159–178.

Böhringer, C., A. Löschel, and T. F. Rutherford (2006). "Efficiency Gains from What-Flexibility in Climate Policy. An Integrated CGE Assessment." *The Energy Journal*, Multi Greenhouse Gas Mitigation and Climate Policy Special Issue: 405–424.

FOEN (2010). "Emissionen nach CO_2-Gesetz und Kyotoprotokoll." Federal Office for the Environment, Berne.

IEA (2009). "CO_2 Emissions from Fossil Fuel Combustion." International Energy Agency, Paris.

Kiuila, O., T. F. Rutherford (2010). "Abatement Options and the Economy-Wide Impact of Climate Policy." Unpublished paper presented at the International Energy Workshop 2010, Stockholm.

McKibbin, W. J., P. J. Wilcoxen (1999). "The theoretical and empirical structure of the G-Cubed model." *Economic Modeling* 16(1): 123–148.

McKinsey (2009). "Swiss Greenhouse Gas Abatement Cost Curve." McKinsey & Company, Zurich.

Nathani, C., M. Wickart, and R. van Nieuwkoop (2008). "Revision der IOT 2001 und Schätzung einer IOT 2005 für die Schweiz." Working Paper.

OECD (2009). "National Accounts at a Glance 2009." Organisation for Economic Co-operation and Development, Paris.

OECD (2010). "Electricity Information (2010 Edition)." Organisation for Economic Co-operation and Development, Paris.

Uzawa, H. (1969). "Time Preference and the Penrose Effect in a Two-Class Model of Economic Growth." *The Journal of Political Economy* 77(4): 628–652.

APPENDIX A: WELFARE COMPARISON OF INSTRUMENTS

Comparing the cost-effectiveness of different policy measures as defined in our scenarios in section 2 is not a simple exercise. Our scenarios differ in their effects on consumer welfare as well as on energy usage. Since marginal CO_2 abatement costs usually increase with the abatement level, direct comparisons of the welfare effects are not possible by simply taking average costs per ton of CO_2

reduced. To deal with this problem, we defined four new scenarios that are alike in terms of emission reduction:

Comparable Standard Case (SS2)

This scenario implements the same standards as in our basic standards case (SS) but includes an additional cap-and-trade permits system with a quantity of allowances following the BAU emission path. This feature prevents an overshooting of the BAU emissions path.

Carbon Fee with Emission Path of SS2 (CT_{SS})

This scenario features a carbon tax which is implemented such that the emission path follows the one of the SS2 scenario.

Comparable Subsidy Case (SUB2)

In this scenario we implement a subsidy with a constant rate such that the cumulative emissions until 2050 equal that of the comparable standards case.

Carbon Fee with Emission Path of SUB2 (CT_{SUB})

A carbon tax is implemented such that the realized emission path equals the one under the comparable subsidy case.

The emission paths in Figure 12 portray the effect on CO_2 emissions in a model without the investment distortion. The introduction of the distortion hardly affects emissions. In all scenarios, cumulative CO_2 emissions are reduced by 55 million tons in the second-best world and 53 million tons in the third-best world, respectively.

Table 6 lists results for all four scenarios with and without the additional distortion. In a world without the additional distortion, the cost-effective measure is a carbon tax that follows a smooth abatement path (CT_{SUB}). The difference in the realized equivalence variation between this case and a carbon tax that follows the emission path of the standards case (CT_{SS}) demonstrates the cost advantage of balanced emission reductions. Second, the loss from not equalizing marginal abatement costs becomes visible when comparing the carbon tax to the standards case.

The right column of Table 6 shows the same results for a model where investment in energy capital is distorted. Although a carbon tax can reduce emissions at negative costs, it is no longer the cost-effective instrument. A subsidy on energy capital addresses the investment distortion directly and increases welfare the most.

Figure 12: Reduction of CO_2 Emissions from BAU in %

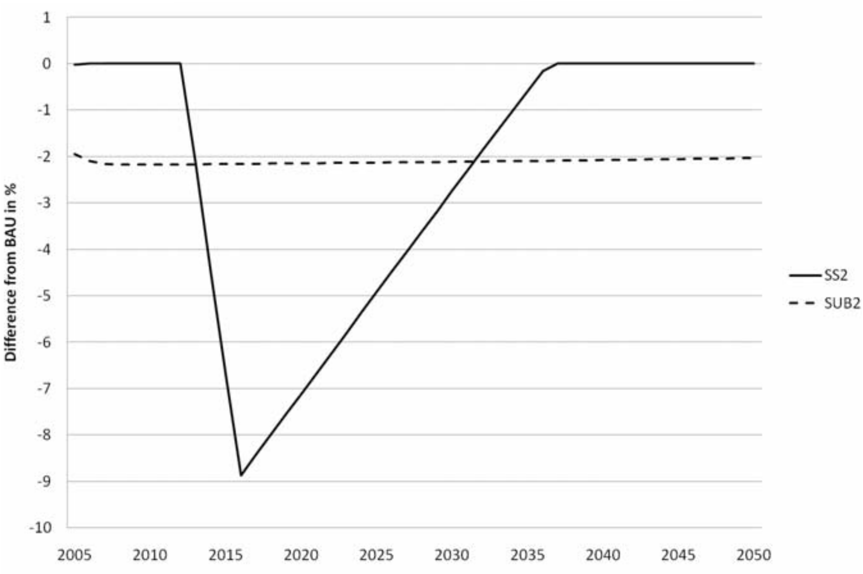


Table 6: Cumulative Losses/gains in Consumption until 2050 [billion CHF]

Scenario	2nd-best world	3rd-best world
SS2	–7.8	6.9
CT_{SS}	–1.5	1.7
SUB2	–62.7	266.7
CT_{SUB}	–0.5	2.3

Policy Effectiveness in Energy Conservation and Emission Reduction

Mei Yuan†, Sugandha Tuladhar*, Paul Bernstein*, and Lee Lane[#]*

In an effort to compare the effectiveness of possible policy options to tackle a range of energy and environmental issues, we employ an integrated assessment model which couples a technology-rich bottom-up model of the U.S. electricity sector with a fully dynamic forward-looking general equilibrium model of the U.S. economy. The model provides a unique and consistent modeling framework for energy and environmental policy analysis. The results from the model show that a carbon tax would be the most cost-effective tool for lowering carbon dioxide emissions, and an energy tax would most cost-effectively lower total energy consumption. Though energy efficiency standards are found to be the least cost-effective at reducing energy usage or mitigating carbon emissions, their appeal is likely to rest on assumptions about specific market failures or on political factors. doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-9

1. INTRODUCTION

As the on-going debates vividly illustrate, United States (U.S.) energy policy strives to achieve multiple goals. It seeks to lower greenhouse gas (GHG) emissions and to lessen total energy use. Elected officials often want to reach these goals without being seen to have raised their constituents' energy prices. The links between energy policy and economic growth are much debated if not clearly understood. To what extent can these diverse goals be reconciled, and what are the best policy tools for doing so? This paper seeks to explore these questions.

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* NERA Economic Consulting, Washington DC 20037, United States.

[#] Hudson Institute, Washington, DC 20005, United States

† Corresponding author. E-mail address: mei.yuan@nera.com.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-9

Many policy options are in play. GHG cap-and-trade has dominated the recent debate. Yet the US has in fact adopted a mix of sectoral policies. Corporate average fuel efficiency (CAFE) standards are meant to reduce oil use in the transportation sector. In the electric sector, appliance efficiency standards are in place, and the country continues to debate still more command-and-control schemes.

To explore the implications, this paper develops and compares four scenarios. It simulates two price-based policies: a carbon tax and an energy tax. A third scenario explores command-and-control options aimed at raising both CAFE standards and appliance efficiency standards. These scenarios assume that the taxes or standards would be applied in the most cost-effective way possible. However, the drift of the current debate suggests that a mix of approaches might someday emerge. Hence, we also simulate a combined policy; it links a carbon tax with CAFE and appliance standards. We compare each of these four scenarios with a baseline and we measure their effectiveness in reducing end-use energy consumption and carbon dioxide (CO_2) emissions.

The results from the model are meant to provide insights for policymakers rather than to recommend a specific policy. Each policy tends to be relatively more effective in reaching some goals and less in reaching others. To state the matter another way, the policy that lowers GHG emissions at the least cost may not be the one that most curbs energy consumption or fuel use. Multiple goals might suggest relying on a mix of policies.

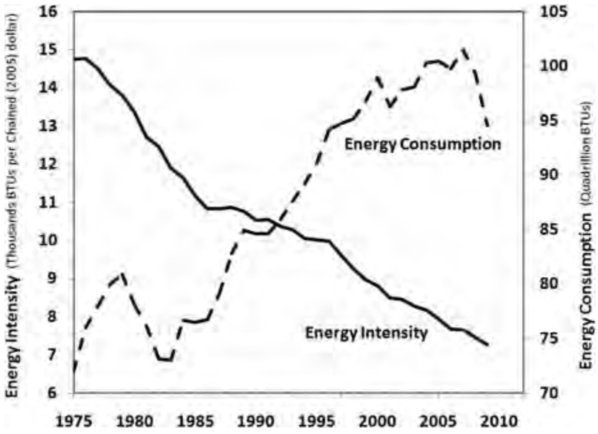
The carbon tax analyzed here would apply to all fossil fuels, and it would be based on their carbon content. Thus, it would alter the relative prices of fossil fuels. Coal, with the highest carbon content, would increase the most in price. Oil would suffer the next highest price boost, and natural gas would be the least affected; however all fossil fuels would be handicapped vis-à-vis carbon- free energy sources. The results would of course be to replace high-carbon fuels with either lower-carbon ones or carbon-free energy sources.

The energy tax analyzed here would apply to all energy sources, and it would be based on their energy content. Such a levy would discourage carbon emissions only as a side effect. Its main impact would be to induce consumers to substitute away from energy use and from goods and services that embody high amounts of energy use. Consumption patterns would change and the economy would substitute capital, labor, or other natural resources for all sources of energy.

Efficiency standards differ from both of these tax policies. Standards of the kind assessed here do not cause energy price hikes. To the extent that greater energy efficiency reduces energy costs per dollar of output, it can lower the energy demand and emissions while maintaining the same economic growth rate. But efficiency regulations can achieve energy savings at too high a cost. Also, if the standards have the effect of lowering energy operating costs, they can cause a rebound effect; that is, more use or more intense use can offset some of the hoped-for savings.

Overall energy consumption can still rise if energy savings are outweighed by the increase in energy demand caused by economic growth. The US

Figure 1: Historic Trend of U.S. Energy Consumption and Energy Intensity (1975–2009)



has exhibited just this pattern (see Figure 1). From mid-1980s to 2007, total U.S. energy consumption has grown by 1.3 percent per year. During these same years, energy efficiency rose at an annual rate of 1.7 percent. As a result the U.S. is twice as energy-efficient today as it was in 1975.[1] However, the gains in energy efficiency have not been enough to reduce the overall energy consumption. Partly for this reason, GHG emissions have also been rising.

To conserve energy without slowing down economic growth, energy efficiency is still a promising strategy. Had efficiency improvement been stagnant in the past, we would have seen much higher demand creating a more pressing need for energy supply. Further improvement in energy efficiency can bring more energy savings and slow down emission growth, though it can be costly and take time to realize.

To analyze how the U.S. economy energy consumption and energy intensity would respond to different policies, we employ a fully integrated top-down bottom-up model. The rest of the paper is organized as follows. In section 2, we describe the top-down model, Multi-Region National Model (MRN), and the bottom-up model, North American Electricity and Environment Model (NEEM), which we use in the policy analysis. Section 3 explains our approach to modeling energy efficiency. We briefly present scenario descriptions in section 4. Section 5 presents model results with comparisons across scenarios. We report the policy impacts on the commercial, transportation, and electric sectors as well as on the aggregate economy. We conclude in section 6 with model caveats and policy discussion.

1. See U.S. Energy Information Administration (EIA)'s Monthly Energy Review June 2010.

2. MODEL DESCRIPTION

The MRN-NEEM model[2] combines two economic models: the MRN model and the NEEM model. As a top-down model, MRN characterizes production technologies and consumption preferences in the economic system with smooth functions and captures the economy-wide effects through interrelated markets. As a bottom-up model, NEEM represents the electricity sector at the unit level and models the evolution of the North American power system taking account of the electricity demand growth, available generation, environmental technologies and environmental regulations both present and future.

2.1. Overview of the MRN Model

MRN is a forward-looking, dynamic computable general equilibrium model of the U.S. economy. In the version used for this analysis, all states are aggregated to be represented by a single representative agent. The inter-temporal budget constraint of the households equates the present value of consumption gross of tax to the present value of income earned in the labor market and the value of the initial capital stock minus the value of post-terminal capital. The infinitely-lived representative agent optimally distributes wealth over the horizon by choosing how much output in a given period to consume and how much to save. The income-balance and zero-profit conditions ensure that the infinitely-lived economic agent makes inter-temporal decisions to optimize consumption, production, and investment in any period.

The model includes twelve sectors: 5 energy sectors and 7 non-energy sectors.[3] All sectors except electricity and coal are modeled using nested CES technologies in the MRN model. Electricity and coal sectors are characterized by detailed processes in the NEEM model.

The model also includes four different types of low-carbon fuels for personal transportation that are used for blending gasoline: aggregate refined petroleum products or oil (blend of gasoline and diesel), conventional corn-based ethanol, low-GHG bio-fuel (blend of bio-diesel and cellulosic and sugar-based ethanol), and a carbon-free transportation fuel. Each fuel is characterized by its emission factor, cost, and maximum allowable penetration. Corn-based ethanol production is associated with an emission factor of 76% of that of gasoline, measured in grams of CO_2 per mega joule (gCO_2/MJ), while for the low-GHG fuel, the emission factor is 20% of conventional gasoline. The zero-carbon transportation fuel, as the name suggests, embodies no carbon.

2. The MRN-NEEM model is a CRA proprietary model.

3. Energy sectors include: (1) Electricity (ELE); (2) Coal (COL); (3) Refined petroleum products (OIL); (4) Natural gas (GAS); and (5) Crude oil (CRU). Non-energy sectors include: (1) Agriculture (AGR); (2) Energy-intensive sectors (EIS); (3) Manufacturing (MAN); (4) Construction; (5) Services (SRV); (6) Commercial transportation (TRN); and (7) Motor vehicle (M_V).

2.2. Overview of the NEEM Model

The North American Electricity and Environment Model (NEEM) fills the need for a flexible, partial equilibrium model of North American electricity markets that can simultaneously model both system expansion and environmental compliance over a 50-year time frame. The model employs detailed unit-level information on all of the generating units in the United States and large portions of Canada. The version of NEEM used in this analysis dispatches load based on a three-period load duration curve. NEEM models the evolution of the North American power system, taking account of demand growth, available generation, environmental technologies, and environmental regulations both present and future. The North American interconnected power system is modeled as a set of regions connected by a network of transmission paths.

NEEM has a rich representation of technologies for electric power generation, which are characterized in terms of capital cost, operating cost, and heat rates, all of which can be assumed to improve over time. New technologies like Integrated Gasification Combined Cycle (IGCC) with carbon capture and sequestration (CCS) are characterized by dates of availability and introduction constraints. Since coal is the primary fuel used by the electricity sector, a detailed representation of the supply structure of this fuel is important. NEEM contains 21 supply curves that represent different regional sources, ranks, sulfur, and mercury content.

2.3. MRN-NEEM Integration Methodology

Following the approach outlined by Bohringer-Rutherford (Bohringer and Rutherford 2006), the MRN-NEEM integration methodology follows an iterative procedure to link top-down and bottom-up models. The method utilizes an iterative process where the MRN and NEEM models are solved in succession, reconciling the equilibrium prices and quantities between the two models. The solution procedure, in general, involves an iterative solution of the top-down general equilibrium model given the net supplies from the bottom-up energy sector sub-model followed by the solution of the energy sector model based on a locally-calibrated set of linear demand functions for the energy sector outputs. The two models are solved independently using different solution techniques, but linked through iterative solution points.

Specifically, the NEEM model passes the electricity supply, non-electric coal supply, and electric natural gas demand to the MRN model. The MRN model optimizes and returns to the NEEM model the electricity prices, natural gas prices, and the coal demand from the non-electric sectors. The iterative process involves NEEM resolving given MRN feedbacks. The iterating continues until energy prices and quantities converge. The same procedure applies under a carbon policy analysis where carbon allowances are passed between the two models until there is equalization of marginal abatement costs between the two models.

3. MODELING ENERGY EFFICIENCY IN MRN-NEEM

This paper seeks to represent gains from raising energy efficiency. To do so, we extend the standard MRN-NEEM model. This task requires modeling energy efficiency in MRN. Our approach is to introduce energy efficiency capital investment into the production activity. The investment would, of course, lower energy input per unit of economic output.

This approach differs from that taken in many previous studies that have used an exogenous Autonomous Energy Efficiency Improvement (AEEI) index (Kasahara et al. 2007). The AEEI purports to measure the reduction in energy consumed in order to yield a given amount of output. Such an approach fails to account for the full costs of technological change. The result typically understates costs of efficiency gains or overstates their benefits.

This paper's approach requires making assumptions about the source of the efficiency-enhancing capital. Here, we think of technological improvement as derived from self-investment. In this framework, part of the sales revenue is diverted to invest in an R&D program that is designed to raise energy efficiency. For instance, auto makers might invest in more efficient engines.

Other assumptions about the possible sources of investment are possible. Private investment, government subsidies or even venture capital might fund the R&D. Or we might assume that knowledge acquired through R&D activities could lower the cost of raising efficiency (Bosetti 2006). So making different assumptions about the source of the investment might change the results that we show here, but we leave to future analysis the task of exploring the implications of other assumptions about the sources of investment.

Another key decision with our approach relates to the matter of where to introduce the compensating cost in the top-down representation of production activities. This choice, too, will have cost implications. Boeter (2007) has suggested three options. One would be to add the additional cost as a perfect complement at the top level of the production nest. A second would be to add to the capital input in the value-added nest, and the third would be to add energy efficiency capital directly to the energy input nest (Laitner and Hanson 2006).

In MRN, the elasticity of substitution across sub-nests in the production function differs for the residential and the commercial sectors. By inference, placing the efficiency investment in the value-added nest will likely entail a different isocost curve than would placing the investment in the energy nest. Regarding the capital investment as energy-carrier-specific and fuel-specific strikes us as being a more intuitive choice. Thus, this analysis adds the capital directly to the energy input. We applied efficiency capital investments in natural gas and in electricity for the residential and commercial sectors, respectively.

The ACEEE's impact assessment of energy efficiency provisions in American Clean Energy and Security Act (ACESA) (see Gold et al. 2009) was the starting point of this analysis. It provides the potential energy, carbon, and economic savings resulting from the efficiency improvement in the residential, commercial, transportation, and industrial sectors. For ease of modeling, we calculated the aggregate energy savings by energy type (natural gas and electricity) in Subtitle A—Building Energy Efficiency and Subtitle B—Lighting and Appliance Energy Efficiency Programs and apply those as the energy-saving targets for the residential and commercial sectors in the model. We then let the model endogenously determine the economic savings from the efficiency improvements and the costs of efficiency capital investment required for installing the efficiency technologies.

Combining the approaches we use to source and place the efficiency capital investment, the modeling strategy in the top-down bottom-up integrated framework involves iteration. The process involves the following steps. First, we derive an energy-intensity target given the energy savings target relative to the baseline energy consumption. The top-down model finds the amount of investment needed to meet the energy-intensity target. At the same time, it produces the prices for electricity and natural gas. These prices are then passed to the bottom-up electricity dispatch model. Using this information, the bottom-up electricity dispatch model determines the amount of generation to supply and the volume of natural gas consumed in power generation. These results are passed back to the top-down model.

In the second iteration, the top-down model uses the electricity supply and electricity natural gas consumption passed from the electricity model. It produces new prices for electricity and natural gas which are passed in turn back to the bottom-up electricity model. The process repeats until both models converge in electricity and natural gas prices as described above in the model description section.

4. SCENARIO DESCRIPTIONS

This section describes the model baseline and introduces the EMF 25 policy scenarios that are simulated in the analysis.

4.1. Baseline

The primary component of the MRN dataset is based on the Social Accounting Matrix (SAM) developed by the Minnesota IMPLAN Group, Inc. (MIG). The SAM represents the economic flows of the 50 United States and the District of Columbia for the year 2002. It provides data on employment, industry output, value added, institutional demand, national input-output structural matrices (use and make tables), and inter-institutional transfers. The model is calibrated to the energy and economic dataset so that the resulting input-output tables for each state balance and the energy values in the dataset match up with the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) forecasted energy quantities and prices.

We used the AEO 2009 stimulus reference case (AEO 2009) to calibrate baseline energy use, carbon emissions from fossil fuels for the non-electric sectors, natural gas price, world price of crude oil and petroleum price. The electric sector is characterized as a partial equilibrium problem; therefore, the electricity supply is specified separately. Exogenous coal supply curves are incorporated into the electric sector model. The fuel consumption in the electric sector is determined endogenously given the coal supply curve and AEO 2009 natural gas price forecast. Hence, the carbon emissions associated with electric generation are determined in the model rather than calibrated to the AEO 2009 projections like the other sectors.

The AEO 2009 includes the forecasted effects of the American Recovery and Reinvestment Act (ARRA). ARRA provides significant new Federal funding, loan guarantees, and tax credits to stimulate investments in energy efficiency and renewable energy. It also includes energy-specific ARRA provisions such as weatherization of assisted housing, energy efficiency and conservation block grant programs, state energy programs, a plug-in hybrid vehicle tax credit, an electric vehicle tax credit, updated tax credits for renewables, loan guarantees for renewables and biofuels, support for CCS, and smart grid expenditures (EIA 2009). The inclusion of these energy-efficiency programs in the AEO 2009 baseline implies a lower US energy intensity.

Most forecasts extensions beyond 2030 are based on the growth rates between 2020 and 2030. In some cases, though, we adjust the post-2030 growth rates to avoid inconsistencies. For example, in the transportation sector we adjust the vehicle miles travelled (VMT) post-2030 growth rate so that the implied miles per gallon (mpg) growth matches our assumptions of 1.5% per year.

4.2. Carbon Tax ("carbontax")

The carbon tax policy assumes a charge of $30 (in 2007 dollars) per metric ton of carbon dioxide equivalent on all fuel sources. It starts in 2010 and the tax rate rises by 5% per year. All carbon tax revenues are assumed to be returned to households in lump-sum payments.

4.3. General Energy Sales Tax ("energytax")

The energy tax policy assumes the imposition of a 15% excise tax rate on all delivered energy sources. The 15% tax rate is selected so that the carbon tax policy and energy tax policy produce the same amount of tax revenue in 2010. The energy tax starts in 2010 and the tax level rises by 5% per year. All energy tax revenues are assumed to be returned to households in equal lump-sum payments.

4.4. Residential, Commercial and Transportation Sector Standards ("standards")

This paper uses an energy efficiency study by ACEEE to estimate two sources of energy savings. These sources are savings from building energy effi-

Table 1: Light-Duty Vehicle Fuel Efficiency for Vehicle Stock (miles per gallon)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Fuel Efficiency (baseline)	20.0	21.0	23.9	26.6	29.5	31.7	34.1	36.7	39.4
Fuel Efficiency Target	20.0	23.1	26.7	29.5	31.6	33.3	34.6	36.8	39.4

ciency and lighting and appliance energy efficiency programs. By 2020, the energy-efficiency standards in new residential and commercial building and equipment save 133 tera-Watt hours (TWhs) of electricity per year. By 2030, savings reach 284 TWhs. By 2020 these savings could reach 655 trillion British thermal units (TBtus) of natural gas per year, and by 2030, savings would be 1524 TBtus. This paper assumes that post-2030 energy savings are assumed to remain at the 2030 level.

In May 2009, Present Obama also imposed new CAFE standards. They require the automakers' passenger fleets to achieve a combined average fuel economy standard of 35.5 mpg by 2020. The standards require 39 mpg for cars and 30 mpg for light trucks and SUVs. Between 2012 and 2016, the standards become more stringent by an equal amount each year. Thereafter, unless new restrictions are imposed, standards remain constant.

MRN-NEEM does not differentiate passenger cars from the light trucks and SUVs; therefore, this analysis derives an average fuel efficiency for the combined fleet of passenger vehicles. To do so, it uses the shares of vehicle types from AEO 2009 and our exogenous assumptions of the vehicle depreciation rate and annual sales. This average fuel efficiency is taken as the target applied to the on-road vehicles (see Table 1). Note that in 2020–2025, the efficiency standards demand a fleet average that is about 3 mpg above the baseline. By 2045, the gap between the standards and the baseline has disappeared and the standards become non-binding.

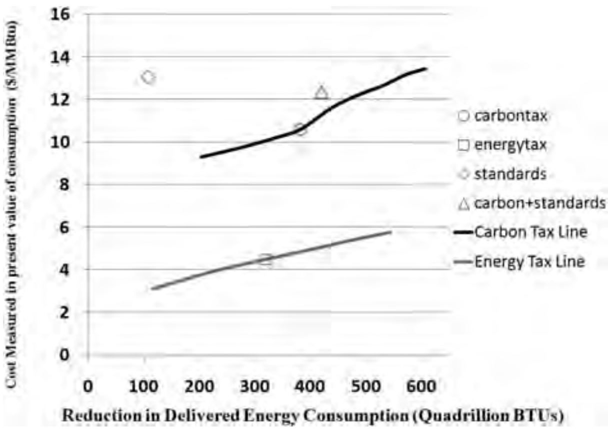
4.5. Standards with Carbon Fees ("carbon + standards")

This policy scenario combines the carbon tax with mandated energy-efficiency standards. In cases where the carbon tax policy induces lower energy use than that required by the standards, we assume the standards do not bind.

5. MODEL RESULTS

We focus on the broader economic impacts in order to assess the cost-effectiveness of each option and to illuminate trade-offs among them. We discuss the policies' impacts on energy intensity, energy prices, energy demand, and carbon emissions. The analysis also shows more detailed results for the commercial and transportation sectors. It is these sectors on which the mandates would fall.

Figure 2: Cost-Effectiveness in Delivered Energy Reduction



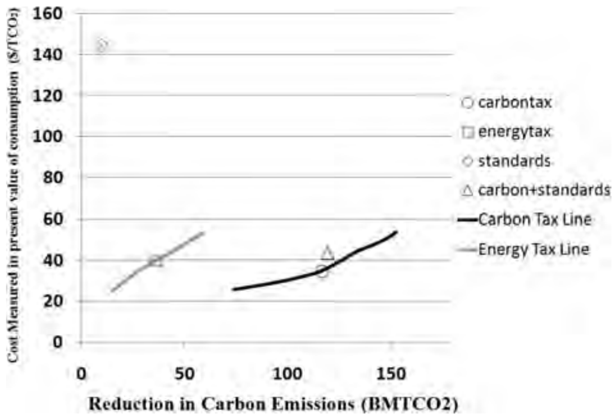
5.1. Discussion of cost-effectiveness of energy-efficiency policies

In order to compare the costs of achieving a given amount of reduction in energy demand and carbon emissions, we derive a cost measure which is based on the loss in the present value of consumption relative to the total reduction in energy demand or carbon emissions over the model horizon.

Figure 2 shows the policy costs corresponding to the reductions in total energy demand. To facilitate the comparison, we include a series of carbon tax and energy tax cases that form a cost-effectiveness frontier for each tax policy. These two frontiers suggest that the energy tax is much more cost-effective in reducing energy consumption. To achieve the same amount of energy reduction, the energy tax policy incurs half of the cost of the carbon tax policy, and about a quarter of the cost of the standards. At about the same cost level, the carbon tax achieves more than 4 times more reduction in energy demand than the standards. When combining the standards with the carbon tax, additional reduction in energy demand occurs but with extra cost in consumption. If lowering energy intensity were the primary goal, the energy tax would be the most cost-effective means of reaching it as one would expect since this policy deals directly with the quantity that one is trying to control.

Figure 3 demonstrates that the carbon tax is far more cost-effective in reducing carbon emissions than the energy tax and the standards. At about the same cost level, the carbon tax achieves about 2 times more reduction in carbon emissions than the energy tax. The carbon tax internalizes the cost of climate change caused by carbon emissions; thus it motivates actions that lower emissions for the least cost needed to achieve a given level of abatement. Neither raising energy prices through the energy tax nor improving energy efficiency through the standards provides equally direct incentives for deploying carbon-free technology.

Figure 3: Cost-Effectiveness in Carbon Emissions Reduction



As a result, neither lowers emissions as cost-effectively as would a carbon tax. The standards are the least cost-effective measure in emission reductions in that the emission reduction tends to be offset by the rebound effect. Consequently, combining the standards with the carbon tax results in additional emission reduction but lowers cost-effectiveness.

Other macroeconomic indicators such as GDP and welfare (Hicksian equivalent variation) give similar rankings of cost-effectiveness of different policy measures.

5.2. Impact on Energy Intensity

Figure 4 compares the percentage change in energy intensity relative to the baseline level. Energy intensity experiences the largest reduction in the carbon + standards case and the smallest reduction in the standards alone case. The change in energy intensity is relatively similar between the carbon tax and energy tax policies.

The rebound effect is an unintended consequence of efficiency improvement that leads to lower energy prices. These lower prices lead to inefficient energy use in the sectors where no standards are implemented or efficiency opportunities are more limited. Much of the reduction in energy use attributable to standards is offset by inefficient energy use outside the regulated activities, especially after 2025 when reductions in energy use attributable to efficiency standards largely evaporate.

5.3. Impacts on energy prices

Carbon dioxide emission factors differ across fuels. For the same amount of energy output, coal emits the most CO_2. For an equal energy output, refined

Figure 4: Energy Intensity (percentage change from the baseline level)

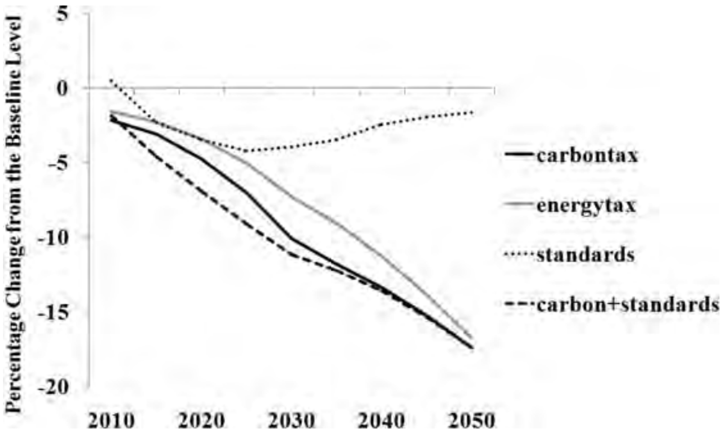


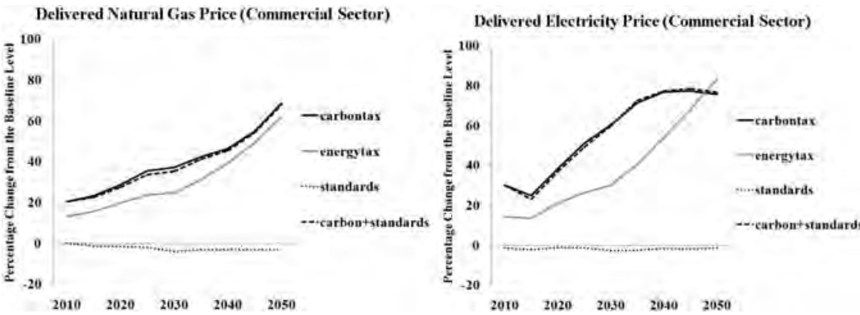
Table 2: Equivalent Tax on Energy ($2007 per MMBtu)

Energy	Sector	Policy	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	Commercial	carbontax	2.8	3.6	4.6	5.8	7.4	9.5	12.1	15.5	19.7
		energytax	0.3	0.3	0.4	0.5	0.7	0.9	1.1	1.5	1.9
Natural Gas	Commercial	carbontax	1.6	2.0	2.6	3.3	4.2	5.4	6.9	8.8	11.2
		energytax	1.5	1.9	2.4	3.0	3.9	4.9	6.3	8.0	10.2
Refined Oil	Transportation	carbontax	1.9	2.4	3.0	3.8	4.8	6.1	7.8	9.9	12.4
		energytax	2.7	3.5	4.4	5.6	7.2	9.2	11.7	15.0	19.1
Electricity	Commercial	carbontax	5.9	7.0	7.7	7.1	5.5	3.9	3.0	2.7	2.8
		energytax	2.6	3.7	5.1	6.6	7.9	10.3	13.1	16.8	21.6

oil emits about two thirds as much CO_2 as coal, and natural gas emits about half as much as coal. Delivered energy price per million Btu (MMBtu) also varies across energy sources. Some fuels like coal are high in carbon but relatively low in delivered price. Thus, the incidence of the two levies is quite different.

By inference, a carbon tax and an energy tax will have different effects on the relative price of fuels. To compare the carbon tax and the energy tax from the policy scenarios in the same terms, we convert the carbon tax to a price per energy unit. As shown in Table 2, for 2010, the carbon tax would add $2.81 per MMBtu to the price of coal. The energy tax, which was set initially to yield about the same total revenue as the carbon tax, would add only $0.26 to the price of using the same amount of coal. The two levies would have a far more similar impact on natural gas prices. The carbon tax would add $1.59 per MMBtu. The energy tax would raise the price by $1.45 per MMBtu. For transport sector refined petroleum product prices, though, the energy tax boosts end-use price more than the carbon tax does.

Figure 5: Delivered Energy Prices (percentage change from the baseline level)



Electric power production uses a mix of fossil and non-fossil primary fuel inputs. In response to the rising prices of carbon-based fuels, power becomes more costly for consumers, and the electric sector substitutes lower-carbon or carbon-free energy sources for coal. The CO_2 intensity of electric power falls. Therefore, the carbon tax paid on every MMBtu of electricity output decreases over time. The response to the carbon tax erodes the tax base.

The energy tax, unlike the carbon tax, would raise costs based on the baseline delivered energy prices, rather than based on carbon intensity of the energy sources. Electricity has the highest delivered energy price among all energy sources after 2010; therefore, the energy tax raises electricity prices more than any other form of energy. The magnitude of the two levies diverges further over time. The carbon tax compels the power sector to switch to lower-carbon or carbon-free fuels, resulting in a lower carbon tax payment per unit of electricity generation. No such effect occurs with the energy tax which takes no account of carbon intensity.

The incremental cost introduced under the tax cases increases end-use prices. This increase in price leads to reduction of demand for energy or substitution away from the high-cost energy inputs. The level of substitution response depends on how elastic the substitution possibilities are. The lower demand caused by taxes induces lower producer prices at equilibrium.

Figure 5 shows the percentage change in natural gas and electricity prices in the commercial sector. Compared to the energy tax, the carbon tax causes larger price increases in all these energy markets.

By 2010, the natural gas price increases by 21% under the carbon tax and 13% under the energy tax. The taxes' economic impacts grow over time as the tax rates rose. By 2050, the carbon tax raises natural gas prices by 69% and the energy tax boosts them by 62%. Two drivers explain the difference. First, the carbon tax causes a bigger first-order increase in the natural gas price than does the energy tax. Second, as the electric power sector shifts to lower-carbon fuels, it augments total demand for natural gas, and natural gas prices rise. In contrast, the impact of the energy tax on natural gas use by both the electric and non-electric sectors is to lower demand, moderating the price increase caused by the tax itself.

The divergence of the two taxes' price impacts is greatest in the electric power sector. By 2010, the carbon tax raises electricity price by 30%; whereas, the energy tax leads to a price hike of only 13%. Electricity has higher carbon emissions per MMBtu than other fuels because of the large amount of coal used in power generation. Over time, though, the price trends converge as the carbon-content of electricity generation falls. By 2045, the electricity prices rise by 77% with the carbon tax and 70% with the energy tax, and by 2050, the impact from the energy tax is greater than from the carbon tax case. Delivered electricity price rises by 76% under the carbon tax case but they grow by 84% under the energy tax. The driving force behind the climb in the electricity price impacts of the carbon tax is the steep rise in the cost of making further cuts in the power sector's carbon emissions. As higher-cost low-carbon energy sources drive cheap coal from the market, generating costs rise at an increasing rate. Should these carbon-free energy sources fail to materialize, the carbon tax would lead to prices that were higher still. If, however, carbon-free technologies become available (as we assume in this analysis), the rise in prices moderates. The second graph in Figure 5 illustrates this possible outcome. By 2050, the carbon tax and assumed emerging availability of the hypothetical carbon-free energy sources cause less severe price increases than those that the energy tax would impose.

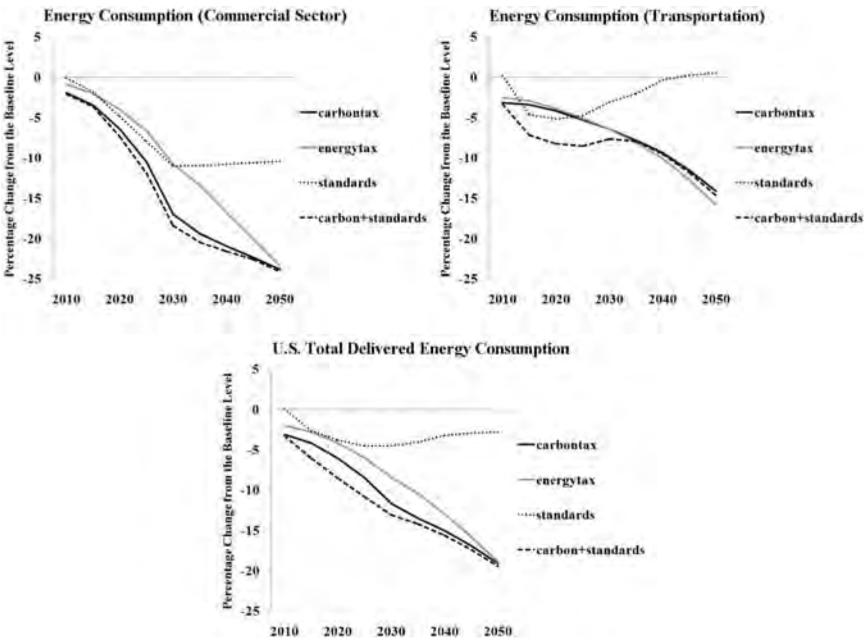
Contrary to the tax cases, the use of standards would lower energy prices in the sectors where they lead to energy savings. If such programs induce energy savings that lower aggregate demand, energy prices would fall. In our standards case, natural gas and electricity prices fall by about 1% to 5%. When combined with the carbon tax policy, the efficiency standards help moderate the energy price increases unless the accompanying rebound effect becomes large enough to offset the total energy savings. The energy price impacts under the combined policy are lower than the carbon tax alone case. This does not mean that the overall economic costs of efficiency standards are less than those of taxes, as discussed in Sections 5.1 and 6.

5.4. Impacts on Energy Demand

Under the current analysis, the carbon tax achieves more reduction in overall energy consumption, compared to the energy tax and the standards cases (see Figure 6). This result occurs because the carbon tax case impels the use of such costly carbon-free technology that energy prices rise more steeply than they do with energy taxes.

Within the commercial sector, between 2010 and 2030, the efficiency standards alone are able to achieve more demand reduction than occurs under the energy tax. Perhaps more importantly, though, the energy tax achieves far more total energy savings. The CAFE policy causes more near-term reduction in trans-

Figure 6: Delivered Energy Consumption (percentage change from the baseline level)



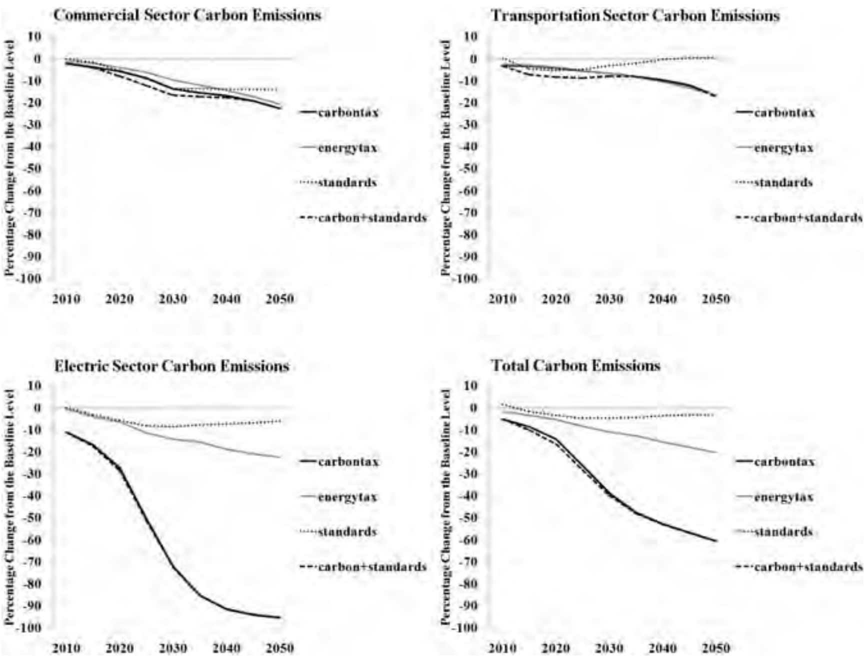
portation energy use than does either the carbon tax or the energy tax. These results demonstrate the near-term effectiveness of the efficiency standards. The pattern can be largely attributed to our assumption of the constant energy savings after 2030. A rebound in energy usage happens in response to the lower energy price induced by efficiency improvement, resulting in less than a 5% drop in overall energy usage.

Combining the carbon tax with the efficiency standards leads to still less energy use. The lower energy use takes place where the standards mandate less energy use than would be needed for a least-cost curb on emissions. In the cases where the carbon tax has induced some gain in energy efficiency, the additional reduction contributed by efficiency standards is less than what is achieved in the standards alone case. Also, the rebound effect tends to be smaller in the presence of the carbon tax, because the energy prices will not be as low as in the standards alone case.

5.5. Impact on Carbon Emissions

The carbon tax case would be more effective in cutting carbon emissions relative to either the energy tax or standards. One would expect this result since this tax directly targets carbon emissions. As the main source of carbon emissions,

Figure 7: Carbon Emissions (percentage change from the baseline level)



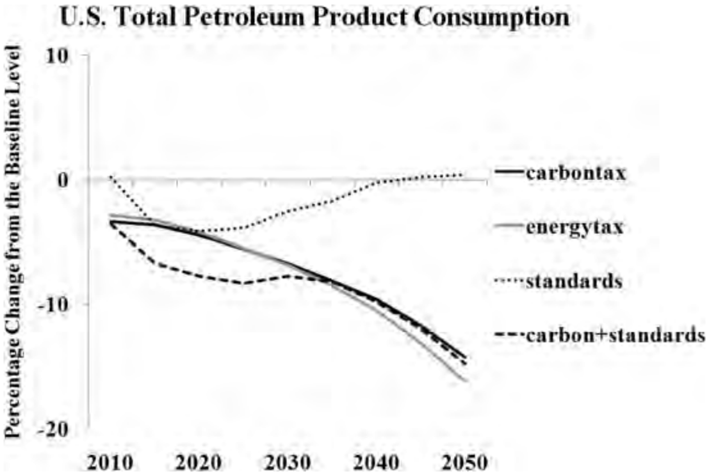
coal is taxed more heavily in the carbon tax case, and so reduction in coal use contributes the largest portion of the emission abatement.

Relative to the energy tax case, the carbon tax achieves larger percentage reduction in emissions than it does in energy consumption. This effect is apparent in the electric sector. There the carbon tax induces a switch from carbon-based fuels first to natural gas and then to nuclear and renewables. It also prompts introduction of CCS technology. As the tax rises, so does the amount of abatement.

The energy tax also curbs electric power sector CO_2 emissions but to a lesser extent. This is because under the energy tax, the emission reduction in the electric sector is mostly due to the lower demand for electricity caused by the tax, and not to any direct action to switch to a lower-carbon mix of generation sources. The adjustment on the fuel mix is based on the marginal cost of generation without regard to carbon content of the fuels. This can often reduce natural gas generation more than coal-fired generation. Therefore, the energy tax case foresees far less emission abatement than the carbon tax case.

Similar to the energy tax case, efficiency standards call for electricity savings resulting in emissions abatement from reduced carbon fuel consumption. Patterns of emissions reduction in non-electric sectors therefore follow closely with that of demand reduction (see Figure 6). The aggregate emission abatement

Figure 8: Total Consumption of Petroleum Product (percentage change from the baseline level)



is quite small, resulting from the rebound effect and the lack of efficiency improvement opportunities in most sectors.

5.6. Implication for Energy Security

Energy security is tied to reliance on energy from insecure overseas sources. As a proxy for energy security, we compare the change in the consumption of petroleum products. Lower levels of petroleum product consumption imply higher levels for energy security.

As Figure 8 shows, none of the policies in discussion does much to improve energy security. Over the model horizon, the energy tax achieves 8% cumulative reduction in petroleum product consumption, and the carbon tax results in 7.7% cumulative reduction. The near-term stringency of the standards, mostly the CAFE standard, leads to only very slightly better reductions than in the energy tax and the carbon tax cases (i.e., by 2020); however, the impact of the standards tapers off after 2020, whereas petroleum product consumption continues to decline when measured as percentage change from the baseline level under the energy tax and the carbon tax cases. To summarize, we find that to greatly strengthen energy security would require much higher tax levels or much more stringent fuel economy standards for vehicles or both.

6. CONCLUSION AND DISCUSSION

This paper has examined four different types of policy options that aim to reduce energy consumption and carbon emissions. We employ a top-down macro-economic model of the U.S., MRN, that is fully integrated with a bottom-up electricity model, NEEM. The integrated model (MRN-NEEM) enables us to analyze in detail impacts on the electricity sector and the non-electric energy markets.

Delivered energy prices increase the most under the carbon tax policy, while the energy tax policy also raises energy prices. Energy efficiency standards, however, tend to lower delivered energy prices. Increases in delivered energy prices observed in the carbon tax and the energy tax cases lead to reduction in total energy consumption. The carbon tax instrument is the most effective policy option to achieve overall carbon emissions reduction.

Under the standards policy, the overall reduction in energy consumption is small. There are two main reasons. First, the standards policy is only applied to a few sectors. Second, even though the delivered energy demand reduction through the standards is much larger than through the energy tax in the short run for the sectors in which the standards are implemented, the rebound effect offsets the energy savings the standards address. The efficiency standards fail to cover all sectors so over time the reduction in energy usage and emissions deteriorates as the uncontrolled sectors become more energy-intensive than in the baseline because energy prices are lower. The key insight for the transportation sector is that it is difficult to reduce oil use in transportation through broad energy policies, leaving targeted gasoline and diesel taxes or efficiency standards as the domestic policy instruments needed to address energy security.

It is important to recognize that the model used for this study assumes that current markets are efficient. In other words, our analysis assumes that the transaction costs and deadweight losses of policy interventions would exceed the net private energy cost savings that they would yield.[4] Hence, policy interventions always entail costs. That is they cause the market to deviate from the optimal path on which it is currently assumed to be. However, this or any other model is likely to underestimate the costs of real-world regulatory programs that are superimposed on otherwise efficient markets. The reason is that no model can contain full information on how individuals and businesses make decisions in light of their own circumstances. Therefore, it is not possible to calculate all the ways in which regulations cause private decisions to deviate from the efficient choices made in response to market prices. Indeed, if such a model did exist the regulator could use it to design a regulation that exactly replicated private decisions. A reasonable approximation of circumstances may be good enough for forecasting, but in assessing the deadweight loss of an efficiency standard errors do not cancel out—forcing one household to have too much energy efficiency and another too little creates two additive deadweight losses.

It is also true that our approach could overestimate the cost of a policy if it could at low cost correct a prior pervasive market failure. In fact, at least

4. Robert N. Stavins, Judson Jaffe and Todd Schatzki, "Too Good to be True? An Examination of Three Economic Assessments of California Climate Change Policy".

some cost-free options to save energy are likely to exist, but Jaffe, Newell, and Stavins (1999) shows that these options are more limited than some have suggested. At the same time, standards imply transaction costs—sometimes high ones for administration, enforcement, and compliance. Further, standards are very likely to mandate changes in energy use that differ from those that consumers and businesses would choose on their own were their knowledge more complete and their rationality less tightly bounded. If the gap is large between the mandated choices and those that a perfect market would have made, regulation can lead to net costs rather than net benefits (Montgomery et al. 2010).

At least two reasons exist for thinking that government mandates often stray very far from those that would emerge from a perfectly functioning market. For one thing, it is often impossible for regulators to know what complex set of steps would actually minimize social costs (Coase 1960). More important still, mandates are often distorted by rent seeking and by agency problems that affect the actions of legislators and regulators (North 1990). For both these reasons, mandates may in practice produce far from optimal outcomes and may impose net costs. Our study makes no attempt to assess such factors. It does not conduct a cost-benefit analysis. On the one hand, the model that we use does not account for other potential policy benefits, such as energy security, health improvement, environmental quality, or and the innovation of new technology. On the other hand, it also takes no account of the transaction costs of regulation or of the costs that arise from flaws in the regulatory process.

The policies simulated in this paper have twin objectives: reduce emissions or energy consumption and attain reduction at the least cost. The carbon tax is the most cost-effective policy in reducing carbon emissions and the energy tax the most efficient in reducing energy use. The carbon tax internalizes the carbon cost thus driving the cost minimization behavior throughout the economy in reducing the emissions, whereas raising energy prices through the energy tax and improving energy efficiency through standards provide no direct incentives for carbon-free technology deployment, thus ending up with a less cost-effective policy for reducing carbon emissions. In terms of overall energy usage, the energy tax internalizes the cost of all energy usage thus leading to the cost minimizing solution for reducing energy consumption; whereas imposing a carbon tax only addresses consumption of fossil fuels and improving energy efficiency through standards provides incentives to reduce energy usage per unit of output, but places no direct incentive to reduce overall energy usage. The standards are the least cost-effective measure as reduction in energy and emissions is partially offset by the rebound effect.

REFERENCES

Balistreri, Edward and Thomas F. Rutherford (2001). "Dynamic General Equilibrium Analysis at the state level: Assessing the Economic Implications of the Kyoto Protocol." Presented at the 4th Annual Conference on Global Economic Analysis. Purdue University, Indiana, USA, June 27–29.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni (2006). "WITCH: A World Induced Technical Change Hybrid Model", *The Energy Journal*, Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, 13–38.

Bohringer, Christoph, Andreas Loschel, and Thomas F. Rutherford (2006). "Decomposing the Integrated Assessment of Climate Change." *Journal of Economic Dynamics and Control* 31(2): 683–702.

Bohringer, Christoph and Thomas F. Rutherford (2006). "Combining Top-Down and Bottom-up in Energy Policy Analysis: A Decomposition Approach." Discussion Paper 06-07, Centre for European Research (ZEW).

Coase, Ronald (1960). "The Problem of Social Cost." *Journal of Law and Economics* 3(1): 1–44.

Energy Information Administration, Monthly Energy Review June 2010: 16.

Energy Modeling Forum (EMF) (2010). "EMF 25 Scenario Design." Stanford University, Stanford, CA. Document available online at http://emf.stanford.edu/files/res/2372/25design2.pdf.

Gillingham, Kenneth, Richard G. Newell, and Karen Palmer. (2009). "Energy Efficiency Economics and Policy." The RFF Discussion Paper RFF DP 09-13.

Gold, Rachel, Laura Furrey, Steven Nadel, John A. "Skip" Laitner, and Elliott, R. N. (2009). "Energy Efficiency in the American Clean Energy and Security Act of 2009: Impacts of Current Provisions and Opportunities to Enhance the Legislation." ACEEE Report E096.

Goulder, Lawrence and Ian W.H. Parry (2008). "Instrument Choice in Environmental Policy." *Review of Environmental Economics and Policy* 2(2): 152–174.

Kasahara, Satoru, Sergey Paltsev, John Reilly, Henry Jacoby, and A. Denny Ellerman (2007). "Climate Change Taxes and Energy Efficiency in Japan." *Environmental & Resource Economics* 37(2): 377–410

Laitner, John A. "Skip" and Donald A. Hanson (2006). "Modeling Detailed Energy-Efficiency Technologies and Technology Policies within a CGE Framework," *Energy Journal*, Hybrid Modeling of Energy-Environmental Policies: Reconciling Bottom-up and Top-down, Special Issue 2006.

Lane, L. Lee (2002). "Greenhouse Gas Abatement Costs." Climate Policy Center (http://www.cleanair-coolplanet.org).

Minnesota IMPLAN Group (2004). IMPLAN Pro software and database, Minnesota.

Montgomery, W. David, Paul Bernstein, L. Lee Lane, Anne Smith, and Sugandha D. Tuladhar (2010). "Discussion of Market Failures." Charles River Associates Analysis of the California ARB's Scoping Plan.

North, Douglass C. (1990). *Institutions, Institutional Change, and Economic Performance*. New York: Cambridge University Press.

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

Rutherford, Thomas F. (1999). "On the Assessment of Economic cost in Dynamic Economic Models." Preliminary Notes, University of Colorado. Available from www.mpsge.org

Stavins, Robert, Judson Jaffe, and Todd Schatski (2007). "Too Good to Be True? An Examination of Three Economic Assessments of California Climate Change Policy." Working Paper Series rwp07-016, Harvard University, John F. Kennedy School of Government.

Tuladhar, Sugandha D., Mei Yuan, Paul Bernstein, W. David Montgomery, and Anne Smith (2009). "A top-down bottom-up modeling approach to climate change policy analysis." Energy Economics 31, Supplement 2, International, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22: S223-S234.

U.S. Department of Energy, Energy Information Administration. (2009). "Annual energy Output 2009 Stimulus (AEO09)." DOE/EIA-0383(2008). Washington, DC: US Department of Energy.

Energy Demand Analytics Using Coupled Technological and Economic Models

Samuel G. Steckley, Douglas S. Meade**, Carol Shay Lenox***, Kenneth C. Hoffman*, David H. Reid*, and Bradley C. H. Schoener**

Impacts of a range of policy scenarios on end-use energy demand are examined using a coupling of MARKAL, an energy system model with extensive supply and end-use technological detail, and Inforum LIFT, a large-scale model of the U.S. economy with inter-industry, government, and consumer behavioral dynamics. Responses in end-use energy demand are the result of energy efficiency improvements, fuel switching, and indirect economy-wide impacts. Carbon emissions reductions attributed to end-use demand response are analyzed and compared to carbon emissions reductions attributed to changes in the electric sector. Scenarios with the greatest impacts are a carbon tax case, resulting in a shift away from coal generation in the electric sector, and a normative case using a 7% discount rate for end-use technology investment decisions, resulting in increased adoption of energy efficient technology. In the course of addressing the specific EMF 25 scenarios and specified assumptions, a number of interesting issues were identified for follow-on analyses.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-10

1. INTRODUCTION

Energy services that provide comfort, mobility, sustenance and a productive workplace are essential to the U.S. economy. How those services are provided using specific fuel and energy forms coupled with end-use technologies is also inextricably linked to environmental, health, and global climate change issues. The Energy Modeling Forum's study of end-use energy efficiency and energy demand (EMF 25) is comparing a number of different energy economic

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* The MITRE Corporation.
** Interindustry Economic Research Fund, Inc.
*** EPA Office of Research & Development, Air Pollution Prevention & Control Division.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-10

models across a set of eight scenarios. This paper describes the application as part of EMF 25 of MARKAL, a widely used energy system model with extensive technological detail and simulation capability, in conjunction with Inforum *LIFT*, a large-scale model of the U.S. economy with inter-industry dynamics. This coupling effort allows for the analysis of the response in end-use energy demand, including the changes in end-use technology choices, and the effects on system-wide carbon dioxide emissions.

The analysis considers the complex interrelationships between the U.S. economy and the public, the energy services they use as well as the embedded energy in non-energy products consumed, and the primary and secondary energy forms that are produced and delivered. MARKAL's rich descriptions of the cost and efficiency of end-use devices that convert fuels and electricity into energy services are key components of the analysis of end-use demand, as are the structure of the U.S. economy and consumer behaviors that govern the demand for all products which are captured in *LIFT*. The modeling approach, coupling technological and economic models, provides insights into:

- demand responses to increase the efficiency of end-use devices,
- fuel switching to increase efficiency and reduce CO_2 emissions,
- the effect of household income changes on energy demand,
- indirect market basket responses of consumers towards less energy and carbon intensive products and services, and
- other behavioral responses that affect the demand for energy services.

In this analysis these capabilities are exploited to examine the role that the end-use energy demand response may play in CO_2 emissions reductions for a number of scenarios.

This paper focuses primarily on two of the EMF scenarios: a carbon tax scenario where a carbon dioxide emissions tax is applied across the energy system; and a "7% Solution" scenario (referred to as the "7%" scenario in this paper) where consumers select energy equipment based on life-cycle costs calculated with a seven percent discount rate. The discount rate is used to discount future cash flows in order to trade off future energy cost savings against higher investment cost for more efficient end-use technology. In the reference scenario and all EMF scenarios other than the "7%" scenario, the discount rate used in MARKAL for modeling consumer investment choices for energy technology is much higher (15% or more), can vary by technology, and is generally higher for new end-use technologies to reflect barriers to investment by consumers in these new technologies. The "7%" scenario can be considered a normative approach, delivering energy services to consumers at minimum cost within environmental constraints. The carbon tax scenario and the "7%" scenario were chosen for our focus because these two scenarios provided the largest response in delivered energy and carbon emissions, allowing for the best opportunity to analyze the coupling between MARKAL and LIFT. Additional EMF scenarios include the application of a general delivered energy tax, the implementation of standards on end-use technology efficiency, and the use of subsidies to promote use of more efficient technology options. The details of all of these scenarios can be found in EMF (2010).

For all of the scenarios, the coupled model runs suggest that the most significant end-use response is in the commercial and residential sectors and the results discussed in this paper are focused in these areas. It should be noted that the version of MARKAL used for the study has considerably more energy efficient technology options available in the residential and commercial sectors as compared to the industrial sector. The potential for response in the industrial sector requires further study. Also, the scenarios did not address the aggressive policies targeted at transportation such as renewable fuel standards or subsidies for high efficiency and electric vehicle technology.

The remainder of this paper is organized into three sections. Section 2, Methodology, provides overview descriptions of MARKAL, *LIFT*, and the linkage between the two for this analysis. Section 3, Results, presents highlights of the results of the analysis, with a focus on the relative importance of energy efficiency improvements in reducing delivered energy and CO_2 emissions. Section 4, Conclusions, summarizes preliminary conclusions and outlines further research steps.

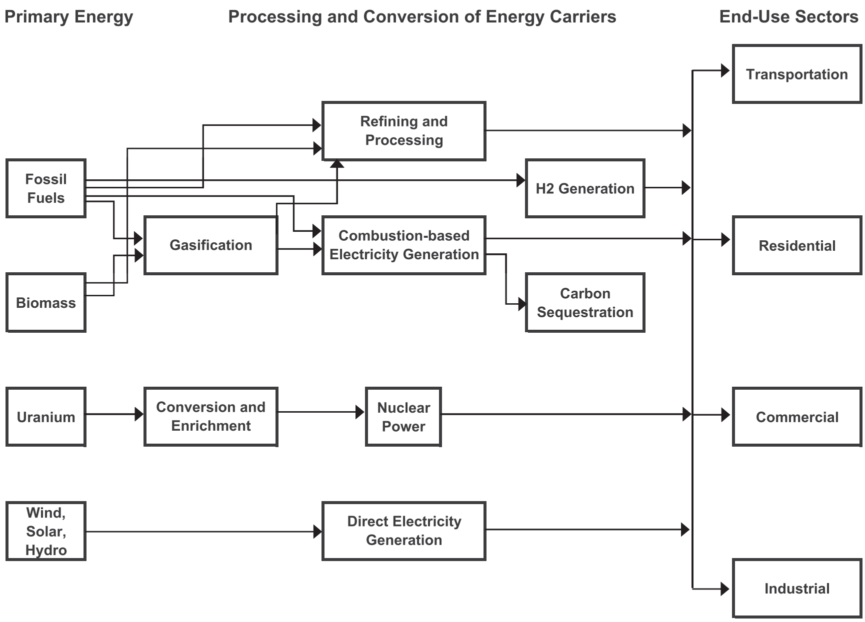
2. METHODOLOGY

The focus of EMF 25 on demand analytics requires a modeling effort with a detailed description of end-use devices that convert fuels and electricity into energy services. It also requires a rich description of the structure of the economy including the energy intensive sectors and behaviors that govern those sectors. EMF 25 calls for a hybrid, multi-scale, modeling approach to describe energy services and technology options in detail, and to address the related aspects of behavioral, economic, and environmental factors. In this modeling effort, MARKAL, a technology rich energy system model, is coupled with Inforum *LIFT*, a large-scale model of the U.S. economy with detailed representations of the producing sectors, consumers, and foreign trade. In this section these two models along with the coupling methodology are described.

MARKAL EPA USNM50

The MARKAL (MARKet ALlocation) model is a data driven, bottom-up energy systems model. The initial version of the model was developed in the late 1970s by international teams at Brookhaven National Laboratory and Kernforschungsanlage-Juelich, and has been sponsored by the IEA Energy Technology Assessment Systems Analysis Program (ETSAP). The model currently is used by many countries for research and energy planning. At its core, MARKAL is a least cost optimization model which incorporates numerous dynamic relationships and user-defined constraints which allow for a simulation of the energy system.

Figure 1: Reference Energy System



The MARKAL energy system representation is formed by an input database that captures the flow of energy and technology adoption associated with the extraction or import of resources, the conversion of these resources into useful energy, and the use of this energy in meeting the end-use demands. MARKAL optimizes technology penetrations and fuel use over time, using straightforward linear programming techniques to minimize the net present value of the energy system cost while meeting required energy service demands and various energy, emissions, and behavioral constraints. Outputs of the model include a determination of the technological mix at intervals into the future, estimates of total system cost, use of energy carriers (by type and quantity), estimates of criteria and greenhouse gas (GHG) emissions, and estimates of marginal energy commodity prices. MARKAL outputs a least cost pathway to meet energy needs, but using scenario analysis, the model can also be used to explore how the least cost pathway changes in response to various model input changes, such as the introduction of new policy measures like a carbon tax or subsidies on energy efficient technologies. The multi-sector coverage of a MARKAL database allows simultaneous consideration of both supply- and demand-side measures in meeting emissions or other system goals.

The basis of the MARKAL model framework is a network diagram called a Reference Energy System (RES), which is pictured in Figure 1. The RES represents energy sources and flows that comprise an energy system. Coverage of the energy system ranges from the import or extraction of primary energy resources, to the conversion of these resources into fuels, and through the use of these fuels by specific technologies to meet end-use energy demands. End-use demands include items such as residential lighting, commercial air conditioning, and automobile vehicle miles traveled. Data used to represent these items include fixed and variable costs, technology availability and efficiency, and pollutant emissions. For a more detailed description of MARKAL see Loulou et al. (2004).

The MARKAL analysis done for this research uses the U.S. EPA's Office of Research and Development (ORD) USNM50 database. This database contains detailed representations of the U.S. energy system at the national level, over a modeling time horizon that extends from 2000 through 2050. The database covers the supply sectors including power generation and petroleum refining, offering numerous technology options across these sectors. The database also covers the end-use sectors: residential, commercial, transportation, and industrial. Spread across these four sectors, there are 87 energy service demands that can be met by numerous (~1700) end-use technology options of varying efficiency and cost. For example, the commercial and residential sectors have specific technological detail for the following energy service demands: space heating, space cooling, water heating, lighting, ventilation, refrigeration, cooking, and freezing. There are additional "other" technologies that represent aggregate use of electricity, natural gas, and petroleum fuels to meet demands for clothes washing and drying, televisions, personal computers, office equipment, and other electrical demands. The database also contains a detailed representation of air pollutants and GHG emissions, including system-wide coverage of emission factors for CO_2, NO_x, SO_2 and PM_{10}. For a more detailed description of an older version of the database see Shay et al. (2006).

The primary source of data for the database is the Department of Energy's 2009 Annual Energy Outlook (AEO) release (EIA, 2009), which included the economy's response to the American Reinvestment and Recovery Act (ARRA). This information is supplemented with technology and emissions data from other sources, such as the EPA's Office of Transportation and Air Quality and Office of Air Quality Planning and Standards. The reference case is calibrated to the AEO for resource supply and sector fuel and technology use out to the year 2030.

Inforum *LIFT*

The Inforum *LIFT* (Long-term Interindustry Forecasting Tool) model is unique among large-scale models of the U.S. economy in that it is based on an input-output (IO) core, and builds macroeconomic forecasts from the bottom up (Meade, 2001). In fact, this characteristic of *LIFT* is one of the principles that has guided the development of Inforum models from the beginning. This is in part because the understanding of industry behavior is important in its own right, but also because this parallels how the economy actually works. Investments are made in individual firms in response to market conditions in the industries in which those firms produce and compete. Aggregate investment is simply the sum of these industry investment purchases. Decisions to hire and fire workers are made jointly with investment decisions with a view to the outlook for product demand in each industry. The net result of these hiring and firing decisions across all industries determines total employment, and hence the unemployment rate.

LIFT models 97 producing sectors. The energy sectors include coal, natural gas extraction, crude petroleum, petroleum refining, fuel oil, electric utilities, and natural gas distribution. Despite its industry basis, *LIFT* is a full macroeconomic model with more than 1200 macroeconomic variables determined either by econometric equation, exogenously or by identity. Certain macrovariables provide important levers for studying effects of government policy. Examples are the monetary base and the personal tax rate. Other macrovariables, such as potential GDP and the associated GDP gap provide a framework for perceiving tightness or slack in the economy.

In the last several years, the *LIFT* model has been extended through the incorporation of several modules that can be used to study energy demand and supply, and the implications of energy use on carbon emissions. Examples of energy studies performed using *LIFT* in recent years include Henry and Stokes (2006) and the Electrification Coalition (2010).

The model solves annually, and the extensive simultaneity in the model requires an iterative solution for each year. At the beginning of each year's solution, first guesses are made for some important endogenous variables, such as output and prices by industry, import shares, and many macrovariables. Assumptions for exogenous variables are also established. Then the model loop runs, until outputs and other variables converge.

A more detailed discussion of the model loop can be found in (Meade, 2001). The key steps in the model loop include determining real final demand expenditures, solving the input-output (IO) equations jointly for output, imports, and inventory change, computing employment, and finally computing prices. Final demand expenditures include personal consumption, government expenditures, exports, equipment investment, and construction investment. Personal consumption of individual products is modeled in the consumer demand system known as the Perhaps Adequate Demand System (PADS). This system allows the classification of consumption goods into related expenditure groups, such as food, transportation or medical care. In the demand system, electricity prices affect the demand for natural gas since electricity and natural gas are substitutes in many cases. The demand system's parameters are estimated from historical consumption data. It is possible to guide the level of consumption for individual products. For example if more efficient electric heat pumps are expected to come on line, the amount of electricity consumed can be reduced accordingly. For a more extensive discussion of the consumer demand system, see Almon (1996). The IO equations are determined by the IO coefficients which represent the quantity of an input per unit output of a product and are specified to change over time.[1] However, individual coefficients can also be modified, to model changes in price or technology.

The *LIFT* model was calibrated to be consistent with the AEO 2009 release that includes ARRA. Calibration was done in two stages. In the first stage, industry variables, macroeconomic variables, and IO coefficients were modified to produce a macroeconomic forecast consistent with the AEO. In the second stage, imports, exports, personal consumption expenditures and IO coefficients were modified to calibrate energy and carbon projections from the AEO. For this study, the *LIFT* projections were made to 2030. As directed by the scenario definitions for this study, the revenue for the tax scenarios is returned to the households annually in the form of lump sum transfer payments.

Model Coupling Methodology

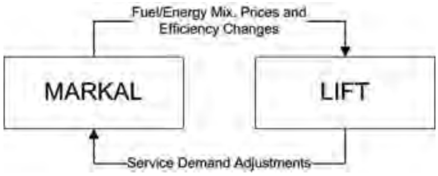
The idea of the model coupling is to combine the detailed treatment of the energy system and technology options for energy supply and utilization in MARKAL EPA USNM50 with the detailed treatment of the U.S. economy in Inforum *LIFT*. The aim is to capture insights on the response of the energy system to the various scenarios, including changes to the energy mix and end-use technologies, and see how these changes interact with the broader economy.

In this application, prior to the coupling, both models ran the reference scenario calibrated to AEO 2009 as described above. For each of the policy scenarios, the policy was first implemented in MARKAL and the resulting fuel mix and efficiency changes for the entire period out to 2030 relative to the reference case were then incorporated into a *LIFT* policy run. The *LIFT* policy run therefore captures the interaction of the broader economy with the policy and energy system responses induced by the policy as measured in MARKAL. Following the *LIFT* policy runs energy service demands from the *LIFT* run were estimated and compared to the exogenous MARKAL energy service demands. For any deviations judged to be significant the MARKAL service demands would have been adjusted and the coupling procedure repeated. More detail on this topic is given in the next section discussing the implementation. The methodology used to guide the coupling is shown in Figure 2.

The coupled model runs reveal what role various parts of the energy system and economy may play in altering energy supply and demand and reducing carbon emissions for the different scenarios. The MARKAL output provides insights into the opportunity for end-use efficiency improvements. It also reveals what role fuel switching may play in different parts of the energy system. The *LIFT* output from the coupled runs provides insight into what might happen to

1. In some cases the IO coefficients are estimated to change over time according to a logistic curve that is estimated from historical data. In other cases, industry forecasts (e.g., the AEO) are used to guide the movements of the IO coefficients in future years.

Figure 2: Model Coupling Methodology



household income and the product mix and how these indirect changes may alter the direct changes in energy use and emissions revealed in MARKAL.

Notes on the Implementation

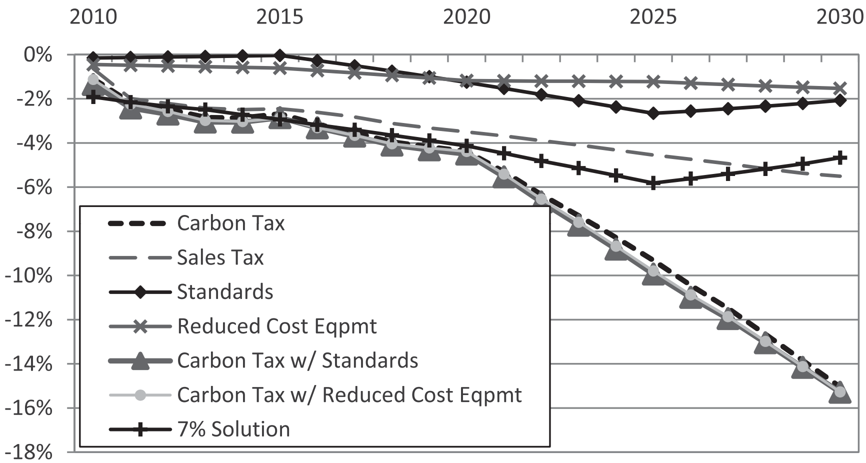
For each of the scenarios the most significant responses in the energy system occurred within the electric sector, residential sector, commercial sector, and to a lesser extent, the industrial sector. The energy system information extracted from MARKAL and incorporated into *LIFT* was therefore limited to these areas. For the electric sector and the end-use sectors, the MARKAL response in fuel mix and efficiency was incorporated into the *LIFT* policy runs. More specifically, the percentage changes in fuels used by the electric sector and fuels and electricity used by the end-use sectors observed in MARKAL were used to modify *LIFT*'s IO coefficients for the producing sectors and guide the energy products consumed in the demand system PADS. An exception was made for the residential sector in the tax cases. In those cases the response in delivered energy measured in MARKAL was not used to guide PADS. Instead the response in delivered energy was determined by PADS alone. These exceptions were driven by decisions made early in the development of the methodology when it was believed there was an important behavioral response in the tax cases that is captured (implicitly) by *LIFT*'s demand system. The decision to fully rely on PADS has led to an interesting comparison in the demand response dynamics in MARKAL and *LIFT* that will be discussed in the results.

Rules of thumb were developed in some initial test runs for this study to determine how large the change in the service demand needed to be in order to warrant further iteration of the coupling methodology. Based on these rules it was determined that iteration was not necessary for any of the scenarios. The estimated service demand changes were relatively small across the scenarios. In a few instances an individual sector's service demand change was as high as 3% but was typically less than 1.5%.

For all of the data that were extracted from MARKAL and incorporated into *LIFT*, a simple moving average algorithm was applied to remove some of the volatility that is characteristic of energy optimization models.

These models react to cost estimates and price changes as well as numerous constraints and relationships derived from technical and econometric

Figure 3: Percent Change in Carbon Dioxide Emissions Relative to the Reference Scenario



analyses. Given the uncertainties regarding future costs and prices in particular, sensitivity analysis is extremely important.

3. RESULTS

Figure 3 shows that all of the EMF scenarios in the coupled model runs lead to reductions in carbon dioxide emissions, though there is significant variation in the magnitude of the reductions across the cases. In this section of the paper the drivers of these reductions are considered. First the responses in end-use energy demand are studied including energy efficiency improvements, fuel switching, and any indirect economy-wide impacts. Second the carbon emissions reductions attributed to the end-use demand response are compared to the carbon emission reductions attributed to changes in the electric sector. The results presented here are primarily focused on the carbon tax and “7%” scenarios which exhibit relatively large reductions in carbon emissions as shown in Figure 3.

End-use Energy Demand Responses

For all of the EMF scenarios the most significant responses in delivered energy occurred in the residential and commercial sectors. Figure 4 compares the 2025 reductions in delivered energy in these sectors for selected cases. As the figure indicates, the reductions in delivered energy were moderate for all of the scenarios except the “7%” scenario.

The reductions in delivered energy are driven by a number of sources. Figure 5 shows the mix of delivered energy for commercial and residential space

Figure 4: Percent Change in Commercial and Residential Delivered Energy Relative to the Reference Scenario in 2025

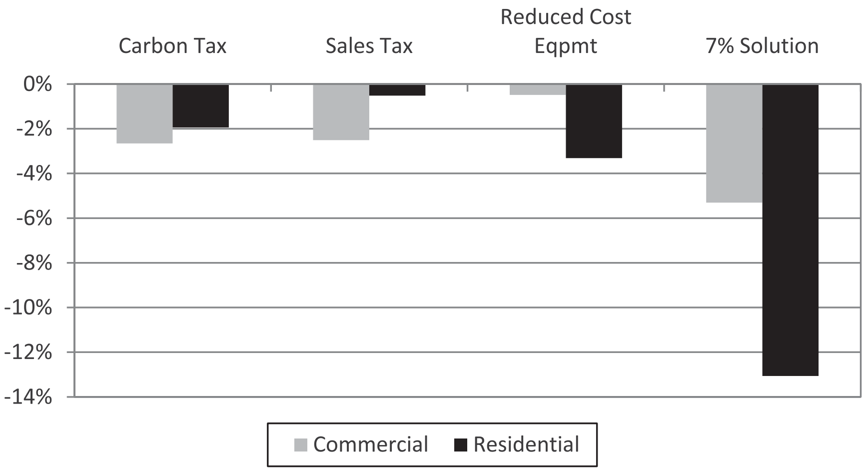
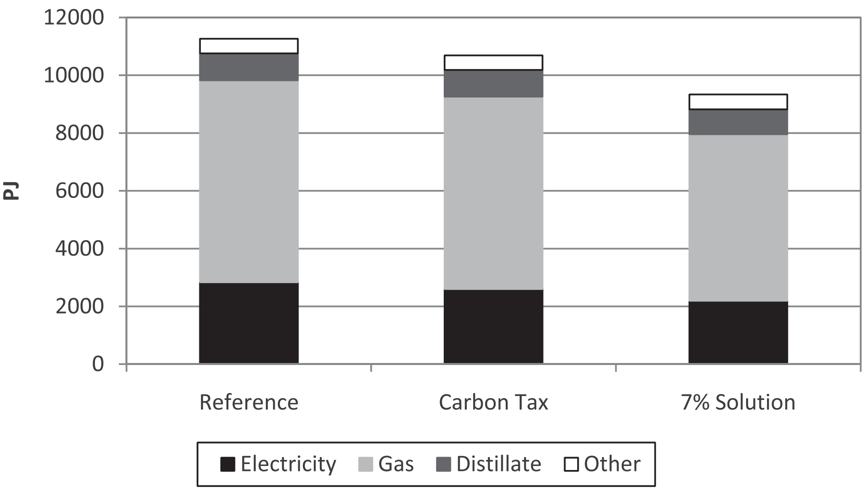


Figure 5: Commercial and Residential Delivered Energy for Space Heating, Cooling, and Water Heating in 2025



heating, space cooling, and water heating for selected scenarios in 2025. Note that in the coupling of the models the fuel mix changes and efficiency improvements were extracted from MARKAL and incorporated into the *LIFT* policy runs for most sectors (see the coupling discussion above for specifics). The data presented in Figure 5 is taken directly from the MARKAL runs. As the bar charts in Figure 5 indicate there is not a significant shift in the delivered energy mix for these services. The efficiency improvements on the other hand appear to be substantial especially in the "7%" scenario. Overall, delivered energy for these services decreases by 5% and 13% for the carbon tax scenario and "7%" scenario, respectively, relative to the reference scenario.

Turning to the end-use device efficiency improvements, consider the electric devices used to satisfy space heating, cooling, and water heating demands. Relative to the reference scenario, the mix of these devices is 9% more efficient with the carbon tax and 34% more efficient in the "7%" scenario. Figure 6 gives the percentage changes in residential electricity use efficiency for each of the service demands individually in the "7%" and carbon tax scenarios. Similar to Figure 5 it is taken directly from the MARKAL runs. The figure indicates that there is a significant opportunity for efficiency improvement in electric water heating technology. The carbon tax leads to a partial replacement of the primary reference case electric water heating technology with instantaneous electric water heating technology which has an efficiency that is approximately two and half times greater and whose capital cost is nearly three times greater. In the "7%" scenario the reference case electric water heating technology stock is entirely replaced with the instantaneous electric water heating technology.

The efficiency improvements in commercial electric water heating were equally impressive in the carbon tax and "7%" scenarios. The commercial sector improvements were driven by the penetration of solar water heating technology. In the carbon tax case, solar water heaters performed 25% of the water heating by 2030. This percentage increased to 35% in the "7%" scenario.

The substantial efficiency improvements for electric space heating and cooling devices in the "7%" scenario shown in Figure 6 are driven by a considerable penetration of ground source heat pumps. By 2025, over 11% of space heating demand is satisfied by ground source heat pumps. None of the other scenarios approached this level of penetration.

The "7%" scenario extends the concept of least cost capacity expansion as applied in the electric utility sector to the entire energy system. The modeling results demonstrate that by applying the same investment criteria to both supply and end-use technologies the "7%" scenario encourages more balanced investment patterns that results in much higher efficiency in the end-use devices as compared to the reference case and the other alternative scenarios.

Sensitivity runs were performed for the carbon tax scenario in which the sensitivity of the efficiency improvements to delivered energy prices was examined. Changing the delivered energy prices had little impact on the efficiency improvements in response to the carbon tax. The efficiency responses observed in carbon tax runs in which pre-tax prices were either increased or decreased by 15% were typically within one percent of the carbon tax results presented here. The responses were within two percent when prices were changed by 25%.

The tax scenarios in which *LIFT*'s consumer demand system PADS solely determined the response in delivered energy for the residential sector pro-

Figure 6: Percent Change Relative to the Reference Scenario in Residential Electric Device Efficiency by Service Demand in 2025

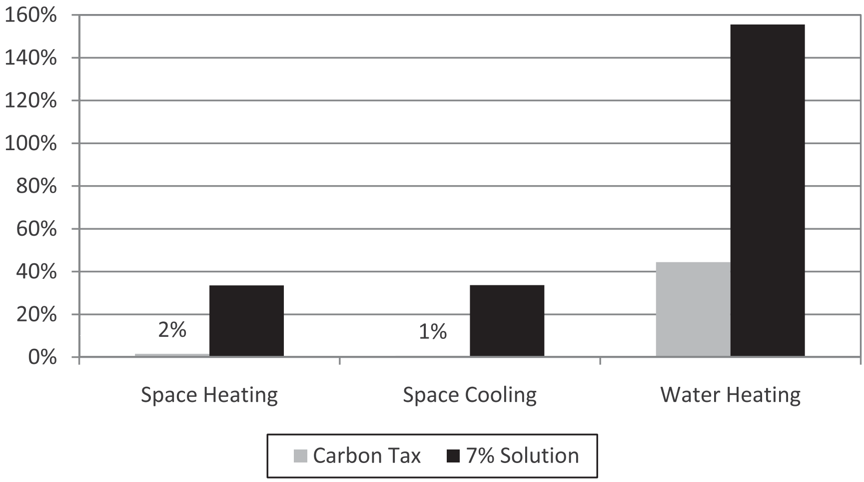
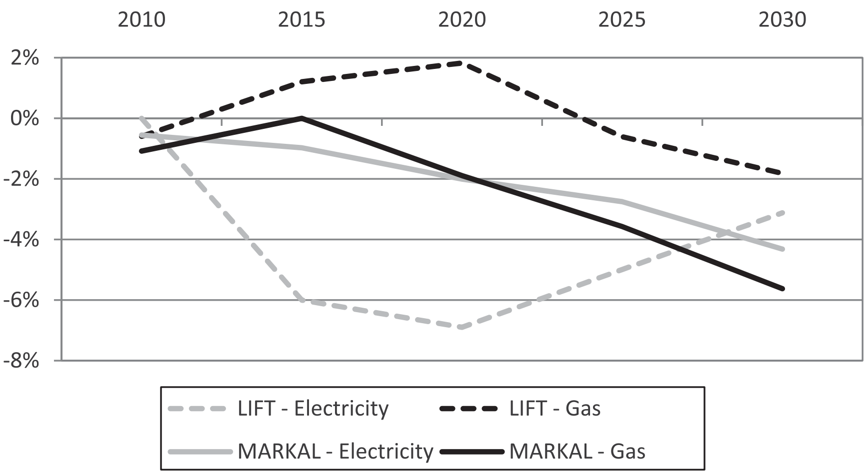
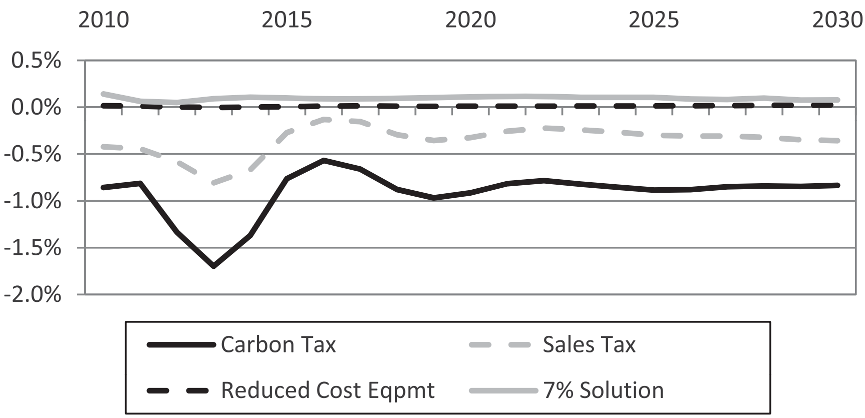


Figure 7: Percent Change in Residential Delivered Electricity and Gas Relative to the Reference Scenario



vided an interesting contrast to the delivered energy response seen in MARKAL. Figure 7 plots the percentage change in natural gas and electricity use for the two models for the carbon tax scenario. Note that the *LIFT* results suggest a much stronger fuel switching effect than the MARKAL results.

Figure 8: Percent Change in Real Disposable Income Relative to the Reference Scenario



These differences illustrate the challenge of linking as well as the value of employing two types of models. *LIFT's* consumer demand system PADS does not model end-use technologies explicitly but does take into account historically observed behaviors. The fuel switching observed in the *LIFT* output in the carbon tax scenario warrants further investigation.

In addition to the efficiency improvements and fuel mix changes, the broader economy can impact the delivered energy response. The scenarios affecting the energy system can affect the health of the economy and thus influence household income and the overall activity of the economy. The policies can also impact the product mix which may lead to structural change in the economy.

The results indicate, however, that these indirect effects on delivered energy are dominated by the direct effects of fuel switching and efficiency improvements discussed above. This dominance was seen in all modeled scenarios. The indirect effects are however important in their own right.

Figure 8 shows the percentage change in real disposable income for selected EMF scenarios. The carbon tax scenario has the largest impact on income (and GDP). For this scenario income is nearly one percent below the reference case level by 2025. Note that this decrease could be impacted by a number of factors including implementation of similar policies by other countries. These results assume other countries do not implement similar policies.

The carbon tax and sales tax result in some volatility in the deviation of real disposable income from the reference case. The *LIFT* model, like the actual economy, follows a long-run potential growth path that is determined by average labor force growth and average labor productivity growth. When the actual path of GDP is above the potential GDP level, interest rates rise, inflation accelerates, income support payments decline, and average tax rates increase. When GDP is below potential, the opposite effects occur. After an economy-wide price shock

Figure 9: Percent Change in Output by Aggregate Sector for the Carbon Tax Scenario Relative to the Reference Scenario

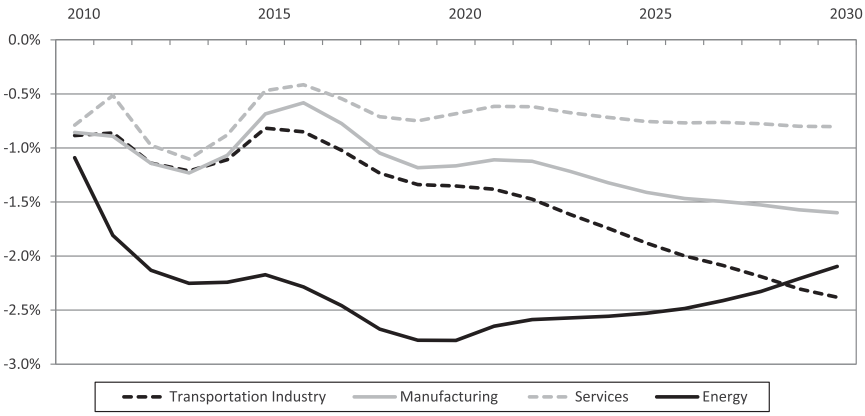
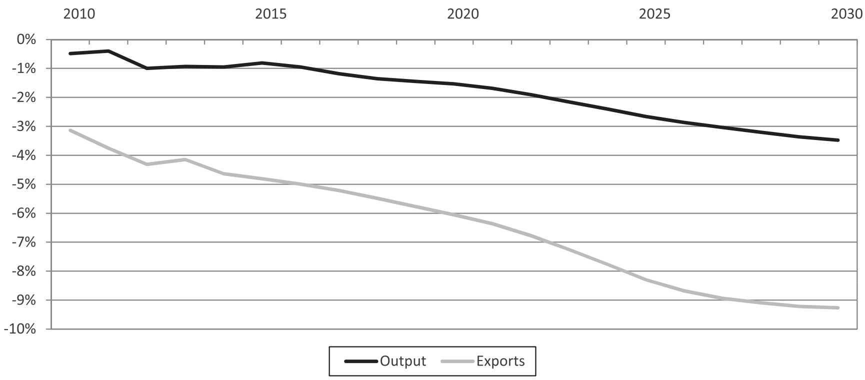


Figure 10: Percent Change in Output and Exports for the Agriculture, Forestry, and Fisheries Industry Relative to the Reference Scenario

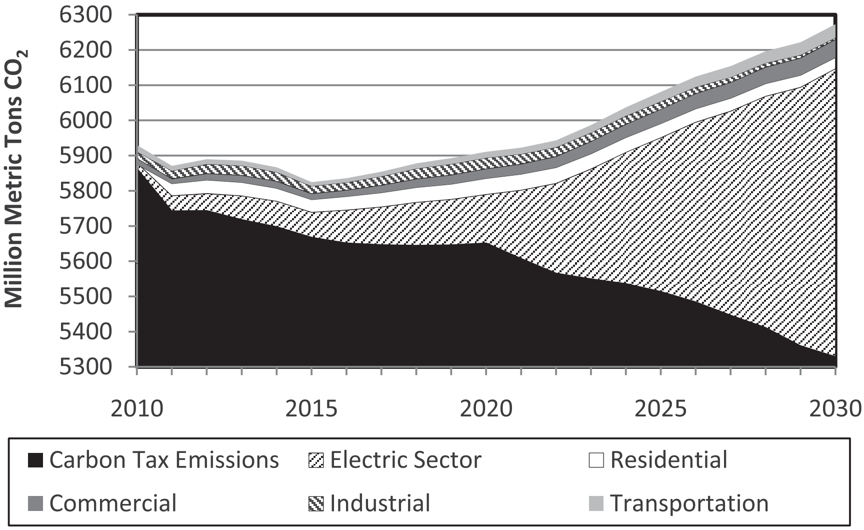


such as an oil price increase or a carbon tax, GDP growth is reduced, but these "automatic stabilizers" tend to bring GDP back to the long-run growth path.

Figure 9 shows the product mix changes at an aggregate level for the carbon tax scenario. As expected the magnitudes of the percentage changes in output reflect the carbon intensity of the sectors with the largest decrease in the energy sector and the smallest in the service sector. Note that the transportation industry refers to the sector in which transportation services are sold as a commodity.

Figure 10 illustrates that certain industries can be more adversely affected than what is seen in the aggregate. The figure shows output for the agri-

Figure 11: Carbon Tax Scenario Carbon Dioxide Emissions Reductions by Source



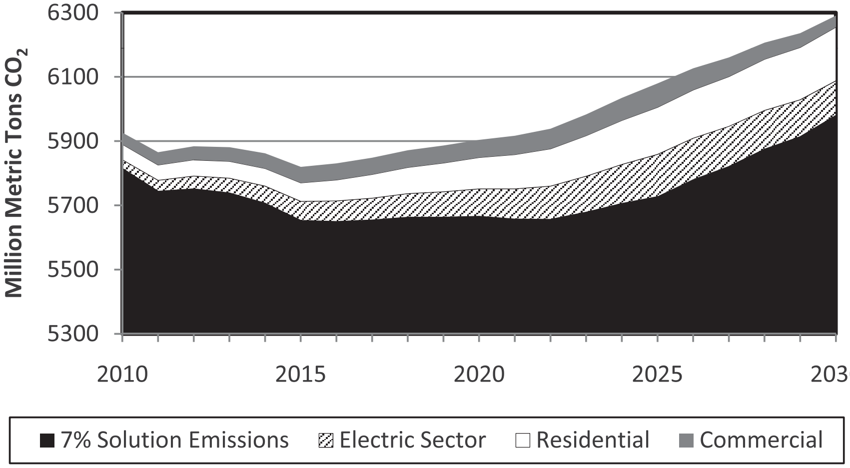
culture, forestry, and fisheries industry is down over 3% by 2030 in the carbon tax scenario. Further examination of the output data reveals that while there is a small contraction in domestic demand (1.7% by 2030) the reduction in output is primarily attributable to a reduction in exports which is also plotted in the chart. The reduction in exports is due to higher costs associated with the tax but it should again be noted that these results could be impacted by many factors including other countries implementing similar taxes.

In concluding the discussion of the end-use energy demand responses, the mostly moderate and sometimes significant ("7% scenario") reductions in delivered energy are driven by direct energy efficiency improvements. Fuel switching and indirect economy-wide impacts on energy demand play a secondary role although impacts on output for certain industries could potentially be significant.

Carbon Emissions Reductions

The decrease in end-use demand does reduce emissions but the magnitudes of these emissions reductions are much less than those associated with decarbonization in the electric sector. Figure 11 and Figure 12 show the reductions in carbon dioxide emissions from the reference case for the carbon tax scenario and "7%" scenario, respectively, and attributes the reductions to the end use or the electric sector. In this decomposition the end use is credited with the emissions reductions in the electric sector that are due to reduced electricity demand as well

Figure 12: "7% Solution" Scenario Carbon Dioxide Emissions Reductions by Source



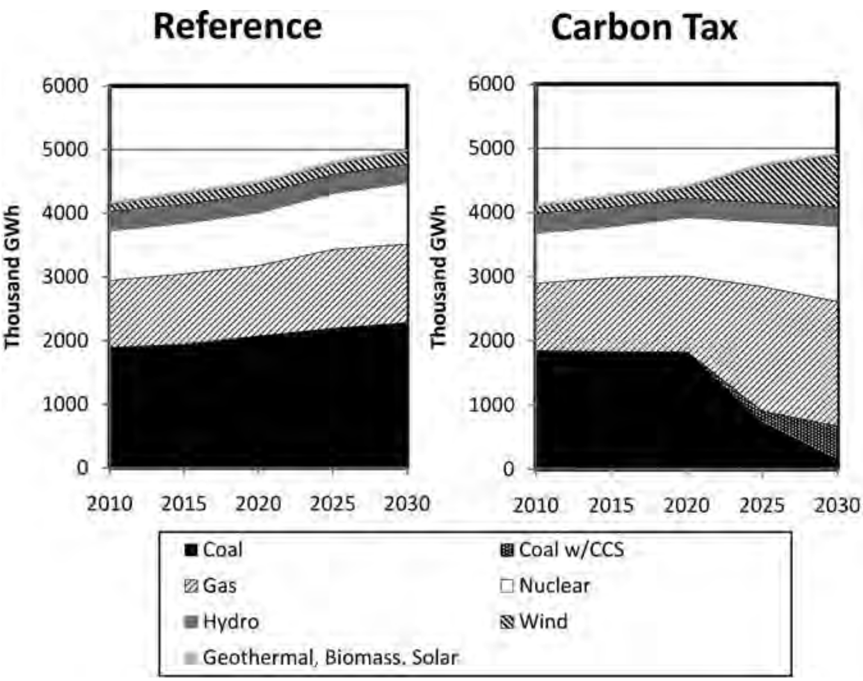
as the reductions in emissions that occur at the end use. The electric sector is credited with emissions reductions due to fuel switching and other technology changes within the electric sector that affects the carbon intensity of the sector. The details of the decomposition of the carbon emissions reductions in the electric sector are as follows. Let ΔEMS_{elc} be the total emissions reductions in the electric sector for a given policy scenario. Then ΔEMS_{elc} is given by $EMS_{elc,ref} - EMS_{elc,policy}$ where $EMS_{elc,ref}$ and $EMS_{elc,policy}$ are the total electric sector emissions for the reference scenario and policy scenario, respectively. It follows that ΔEMS_{elc} can be decomposed into $A + B$, where A represents the emissions attributed to the electric sector and is given in equation (1), and B represents the emissions attributed to the end use and is given in equation (2). In these equations $DEL_{elc,ref}$ and $DEL_{elc,policy}$ are delivered electricity in the reference and policy scenarios, respectively.

$$A = DEL_{elc,ref}\frac{EMS_{elc,ref}}{DEL_{elc,ref}} - DEL_{elc,ref}\frac{EMS_{elc,policy}}{DEL_{elc,policy}} \quad (1)$$

$$B = DEL_{elc,ref}\frac{EMS_{elc,policy}}{DEL_{elc,policy}} - DEL_{elc,policy}\frac{EMS_{elc,policy}}{DEL_{elc,policy}} \quad (2)$$

The end-use wedges account for the reductions due to both fuel switching and the more dominant efficiency improvements. Clearly the most significant emissions reductions are in the carbon tax case and this is driven by the fuel switching and carbon sequestration in the electric sector. Figure 13 gives the

Figure 13: Electricity Production by Fuel and Type



electricity production by fuel and type for the reference and the carbon tax scenarios. The mixes of electricity production for the other policy scenarios were very similar to the reference scenario.

For these alternative scenarios which did not lead to much de-carbonization in the electric sector the overall emissions reductions were more modest. Even so Figure 12 shows that the emissions reductions in the "7%" scenario were not insignificant. In this case the largest reductions were attributed to the residential sector in which there were significant end-use efficiency improvements. Note that the industrial and transportation sector wedges are not shown because they were negligible.

4. CONCLUSIONS

The application of a detailed and technology-rich model of the U.S. energy system coupled with a dynamic inter-industry model of the U.S. economy is particularly relevant to the analysis of tax and regulatory policies and standards designed to transform the energy system to a more efficient and lower carbon state. The hybrid modeling methodology that has been demonstrated here provides insight into the interactions of technological and behavioral factors in response to energy policy shifts.

The dominant responses to the policy scenarios defined for EMF 25 are fuel switching, primarily in the electric sector, as a result of the carbon tax, and end-use efficiency improvements resulting from the life-cycle optimal investments on the demand side captured in the normative "7%" scenario.

The efficiency responses to the alternative policies were modest. This reflects the simulation of consumer behaviors by requiring a short-term payback for investments in more efficient but higher cost end-use devices. While this descriptive formulation, keyed to consumer expectations for a period of ownership less than the equipment lifetime, does capture consumer behavior it does not represent a life-cycle payback formulation that is in the societal interest. The "7%" scenario takes a normative approach from the perspective of a notional Energy Services Utility that delivers energy services at minimum cost within environmental and economic constraints. This normative approach was one of the original design concepts embodied in MARKAL through a robust description of energy services and options. Thus, MARKAL can extend the concept of least-cost capacity expansion as applied in the electric utility sector to the entire energy system encompassing all fuel and energy forms and all essential energy services. The results of the "7%" scenario show an improved balance between investments in energy supplies and end-use systems with a significant impact on end-use efficiency, even without tax incentives. It illustrates the larger potential for more efficient technologies that could be captured through aggressive standards and regulation as well as more informed consumer responses using "smart" end-use devices.

Future Research

In addition to demonstration of the coupled model approach on EMF scenarios, experience using MARKAL and LIFT has provided insights for potential future energy policy analysis:

- Significant efficiency improvements seem possible in end-use systems that are cost-effective, but limited by behavioral and market factors. The end-use efficiency in the EMF scenario in which the carbon tax was coupled with more stringent standards was only slightly improved from the carbon tax scenario. Given the large improvements in energy efficiency in the "7%" scenario over what was achieved with the carbon tax it appears that significant potential exists to combine policies to overcome barriers to investment in efficient technology with tax incentives to switch to less carbon intensive fuels.
- Limited analysis on a regional basis using the EPA US9r MARKAL database which represents the U.S. in nine regions indicates major variations across the U.S., highlighting the need for increased regional analysis of technical opportunities and constraints, such as solar availability, water, and land use.

- Examination of parameters characterizing end-use technologies in the residential, commercial, and transportation sectors shows significant differences between city, suburban, and rural environments. An increased focus and research appears to be required on the unique aspects of high population density urban areas that offer potential for new end-use technologies, but that also pose severe infrastructure challenges.
- The large reduction in carbon emissions observed in the carbon tax scenario due to a shift away from coal in the electric sector suggests the potential for future carbon reductions by extending the capabilities for fuel switching beyond the electric sector to residential, commercial, and transportation sectors using dual fuel technologies.
- The significant efficiency improvement observed in the "7%" scenario raises the controversial issue of the appropriate discount rate for future analysis. Further sensitivity analysis with respect to this parameter could produce some interesting results.

Disclaimer. This document has been reviewed in accordance with U.S. Environmental Protection Agency peer and administrative review and approved for publication. The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

REFERENCES

Almon, Clopper (1996). "A Perhaps Adequate Demand System." INFORUM, Working Paper No. 96-007. July 1996. Document available online at http://www.inforum.umd.edu/papers/research.html.

Electrification Coalition (2010). "The Economic Impact of the Electrification Roadmap." Document available online at http://www.electrificationcoalition.org/media/EC_ImpactReport.pdf

Energy Information Administration (EIA) (2009). "Annual Energy Outlook 2009." Document available online at http://www.eia.doe.gov/oiaf/archive.html.

Energy Modeling Forum (EMF) (2010). "EMF 25 Scenario Design." Stanford University, Stanford, CA. Document available online at http://emf.stanford.edu/files/res/2372/25design2.pdf.

Henry, David K., and H. Kemble Stokes, Jr. (2006). "Macroeconomic and Industrial Effects of Higher Oil and Natural Gas Prices." Economics and Statistics Administration, U.S. Department of Commerce. December 2006. Document available online at http://www.esa.doc.gov/reports.cfm.

Loulou, R., G. Goldstein, and K. Noble (2004). "Documentation for the MARKAL Family of Models." Document available online at http://www.etsap.org/documentation.asp.

Meade, Douglas S. (2001). "The LIFT Model." INFORUM, Working Paper No. 01-002. June 2001. Document available online at http://www.inforum.umd.edu/papers/research.html.

Shay, C., J. DeCarolis, D. Loughlin, C. Gage, S. Yeh, S. Vijay, E. L. Wright (2006). "EPA U.S. National MARKAL Database: Database Documentation." U.S. Environmental Protection Agency, Office of Research and Development. February 2006. Document available online at http://oaspub.epa.gov/eims/eimscomm.getfile?p_download_id=461323.

Strategies for Mitigating Climate Change Through Energy Efficiency: the RFF Haiku Electricity Market Model

Anthony Paul, Matt Woerman*, and Karen Palmer**

This analysis uses the RFF Haiku electricity market model to analyze several of the policies under consideration for EMF-25: an energy (electricity) tax, a carbon tax, a subsidy to energy efficiency and a combination of the last two policies. Reported results include the effects of these policies on electricity demand, electricity price, and emissions of CO_2 from the electricity sector. This analysis also reports a partial equilibrium measure of the net economic benefits of each policy that accounts for the economic benefits of CO_2 emissions reductions and the electricity market economic surplus costs of each of the policies. The findings suggest that policies that increase electricity prices can actually increase total economic surplus in electricity markets in some parts of the country. This result hinges on electricity market regulation and the price impact of the policy. Given the scale of the policies modeled here and for mid-range estimates of the social costs of CO_2 emissions, the carbon tax policy produces the largest increase in net economic surplus. doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-11

INTRODUCTION

The level of interest in policies and programs to encourage greater energy efficiency in the US economy has fluctuated over the years since the energy crisis of the 1970s. Recently, concerns about the anticipated effects of climate change and the search for ways to reduce emissions of greenhouse gases (GHGs) have reignited interest in improving the efficiency of energy-consuming capital equipment. Foremost among the technologies for which efficiency improvements will engender GHG emissions reductions are those that consume electricity. This paper focuses exclusively on the electricity sector in the 48 contiguous U.S. states

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Resources for the Future

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-11

and emissions of carbon dioxide (CO_2) from the sector. Three types of policies that would stimulate efficiency improvements in electricity consumption and reduce CO_2 emissions are a subsidy to electricity consumption efficiency and conservation, an electricity tax, and a CO_2 emissions tax. The efficacy of these policies in reducing CO_2 emissions is the subject of this paper. Also considered is a policy that incorporates the CO_2 emissions tax and the efficiency subsidy. The analysis is conducted using the Haiku electricity market model.

The Haiku model finds electricity market equilibrium prices and quantities that account for the endogeneity between the demand and supply sides of the market. This formulation is critical to evaluating the simultaneous consumption and emissions reductions that would result from the policies under consideration. In the case of an energy efficiency subsidy or an electricity tax, consumption reductions would drive emissions reductions simply due to a reduction in electricity generation. In contrast, a tax on CO_2 emissions would work differently with consumption reductions being driven by higher electricity prices due to increased production costs. Production costs would rise because of the tax and because of a shift toward a less carbon-intensive, but more expensive, stock of electricity generation capacity. The supply side of Haiku makes the conventional assumption that producers will pursue a cost-minimizing strategy to satisfy electricity demand. The demand side of the model merits more discussion next. A description of the entire model follows in a later section of the paper.

Haiku characterizes electricity demand separately for three sectors of the economy—residential, commercial, and industrial—as top-down processes using demand functions that are dynamic, econometrically estimated relationships between electricity consumption and its determinants, including electricity price, income, weather, and other factors. This system has no detail about electricity end-uses or technologies. The energy efficiency of the capital stock that transforms electricity into energy services—such as cooling or refrigeration—is not an explicit parameter in the model, but it is implicit in the levels of the demand functions. The functions are estimated and implemented assuming that electricity demand follows a partial adjustment process in which the levels of the demand functions in any time period depend on the levels of consumption in the previous time period. Electricity demand is therefore sticky in the sense that a low level of consumption in any time period will yield a lower level of demand in the following period than a higher realization of consumption in the first period, holding prices, income, and other factors fixed. This stickiness is attributable to long-lived capital and behavioral inertia and captures the long-run effects of policies that induce changes in capital or behavior. The only variable in the demand functions that is endogenous for the policy simulations is the electricity price, and the functional form of the demand functions assumes a constant price elasticity. This approach to modeling electricity demand cannot accommodate policies that are technology specific, like appliance standards, and therefore this paper focuses exclusively on the four previously mentioned price-oriented policies and does not address the other policies that are under consideration in this 25th Energy Modeling Forum.[1] Also, we are unable to account for the emissions benefits of reduced consumption of other forms of energy that would result under a broader based energy tax or tax on CO_2 emissions.

POLICY SCENARIOS

There are four policy scenarios under consideration that will be compared with each other and against a baseline scenario. The baseline is a business-as-usual scenario designed to capture the policies and institutions related to the electricity sector that are currently in effect, but none of the policies that are under consideration in this paper. The existing policies modeled in the baseline include the Title IV cap on national SO_2 emissions, U.S. Environmental Production Agency's (EPA) Clean Air Interstate Rule caps on emissions of SO_2 and NO_x, the Regional Greenhouse Gas Initiative (RGGI) cap on CO_2 emissions in 10 northeast states, and the national production tax credit and investment tax credit for renewables. The model is calibrated to the revised version of the Annual Energy Outlook 2009 that includes the provisions of the American Recovery and Reinvestment Act of 2009. The baseline and each of the policy scenarios is solved for 6 years between 2010 and 2030: 2010, 2012, 2016, 2020, 2025 and 2030.

The first of the policy scenarios simulates a government subsidy to end-use energy efficiency in the form of a subsidy payment per kWh of reduced electricity consumption.[2] This scenario uses the demand conservation incentive module in the Haiku model. The module simulates a hypothetical auction for electricity consumption reductions where the supply of saved kWh depends on the electricity demand functions. It works by taking a dollar amount of total funding for energy efficiency as input and returning the subsidy price and consumption reductions that are in equilibrium with the supply side and in compliance with all policies specified in the model. The funding level used is specified to the aggregate subsidy amount determined by the Energy Information Administration's National Energy Modeling System (NEMS) model for an energy efficiency subsidy scenario that assumed a 50 percent subsidy of the capital cost difference between the most efficient model of an appliance or piece of equipment and the standard model. It is equal to \$3.5 billion[3] in 2010 and increases to \$7.8 billion by 2030. The distribution of these funds among customer classes is also

1. The excluded scenarios are an efficiency standards policy that includes increased building codes, residential and commercial equipment efficiency standards, and light-duty vehicle fuel economy standards; the efficiency standards policy in combination with a carbon tax; and a scenario in which consumers use a 7% discount rate to select their energy-using equipment.

2. The policy that we model is a subsidy to kWh of electricity consumption reduced, and thus it could be a subsidy to conservation as well as to efficiency. In the case of efficiency investment, the subsidy should be interpreted as offsetting capital costs borne by consumers for investment in energy efficient equipment. In the case of conservation, the subsidy should be interpreted as a payment to consumer to offset surplus losses from reduced electricity consumption.

3. All monetary values are in 2004 dollars unless indicated otherwise.

equivalent to the annual average distribution used in the NEMS model, which gives 91% of the subsidy funding to the residential sector and 9% of the funding to the commercial sector. Further discussion of the demand conservation incentive follows later in this section.

The second policy is an energy tax, but since Haiku covers only the electricity sector, this policy amounts to an electricity tax. The electricity tax is assessed on retail electricity sales and in 2010 is equal to 15% of the retail electricity price. Since the electricity price varies by region and customer class, the amount of the tax in terms of $/MWh also varies. After 2010, the $/MWh value of the tax increases by 5% each year. Since retail electricity price increases over time are projected in the baseline model to have regional and customer class variability, the electricity tax rates beyond 2010 also will vary. By 2030 this results in tax rates in the range of 25–45%.

The third policy is a tax on carbon emissions that is assessed on emissions from electricity generation facilities and in 2010 is equal to $30 per metric ton of CO_2 (2007 dollars). This tax increases at a rate of 5% annually, resulting in a tax rate of nearly $80 per metric ton of CO_2 in 2030. Although this scenario is described as a carbon tax, the tax rate is actually based on the amount of carbon dioxide emitted, not the amount of carbon emitted.

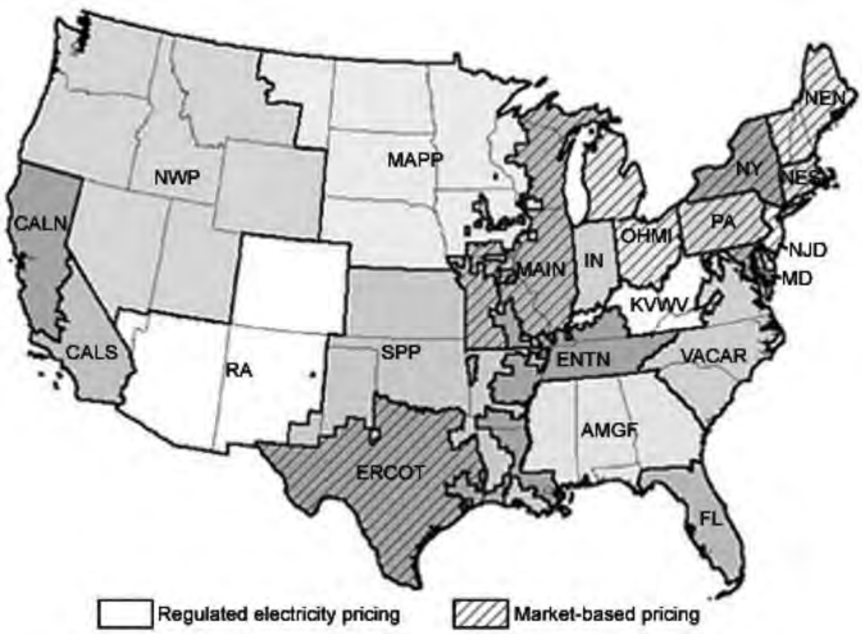
The fourth policy is a combination of the efficiency subsidy and the carbon tax. This scenario includes both the efficiency funding level in the efficiency subsidy policy and the tax rate on carbon emissions in the carbon tax policy.

HAIKU MODEL

The baseline scenario and each of these four policy scenarios is simulated by the Haiku electricity market model (see Paul et al 2009a for complete model documentation). Haiku is a deterministic, highly parameterized simulation model that calculates information similar to the Electricity Market Module of NEMS used by the Energy Information Administration (EIA) and the Integrated Planning Model developed by ICF Consulting and used by the U.S. EPA. The model is capable of solving for up to six simulation years, selected by the model user, over a twenty-five-year simulation horizon that extends to 2035.

Haiku simulates equilibria in regional electricity markets and interregional electricity trade with an integrated algorithm for emission control technology choices for SO_2, NO_x, CO_2 and mercury. The composition of electricity supply is calculated using a fully integrated algorithm for capacity planning and retirement coupled with system operation in temporally and geographically linked electricity markets. The model solves over twenty-one regional markets that comprise the 48 contiguous U.S. states. Each of the regions is classified by its method for determining the prices of electricity generation and reserve services as either market-based competition or cost-of-service regulation. Figure 1 shows the regions and pricing regimes. Electricity markets are assumed to maintain their cur-

Figure 1: Haiku market regions and electricity pricing regimes



rent regulatory status throughout the modeling horizon; that is, regions that have already moved to market-based pricing of generation continue that practice, and those that have not made that move remain regulated.[4] The retail price of electricity does not vary by time of day in any region, though all customers in market-based regions face prices that vary from season to season.

Each year is subdivided into three seasons (summer, winter, and spring-fall) and each season into four time blocks (superpeak, peak, shoulder, and base). For each time block, demand is modeled for three customer classes (residential, industrial, and commercial). Supply is represented using model plants that are aggregated from the complete set of commercial electricity generation plants in the country according to their technology and fuel source. Investment in new generation capacity and the retirement of existing facilities is determined endogenously in a dynamic framework, based on capacity-related costs of providing service in the future ("going forward costs"). Operation of the electricity system ("generator dispatch") in the model is based on the minimization of short-run variable costs of generation.

4. There is currently little momentum in any parts of the country for electricity market regulatory restructuring. Some of the regions that have already implemented competitive markets are considering reregulating and those that never instituted these markets are no longer considering doing so.

Equilibrium in interregional power trading is identified as the level of trading necessary to equilibrate regional marginal generation costs net of transmission costs and power losses. These interregional transactions are constrained by the level of the available interregional transmission capability as reported by the North American Electric Reliability Council (2003a, 2003b).[5] Factor prices, such as the cost of capital and labor, are held constant. Fuel prices are benchmarked to the forecasts of the revised Annual Energy Outlook 2009 for both level and elasticity (U.S. EIA 2009). Coal is differentiated along several dimensions, including fuel quality and content and location of supply, and both coal and natural gas prices are differentiated by point of delivery. The price of biomass fuel also varies by region depending on the mix of biomass types available and delivery costs. All of these fuels are modeled with price responsive supply curves. Prices for nuclear fuel and oil are specified exogenously without any price responsiveness.

Emissions caps in the Haiku model, such as the Title IV cap on national SO_2 emissions, EPA's Clean Air Interstate Rule caps on emissions of SO_2 and NO_x, and the Regional Greenhouse Gas Initiative (RGGI) cap on CO_2 emissions, are imposed as constraints on the sum of emissions across all covered generation sources in the relevant regions. Emissions of these pollutants from individual sources depend on emission rates, which vary by type of fuel and technology, and total fuel use at the facility. The sum of these emissions across all sources must be no greater than the total number of allowances available, including those issued for the current year and any unused allowances from previous years when banking is permitted.

Partial Adjustment Demand and Consumer Surplus

For this study of energy efficiency, the two most relevant components of the Haiku model are the partial adjustment demand functions and the demand conservation incentive, which simulates a subsidy to consumption efficiency. Both of the modules employ a top-down modeling approach that does not characterize energy consuming technologies but does capture aggregate demand behavior. This approach is in contrast to most of the models that appear in the burgeoning literature on the potential for efficiency improvements in end-use

5. Some of the Haiku Market Regions are not coterminous with North American Electric Reliability Council (NERC) regions and therefore NERC data cannot be used to parameterize transmission constraints. Haiku assumes no transmission constraints among OHMI, KVWV, and IN. NEN and NES are also assumed to trade power without constraints. The transmission constraints among the regions ENTN, VACAR, and AMGF, as well as those among NJD, MD, and PA, are derived from version 2.1.9 of the Integrated Planning Model (EPA 2005). Additionally, starting in 2014, we include the incremental transfer capability associated with two new 500-KV transmission lines into and, in one case, through Maryland, which are modeled after a line proposed by Allegheny Electric Power and one proposed by PEPCO Holdings (CIER 2007). We also include the transmission capability between Long Island and PJM made possible by the Neptune line that began operation in 2007.

consumption, which are bottom-up models that characterize end-use technologies by their operational and cost parameters. (Chandler and Brown 2009, EPRI 2009, Granade et al. 2009, Creyts et al. 2007). The bottom-up modeling approach is ideal when data are abundant and consumer decisions about technology adoption can be well-characterized through time. However, the variety of end-use technologies for electricity consumption is vast and the technologies that will emerge in the coming decades are difficult to anticipate. Furthermore, the characterization of consumer behavior with respect to electricity end-use technology is fraught with problems as consumers often fail to make technology choices that accord with the engineering cost-minimization principle that underpins most bottom-up models and the limited data that are available to parameterize them. The top-down approach employed by Haiku skirts these problems, but lacks the technology richness that exists in bottom-up models.

The Haiku electricity demand functions are based on the partial adjustment framework put forth by Houthakker and Taylor (1970). The demand system finds monthly electricity demand by customer class given a sequence of electricity prices and is dynamic in that the electricity price in any time period is one of the determinants of demand in all subsequent time periods. The model simultaneously captures the short- and long-run price elasticities of electricity demand and is implemented inside of Haiku to project demand using the parameterized functions and endogenous electricity prices. For the details of the partial adjustment demand system estimation, see Paul et al (2009b). Equation (1) illustrates a Haiku electricity demand function for a customer class in a region in a month. Q_t is electricity consumption (MWh) in month t, Q_{t-1} and Q_{t-12} are electricity consumption (MWh) lagged one and twelve months, respectively, α_1 and α_{12} are the coefficients on lagged consumption, X_t are the demand covariates in month t other than lagged consumption and contemporaneous price, β are the coefficients on the covariates, P_t is the electricity price ($/MWh) in month t, and ε is the price elasticity.

$$Q_t = Q_{t-1}^{\alpha_1} Q_{t-12}^{\alpha_{12}} X_t^{\beta} P_t^{\varepsilon} \qquad (1)$$

This partial adjustment structure yields static demand functions in any particular year (other than the first year) that are not necessarily constant across scenarios because electricity prices in prior periods, which vary across scenarios, determine the level of the functions in price/quantity space. The time-lagged shift in the demand function is the result of consumer choice over the long-lived capital stock used to consume electricity. Since the demand functions are not constant across scenarios, it is impossible to use the conventional Harberger approach (1964) to calculate the exact change in consumer surplus between scenarios. For example, as electricity prices rise under one of the tax policies, consumers will respond by shifting to a more efficient capital stock that will yield electricity demand functions in subsequent time periods that are shifted down and to the left because of the lag terms in the partial adjustment framework. This shift would result in an apparent reduction in consumer surplus at any electricity price, but that would be mistaken because the lower curve delivers more electricity services to the consumer per unit of electricity consumed and the improved capital stock should yield an increase in consumer surplus at any electricity price. The value of the surplus increase from efficiency improvement will exceed the cost of the improvement because of the well-documented efficiency gap (Gillingham et al 2006, Jaffe and Stavins 1994, and Hausman and Joskow 1982). Since consumers tend to underinvest in energy efficiency, holding a more efficient capital stock will yield more consumer surplus at any electricity price. This is true up to the point where the efficiency gap is eliminated and any improvement beyond that level will be welfare reducing.

To solve this problem, consumer surplus in the electricity market is calculated in Haiku for every scenario using the demand curves from the baseline scenario. Holding the curves constant at the baseline levels, the calculation takes the area under the demand curve between the baseline electricity price and the price observed in each scenario. This method treats the capital stock as fixed across scenarios, which is not true, but it does provide a bound on the value of the consumer surplus effects of each policy. In the efficiency subsidy scenario, the funds are used to directly improve the efficiency of the capital stock.[6] In the two tax scenarios, elevated electricity prices lead consumers to invest in more efficient capital as well as to reduce consumption of energy services. Thus, in all three scenarios, using the baseline demand curves underestimates the efficiency of the capital stock. The magnitude of the underestimate is increasing in electricity prices, assuming that efficiency improvements have not reached a level sufficient to eliminate the efficiency gap, and since the level of electricity consumption is monotonic in electricity prices it can be used as a proxy for the magnitude of the underestimate of the efficiency of the capital stock.

Demand Conservation Incentive

The demand conservation incentive simulates a publicly administered and funded subsidy to electricity conservation resulting from either reduction in consumption of energy services or from investment in more energy-efficient capital equipment. The module returns the amount of electricity saved monthly based on a stream of funding levels, the parameters of the electricity demand functions, and endogenously determined retail electricity prices. The core concept of the demand conservation incentive is that consumers will be paid for each unit of electricity conserved and will choose to accept the payment rather than consume electricity if the value of the payment exceeds the value of the energy services derived from another unit of consumption. The subsidy to conservation effectively increases the cost of consumption, thus lowering demand for electricity and therefore retail prices. It is implemented in conjunction with the partial adjustment

6. Alternatively, the funds could be used to compensate consumers for losses in consumer surplus associated with energy conservation.

demand functions to simulate the future consumption reductions that result from a change in the long-lived stock of electricity consuming capital goods.

The demand conservation incentive accounts for the cost of program administration (assumed to be 40% of total costs) and is calibrated to capture any inefficiencies associated with compelling consumers to take up the subsidy. The calibration determines a factor that adjusts the efficiency gains available to be harvested at any subsidy price to yield a 1.07% reduction in electricity consumption between 2010 and 2026 at an average cost of $64.1 for each MWh reduced (2007 dollars) by annual program funding from 2010 to 2020 equal to 0.574% of total electricity expenditures. These parameters match the historical annual expenditures and average cost of electricity saved as reported in Arimura et al. (2009). The calibration factor is held constant in all other scenario simulations.

Equation (2) is the equilibrium condition for the demand conservation incentive in the Haiku model. It says that the quantity of avoided units of electricity consumption purchased by the program administrator in year *Y* (left-hand side) must be equivalent to the quantity supplied by consumers (right-hand side). F_Y is the funding level ($) in year *Y*, *A* is the fraction of funds that are dedicated to program administration, D_Y is price on the subsidy to avoided consumption ($/MWh) in year *Y*, Q_t is the level of electricity consumption (MWh) that would have occurred in the absence of an efficiency program, and *C* is the calibrator.

$$\frac{F_{Y:t\in Y}(1-A)}{D_{Y:t\in Y}} = \sum_{t:t\in Y} Q_t\left[1-\left(1+\frac{D_{Y:t\in Y}}{P_t}\right)^{\varepsilon}\right]C \qquad (2)$$

RESULTS

In this study, we are interested in the contribution of energy efficiency gains to emissions reductions under the four policy scenarios described above. The scenarios are compared on two bases: emissions avoided per unit of electricity consumption reduced and net social benefits. The latter measure is comprised of partial equilibrium economic welfare analysis in electricity markets and the social benefits from avoided carbon emissions. Since the consumer surplus calculations are lower bounds, not precise estimates, the social benefits analysis focuses on rank ordering the policies. Initially the analysis will focus on the three single policy scenarios and the combination policy scenario will be discussed later.

Prices, Consumption, Emissions and Generation Mix

Electricity consumption reductions in the electricity tax and carbon tax scenarios are driven by electricity price increases, shown in the left-hand panel of Figure 2. In the efficiency subsidy scenario, consumption reductions are not driven by price increases, but by a government funded subsidy to avoided consumption. In fact this subsidy will result in very small electricity price reductions

Figure 2: Electricity Price and Consumption under Different Policies

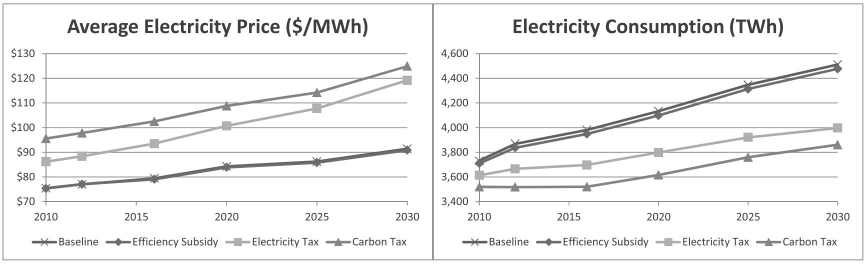
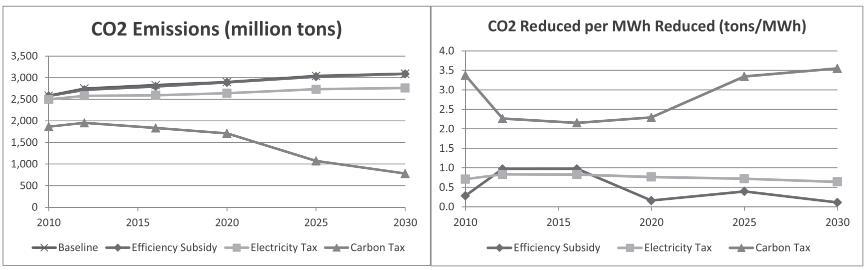


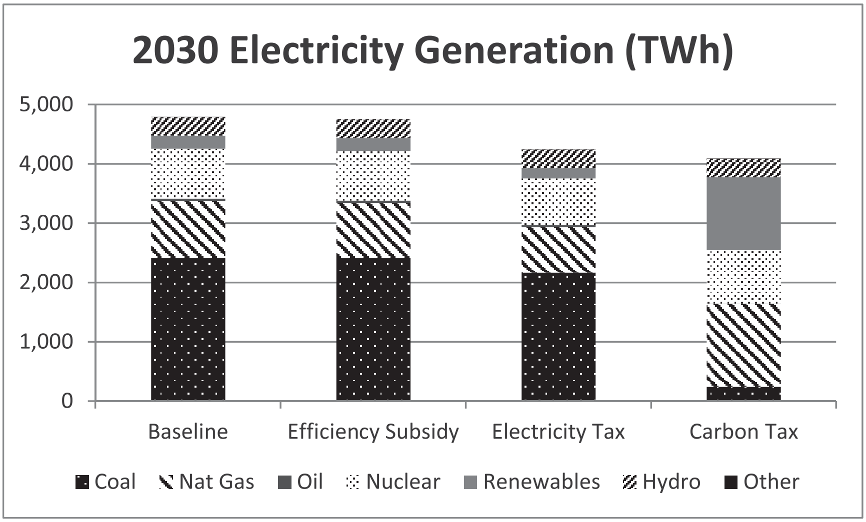
Figure 3: CO_2 Emissions and Emissions Reductions under Different Policies



due to reduced consumption, but the price reductions will be negligible and thus the efficiency subsidy scenario is indistinguishable from the baseline in the figure. The levels of electricity consumption in the electricity tax and carbon tax scenarios, shown in the right-hand panel of Figure 2, follow from electricity prices. These reductions are substantial, amounting to 11.4% and 14.4%, respectively, of baseline consumption in 2030, and are much greater than the 0.8% reduction achieved in the efficiency subsidy scenario in 2030. The three scenarios are of significantly different scale, which has important implications for both costs and benefits as shown below.

Reductions in electricity consumption will lead to reductions in CO_2 emissions. Emissions levels are shown in the left-hand panel of Figure 3, with the greatest reductions occurring in the carbon tax scenario and the smallest reductions occurring in the efficiency subsidy scenario. In the electricity tax and efficiency subsidy scenarios, these emissions reductions are driven strictly by reduced consumption, but in the carbon tax scenario a shift toward less carbon-intensive production technologies also contributes to emissions reductions. The right-hand side of Figure 3 reveals the CO_2 emissions reductions benefits for each unit of consumption avoided in the three scenarios. The carbon tax scenario yields significantly more emissions benefits per unit of avoided consumption than the

Figure 4: Composition of Electricity Generation in 2030



other scenarios because of the supply-side shift away from carbon-intensive technologies.

Figure 4 shows the breakdown of fuel types used to satisfy the demand requirements in each scenario in 2030. The minimal change in electricity consumption between the baseline and efficiency subsidy scenarios results in almost no change in the supply side of the market. The electricity tax scenario produces significantly lower consumption and thus a significant decline in total electricity generation, but this decline is borne approximately equally by all fuel types. The carbon tax scenario also requires significantly less total electricity generation, but in this scenario the mix of fuel types is also altered, with a large shift out of coal and into natural gas and renewables.

Costs and Net Benefits

The cost of obtaining these CO_2 emissions reductions can be evaluated by looking at the effects of the policy on total economic surplus in electricity markets. Total economic surplus is the sum of consumer surplus, producer surplus, and government surplus. These four metrics are shown in Table 1 as the net present value of the change in surplus induced by the policies relative to the baseline over the modeling horizon, assuming an 8 percent discount rate for all agents. Because of the dynamic nature of our electricity demand functions and our inability to observe the changes in capital stock efficiency that result from these policies, our measures of consumer surplus represent lower bounds that don't account for changes in capital stock energy efficiency. However, since the

Table 1: Welfare Costs, Emissions Reductions and Net Benefits of Policies

	National			Cost-of-Service Regions			Competitive Regions		
	Efficiency Subsidy	Electricity Tax	Carbon Tax	Efficiency Subsidy	Electricity Tax	Carbon Tax	Efficiency Subsidy	Electricity Tax	Carbon Tax
NPV of Change in Consumer Surplus (billion \$)[a]	8.7	–652.6	–975.4	4.8	–408.5	–571.5	3.8	–244.1	–403.9
NPV of Change in Producer Surplus (billion \$)	–1.7	–33.9	68.2	0.2	0.2	–0.1	–2.0	–34.1	68.4
NPV of Change in Government Surplus (billion \$)	–64.8	685.5	607.9	–47.0	429.3	361.1	–17.8	256.3	246.9
NPV of Change in Total Economic Surplus (billion \$)[a]	–57.8	–0.9	–299.2	–41.9	21.0	–210.5	–16.0	–21.9	–88.6
Total CO_2 Reductions (million tons)	331.3	5,240.2	29,526.7	92.0	3,808.6	20,461.1	239.3	1,431.6	9,065.6
NPV of CO_2 Benefits with Avg. SCC Discounted at 3% (billion \$)	5.4	82.8	463.7	1.5	60.2	321.5	3.9	22.5	142.1
NPV of Total Welfare Change with Avg. SCC at 3% (billion \$)[a]	–52.4	81.9	164.5	–40.3	81.2	111.0	–12.1	0.6	53.5

[a] These values are a lower bound, as discussed in the description of the demand system.

ranking of the policies by welfare improvement turns out to be the same as the ranking by capital efficiency improvement, the differences among the welfare measures are an indication of policy preference.[7] The table shows national totals as well as the breakdown between regions of the country that price electricity generation services in competitive markets and those that price it on a cost-of-service basis. This breakdown according to regulatory structures that govern electricity markets is critical because of the asymmetric effects on economic surplus in the two types of regions.

In the competitive regions, where electricity generation is priced at marginal cost, any tax will necessarily reduce total surplus because retail prices above marginal production costs yield dead-weight loss. This result is apparent in Table 1. In the cost-of-service regions, where electricity is priced at average production costs instead of on the margin, total surplus need not necessarily decline under the imposition of a tax. Indeed if retail prices are below marginal costs in the absence of a tax then the imposition of a tax that brings prices closer to marginal costs will yield an increase in economic surplus.[8] This is, on average, the outcome that is apparent for the electricity tax scenario, in which the increase in surplus generated in the cost-of-service regions is approximately equal to the decrease in surplus in the competitive regions. The change in total surplus across both types of regions is therefore negligible. The carbon tax scenario yields greater increases in electricity prices that go beyond what is required to align price with the marginal costs of production in the cost-of-service regions, resulting in a significant decline in total surplus in those regions. This policy, which is substantially more stringent[9] than the electricity tax, yields a nationwide reduction in electricity market surplus through 2030 of about $300 billion in net present value terms. The efficiency subsidy scenario is like the carbon tax scenario in that both types of regions experience a reduction in economic surplus, resulting in a nationwide reduction in electricity market surplus of about $60 billion in net present value terms. Recall that these values are lower bounds that don't account for capital efficiency improvement or the benefits of emissions reductions.

Since the carbon emissions reductions projected under the three policies are substantially different and correlated with the economic costs, accounting for

7. The values in table 1 represent comparisons with the baseline scenario. For the efficiency subsidy scenario, the negative values do not indicate that the baseline is preferred to the subsidy because the rankings between those policies are not the same. The subsidy has negative total welfare change, but superior capital efficiency and so no policy ranking is possible.

8. The form of electricity price regulation is also important for the welfare effects of different approaches to tax revenue allocation under a tax approach to controlling carbon. In particular, not recycling revenues through the electricity sector will go further toward correcting such inefficiencies in electricity pricing than an approach that does allocate tax revenues into the electricity sector (Burtraw et al. 2001).

9. The carbon tax policy is more stringent in the sense that it induces greater price and consumption effects and more changes on the supply side than the electricity tax.

the benefits of emissions reductions is important for ranking the policies.[10] The United States Government Interagency Working Group on Social Cost of Carbon (2010) has estimated the social cost of carbon (SCC) emissions that occur in each year from 2010 to 2050. This cost is the average future cost to society of a ton of CO_2 emissions, where the stream of costs that extend into the future are discounted back to the emission year using a range of discount rates—5 percent, 3 percent, and 2.5 percent.[11] We adopt the central case estimates associated with assuming a 3 percent discount rate. The cost per ton of CO_2 emissions in this case ranges from $21.40 per metric ton in 2010 to $32.80 per metric ton in 2030 (in 2007 dollars). These costs are discounted to the present using the same 3 percent discount rate used to calculate the SCC. The middle rows of Table 1 report the cumulative CO_2 reductions from 2010 to 2030 achieved by each of the three policies, as well as the net present value of CO_2 reduction benefits using the central case social cost assumptions. The sum of the change in net present value of total economic surplus and the CO_2 benefits results in the total welfare change shown in the bottom row of Table 1.

The last row of Table 1 indicates that the electricity tax would yield an approximate $130 billion improvement in social welfare over the efficiency subsidy. This measure fails to account for the surplus effects of the superior capital efficiency in the electricity tax scenario, but its inclusion would only exacerbate the difference. Actually, the methodology employed by Haiku to simulate the subsidy scenario will necessarily lead to greater costs than an electricity tax policy that achieves the same level of avoided consumption because both types of policies reduce consumption by raising effective electricity prices. The price elasticities are identical in all scenarios and so the extra costs incurred by the efficiency subsidy policy—administration, inefficiencies associated with compelling consumers to take-up the subsidy, and payments to consumers who would have invested in efficiency without the subsidy—will necessarily render an electricity tax a cheaper means to reduce consumption than an efficiency subsidy. Since the policies yield similar emissions reductions per unit of reduced consumption, as seen in Figure 3, the electricity tax provides a greater increase in total welfare than the efficiency subsidy.

It is also possible to rank the carbon tax above the electricity tax policy. Table 1 shows that the carbon tax yields both substantially higher emissions reductions and higher estimates of net welfare benefits than the electricity tax.

10. There may also be other benefits associated with these policies, such as the human health and environmental effects of reductions in emissions of conventional air pollutants, such as nitrogen oxides or sulfur dioxide, or hazardous air pollutants, such as mercury. These benefits are not included here, but many of them are likely to be highly correlated with reductions in CO_2 emissions and thus are unlikely to alter the ranking of the policies.

11. The interagency working group report also includes a SCC calculated using the 95th percentile of expected future costs of emissions and discounted at 3 percent to represent the case of higher than expected future damages. We adopt the midrange values reported in the report to provide a mid-range estimate of the net benefits of different policies that we model.

The carbon tax also produces a larger drop in electricity demand in all years as shown in figure 2 and thus the size of the downward bias in the lower bound welfare change estimates is greater for the carbon tax than for either of the other two policies. If the lower bound on net benefits is higher for this policy than the others and the extent of the bias is also higher, then the carbon tax is superior on welfare grounds to either of the other two. This is consistent with the economic theory that an emissions tax targeted at a pollutant will typically be more efficient at reducing emissions than a policy targeted elsewhere. While both policies result in reduced electricity consumption due to increased retail electricity prices, the carbon tax also induces a supply-side shift to less carbon-intensive technologies to generate electricity.

In sum, in economic welfare terms, the carbon tax is preferred to the electricity tax, which is preferred to the efficiency subsidy, and these results are generally robust across the range of SCC estimates endorsed by the Interagency Working Group.[12]

Combination Policy

The final policy simulated was a combination of the efficiency subsidy and the carbon tax. This simulation can be compared to the baseline to determine the overall effects of these two policies in combination, and it can also be compared to both the efficiency subsidy and the carbon tax to examine the incremental effect of adding a second policy to the first.

In the combined policy, reductions in electricity consumption are driven both by an increase in the retail price of electricity due to the carbon tax, as well as by a government subsidy to avoided electricity consumption, as shown in Figure 5. The incremental addition of the efficiency subsidy to the carbon tax causes a negligible reduction in prices, making the price effect of the policy essentially the same as the carbon tax alone, but the efficiency subsidy yields additional consumption reductions. In total the combined policy yields reductions equal to 15.2% of baseline consumption in 2030.

The combination of an efficiency subsidy and a carbon tax also leads to reductions of CO_2 emissions, as shown in the left-hand panel of Figure 6. Under the combined policies, these reductions are driven by consumption reductions due to both policies, as well as a shift to less carbon-intensive generation technologies due to the carbon tax. The combined policies compared to the carbon tax alone, however, result in very few additional emission reductions, similar to the effi-

12. The one exception to this is for the lowest set of SCC values reported, which range from $4.70 in 2010 to $9.70 in 2030, the carbon tax actually ends up having a net negative effect on economic welfare while the electricity tax has a small positive effect. However, the marginal costs of carbon abatement are convex and so a policy that goes further in reducing emissions will necessarily incur greater marginal costs. If the electricity tax policy were scaled to achieve the same level of emissions reductions as in the carbon tax policy, it would have much greater welfare costs than the carbon tax policy, even for the lowest set of SCC values.

Figure 5: Electricity Price and Consumption

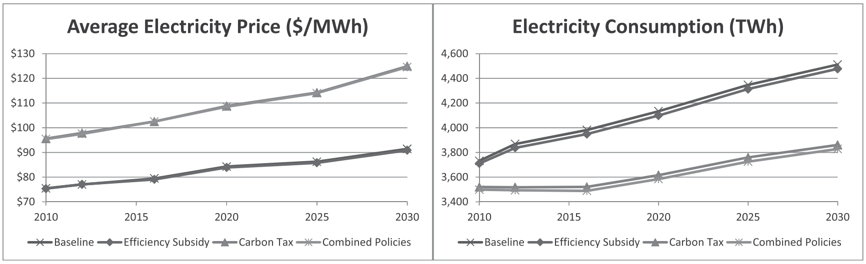
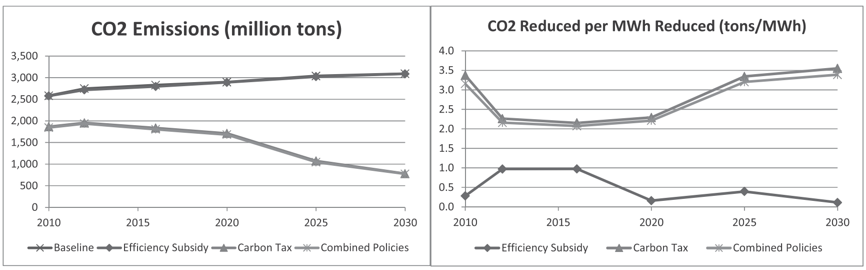


Figure 6: CO_2 Emissions and Emissions Reductions under the Combination Policy and Components



ciency subsidy compared to the baseline. In fact, the total emission reductions under the combined policies scenario is approximately equal to the sum of reductions achieved under each policy individually. The emissions reductions per unit of avoided electricity consumption are shown in the right-hand panel of Figure 6. Although the electricity consumption reductions achieved under the combined policies are much more carbon-intensive than those under the efficiency subsidy alone, they are slightly less carbon-intensive than the carbon tax alone. This difference is because the carbon tax causes generators to switch to a much less carbon-intensive mix of fuels, while the efficiency subsidy leads to a similar reduction among all generation fuels. Consequently, the incremental effect of the carbon tax in addition to the efficiency subsidy is a large increase in the carbon intensity of the reduced electricity consumption. The incremental effect of the efficiency subsidy, on the other hand, causes a slight reduction in the carbon intensity because the efficiency subsidy reductions are made without regard to the fuel used, so some of these reductions occur in fuels that are minimally carbon-intensive or carbon-free.

The economic surplus and total welfare implications of the combined policies are shown in Table 2. For each of the three surplus components, as well as for total economic surplus, the change due to the combined policies is approx-

Table 2: Welfare Costs, Emissions Reductions and Net Benefits of Combined Policies and Component Policy

	National			Cost-of-Service Regions			Competitive Regions		
	Efficiency Subsidy	Carbon Tax	Combined Policies	Efficiency Subsidy	Carbon Tax	Combined Policies	Efficiency Subsidy	Carbon Tax	Combined Policies
NPV of Change in Consumer Surplus (billion $)[a]	8.7	−975.4	−968.8	4.8	−571.5	−567.1	3.8	−403.9	−401.7
	−1.7	68.2	67.4	0.2	−0.1 361.1	1.0	−2.0	68.4	66.4
NPV of Change in Producer Surplus (billion $)	−64.8	607.9	534.3	−47.0		309.2	−17.8	246.9	225.1
NPV of Change in Government Surplus (billion $)									
NPV of Change in Total Economic Surplus (billion $)[a]	−57.8	−299.2	−367.1	−41.9	−210.5	−256.8	−16.0	−88.6	−110.3
Total CO_2 Reductions (million tons)	331.3	29,526.7	29,996.0	92.0 1.5	20,461.1	20,722.1	239.3	9,065.6	9,274.0
NPV of CO_2 Benefits with Avg. SCC Discounted at 3% (billion $)	5.4	463.7	471.2		321.5	325.7	3.9	142.1	145.5
NPV of Total Welfare Change with Avg. SCC at 3% (billion $)[a]	−52.4	164.5	104.1	−40.3	111.0	68.9	−12.1	53.5	35.2

[a] These values are a lower bound, as discussed in the description of the demand system.

imately equal to the sum of the changes due to each policy individually, and this is also true for avoided CO_2 emissions and their benefits. Based on both metrics, emissions avoided per unit of electricity consumption reduced and total welfare change, the combined policies of an efficiency subsidy and a carbon tax are essentially equivalent to the sum of both policies enacted individually. Thus, the analysis is unable to detect any synergies, either positive or negative, associated with coupling these two policies.

CONCLUSIONS AND CAVEATS

The effects of the three types of policies analyzed here on electricity prices and demand, CO_2 emissions from the electricity sector, and overall economic welfare in the electricity sector depend simultaneously on the scales and designs of the policies and on the costs of policy implementation. The carbon tax scenario yields significantly more emissions benefits per unit of avoided consumption than the other scenarios because of the supply-side shift away from carbon-intensive technologies. The subsidy to energy efficiency and conservation is less cost-effective than the electricity tax at reducing CO_2 because of the high costs of using that approach to get incremental reductions in demand. These high costs are due to a combination of administrative costs, payments to infra-marginal consumers (those who would invest in energy efficiency without the subsidy), and the focus of the policy on residential consumers at the expense of potentially more cost effective savings from other customer classes. Both the efficiency subsidy and the electricity tax are less effective at reducing CO_2 emissions than the carbon tax because they fail to provide an incentive for fuel switching in electricity production. The carbon tax is more stringent than either of the other two policies in that it has more effect on electricity prices and therefore greater incentives for electricity conservation and adoption of energy-efficient, electricity-using technologies. These efficiency gains contribute CO_2 emissions reductions that come at increasing marginal cost, but remain welfare-improving overall compared with the other policies that engender no shift in the carbon intensity of electricity generation.

The relatively poor performance of the energy efficiency subsidy policy does not indict all forms of energy efficiency policy. The policy modeled here is based on the EIA efficient appliance subsidy policy constructed for EMF-25 and over 90% of the subsidy is directed at residential customers, which means that there may be more cost-effective demand reductions from other customer classes that are not being captured. Targeting more of the subsidy to other customer classes or using a market mechanism like a reverse auction to identify the most cost-effective opportunities to reduce electricity demand could increase the savings from any aggregate level of subsidy to energy efficiency. Also, making changes to the policy that reduce administrative costs or make it easier to target truly marginal demand reductions will make it more effective. However, such policies are likely to be substantially less effective and less cost effective than either of the tax policies at reducing CO_2 emissions and their justification relies on the presence of other market and behavior failures in energy efficiency markets.[13] Cataloguing and quantifying these market failures is an important subject for future research.

REFERENCES

Arimura, T. H., R. G. Newell and K. Palmer (2009). Cost-Effectiveness of Electricity Energy Efficiency Programs. Resources for the Future Discussion Paper 09-48.

Burtraw, D, K. Palmer, R. Bharvirkar and A. Paul (2001). The Effect of Allowance Trading on the Cost of CO2 Emissions Reduction, Resources for the Future Discussion Paper 01-30.

Center for Integrative Environmental Research (CIER) (2007). Economic and Energy Impacts from Maryland's Potential Participation in the Regional Greenhouse Gas Initiative.

Chandler, S. and M. Brown (2009). Meta-Review of Efficiency Potential Studies and Their Implications for the South, Georgia Tech, Ivan Allen College of Public Policy Working Paper 51.

Creyts, J., A. Derkach, et al. (2007). Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost, McKinsey & Company

Electric Power Research Institute (EPRI) (2009). *Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the US 2010 – 2030*.

Environmental Protection Agency (EPA) (2005). Standalone Documentation for EPA Base Case 2004 (V.2.1.9) Using the Integrated Planning Model.

Gillingham, K., R. Newell and K. Palmer (2009). Energy Efficiency Economics and Policy. *Annual Review of Resource Economics* 1: 597–619.

Granade, H.C., Creyts, J. et al. (2009) Unlocking Energy Efficiency in the US Economy, McKinsey and Company.

Harberger, A. C. (1964). The measurement of waste. American Economic Review 54(3): 58–76.

Hausman, Jerry A. and Paul L. Joskow (1982). Evaluating the Costs and Benefits of Appliance Efficiency Standards. American Economic Review 72(2): 220–225.

Houthakker, H. S. and L. D. Taylor (1970). Consumer Demand in the United States: Analyses and Projections. Cambridge, MA: Harvard University Press.

Jaffe, Adam B. and Robert N. Stavins (1994). The Energy Paradox and the Diffusion of Conservation Technology. Resource and Energy Economics 16: 91–122.

North American Electric Reliability Council (NERC) (2003a). 2003 Summer Assessment: Reliability of the Bulk Electricity Supply in North America.

——— (2003b). 2003/2004 Winter Assessment: Reliability of the Bulk Electricity Supply in North America.

Paul, A., D. Burtraw and K. Palmer (2009a). Haiku Documentation: RFF's Electricity Market Model version 2.0. Resources for the Future Report.

Paul, A., E. Myers and K. Palmer (2009b). A Partial Adjustment Model of U.S. Electricity Demand by Region, Season, and Sector. Resources for the Future Discussion Paper 08-50.

United States Energy Information Administration (U.S. EIA) (2009). Annual Energy Outlook 2009 with Projections to 2030. DOE/EIA-0383(2009).

United States Government Interagency Working Group on Social Cost of Carbon (2010). Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866.

13. See Gillingham et al. (2009) for a discussion of the justification for policies to promote energy efficiency.

Comparing and Combining Energy Saving Policies: Will Proposed Residential Sector Policies Meet French Official Targets?

Louis-Gaëtan Giraudet, Céline Guivarch**, and Philippe Quirion****

This paper assesses the impact of French policies for residential space-heating energy consumption, both enacted (tax credits for the purchase of energy efficient durables, soft loans for retrofitting actions, stringent building codes) and anticipated (carbon tax, retrofitting obligation). It uses a hybrid energy-economy model incorporating specific features of energy conservation, notably the rebound effect and some "barriers" to energy efficiency such as split incentives and imperfect information. Forward-looking simulations show that (i) stand-alone policies improve the energy efficiency of the building stock but, with the exception of carbon tax, generate a rebound effect; (ii) interactions among instruments are roughly additive; (iii) a combination of all policies fails to meet Government conservation targets. doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-12

1. INTRODUCTION

Analysis of residential buildings suggests both increasing energy demand and a large techno-economic potential for energy savings and carbon dioxide emissions cuts (Levine *et al.*, 2007), but private energy consumption and investment decisions do not necessarily maximize net social benefits. Two reasons are generally noted: first, energy consumption generates externalities, including global warming, and second, the energy efficiency gap or paradox (Jaffe and

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Corresponding author. Université Paris-Est, Ecole des Ponts ParisTech. Marne-la-Vallée, France. Centre international de recherche sur l'environnement et le développement (CIRED). Nogent-sur-Marne, France. CIRED, 45 bis avenue de la Belle Gabrielle, F-94736 Nogent sur Marne Cedex. Tel: +331.43.94.73.62. E-mail: giraudet@centre-cired.fr.

** Université Paris-Est, Ecole des Ponts ParisTech. Marne-la-Vallée, France. Centre international de recherche sur l'environnement et le développement (CIRED). Nogent-sur-Marne, France.

*** Centre national de la recherche scientifique (CNRS). Paris, France. Centre international de recherche sur l'environnement et le développement (CIRED). Nogent-sur-Marne, France.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-12

Stavins, 1994; Sanstad and Howarth, 1994) which is caused by "barriers", such as imperfect information, split incentives or bounded rationality, leads to an under-provision of energy efficient durables, despite their long-term profitability (Sorrell *et al.*, 2004; Gillingham *et al.*, 2009).

This provides justification for public intervention, but policy instruments must be implemented appropriately. First, according to Levine et al. (2007, p.390), "these barriers are especially strong and diverse in the residential and commercial sectors; therefore, overcoming them is only possible through a diverse portfolio of policy instruments *(high agreement, medium evidence)*". This can be seen as the application of the "Tinbergen rule" to energy conservation.[1] Indeed, it is known that standard instruments, such as taxes, subsidies or regulations, are not equally well suited *ceteris paribus* to different policy goals (Goulder and Parry, 2008; Gillingham *et al.*, 2009). Second, *energy efficiency* improvements (be they autonomous or caused by energy efficiency policies) are usually followed by *energy sufficiency* relaxation, *i.e.* increased utilization of energy consuming capital (Alcott, 2008). The resulting discrepancy between effective energy savings and the savings theoretically achievable under a constant utilization assumption is referred to as the direct rebound effect (Sorrell et al., 2009). Third, the joint implementation of multiple instruments can lead to interactions that augment or diminish overall policy outcomes (Bennear and Stavins, 2007; OECD, 2007). As a result, there is neither one outstanding single instrument, nor a ready recipe for combining instruments. In the case of policies for energy conservation, a broad *ex ante* evaluation is required with a careful examination of stand-alone and multiple policies, and the specific determinants of energy efficiency and sufficiency.

Although poorly investigated by the economic literature, policy combination has been routinely used in practice (Bennear and Stavins, 2007). France provides an interesting example in the field of energy conservation. The *Grenelle de l'environnement*, a collective consultation held in 2007, set sectoral targets to combat climate change, including a 38% reduction in energy consumption in existing buildings between 2008 and 2020.[2] Since then, pre-existing tax credits for the purchase of energy efficient durables have been strengthened, zero rate loans for retrofitting have been provided to the household sector, and building codes for new constructions have been revised to set more stringent requirements in 2012 and 2020. In addition, a carbon tax was passed by Parliament in December 2009, but was then cancelled by the *Conseil constitutionnel*, the High Court that checks whether new laws conform to the Constitution. The tax proposal exempted industrial installations covered by the European Union Emission Trading System (E.U. ETS) which, according to the *Conseil constitutionnel*, violated the principle

1. Formally, the Tinbergen rule states that for each and every policy target there must be at least one policy tool (Tinbergen, 1952; Knudson, 2009).

2. *Loi n° 2009-967 du 3 août 2009 de programmation relative à la mise en œuvre du Grenelle de l'environnement, Article 5*. Although the energy unit is not specified yet, it is likely to refer to the *specific* consumption (per square meter), expressed in *primary* energy (Pelletier, 2008, p.27).

of equality before tax, since ETS allowances are freely allocated. The Government has decided not to submit any new proposal, but a carbon or carbon-energy tax is still proposed by some stakeholders. Lastly, growing attention is being paid to a retrofitting obligation. To date, very few forward-looking studies have evaluated the impact of these proposals.

This paper investigates whether French residential targets are achievable with the proposed policy mix, and evaluates alternative means for achieving them. This case study also provides insights into such general questions as: *How do policy instruments rank in terms of energy savings? What is their impact on the specific determinants of energy conservation? To what extent does policy combination bring additive savings?* The simulation model Res-IRF is used for this purpose. It is designed to handle technological and behavioral specificities in the household sector, consistent with the IMACLIM general equilibrium framework.[3] It focuses on energy consumption for space heating which covers 66% of energy demand in the French household sector.

The remainder of this paper is organized as follows. Section 2 provides an overview of Res-IRF. Section 3 details the practical implementation of policy instruments and their representation in Res-IRF. Section 4 compares the outcomes of stand-alone policies. Section 5 assesses different combinations of proposed and hypothetical measures, stressing policy interaction. Section 6 concludes.

2. OVERVIEW OF THE RES-IRF MODEL

Res-IRF builds on a discrete-continuous representation of energy consumption, linking choice of discrete energy efficiency option to continuous adjustments of energy sufficiency (Dubin and McFadden, 1984). According to identity (1), the energy demand for space heating E_{fin} (in kilowatt-hour per year, kWh/y) can be seen as a product of the building stock S (in square meters, m^2), the specific consumption under conventional utilization assumptions E_{conv}/S (in kWh/m^2/y) which is an inverse proxy for the energy efficiency of the stock, and the ratio between conventional and final consumption E_{fin}/E_{conv} , representing a dimensionless "service factor" or utilization rate of the heating infrastructure.

$$E_{fin} = S \frac{E_{conv}}{S} \frac{E_{fin}}{E_{conv}} \tag{1}$$

3. Res-IRF stands for the *residential module of IMACLIM-R France*. IMACLIM is a general equilibrium framework developed at CIRED. IMACLIM-R is a hybrid model linking recursively IMACLIM general equilibrium to technological simulation modules. The national version of IMACLIM-R represents France as a small open economy. Exhaustive descriptions of IMACLIM-R and Res-IRF can be found in Sassi *et al.* (2010) and Giraudet *et al.* (2011), respectively. Key parameters of Res-IRF are outlined in Appendix 1, Table A1.

2.1 Technological Representation of the Building Stock

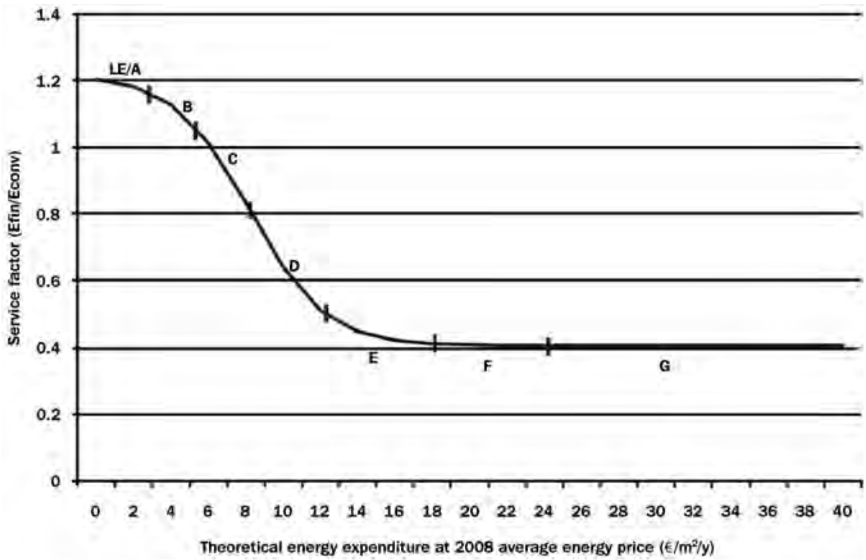
Res-IRF describes the dynamics of the French residential building stock through the construction of new dwellings and the retrofitting of existing ones. The dwelling stock *S* is disaggregated by energy carrier (electricity, gas, fuel oil) and by efficiency class, as labeled by the French energy performance certificate (MEEDDAT, 2008). No explicit technologies are represented, but implicit packages of measures on the building envelope (insulation, glazing) and the heating system that together achieve discrete levels of energy efficiency E_{conv}/S. The performance of existing stock, prior to the calibration year 2007 (hereafter the "existing building stock"), ranges from class G, the least efficient (over 450 kWh/m^2/y of primary energy for heating, cooling and hot water) to class A, the most efficient (below 50 kWh/m^2/y of primary energy). Each year, demand for new construction arises from demolition, population growth, and a demand for increased floor surface per capita. The performance of buildings constructed from 2008 onwards (hereafter the "new building stock") is split into three categories: the 'BC05' or Building Code 2005 level (from 250 to 120 kWh/m^2/y of primary energy, depending on the local climate), 'LE' or Low Energy buildings (50 kWh/m^2/y) and 'ZE' or Zero Energy buildings, for which primary energy consumption is lower than the renewable energy they can produce.

2.2 Drivers of Energy Conservation

In existing dwellings, energy efficiency improvements result from investment that upgrades existing dwellings to higher energy classes (e.g. from G to F,…,A; from F to E,…,A; etc.), as well as from fuel substitution. As in some other models (e.g. CIMS, NEMS), such transitions are determined by logit functions, which allocate to each option a share inversely proportional to its life cycle cost, weighting investment cost against lifetime-discounted energy operating expenditures. In addition, Res-IRF endogenizes the retrofitting rate and enriches this framework with market and behavioral failures[4] that have been empirically established. Heterogeneous discount rates are used to catch the 'landlord-tenant dilemma' (IEA, 2007), which splits incentives between four types of investors: occupying or non-occupying homeowners of individual or collective dwellings. Imperfect information is emphasized through the calibration of "intangible costs" that fill the gap between observed technology choices and choices that would be made under perfect information (Jaccard and Dennis, 2006). The gap is narrowed in the long-run by a decreasing function of intangible costs with cumulative knowledge, representing information acceleration or the "neighbor effect" (Mau *et al.*, 2008; Axsen *et al.*, 2009). The annual number of retrofits is a logistic

4. Market failures such as liquidity constraints, split incentives or imperfect information are assumed to blur cost-minimizing investment decisions, whereas behavioural failures such as bounded rationality move investment decisions away from cost-minimization (Gillingham *et al.*, 2009).

Figure 1: Sufficiency Curve



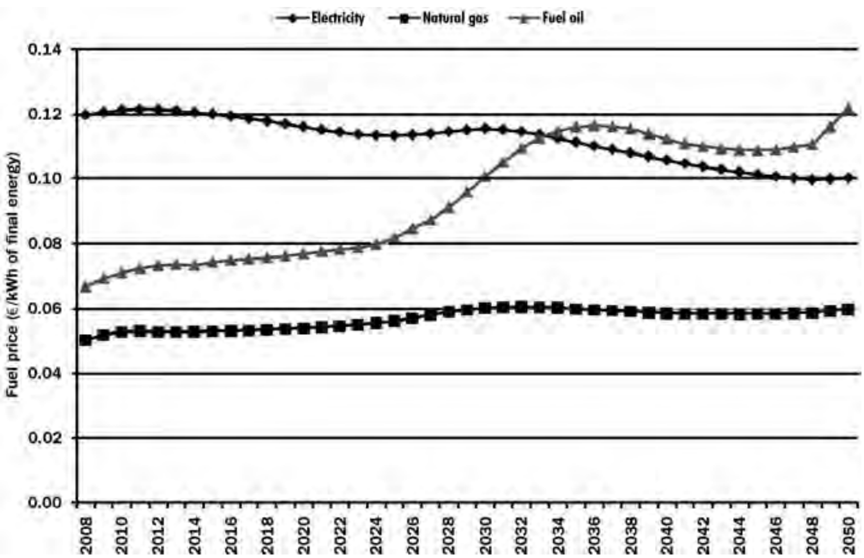
Adapted from Cayre et al. (2011) with indicative location of efficiency classes at 2008 average energy

function of the average net present value of all retrofitting options (including intangible costs), calibrated at the reference year so as to (i) reproduce the observed retrofitting rate and (ii) minimize the weight of negative net present values. In new constructions, one single type of investor more simply chooses one option among nine combinations of potential energy carriers and energy efficiency levels.

As pictured in Figure 1, the final energy demand is adjusted by a logistic curve linking the service factor E_{fin}/E_{conv} to the annual fuel bill at current energy prices, given by the new efficiency of the building stock E_{conv}/S resulting from more numerous and/or efficient retrofits. This relationship is established empirically by Cayre et al. (2011) following empirical specification in Haas *et al.* (1998). It states that the higher (lower) the energy expenditure, the more (less) restrictive the utilization, *i.e.* sufficiency strengthening (relaxation).

Overall, energy efficiency improvements (*i.e.* increased quantity and/or quality—the ambition—of retrofits) result from changes in the relative profitability of various retrofitting options, induced by energy price increase and sustained by retrofitting cost decrease. The latter follows the self-reinforcing process of information acceleration on the demand side, and learning-by-doing on the supply side (Wing, 2006; Gillingham *et al.*, 2008). This evolution is countervailed by the natural exhaustion of the potential for profitable retrofitting actions. From a broader perspective, sufficiency relaxation provides further negative feedback to energy efficiency improvements. Lastly, the recursive hybridization of Res-IRF to IMACLIM-R France ensures macroeconomic consistency (Crassous *et al.*,

Figure 2: Energy Price Scenario



2006; Hourcade *et al.*, 2006). At each time step, the IMACLIM general equilibrium provides households' disposable income and energy prices. These inputs modify energy investment and consumption decisions in Res-IRF, which in turn provides IMACLIM with a new demand for energy and investment in the following period. The domestic energy prices used throughout this paper (Figure 2) are determined by an exogenous world oil price scenario that matches the Annual Energy Outlook 2008 scenario used in the other EMF25 simulations in this issue.

3. IMPLEMENTATION OF THE PROPOSED POLICY MIX IN RES-IRF

Albeit a matter of French concern for about thirty years (Martin *et al.*, 1998; Leray and de La Roncière, 2002), energy conservation has attracted renewed attention with the emergence of climate change issues. The 2005 Energy Law[5] sets a national target of reducing total greenhouse gas emissions (GHG) to a quarter of their 1990 level by 2050. New policies, such as tax credits, have been implemented in the household sector. More recently, the *Grenelle de l'environnement* has set the ambitious target of reducing energy consumption in buildings by 38% in 2020 compared to 2008, and has defined additional policy tools. The present section reviews proposed policies and the way in which they are represented in the model.

5. *Loi n°2005-781 du 13 juillet 2005 de programme fixant les orientations de la politique énergétique*

3.1 Tax Credits on Energy Efficient Durables

The purchase of energy efficient durables, such as double glazing, insulation, efficient boilers or heat-pumps, is eligible for income tax credits, with rates ranging from 15 to 50% of investment cost. This scheme was started in 2005 and grew until, in 2008, it benefited 1.6 million households to the tune of €2.8 billion and an equivalent subsidy rate of 32% (INSEE, 2010). Eligible technologies and subsidy rates were modified in 2009 and the base extended to cover installation expenditures. As such, the scheme has been extended to 2012 and could possibly run until 2020.

Since limited tax credits existed in the calibration year of the model (2007), they are included in the reference scenario. Additional credits from increased rates and the extended base are modeled from 2009 until 2020, through a uniform rebate of 30% of investment cost for all transitions to higher energy classes, capped at €8,000 per dwelling. Tax credits are ultimately paid as a lump-sum to households.

3.2 Zero Rate Loans for Retrofitting Actions

Zero percent interest rates apply for retrofit packages over a base capped at €30,000 per dwelling, for a maximum period of ten years. This can be additional to tax credits but requires a combination of measures on both building envelope and heating system. Launched in 2009, the scheme has benefited 80,000 households in the first year, for average investments of €16,500 per dwelling (SGFGAS, 2010). It is supposed to benefit 800,000 households in 2012 and to last until 2020 (MEEDDM, 2010).

Zero rate loans are implemented in the model as rebates equal to the interest on a conventional ten-year loan at 4%. For example, a €15,000 retrofit would benefit from a €3,490 rebate, provided that the beneficiary paid €1,500 for each of ten annuities, instead of €1,849 under a conventional loan. The base for calculation is total investment costs, net of tax credits and capped at €30,000 per dwelling. It applies to all energy class transitions, assuming that the combination requirement is met when a dwelling is upgraded by at least one energy class.

3.3 Building Code Regulation for New Buildings

Building code regulations have been applied to new residential buildings in France since 1975 and regular tightening has had a traceable impact on the efficiency of the stock (Martin et al., 1998). One of the broadest agreements of the *Grenelle de l'environnement* has been to set future requirements at ambitious levels. Ruled so far by Building Code 2005, new constructions will have to conform to Low Energy level in 2012 (50 kWh/m^2/y of primary energy for heating, cooling, hot water and ventilation) and to Zero Energy level in 2020. Albeit still negligible, the construction of Low Energy buildings is growing very rapidly

(MEEDDM, 2010) in anticipation of the 2012 regulation. Successive regulations are implemented in Res-IRF as a restriction of energy efficiency options in logit choices.[6]

3.4 Retrofitting Obligation

The principle of an obligation to retrofit existing dwellings has been proposed by the non-profit organization négaWatt (Salomon et al., 2005) and was discussed during the *Grenelle de l'environnement* (Pelletier, 2008, p.86). The implementation of this measure in Res-IRF assumes that for every change in dwelling occupancy, homeowners whose dwelling is below a certain energy performance threshold, must upgrade it. The retrofitting rate of dwellings that are below the performance threshold is forced to match occupancy change cycles, estimated to affect 3.5% of owner-occupied dwellings and 18% of rented dwellings annually, i. e. on average 7% of the total stock (CGDD, 2009). Retrofitting choices for these dwellings are restricted to options above the threshold. In addition to mandatory retrofits, *business as usual* endogenous retrofits are still taken into account, net from the retrofits that usually follow changes in occupancy.[7]

The performance threshold is set at class C (below 150 $kWh/m^2/y$ of primary energy). A reasonable assumption is that the obligation will be phased in to avoid bottlenecks on the supply side and high control costs. Accordingly, the obligation is placed on class G dwellings in 2016, on class F dwellings in 2020, on class E dwellings in 2024 and finally on class D dwellings in 2028.

3.5 Carbon Tax

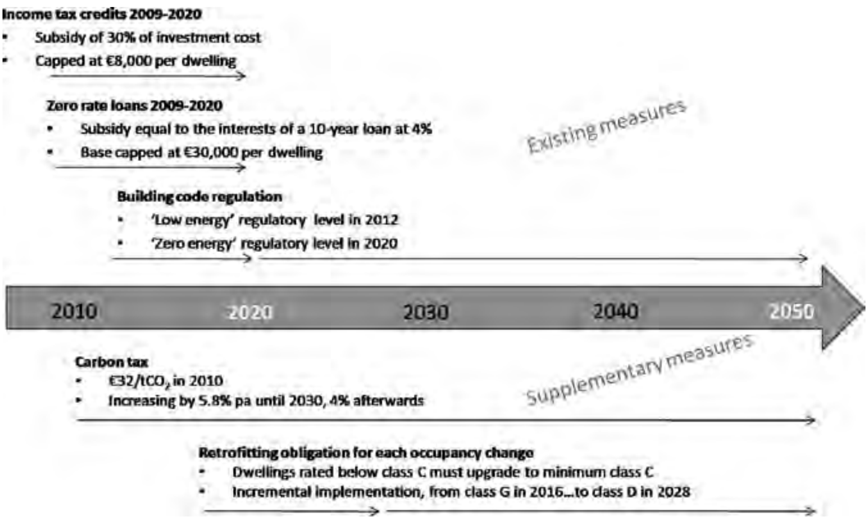
Two successive Government reports have investigated the French social value of carbon (Boiteux and Baumstark, 2001; Quinet *et al.*, 2008). Through modeling exercises, the Quinet report has established a CO_2 price trajectory that would meet the E.U. GHG commitment. The CO_2 tax implemented in Res-IRF follows this recommendation. It is set at €32 per ton of CO_2 in 2010, increases annually by 5.8% until 2030 and by 4% afterwards, thus reaching €217/tCO_2 in 2050. Its revenues are rebated as a lump-sum to households, as in the proposal accepted by Parliament. While ex tax energy prices are myopically expected, the tax is perfectly expected. CO_2 emissions from electricity production are not taxed but electricity consumption is taxed based on the assumption of 180 gCO2/kWh, as was the case in the 2000 French carbon-energy tax proposal.[8]

6. This work has been conducted prior to the signature of a decree stating that the regulation will come into force in residential dwellings on January 1, 2013 *(décret n° 2010-1269 du 26 octobre 2010 relatif aux caractéristiques thermiques et à la performance énergétique des constructions)*. In addition, the decree allows energy consumption higher than 50 $kWh/m^2/y$ is some buildings.

7. Such overlaps represent around 27% of annual retrofits, according to data from OPEN (2009).

8. *Projet de loi de finances rectificative pour 2000*

Figure 3: Summary of Policy Parameters



Note that these five instruments can be ordered in three classes: subsidies that lower upfront cost (tax credits and soft loans), taxes that increase energy-related operating costs and regulations that restrict efficiency choices (building code and retrofitting obligation).

4. STAND-ALONE POLICY COMPARISON

The primary purpose of this paper is to assess the extent to which enacted and proposed policies contribute to the achievement of national abatement targets, namely, a 38% reduction in energy consumption in existing buildings between 2008 and 2020, and a 75% reduction of total CO_2 emissions in 2050 compared to 1990. Admittedly, these targets apply to more sectors and uses than those addressed by the model. Yet aggregate targets are unlikely to be reached if they are not met on the residential space heating perimeter, as this is recognized as having the largest potential for energy conservation for the lowest cost (Baudry and Osso, 2007). Given the specificity of the French electricity generation mix, as developed in Appendix 2, only direct emissions from the consumption of natural gas and fuel oil for space heating are considered.[9] In addition, the same table provides the absolute electricity consumption for every scenario, so that the reader can compute indirect emissions, assuming a given CO_2 intensity of power generation

9. More generally, direct CO_2 emissions and primary energy consumption are deduced from final energy, which is the main output of Res-IRF using conventional assumptions regarding the French energy supply system (see Appendix 1, Table A2).

The following assessment emphasizes policy *effectiveness*, *i.e.* the quantification of energy savings achieved by policies with respect to targets. Drivers of effectiveness are broken down into energy efficiency improvements and sufficiency effects. Efficiency improvements are further split into the number and quality of retrofits. Sufficiency is examined through service factor trajectories and the rebound effect is assessed as an *absolute* rebound effect for each scenario, including the reference, and as a *policy-induced* rebound effect[10]. The *dynamic efficiency* of policy instruments is also assessed by their impact on investment costs through learning-by-doing. All simulations assume constant climate, and numerical results are disclosed in Tables 1 and 2.

4.1 Overview of the Reference Case

Before detailing policy results, it is worth briefly analyzing the reference case. Table 1 and Figure 4 show that the reference scenario generates few final energy savings in 2020 and 2050 compared to 2008. Table 2 reveals a significant fuel switch, mainly from fuel oil to electricity, leading to a net increase in primary energy. The low CO_2 emission cuts in 2050 compared to 1990 can be explained by a 17% increase in CO_2 emissions between 1990 and 2008 (CITEPA, 2010).

The slight decrease in final energy consumption and CO_2 emissions results from the combination of a decrease in specific consumption and emissions, and an increase in the building stock. In 2050, the total housing floor space is expected to be 37% larger than in 2008. Note that 62% of this stock is made up of buildings already in existence in 2007 so that retrofitting issues are crucially important.

Despite an increase in stock, consumption and emissions would decrease significantly, assuming the service factor remains the same, *i.e.* without sufficiency relaxation. It turns out that the service factor increases in the reference scenario (Figure 5). At the end of the time frame, what is referred to as the "absolute rebound effect" reaches 35% (Table 2), which is at the high-end of rebound effect estimates collected for space heating by Sorrell *et al.* (2009). Note that the energy price scenario used is quite stable (*cf.* Figure 2) and does not strengthen sufficiency.

4.2 Policy Ranking

With respect to the implementation of stand-alone policies, Figure 4 and Tables 1 and 2 allow the instruments to be ranked according to their effectiveness

10. The rebound effect is approximated by the growth rate of the service factor compared to a reference situation: $\Delta(E_{fin}/E_{conv})/(E_{fin}/E_{conv}) \approx (\Delta E_{fin}/E_{fin})/(\Delta E_{conv}/E_{conv})$. This can be seen as the elasticity of energy demand to an efficiency term, which is the genuine way of defining the rebound effect (Sorrell *et al.*, 2009). The *absolute* rebound effect compares each scenario at the time considered to the 2008 situation; the *policy-induced* rebound effect compares policy scenarios to the reference scenario.

Table 1

		Evolution of primary energy, including rebound, compared to 2008								Evolution of final energy, over the total stock, compared to 2008					
		Specific consumption in existing buildings		Specific consumption in new buildings		Specific consumption in the total stock		Total consumption in the total stock		Specific consumption, including rebound		Total consumption, including rebound		Total consumption, excluding rebound	
		2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	**2020**	**2050**	2020	2050
Benchmark objective		***−38%***													
Ref	Reference scenario	−8.1%	−19.5%	−0.6%	−1.7%	−11.3%	−23.0%	1.2%	5.2%	−15.6%	−34.2%	**−3.6%**	**−10.0%**	−11.4%	−33.4%
Single policies															
C	Tax credits	−9.2%	−20.7%	−0.6%	−1.7%	−12.3%	−23.8%	0.2%	4.2%	−16.6%	−34.8%	**−4.8%**	**−10.9%**	−13.8%	−34.9%
L	Zero rate loans	−9.0%	−20.4%	−0.6%	−1.7%	−12.0%	−23.6%	0.4%	4.4%	−16.4%	−34.7%	**−4.5%**	**−10.7%**	−13.2%	−34.6%
R	Building code regulation	−8.1%	−19.5%	−44.6%	−78.7%	−16.9%	−44.0%	−5.0%	−23.4%	−19.7%	−49.7%	**−8.3%**	**−31.2%**	−14.0%	−44.6%
T	Carbon tax	−14.5%	−35.2%	−4.4%	−15.9%	−17.1%	−36.7%	−5.3%	−13.5%	−22.9%	−50.1%	**−11.9%**	**−31.8%**	−13.6%	−38.0%
O	Retrofitting obligation	−10.7%	−29.1%	−0.6%	−1.7%	−13.5%	−29.1%	−1.2%	−3.0%	−17.6%	−39.5%	**−5.9%**	**−17.3%**	−14.6%	−48.7%
Proposed packages															
E	Combination of C,L,R	−10.3%	−22.1%	−44.6%	−78.7%	−18.7%	−45.6%	−7.1%	−25.6%	−21.6%	−50.9%	**−10.5%**	**−32.9%**	−18.6%	−47.5%
S1	CLR enriched with T	−16.9%	−37.3%	−46.4%	−81.0%	−24.4%	−55.8%	−13.7%	−39.5%	−28.9%	−62.7%	**−18.8%**	**−49.1%**	−21.8%	−51.5%
S2	CLR enriched with O	−12.7%	−31.0%	−44.6%	−78.7%	−20.6%	−51.2%	−9.4%	−33.3%	−23.3%	−55.8%	**−12.5%**	**−39.5%**	−21.5%	−61.2%
S3	CLR enriched with T and O	−19.3%	−43.8%	−46.4%	−81.0%	−26.3%	−59.8%	−15.9%	−45.0%	−30.6%	−67.0%	**−20.7%**	**−54.8%**	−24.4%	−63.8%
Ambitious packages															
A	S3 with aggressive T	−36.9%	−67.0%	−56.4%	−89.0%	−42.2%	−76.4%	−34.0%	−67.8%	−51.2%	−82.3%	**−44.3%**	**−75.8%**	−37.5%	−72.3%
A+	A with extended C and L	−36.9%	−68.1%	−56.4%	−89.0%	−42.2%	−77.1%	−34.0%	−68.8%	−51.2%	−83.2%	**−44.3%**	**−77.1%**	−37.5%	−75.1%
A++	A+ with aggressive O	−36.9%	−69.3%	−56.4%	−89.0%	−42.2%	−77.9%	−34.0%	−69.8%	−51.2%	−84.4%	**−44.3%**	**−78.7%**	−37.5%	−79.0%

Table 2

		Evolution of fuel share in final energy consumption (in percentage points)						Direct CO2 emissions compared to 1990		Electricity consumption in TWh (in 2008: 58.0 TWh)		Rebound effect			
		Electricity (share 2008: 23%)		Natural gas (share 2008: 53%)		Fuel oil (share 2008: 24%)						Absolute		Policy-induced	
		2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
Benchmark objective									***−75%***						
Ref	Reference scenario	4.4	14.6	0.5	0.7	−4.8	−15.3	5.0%	−18.6%	66.5	85.6	8.8%	35.1%	—	—
Single policies															
C	Tax credits	4.5	14.5	0.7	0.8	−5.2	−15.4	3.5%	−19.3%	66.1	84.6	10.5%	37.0%	1.6%	1.4%
L	Zero rate loans	4.4	14.5	0.6	0.8	−5.1	−15.4	3.9%	−19.1%	66.2	84.8	10.1%	36.5%	1.2%	1.1%
R	Building code regulation	3.1	9.8	0.7	2.6	−3.8	−12.4	1.9%	−32.4%	60.4	57.0	6.5%	24.2%	−2.1%	−8.0%
T	Carbon tax	6.4	23.1	−0.6	−8.2	−5.8	−14.9	−6.9%	−46.1%	65.5	79.7	2.0%	10.0%	−6.3%	−18.6%
O	Retrofitting obligation	4.3	14.8	0.9	2.8	−5.2	−17.6	2.5%	−26.2%	64.8	79.1	10.2%	61.3%	1.3%	19.4%
Proposed packages															
E	Combination of C,L,R	3.2	9.4	1.2	2.9	−4.4	−12.3	−0.9%	−33.7%	59.3	54.9	10.0%	27.8%	1.1%	−5.4%
S1	CLR enriched with T	5.4	16.2	0.6	−4.3	−6.0	−11.9	−13.1%	−54.3%	58.3	50.5	3.8%	5.0%	−4.6%	−22.3%
S2	CLR enriched with O	3.1	8.9	1.6	5.6	−4.7	−14.5	−3.0%	−40.4%	50.1	41.2	11.5%	56.0%	2.4%	15.5%
S3	CLR enriched with T and O	5.3	18.7	1.0	−4.2	−6.2	−14.5	−15.1%	−61.5%	56.6	47.7	4.9%	24.8%	−3.6%	−7.6%
Ambitious packages															
A	S3 with aggressive T	15.9	28.5	−5.9	−13.6	−9.9	−15.0	−49.3%	−82.7%	54.8	31.6	−10.9%	−12.8%	−18.1%	−35.4%
A+	A with extended C and L	15.9	31.3	−5.9	−15.3	−9.9	−16.0	−49.3%	−84.5%	54.8	31.5	−10.9%	−8.0%	−18.1%	−31.9%
A++	A+ with aggressive O	15.9	35.9	−5.9	−19.1	−9.9	−16.8	−49.3%	−87.0%	54.8	31.8	−10.8%	1.4%	−18.1%	−24.9%

Figure 4: Stand-alone Policy Impact on Final Energy Consumption for Space Heating

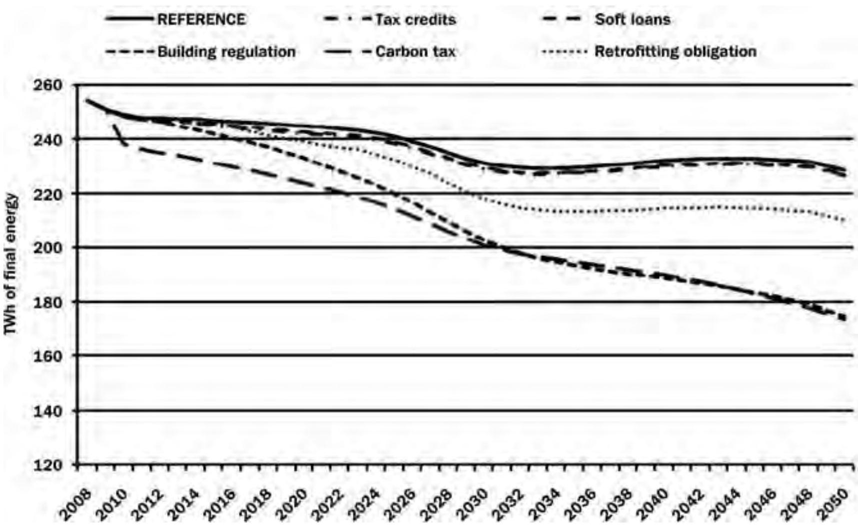


Figure 5: Stand-alone Policy Impact on Sufficiency

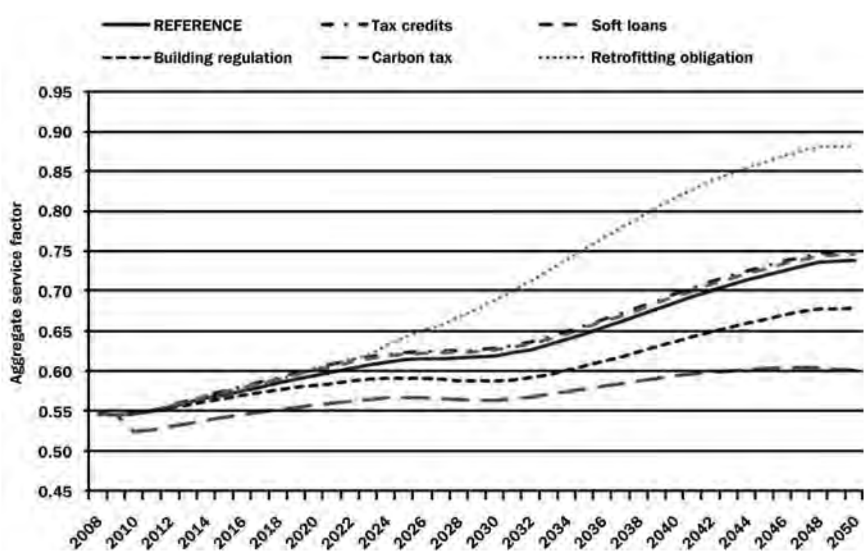
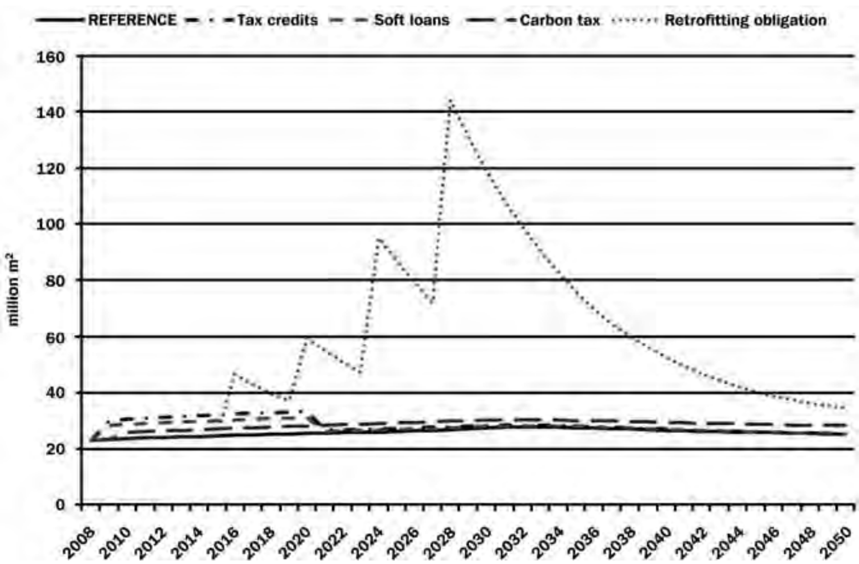


Figure 6: Stand-alone Policy Impact on the Retrofitting Rate



in achieving the targets. Tax credits and soft loans generate the weakest energy savings, notably because they have the shortest duration. Compared to the reference, they increase the number of retrofits whilst they are in place (Figure 6). They also improve the quality of retrofits, as indicated by the decrease of "inefficient" classes (G to D) and the increase of more "efficient" classes (C to A) (Figure 7). The resulting energy efficiency improvements generate a small policy-induced rebound effect (Table 2) by a service factor higher than in the reference case, as illustrated on Figure 5.

The retrofitting obligation ranks next. Each tightening of the obligation to a higher efficiency class is followed by a tremendous increase in retrofitting rate[11], automatically followed by an equally tremendous exhaustion of the potential for profitable retrofits. This explains the switchback time profile of the retrofitting rate shown in Figure 6, as well as the massive decrease in investment costs in response to learning-by-doing depicted in Figure 8. However, such an increase in retrofitting may also face supply side bottlenecks resulting in higher investment costs in the short-term. Such processes are not included in the model but, nevertheless, the building stock structure is dramatically impacted by restricting efficiency choices to the best options (Figure 7). This tool appears especially effective in addressing the landlord-tenant dilemma, as illustrated by the

11. Each year a new efficiency class becomes subject to the obligation, it is as if the retrofitting rate surged from the reference value of 1% to 7%, which corresponds to the average rate of occupancy change.

Figure 7: Stand-alone Policy Impact on the Efficiency of Existing Dwellings in 2050

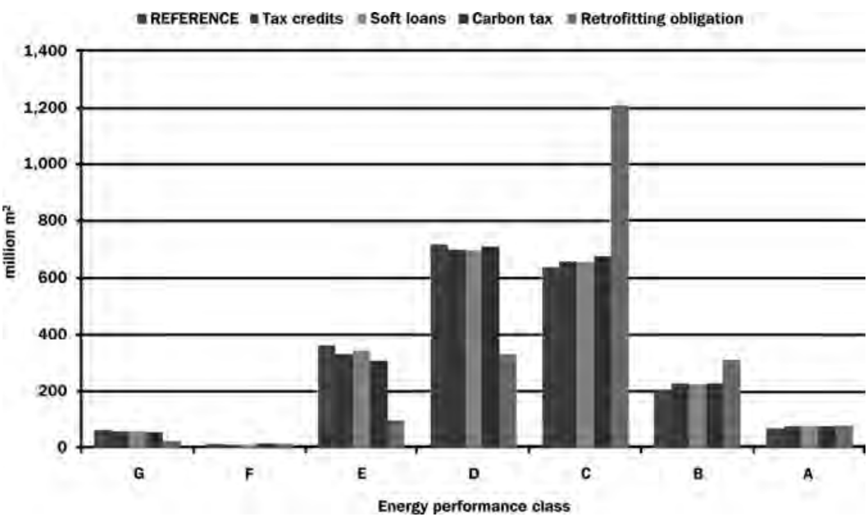
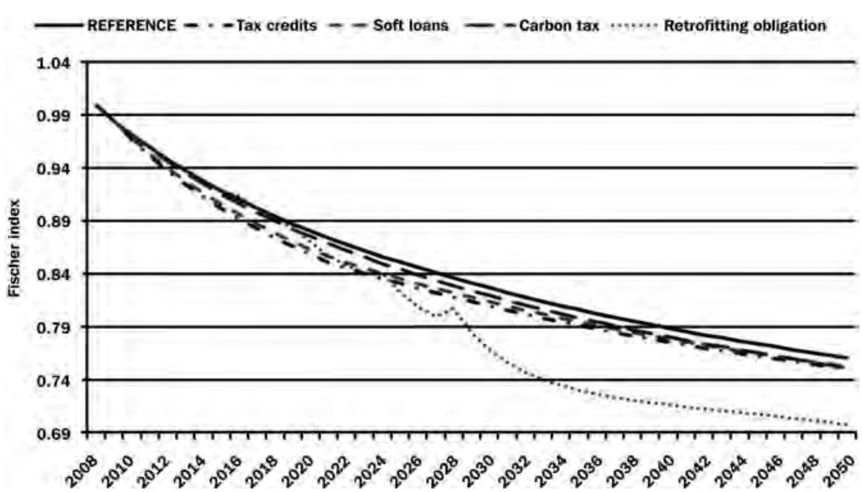
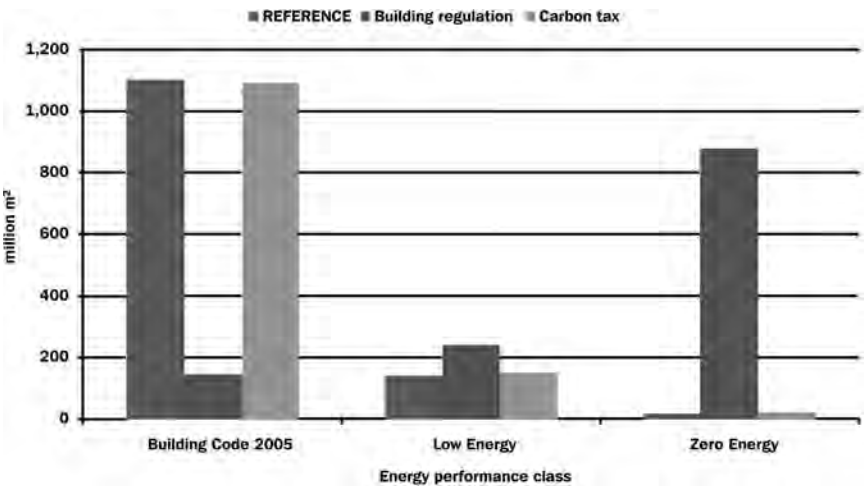


Figure 8: Stand-alone Policy Impact on Retrofitting Costs through Learning-by-doing



large disappearance of classes G, F and E. Because of high discount rates, rented dwellings are poorly retrofitted in reference, as well as in subsidy cases, but the obligation forces the retrofitting of all type of dwellings. It actually applies more often to rented dwellings where occupancy changes are more frequent. However,

Figure 9: Stand-alone Policy Impact on the Efficiency of New Dwellings in 2050

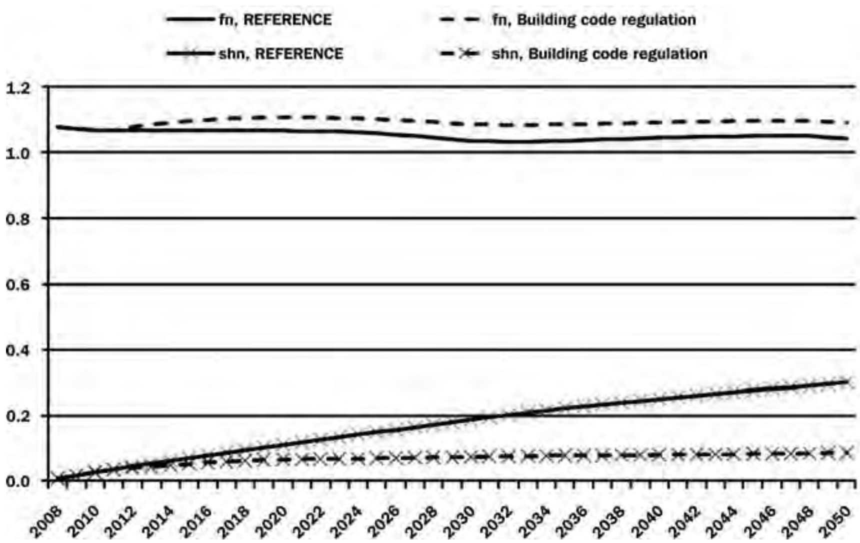


those higher energy efficiency improvements are partly cancelled out by the largest rebound effect of all policies (Table 2) because the obligation threshold lies in the steepest part of the service factor curve (*cf.* Figure 1).

The two highest ranking policies, namely building codes and the carbon tax, last the longest and affect sufficiency strengthening in the same direction. However, a closer look at energy conservation drivers shows different mechanisms. The carbon tax slightly increases the retrofitting rate over the whole time frame, but has a smaller effect than subsidies (Figure 6). Consequently, it entails a lower decrease in investment costs through learning-by-doing, as long as both types of instrument coexist (Figure 8). It improves, however, the ambition of the retrofits, so that its final impact on the efficiency of existing dwellings is comparable to that of subsidies (Figure 7). Its effect on the structure of new building stock is tenuous compared to the reference case (Figure 9) because of a low weight of energy operating expenditures against construction costs. Lastly, the carbon tax generates a massive switch from fossil fuels to electricity (Table2) which, in France, has a low average CO_2 intensity (see Appendix 2). In response to those modest energy efficiency improvements, the potential fuel bill alleviation (*i.e.* shift to the left of the service factor curve, *cf.* Figure 1) is more than compensated by the energy price increase (*i.e.* to the right), thus lessening sufficiency relaxation and lowering the rebound effect compared to the reference scenario.

Building codes have the opposite effect. They turn out to be the only means to significantly increase the efficiency of new building stock. This is followed by a counter-intuitive sufficiency strengthening (Figure 5) due to a composition effect between new and existing building stocks. To explain this, let f be the total service factor, f_e (f_n) the service factor specific to the existing (new)

Figure 10: Sufficiency Effects in New Dwellings (see Equation 2)



building stock and sh_e (sh_n) the share of existing (new) buildings in total conventional energy demand. The total service factor can be written as the weighted average of specific factors (see Appendix 1 for expansion):

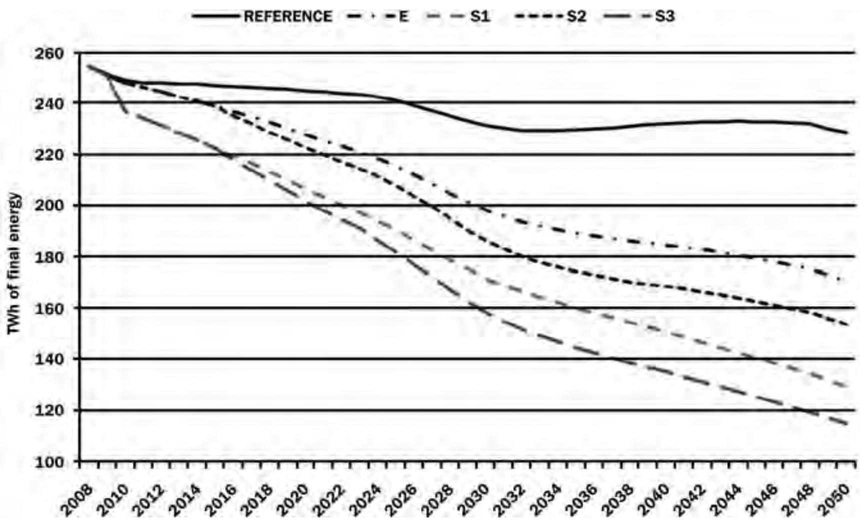
$$f = sh_e f_e + sh_n f_n \tag{2}$$

Figure 10 depicts the evolution of f_n and sh_n in the reference and building code cases. Building codes do relax the service factor specific to new buildings in the wake of efficiency improvements. However, they also reduce the share of new buildings in total energy demand compared to the reference scenario, energy consumption in very efficient constructions being close to zero. As a result, the net effect of the relative increase in f_n and the relative decrease in sh_n with building codes compared to the reference case is negative, thus lowering the total service factor.

In conclusion, financial incentives, such as taxes and subsidies that change relative life-cycle costs, are less effective than regulations in improving energy efficiency[12]. In addition, some more general insights can be drawn. (i) Taxes tend to be dynamically less efficient than subsidies regarding learning-by-doing. (ii) Policies that raise energy efficiency without directly affecting energy prices, such as subsidies and regulations, induce rebound effect. Conversely, the

12. Of course, this conclusion holds only for the tax rates, subsidy levels and retrofitting policies simulated here and not in general.

Figure 11: Combined Policy Impact on Final Energy Consumption for Heating



carbon tax has a virtuous effect on both energy efficiency and sufficiency. This is in line with results from more stylized models (e.g. Giraudet and Quirion, 2008).

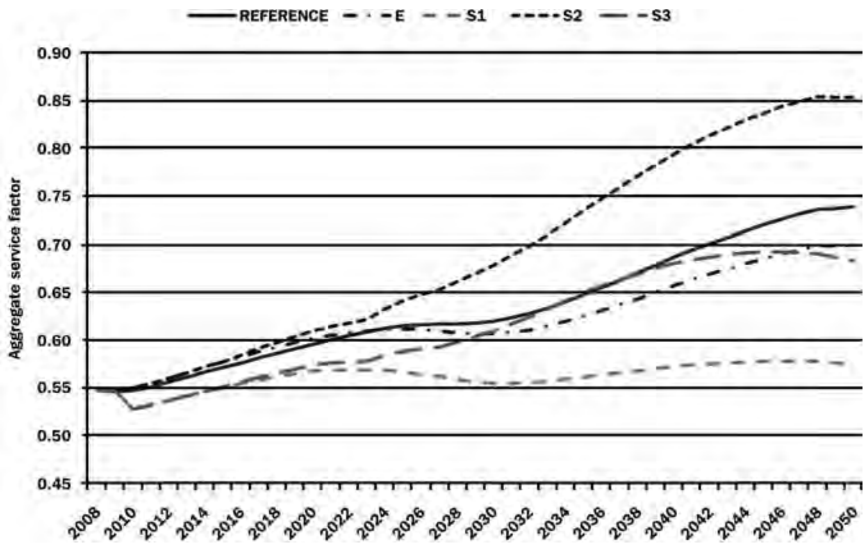
5. POLICY COMBINATION ANALYSIS

In practice, two of the instruments modeled are already in place, one has been partly enacted and two are under discussion. To account for different levels of implementation likelihood, four policy combinations are run. The first package is restricted to “existing” policies whose implementation is effective or certain, namely tax credits, soft loans and building codes (scenario ‘E’). Subsequent hypothetical scenarios add supplementary measures, such as the carbon tax (‘S1’), the retrofitting obligation (‘S2’), and both (‘S3’). Combination outcomes are portrayed in Figure 11.

5.1 Most Likely Policy Package

The basic ‘E’ package saves 10.3% of specific primary energy consumption in existing dwellings in 2020 compared to 2008, and 33.7% of direct CO_2 emissions in 2050 compared to 1990; this is far from the saving targets of 38% and 75% respectively. The specific primary energy savings accruing from the package (net from reference savings, thus 2.2 percentage points [pp]) exceed by 0.2 pp the sum of the separate savings from the two subsidies (*idem*, thus 1.1 pp and 0.9 pp) in existing dwellings in 2020. This indicates that combined savings

Figure 12: Combined Policy Impact on Sufficiency



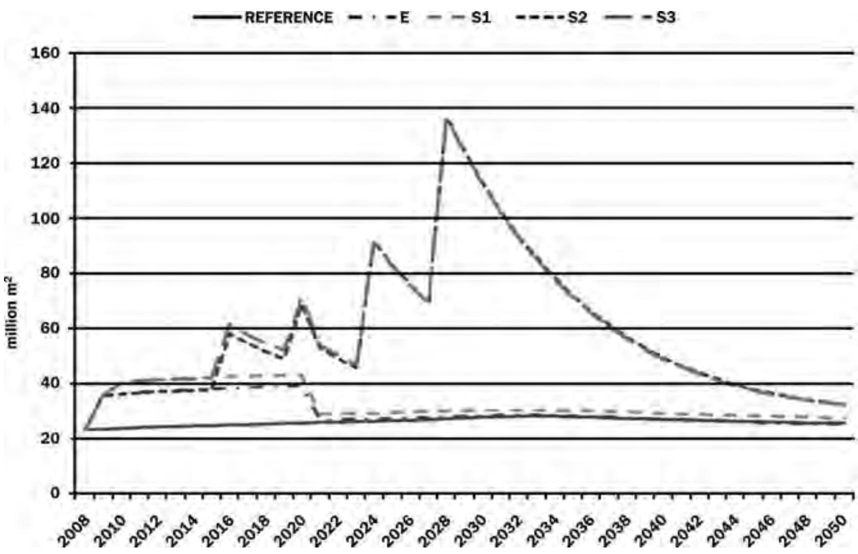
are slightly larger than the sum of separate savings, *i.e.* interactions between tax credits and soft loans are slightly over-additive or, as defined by Boonekamp (2006), reinforcing.

Saving drivers are broken down to further analyze this outcome. Figure 13 shows that the retrofitting rate increase compared to the reference is roughly the sum of separate increases induced by tax credits and soft loans in Figure 6. A closer look shows that the final increase is slightly over-additive. This is due to the non-linear valuation of net present value of retrofitting projects (thanks to a logistic curve, as introduced in Section 2). The addition of two subsidies lowers life-cycle costs, thus increasing the net present value of the average retrofitting project. As a result, the retrofitting rate rises more than proportionally. Together with a qualitative shift towards best energy classes, the building stock turns out to be very efficient in 2050 with combined policies. As a consequence, package 'E' induces a larger rebound effect than the sum of separate policies. This is hardly visible by comparing the 'E' service factor curve on Figure 12 to the curves for separate policies on Figure 5, but it is confirmed by numerical examination.

5.2 Other Hypothetical Policy Packages

Adding a carbon tax and a retrofitting obligation to this basic package provides further energy savings (Figure 11), but even the all-inclusive package 'S3' meets neither the 2020 nor the 2050 target. The comparison of 'S3' final energy savings in 2050 (net from 'E' savings) to the sum of 'S1' (*idem*) and 'S2' savings (*idem*), shows a mitigating interaction between the carbon tax and the

Figure 13: Combined Policy Impact on the Retrofitting Rate



retrofitting obligation (Figure 16). This interaction is of larger magnitude than in the one previously analyzed, and underpins different mechanisms.

As can be seen in Figures 13 and 14, the impacts of scenarios 'S3' and 'S2' are very similar on the retrofitting rate and the structure of the existing stock in 2050. This suggests that between the carbon tax and the retrofitting obligation, the latter is the main driver of energy efficiency improvements. The carbon tax slightly moves energy efficiency choices towards the best options, as attested by the more numerous dwellings labeled A, B and C in scenario 'S3' than in 'S2'. Note that these energy performance classes stand in a domain where the service factor reaches a high plateau or, put another way, where the rebound effect saturates (*cf.* Figure 1). As a result, Figure 12 suggests that the net effect of policy combination on the service factor is strengthening and driven by the carbon tax, provided that the 'S3' curve is always closer to 'S1' than to 'S2'. However, this reinforcing effect of the carbon tax on sufficiency does not compensate for the fact that efficiency gains accruing from scenario 'S3' are seemingly lower than the sum of the gains from scenarios 'S1' and 'S2'. For instance, it is clear that the disappearance of the inefficient class E in 'S3' is not as large as the additive effect of 'S1' and 'S2' would suggest (Figure 14).

5.3 Ambitious Scenarios to Meet National Targets

According to the preceding positive assessment, policy packages, *as they are officially defined*, fall short of meeting national targets, despite some reinforcing interactions. This provides grounds for a normative investigation of more aggressive measures.

Figure 14: Combined Policy Impact on the Efficiency of Existing Dwellings in 2050

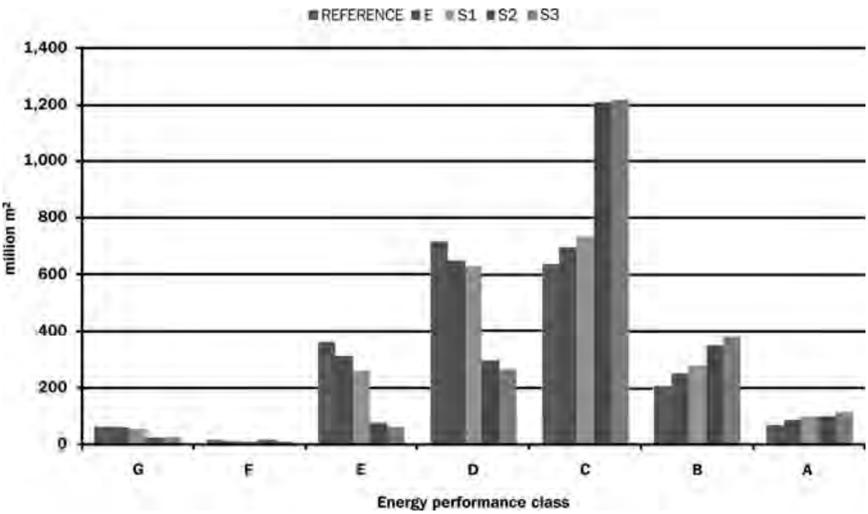
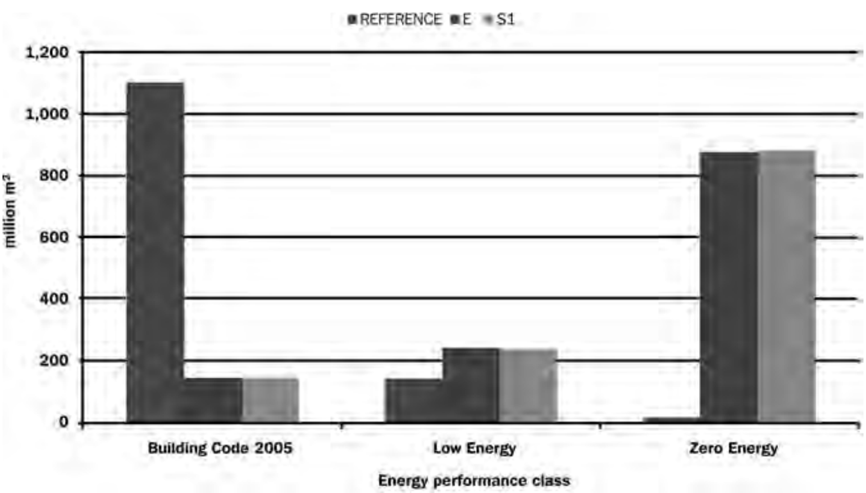


Figure 15: Combined Policy Impact on the Efficiency of New Dwellings in 2050



First, an effective tax is sought through iterative doubling of the initial tax rate within the 'S3' package. As attested by Figure 17, rate increase has a marginally decreasing effect which can be explained by the saturation of the energy service factor at the high-end of the energy classes, thus preventing tax

Figure 16: Gains in Final Energy Consumption in 2050 Compared to 2008

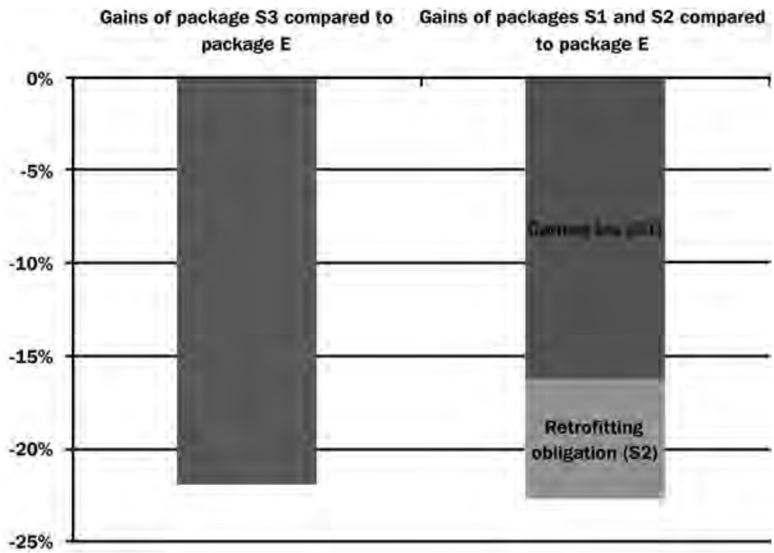


Figure 17: Gains in Specific Primary Energy in Existing Dwellings in 2020 Compared to 2008

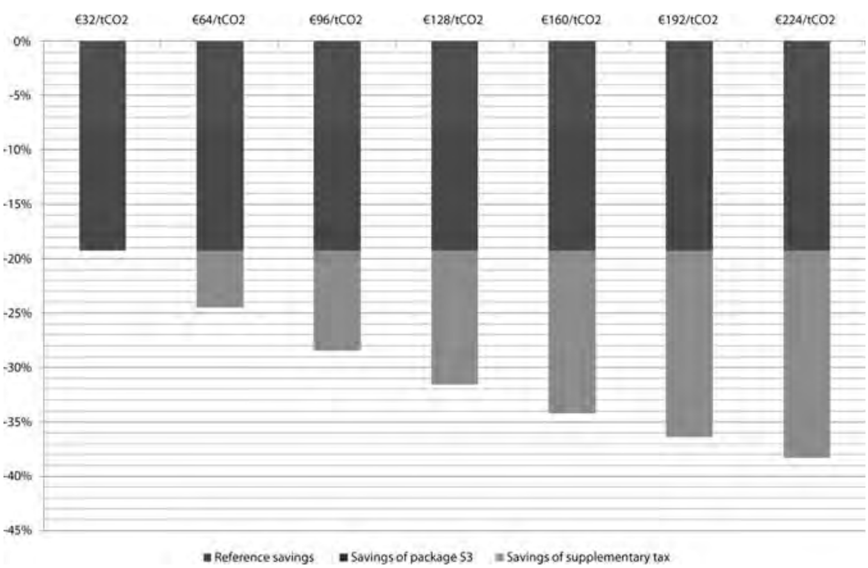


Figure 18: Impact of Ambitious Packages on the Efficiency of Existing Dwellings in 2050

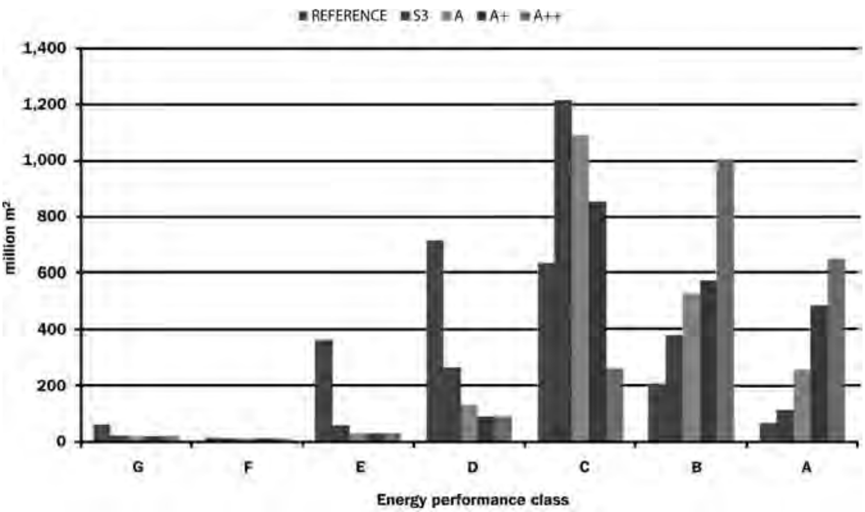
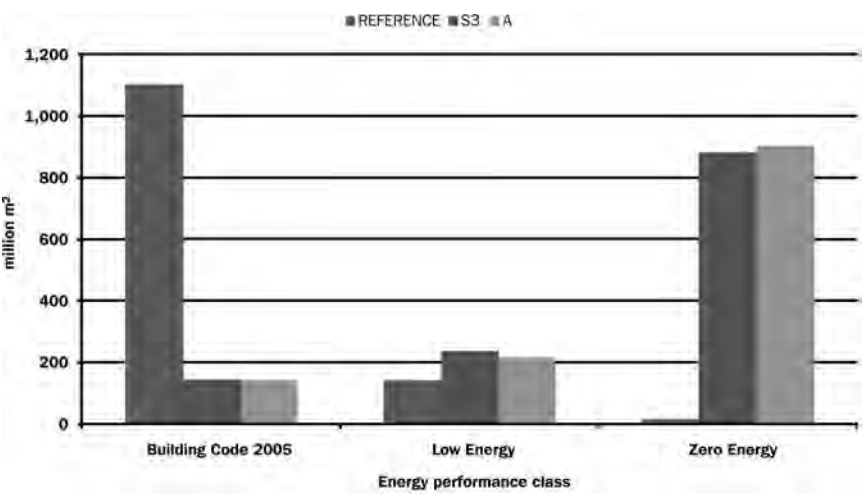
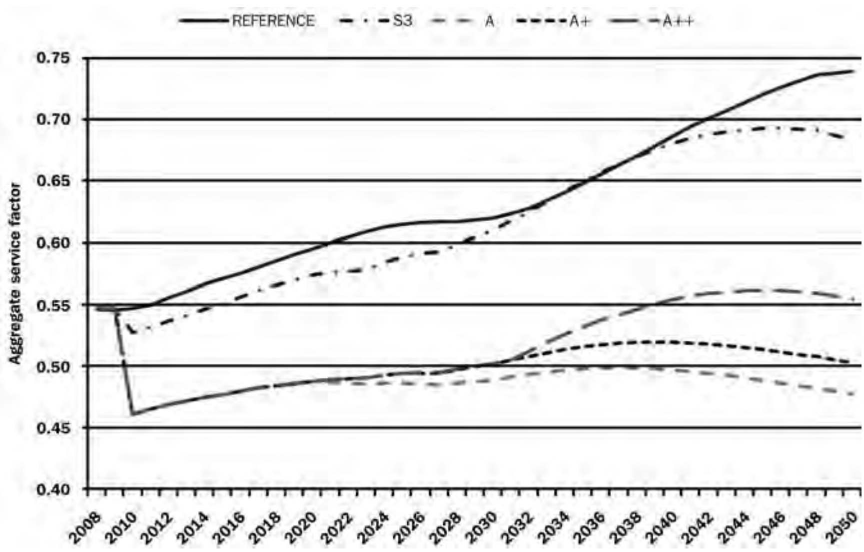


Figure 19: Impact of Ambitious Packages on the Efficiency of New Dwellings in 2050



from further strengthening sufficiency. Eventually, a tax whose 2010 rate is six times higher than the initial one reduces energy consumption by 38% in 2020 compared to 2008. This is captured by the 'A' scenario, which builds on 'S3' and sets the tax at the initial rate of €200/tCO_2 (thus reaching €1,907/tCO_2 in 2050 with the annual increase rate introduced in section 3.5).

Figure 20: Impact of Ambitious Packages on Sufficiency



Two additional "ambitious" scenarios are run to bring heating consumption closer to the 2050 target. Scenario 'A + ' builds on 'A' and extends subsidies to 2050, while in addition, scenario 'A + + ' sets the retrofitting obligation threshold at class B (applied incrementally from class G dwellings in 2016 to class C dwellings in 2032). Results in Figure 18 show that each policy strengthening further moves retrofitting choices towards classes B and A at the expense of other classes. Similar conclusions hold for the new building stock, as attested by Figure 19. In turn, each policy strengthening increases the energy service factor over the 2030–2050 period (Figure 20). Such packages allow CO_2 emissions to be reduced to a quarter of their 1990 levels by 2050 (Table 2).

6. CONCLUSION

This paper assesses the effectiveness of various policy options that target energy consumption in the French residential sector. In particular, it analyses whether various policy packages are able to meet the ambitious targets set by the French public authorities for CO_2 emissions and energy consumption. It uses a hybrid energy-economy model that incorporates specific features of energy conservation, especially the rebound effect and some "barriers" to energy efficiency such as split incentives and imperfect information. Barriers are progressively overcome through information acceleration and learning-by-doing, leading to adoption externalities, but those endogenous dynamics are countervailed by the natural exhaustion of the potential for energy saving and the rebound effect.

The policy packages that are assessed combine subsidies (tax credits and zero rate loans), regulations (building codes and retrofitting obligations) and carbon taxes. Overall, the model unambiguously establishes that they fall short of reducing energy consumption by 38% in 2020 compared to 2008, and they fail to reduce CO_2 emissions due to space heating in residential buildings to a quarter of their 1990 level by 2050. Such a pessimistic result calls for methodological discussion of unaccounted effects and scenario definition.

One possibility for reducing CO_2 emissions is a switch from fossil fuels to wood. The inclusion of this option would require complex linkage with a model of the French forest to represent the limited supply of wood. Another reason for the pessimistic result lies in scenario definition. Price scenarios adopted for electricity, natural gas and fuel oil are quite stable and obviously lead to poor energy savings in the reference case. Finally, policy scenarios concentrate on instruments that fit stylized representations of subsidies, regulations and taxes, but omit complementary measures, such as information campaigns, energy performance contracts, new contracts where retrofitting costs are shared between owners and occupants of rented dwellings, and the obligation put on energy companies to promote energy savings with flexibility options, *i.e.* the trading of so-called "white certificates". The switch to wood, higher (before tax) energy prices and these complimentary policy options might make it possible to meet French national targets, but it is likely that less ambitious packages would fail. This means that a rapid strengthening of climate policy is required. In particular, the importance of the rebound effect suggests that policies specifically targeting sufficiency should accompany the more common energy efficiency policies. This could be achieved by giving households feedback about their energy savings, proven to be very effective, especially when a comparison with other households is provided (Abrahamse *et al.*, 2005; Ayres *et al.*, 2009).

Theoretical insights can also be drawn from this case study. The most salient result regarding stand-alone policies is the virtuous effect of a carbon tax on both energy *efficiency* and *sufficiency*. On policy combination, the analysis of policy interactions exhibits reinforcing effects of tax credits and soft loans, and mitigating effects of carbon taxes and retrofitting obligations. Yet such effects are tenuous and depend upon the specific architecture of the model and the numerical settings of policy parameters. Hence, a more systematic mapping of policy interaction with varying parameters would be needed to provide robust insights. Still, these illustrative examples suggest that fine *policy coordination* is needed (Bennear and Stavins, 2007). In particular, policy-makers should pay attention to setting policies efficiently, *i.e.* in domains where a marginal variation of the main policy parameter induces a more than proportional saving variation (Knudson, 2009). This potentially influences the mitigating or reinforcing nature of any interactions.

Lastly, a comprehensive policy evaluation requires a quantification of the monetary costs and benefits of energy conservation. Further room for improvement would be the assessment of the distributive impact of the various policy options across income groups. This could be achieved in the future from forthcoming developments of the Res-IRF model on both the demand and supply side.

ACKNOWLEDGMENTS

We are indebted to Benoît Allibe for data support. We thank Hill Huntington and the participants to the Energy Modeling Forum 25, which fostered the course of this study. We also thank anonymous referees, as well as Ruben Bibas, Dominique Finon and participants to the 10th European Conference of the International Association for Energy Economics, held in Vienna, September 2009, and to the International Energy Workshop, held in Stockholm, June 2010, for useful comments on earlier versions of this work. This work has been partly funded by the French General Commission for Sustainable Development *(Commissariat général au développement durable)*. We are grateful to Jean-Jacques Becker, Lucile Penot-Antoniou and Olivier Teissier for providing policy guidelines and useful comments.

APPENDIX 1: TECHNICAL COMPLEMENTS

Expansion of Equation (2)

Let f be the total service factor, E_{fin} the final energy consumption and E_{conv} the energy consumed under normalized utilization assumption. Indexes n and e refer to the new and existing building stocks, respectively. The general expression of the service factor $f = \frac{E_{fin}}{E_{conv}}$ can be developed as $f = \frac{E^n_{fin} + E^e_{fin}}{E^n_{conv} + E^e_{conv}}$, or $f = \frac{E^n_{conv} f^n + E^e_{conv} f^e}{E^n_{conv} + E^e_{conv}}$. Now, let sh^i be the share of stock i in the total conventional consumption: $sh^i = \frac{E^i_{conv}}{E_{conv}}$. The total service factor can thus be written as: $f = sh^e f^e + sh^n f^n$

Table A1: Main assumptions of the Res-IRF model

Discount rates	7% for new constructions. 7% and 10% (35% and 40%) for (non) occupying homeowners of individual and collective existing dwellings, respectively
Initial retrofitting rate	1% of the 2007 building stock is assumed to make at least one energy class transition (based on OPEN, 2009)
Information acceleration rate	Intangible cost decrease by 25% for every doubling of the cumulative retrofits, following a logistic curve.
Learning-by-doing rate	Investment cost decrease by 10% for every doubling of the cumulative retrofits in existing buildings and by 15% for every doubling of cumulative constructions in new buildings, following a power curve
Theoretical lifetime of energy efficiency investments	35 years for measures targeting the envelope, 20 years for measures targeting the heating system

Table A2: Conventional assumptions of the French energy supply system

Conversion factor of electricity into primary energy	2.58 kWh of primary energy for each kWh of final electricity (MEEDDAT, 2008)
Direct emissions from final energy consumption	271 gCO2/kWh for fuel oil (ADEME, 2008) 206 gCO2/kWh for natural gas (ADEME, 2008)

APPENDIX 2: ELECTRICITY GENERATION IN FRANCE

In France, almost 90% of the electricity produced is generated by technologies avoiding direct CO_2 emissions, i.e. nuclear power (75% in 2009), hydroelectricity and other renewable energies (13%). The rest (11%) is provided by fossil fuels, mostly coal. This specific situation in the European landscape of electricity generation gives rise to important debate about how to evaluate the carbon content of French electricity. So far, two methodologies have been put forward. The *historical average* carbon content allocates a share of domestic emissions from the electricity generation process to each end-use according to its seasonal time-of-use, whereas the *marginal* content evaluates changes in the generation mix induced by marginal variation of electricity demand. Indeed, most of the time, some fossil fuel thermal plants are in operation and since they incur the highest variable cost, they are switched on or off in priority when electricity demand fluctuates. Applied to space heating, which contributes a lot to winter peak demand, the first method yields 180 grams of CO_2 emitted per kilowatt-hour of final electricity consumed (ADEME and EDF, 2005) while the second yields 500–600 gCO_2/ kWh (ADEME and RTE, 2007).

The assumption of average carbon content has some advantages that could justify its use in Res-IRF. First, it reproduces fairly well the CO_2 emissions at the initial year. Second, it is well suited to the representation of electricity generation that prevails in IMACLIM-R France, assuming a total disconnection from the unrepresented European energy system. However, it turns out to be inappropriate as soon as changes in electricity consumption are considered. The marginal carbon content assumption is seemingly more appropriate for that task, but it can only be applied to marginal variations in electricity demand, thus preventing investigation of long-term changes in the generation mix. Moreover, it does not allow the calibration of CO_2 emissions at the initial year.

For these reasons, the simulations undertaken in this paper do not display indirect CO_2 emissions arising from the generation of electricity consumed for space heating. This issue will be addressed in the future by linking Res-IRF to an explicit module of electricity generation within the IMACLIM-R France framework. In the absence of such sophisticated modeling, the only effect that can be anticipated from the general reduction in electricity consumption for space heating in the short-term is that French fossil-fired electricity imports will decrease, and so will CO_2 emissions in their country of origin, mainly Germany and Belgium (ADEME and RTE, 2007).

REFERENCES

Abrahamse, W., L. Steg, C. Vlek, T. Rothengatter (2005). “A review of intervention studies aimed at household energy conservation.” *Journal of Environmental Psychology*, 25(3): 273–291.

ADEME [Agence de l’environnement et de la maîtrise de l’énergie], EDF (2005). Note de cadrage sur le contenu CO_2 du kWh par usage en France.

ADEME [Agence de l’environnement et de la maîtrise de l’énergie], RTE [Réseau de transport d’électricité] (2007). Le contenu en CO2 du kWh électrique: Avantages comparés du contenu marginal et du contenu par usages sur la base de l’historique. Note détaillée.

ADEME [Agence de l’environnement et de la maîtrise de l’énergie] (2008). *Les chiffres clé du bâtiment*

Alcott, B. (2008). “The sufficiency strategy: Would rich-world frugality lower environmental impact?” *Ecological Economics*, 64(4): 770–786.

Axsen, J., D. C. Mountain, M. Jaccard (2009). “Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles.” *Resource and Energy Economics*, 31(3): 221–238.

Ayres, I., S. Raseman, A. Shih (2009). “Evidence from Two Large Field Experiments that Peer Comparison Feedback Can Reduce Residential Energy Usage.” NBER Working Paper, No. 15386.

Baudry, P., D. Osso (2007). “Uncertainties in the evaluation of energy savings potential.” *Proceedings of the ECEEE summer study*, 583–588.

Bennear, L.S., R.N. Stavins (2007). “Second-best theory and the use of multiple policy instruments.” *Environmental and Resource Economics*, 37(1): 111–129.

Boiteux, M., L. Baumstark (2001). *Transports: choix des investissements et coûts des nuisances.* Rapport pour le Commissariat général au plan, La Documentation française, 2001.

Boonekamp, P.G.M. (2006). “Actual interaction effects between policy measures for energy efficiency—A qualitative matrix method and quantitative simulation results for households.” *Energy*, 31(14): 2848–2873.

Cayre, E., B. Allibe, M.-H. Laurent, D. Osso (2011). “There are people in the house!: How misleading for energy policies are the results of purely technical analysis of residential energy consumption.” *Proceedings of the ECEEE Summer Study*, Paper 7-277, 1675–1683.

CGDD [Commissariat général au développement durable] (2009). « La mobilité résidentielle progresse dans le parc locatif privé et diminue dans le parc social. » *Observation et Statistiques*, n°27.

CITEPA [Centre Interprofessionnel Technique d’Etudes de la Pollution Atmosphérique] (2010). *Rapport national d’inventaire pour la France au titre de la convention cadre des Nations Unies sur les changements climatiques et du Protocole de Kyoto*

Crassous, R., J.-C. Hourcade, O. Sassi (2006). “Endogenous Structural Change and Climate Targets Modeling Experiments with Imaclim-R.” *The Energy Journal*, Special Issue: Endogenous Technological Change and the Economics of Atmospheric Stabilisation, 259–276.

Dubin, J.A., D.L. McFadden (1984). “An Econometric Analysis of Residential Electric Appliance Holdings and Consumption.” *Econometrica*, 52(2): 345–362.

Gillingham, K., R. Newell, W.A. Pizer (2008). “Modeling endogenous technological change for climate policy analysis.“ *Energy Economics*, 30(6): 2734–2753.

Gillingham, K., R. Newell, K. Palmer (2009). “Energy Efficiency economics and policy.” *Annual Review of Resource Economics*, 1: 597–619.

Giraudet, L.-G., P. Quirion (2008). “Efficiency and distributional impacts of tradable white certificates compared to taxes, subsidies and regulations.” *Revue d’économie politique*, 118(6): 885–914.

Giraudet, L.-G., C. Guivarch, P. Quirion (2011). “Exploring the potential for energy conservation in French households through hybrid modeling.” *Energy Economics*, doi: 10.1016/j.eneco.2011.07.010.

Goulder, L.H., I.W.H. Parry (2008). “Instrument choice in environmental policy.” *Review of Environmental Economics and Policy*, 2(2): 152–174.

Haas, R., H. Auer, P. Biermayr (1998). “The impact of consumer behavior on residential energy demand for space heating.” *Energy and Buildings*, 27(2): 109–205.

Hourcade, J.-C., M. Jaccard, C. Bataille, F. Ghersi (2006). “Hybrid Modeling: new answers to old challenges.” *The Energy Journal*, Special issue 2: Hybrid Modeling of Energy Environment Policies, 1–12.

IEA [International Energy Agency] (2007). *Mind the gap: Quantifying principal-agent problems in energy efficiency*. Paris.

INSEE [Institut national de la statistique et des études économiques] (2010). « Le recours au crédit d’impôt en faveur du développement durable: Une résidence principale sur sept rénovées entre 2005 et 2008. » *INSEE PREMIERE*, n°1089.

Jaccard, M., M. Dennis (2006) “Estimating home energy decision parameters for a hybrid energy-economy policy model”, *Environmental Modeling and Assessment*, 11(2): 91–100.

Jaffe, A.B., R.N. Stavins (1994). “The energy-efficiency gap: What does it mean?” *Energy Policy*, 22(10): 804–810.

Knudson, W.A. (2009). “The Environment, Energy, and the Tinbergen Rule.” *Bulletin of Science, Technology and Society*, 29(4): 308–312.

Leray, T., B. de la Roncière (2002). *30 ans de maîtrise de l’énergie*. Association technique énergie environnement, Arcueil.

Levine, M., D. Ürge-Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli Mehlwana, S. Mirasgedis, A. Novikova, J. Rilling, H. Yoshino (2007). *Residential and commercial buildings. In Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Martin, Y., Y. Carsalade, J.-P. Leteurtrois, F. Moisan (1998). *La maîtrise de l’énergie: rapport d’évaluation*. La Documentation française, Paris.

Mau, P., J. Eyzaguirre, M. Jaccard, C. Collins-Dodd, K. Tiedemann (2008). “The ‘neighbor effect’: Simulating dynamics in consumer preferences for new vehicle technologies.” *Ecological Economics*, 68(1–2): 504–516.

MEEDDAT [Ministère de l'écologie, de l'énergie, du développement durable et de l'aménagement du territoire] (2008). *Le diagnostic de performance énergétique*

MEEDDM [Ministère de l'écologie, de l'énergie, du développement durable et de la mer] (2010). *La fiscalité environnementale prend son essor*

OECD [Organisation for Economic Co-operation and Development] (2007). *Instrument Mixes for Environmental Policy*. Paris.

OPEN [Observatoire permanent de l'amélioration énergétique du logement] (2009). Rapport final.

Pelletier, P. (2008). *Rapport au Ministre d'Etat, ministre de l'Ecologie, du Développement et de l'Aménagement durables, Comité opérationnel « rénovation des bâtiments existant »*

Quinet, A., L. Baumstark, J. Célestin-Urbain, H. Pouliquen, D. Auverlot, C. Raynard (2008). *La valeur tutélaire du carbone*. Rapport de la commission présidée par Alain Quinet, Conseil d'Analyse Stratégique, La Documentation française, Paris.

Salomon, T., C. Couturier, M. Jedliczka, T. Letz and B. Lebot (2005) *A negawatt scenario for 2005–2050*. Proceedings of the ECEEE summer study, 89–95.

Sanstad, A.H., R.B.Howarth (1994). "'Normal' markets, market imperfections and energy efficiency." *Energy Policy*, 22(10): 811–818.

Sassi, O., R. Crassous, J.-C. Hourcade, V. Gitz, H. Waisman, C. Guivarch (2010). "IMACLIM-R: a modelling framework to simulate sustainable development pathways." *International Journal of Global Environmental Issues*, 10(1–2): 5–24.

SGFGAS [Société de gestion du fonds de garantie de l'accession sociale à la propriété] (2010). Bilan statistique des éco-prêts à taux zéro émis en 2009.

Sorrell, S., E. O'Malley, J. Schleich, S. Scott (2004). *The economics of energy efficiency: barriers to cost-effective investment*. Edward Elgar Ed. Cheltenham.

Sorrell, S., J. Dimitropoulos, M. Sommerville (2009). "Empirical estimates of the direct rebound effect: A review." *Energy Policy*, 37(4): 1356–1371.

Tinbergen, J. (1952). *On the theory of economic policy*. Amsterdam: North Holland.

Wing, I.S. (2006). "Representing induced technological change in models for climate policy analysis." *Energy Economics*, 28(5–6): 539–562.

An Assessment Study of Energy Efficiency Policy Measures for Japanese Commercial Sector

Masahito Takahashi and Hiroshi Asano**

Building sector is the highest growing sector in energy demand in Japan at present. There is a strong need to reduce this sectoral energy demand to achieve the national carbon emission target.

This study focuses on Japanese commercial sector and shows model analysis results of energy efficiency policy impacts on the sectoral carbon emission trajectory, using CRIEPI's bottom-up energy model. The policy cases we analyzed are consistent with those of other EMF25 model teams. The results indicate that, the introduction of low carbon tax has little impact on the sectoral final energy demand and carbon emission trajectory and, on the other hand, enhanced energy efficiency standard and reduced equipment cost of products are very effective on reducing the sectoral energy demand.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-13

1. INTRODUCTION

To achieve the Kyoto target, Japan has to reduce the carbon emission for 2008–2012 by 6% from the 1990 level, that is, 12% from the 2008 level. Japanese government announced that Japan aims to reduce the carbon emission by 25% in 2020 from the 1990 level as a post Kyoto target, if a fair and effective international framework is established in which all major economies participate and agree to these ambitious targets. This 25% carbon emission reduction is considered a very ambitious emission target for Japan, because Japan is one of the most energy-efficient economies in the world, and therefore further carbon emission reduction efforts could be more costly than for other economies.

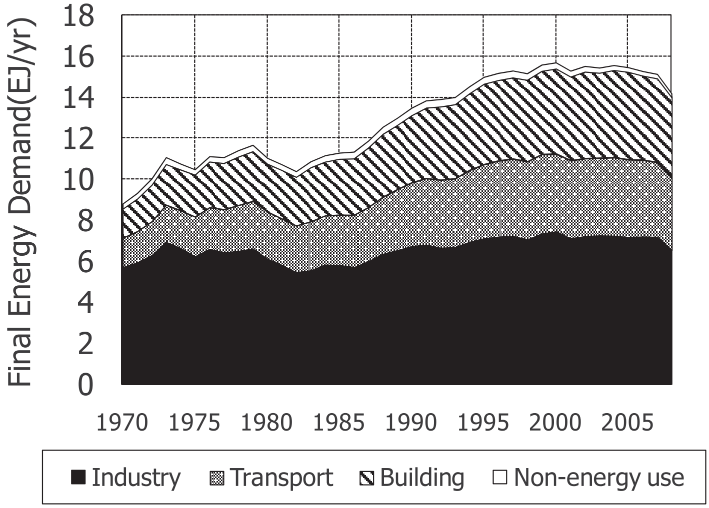
Figure 1 shows a sectoral final energy demand development of Japan from 1970 to 2008. The total energy demand has been increasing steadily through-

The Energy Journal, Special Issue. Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective.

* Central Research Institute of Electric Power Industry, Japan.

doi: 10.5547/ISSN0195-6574-EJ-Vol32-SI1-13

Figure 1: Past Trend of Sectoral Final Energy Demand in Japan



Source: EDMC 2009.

out the period, though it dropped in 2008 because of global recession after Lehman' fall. Industrial sector has shown a saturated energy demand growth in the past decade, but building and transport sectors have been growing steadily in the energy demand. Building sector has grown by 20% and transport sector has grown by 13% in 2008 from the 1990 level. There is a strong need to reduce these two sectoral energy demands to achieve the 2020 national carbon emission target.

Although various policy measures have been already introduced and undertaken in Japan to conserve the sectoral energy use, e.g. energy efficiency standard regulation for energy-using products and designated energy management factories, additional policy measures are needed to cut further the carbon emissions. As the additional policy measures, introduction of a tax for global warming countermeasures was decided by the cabinet on December 16, 2010 and the bill for feed-in tariffs for renewable energy generation was passed through the Diet and will be effective in July, 2012.

This paper focuses on Japanese commercial building sector. The purpose of this paper is to assess the effectiveness of additional carbon emission mitigation policy measures in the commercial building sector and estimate the impact on the sectoral carbon emission trajectory toward 2030. Here we pick up three additional policy measures as follows: (1) carbon tax, (2) strengthening equipment efficiency standards, (3) enhancement of subsidy programs.

There are two key issues to be studied in this paper. One is whether or not introduction of carbon tax has impacts on the sectoral carbon emission trajectory and, if it has, how big of an impact it has. Another is whether or not the carbon tax has a bigger impact on the carbon emission than strengthened equipment standards or enhancement of subsidy programs.

In the second section, we will overview current energy policies for energy conservation and carbon emission mitigation in Japan. In the third section, our model used for assessment of policy measures is explained briefly. The fourth section explains about carbon emission abatement technologies for Japanese commercial sector we considered in the model analysis. The fifth section explains about cases we analyzed and shows model results. The final is a summery.

2. POLICY MEASURES FOR ENERGY CONSERVATION IN JAPAN

Energy Tax

There are a couple of energy taxes already implemented in Japan's economy.

The oil tax was introduced in Japan after two oil crises in the 1970s in combination with other energy efficiency policy measures. Oil products for road transport are mainly taxed and the present tax rate is 53.8 yen/liter for automobile gasoline and 32.1 yen/liter for light diesel oil.[1] The purposes of this oil tax introduction are to save oil consumption, decrease imported oil dependency and provide funding resources for road network building. This oil tax provides the government with the biggest financial resources of all of the energy taxes.

The petroleum and coal tax act was revised in 2003. Under this act, crude oil, oil products, coal, LNG and LPG used in all of the energy-consuming sectors, with a few exceptions, are taxed and the present tax rate is 2.04yen/liter for crude oil and oil products, 0.7yen/kg for coal and 1.08yen/kg for LNG and LPG. This tax rate is expected to be raised in the near future in the context of global warming prevention.

The promotion of power resources development tax was introduced in 1974 after the oil crises to develop and promote alternative power resources to oil in the country, mainly nuclear power. Under this tax system, grid electricity consumed by end users is taxed at 0.375yen/kWh at present.

Top Runner Program

The Top Runner energy efficiency standard regulation for energy-using products was introduced in 1998 and is regarded as the most successful energy efficiency program in Japan (METI, 2010). The Top Runner Program is a maximum standard value system. Under this program, the target value of energy efficiency of energy-using products is set based on the value of the most energy efficient products in the market at the time of the value setting process, consid-

1. This oil tax rate is equal to US$85.5 per barrel for automobile gasoline and US$51.0 per barrel for light diesel oil, supposing a currency exchange rate is 100 yen/US$.

Table 1: Target Products under the Top Runner Program in Japan

1. Passenger vehicle	13. Space heater
2. Air conditioner	14. Rice Cooker
3. Fluorescent light	15. Microwave
4. TV set	16. Gas cooking appliance
5. Copying machine	17. Gas water heater
6. Computer	18. Oil water heater
7. Magnet disc unit	19. Electric toilet seat
8. Freight vehicle	20. Vending machine
9. Video cassette recorder	21. Transformer
10. DVD recorder	22. Router
11. Electric refrigerator	23. LAN switch
12. Freezer	

Source: METI 2010.

ering potential technological improvements in energy efficiency. Manufacturers are required to achieve the target value by making weighted average values on their shipment volume exceed the target value by the target year. This program is different from the Minimum Energy Performance Standard (MEPS) widely used in the world, under which the minimum standard value that all the targeted products must exceed is established. The Top Runner Program started with 9 kinds of energy consuming products and now has expanded to 23 kinds of products at present (March, 2010), mainly home appliances and business equipment (see Table 1).

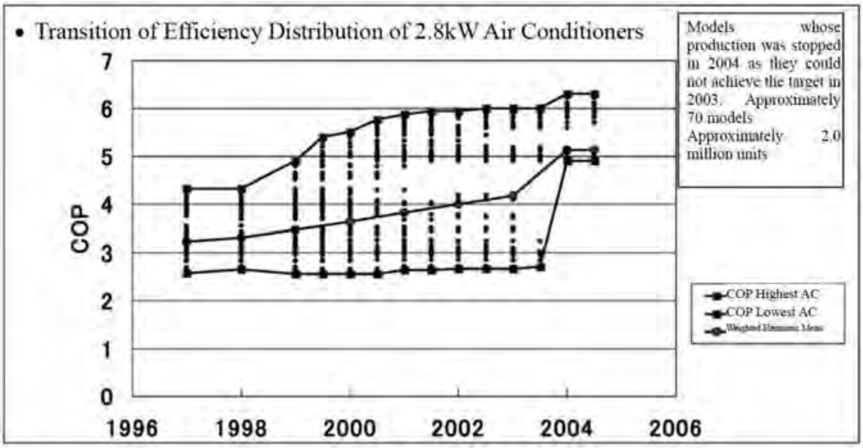
Figure 2 shows efficiency development of residential air conditioners with a cooling capacity of 2.8kW in Japan from 1997 to 2005. The vertical axis is the rated coefficient of performance (COP) of air conditioners on a shipment basis. The top line and the bottom line are the highest and the lowest COP shipped into the domestic market. The middle line is market averaged COP on a shipment basis. The equipment efficiency improved steadily after the standard introduction in 1999 as shown in the figure. In order to meet the target standard by the target year, 2004, manufactures increased the share of shipment of high-COP air conditioners that satisfied the standard.

Thermal insulation standard regulation for residential and commercial buildings has not been introduced in Japan yet, but criteria of rational energy use in buildings are provided to building owners and developers, which gives them a guideline for choosing the rational thermal insulation when buildings are newly constructed or retrofitted.

Carbon Tax and Carbon Emission Trading

Introduction of carbon tax and carbon emission trading system (ETS) is now under public and governmental discussions in Japan, though any carbon pricing mechanism has not been introduced in Japan so far. The government

Figure 2: Efficiency Development of Residential Air Conditioners in Japan, from 1997 to 2005, on a Shipment Basis



Source: METI 2006.

decided the introduction of a tax for global warming countermeasures. An example of tax rate for coal is 1370 yen per ton. The current energy tax rate is 700 yen per ton and additional tax rate is 670 yen per ton. This additional tax rate for coal is equivalent to 289 yen per ton-CO2 as a carbon tax. The effectiveness of carbon pricing is debated in Japan because high energy taxes have been already implemented in Japan's economy. Tokyo Metropolitan has started its regional ETS from 2010 April, taking a lead in implementing ETS prior to the national-wide ETS introduction. In the Tokyo ETS, about 1400 facilities in the Tokyo Metropolitan area, which emit about 20% of the total carbon emissions from this area, are given an obligation to meet their own carbon emission target by the end of a first compliance period from 2010 to 2014.

3. CRIEPI'S BOTTOM-UP ENERGY MODEL FOR COMMERCIAL SECTOR

Figure 3 shows a structure of the bottom-up end-use energy demand model used in this study to analyze a long-term energy demand and carbon emissions of the commercial building sector.

In the model, the commercial building sector is segmented into 33 customer segments by business category and building size, e.g. office building, retail store, hotel, hospital, restaurant, K12 school, university, welfare facility, and the country is divided into ten regions according to a service area of ten regional power companies. The carbon emission analysis and cost assessment is performed taking into consideration different electricity and thermal demand characteristics

Figure 3: Schematic Explanation of CRIEPI's Bottom-up Energy Model

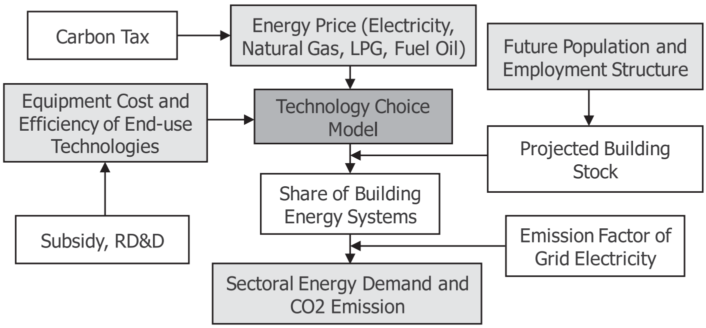


Table 2: Demographic and Employment Projection toward 2030

	Number of Population (mil. person)				Number of Employees (mil. person)			
	Total	**14 or younger**	**15–64 year-old**	**65 or older**	**Total**	**Agriculture, Forestry and Fishery**	**Industry**	**Service and Public**
2000	126.9	18.5	86.4	22.0	63.4	3.1	18.9	41.4
2005	127.7	17.7	84.6	25.4	63.3	2.8	16.9	43.6
2010	127.5	17.1	81.7	28.7	63.7	2.5	15.4	45.8
2020	124.1	15.1	74.5	34.6	62.1	2.2	13.4	46.5
2030	117.6	13.2	69.6	34.8	58.6	1.9	11.4	45.3

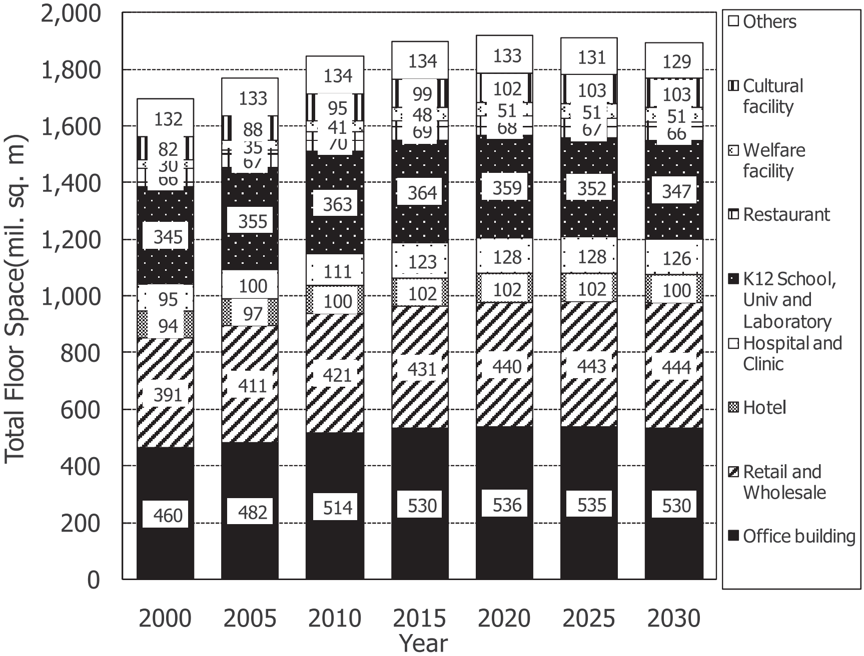
Source: NIPSSR 2002, JILPT 2005

among the customer segments, and different climate conditions and natural gas network accessibilities among the regions.

Future Building Stock Estimation

First, the commercial building stock toward 2030 is estimated for each customer segment and region so that it could be consistent with governmental demographic and employment projection toward 2030, where the governmental projection estimates that Japan's real GDP grows at 1.8% p.a. between 2004 and 2015 and thereafter at 1.6% p.a. between 2015 and 2030. Table 2 summarizes the demographic and employment projection. According to the projection, the population will decrease to 92% of the 2005 level by 2030 due to aging population and declining birthrate in Japan. However, the share of the service and public sector in total employment will increase from 69% in 2005 to 77% in 2030 due to increase of service economy, although the total number of employees will decrease.

Figure 4: Projected Commercial Building Stock in Japan toward 2030



Future commercial building stock is estimated by combining the population and employment projection with a set of equations representing long-term trends of relationships between commercial building stock and number of population and employees at segmental and regional levels, which are developed through past data analysis. Figure 4 is the result of the commercial building stock estimation. The commercial building floor space increases from 1.77 billion sq.m in 2005 to 1.92 billion sq.m by 2020, thereafter decreasing to 1.90 billion sq.m by 2030.

Final Energy Consumption and Cost Analysis of Building Energy System

Second, final energy consumption and cost associated with a building energy system installation and operation are analyzed by an optimization model for finding the cost minimizing system installation and operation during a building owners' acceptable pay-back year, given equipment cost, retail energy price, equipment energy efficiency, and end-use electric and thermal demand characteristics of the building. The pay-back year is set to be three years in this study, which is often observed in many energy-efficient investment criteria surveys in Japan. This is interpreted as a present worth factor for the calculation of total cost of system installation and operation in the equation (1) and (6), PWF , taking the value of three, implying a high market discount rate of about 33%.

The equations shown below outline the model. The equation (1) is the total cost of a building energy system installation and operation during a system lifetime, given a discount rate. The equation (2) is the annual energy cost for purchasing electricity, natural gas and fuel oil, aggregated across different rate classes and hours. The equation (3) is the initial cost for the building energy system installation, aggregated across different types of system components. The equation (4) represents the balance constraints on demand and supply in end-use energy services resulting from business activities in the building.

$$TOTALCOST = CAPCOST + PWF \times ENECOST \tag{1}$$

$$\begin{aligned} ENECOST = {} & PkW(i) \times ELEDMD + \sum_h PkWh(i,h) \times ELEKWH(h) \\ & + PM3h(j) \times GASDMD(j) + \sum_h PM3(j,h) \times GASM3(j,h) \\ & - REDUCECOST + \sum_h POIL \times OILL(h) \end{aligned} \tag{2}$$

$$CAPCOST = \sum_k UC(k) \times CAP(k) \tag{3}$$

$$\begin{aligned} LOAD(u,h) \le {} & \sum_k (EFF(\text{“}ELE\text{”},k) \times ELEKWH(h,k) + EFF(\text{“}GAS\text{”},k) \\ & \times GASM3(h,k) + EFF(\text{“}OIL\text{”},k) \times OILL(h,k)) \end{aligned} \tag{4}$$

$$\begin{aligned} & PkWh = PkWh0 + CELE \times CTAX; PM3 = PM30 + CGAS \times CTAX; \\ & \qquad POIL = POIL0 + COIL \times CTAX \end{aligned} \tag{5}$$

$$PWF = \frac{1-(1+r)^{-TL}}{r} \tag{6}$$

TOTALCOST: Total cost of installation and operation of a building energy system during the lifetime (yen)
ENECOST: Annual energy cost for system operation (yen/year)
CAPCOST: Initial cost for system installation (yen)
h: Hour
i: Type of electricity utility rate
j: Type of natural gas utility rate
k: Type of system component
u: Type of end use
ELEDMD: Contract demand of electricity (kW)
GASDMD: Peak demand of natural gas (cu m/h)
ELEKWH: Purchased electricity consumption(kWh)
GASM3: Natural gas consumption (cu m)

OILL: Fuel oil consumption (L)
PkW: Power demand charge (yen/kW)
PkWh/*PkWh*0: Electricity charge (yen/kWh) with/without carbon tax
*PM*3*h*: Natural gas fixed tariff (yen/cu m)
*PM*3/*PM*30: Natural gas unit tariff (yen/cu m) with/without carbon tax
REDUCECOST: Reduced electricity and gas cost (yen/year)
POIL/*POIL*0: Fuel oil price (yen/L) with/without carbon tax
EFF: End-use energy efficiency of system component
LOAD: Hourly load demand by end use (kWh/h)
CAP: Installed capacity of system component (kW)
UC: Unit cost of system component (yen/kW)
CELE,*CGAS*,*COIL*: Carbon emission factor for grid electricity, natural gas and fuel oil
CTAX: Carbon tax (yen/t-CO2)
PWF: Present worth factor
r: Discount rate
TL: Lifetime of a building energy system, 15 years assumed in this study

Sectoral Carbon Emission Estimation

This study assumes that a commercial building owner chooses the most cost-efficient end-use technology derived in the above model analysis on a three-year total cost basis when the building is newly constructed or retrofitted. In order to cut the carbon emission, the building owner is stimulated to install an energy efficient system to make the per-floor-space carbon emission the lowest. However, the reference case does not stimulate an investment in additional carbon emission cuts. The system choices of the building owners result in change in the market share of building energy systems year after year (see Eq. 7) and, as a result, the change in the market share influences on the sectoral carbon emission trajectory. The multiplication of three numbers— building floor space, per floor space carbon emission, and the market share of a building energy system— gives the sectoral carbon emission toward 2030 (see Eq. 8).

$$SHARE(r,s,k,t+1) = SHARE(r,s,k,t) + dSHARE(r,s,k,t) \qquad (7)$$

$$CO2(t) = \sum_{r,s,k} FLOOR(r,s,t) \times UCO2(r,s,k,t) \times SHARE(r,s,k,t) \qquad (8)$$

*CO*2: Sectoral carbon emission (million tons)
FLOOR: Building floor space (million sq. m)
*UCO*2: Carbon emission per unit of floor space for k-th building energy system(tons/sq.m)
SHARE: Market share of the k-th building energy system(%)
t: Year
s: Building type
r: Region

Table 3: Carbon Emission Reducing Technologies for Commercial Building Sector Considered

Type	Technology	Assumed Equipment Efficiency Improvement and Cost Reduction
Energy Conservation	EE improvement of electric heat pump air conditioner	Annual Performance Factor (APF): 4.4(2006)→5.2(2015)→5.2(2030)
	LED lighting system	Luminance efficiency:120lm/W(2015 or later) Equipment cost reduction: 10yen/lm(2005)→0.5yen/lm(2030)
	Building energy management system	Final energy use reduction rate (actual number in Govt's subsidy program): 4.3%
Fuel Switching	Electric heat pump water heater	Conventional fuel fired boiler→Electric heat pump water heater
	Induction heating (IH) cooker	Gas cooker→Electric IH cooker
	Highly-energy-efficient combined heat and power (CHP) system	CHP system with highly-efficient generator (Gas Engine LHV40%, SOFC LHV50%) and high COP electric-powered chiller

4. CARBON EMISSION ABATEMENT TECHNOLOGIES IN JAPANESE COMMERCIAL BUILDING SECTOR

Table 3 shows a set of end-use energy technologies taken into consideration in the model analysis. These are expected to contribute to carbon emission abatement in Japanese commercial building sector in the governmental energy outlook (METI, 2008).

Heat Pump Air Conditioner

Decentralized heat pump air-conditioner is widely used in Japanese commercial and residential buildings, while centralized air-conditioning system with centrifugal chiller or absorption chiller is mainly used for large buildings and district heating and cooling (DHC). Accelerated COP (Coefficient of Performance) improvements of the decentralized heat pump air conditioner by further R&D efforts of air-conditioner manufactures are assumed as carbon emission reduction measures in this study.

Light Emitting Diode (LED) Lighting System

LED lighting system has been rapidly getting better performance in equipment efficiency and equipment cost due to manufactures' extensive R&D efforts. We assumed based on expert surveys that, luminance efficiency of LED lighting will go beyond 120 lm/W after 2015 (c.f. 100lm/W for high-frequency fluorescent lighting at present) and equipment cost per unit of luminance intensity of LED will steeply decline from 10 yen/lm in 2005 to 0.5 yen/lm by 2030, and as a result, the LED lighting system will be marketed for general lighting use after 2015 instead of fluorescent lighting system.

Building Energy Management System (BEMS)

The BEMS is a system to manage and control energy-consuming facilities and indoor air quality in the building, and is expected to contribute energy conservation through appropriate adjustment of energy usage by the BEMS. According to the results of governmental subsidy programs for BEMS, it contributed to a final energy use reduction of about 4.3% on average.

Electric Heat Pump Water Heater and Induction Heating (IH) Cooker

Electric heat pump water heater is expected as one of the key end-use technologies to cut the carbon emissions deeply from the building sector, because it boils water with relatively low carbon emitting night electric power and it has a high end-use energy efficiency of rated COP of 4.0 at present, expected to reach into 6.0 of COP by 2030. Higher equipment cost of the heat pump water heater than conventional fuel-fired boiler is one of market barriers to large penetration. We assumed in this study that the equipment cost of the heat pump water heater will decline by 44% in 2030 from the 2005 cost. The IH cooker has higher end-use energy efficiency of about 80% than that of the conventional gas cooker, 40–56% and is expected to contribute to the carbon emission cuts.

Combined Heat and Power (CHP)

The carbon impact of CHP system is dependent on two main factors, carbon emission factor of grid electricity avoided by generated electricity of the CHP system, and generating efficiency of the CHP system's generator. In Japan, the carbon emission factor of grid electricity is relatively low because of high share of nuclear generation, 35–40%,[2] and high generating efficiency of fossil fuel fired generation. Therefore, the generating efficiency of the CHP generator should be high enough to be comparable to that of the grid fuel-fired generator of 35–50%. In this study, the gas engine generator and Solid-oxide fuel cell (SOFC) are assumed as CHP generators because they have possibilities to have high generating efficiencies in the near future comparable to that of the grid thermal generator by further R&D efforts of generator manufacturers.

Note here that, improvements of building thermal insulation and utilization of renewable energy are not included in Table 3 and therefore are not taken

2. This share of nuclear generation potentially decreases in the long run as well as in the short run in consequence of Fukushima nuclear accident.

Table 4: Cases Analyzed

Cases	Carbon tax*	Standard**	Subsidy***	Pay-back years or Discount rate****
Reference				3 years or 33%
Carbon tax	30$/t-CO2 from 2010, increase at 5%/year			3 years or 33%
Standard		enhanced standard		3 years or 33%
Reduced Equipment cost			50% subsidy of incremental equipment cost	3 years or 33%
Standard with Carbon tax	30$/t-CO2 from 2010, increase at 5%/year	enhanced standard		3 years or 33%
Reduced cost with Carbon tax	30$/t-CO2 from 2010, increase at 5%/year		50% subsidy of incremantal equipment cost	3 years or 33%
7% solution				7%

* This study assumed 1$ = 100yen.
** Applied to electric air conditioners. Standard is fixed after 2016.
*** Efficient appliances including heat pump water heaters, LED lights and CHP. Standard subsidy is 33% in Japan.
**** Three-year is assumed as building owners' acceptable pay-back years for energy efficiency investment in the CRIEPI model

into consideration in this study, though they can contribute to carbon emission reduction in the Japanese commercial building sector. Therefore the resulting potential amount of carbon emission reduction in this study might be underestimated.

5. CASES AND MODEL RESULTS

To analyze the policy impacts, we made seven cases for Japanese commercial sector shown in Table 4. These are similar to the cases other EMF25 model teams made (EMF 25, 2010), but they differ in some ways from those other model teams made. Reference (REF) case has no carbon tax, no further strengthening energy efficiency standards and no enhancement of subsidy programs. In the REF case, building owners choose energy-efficient equipments and technologies based on acceptable payback years, 3years, which means that high market discount rate is applied for energy efficiency investments.

In the Carbon Tax case, a carbon tax of $30/t-CO2 is introduced from 2010 and increases at 5% per year, which is the same tax rate as other model teams.

In the Standard case, the standard value of energy efficiency in air conditioners for commercial buildings, its annual performance factor (APF), is increased to 5.2 by 2015 from the present value of 4.4, and remains constant after 2016. These values are based on recently revised standards. Other commercial sector's equipments than air conditioners, such as copying machines and routers, are coming under top-runner standard regulation and do not have fixed standard values at present. Therefore we excluded these equipments in this study.

In the Reduced Equipment Cost case, 50% of incremental equipment cost of energy-efficient products relative to conventional products is subsidized, which is the same as other model teams, though the standard subsidy is one third of the incremental cost in Japan. Heat pump water heater, high-efficient CHP and LED lighting are subsidy targets.

In the 7% solution case, a lower discount rate of 7% rather than the market discount rate, 33%, is applied to all energy efficiency investments. The present worth factor in Eq.1, PWF, takes the value of about 9.1, which is interpreted that a building owner evaluates the energy efficiency investment during the longer pay-back period than that in the Reference case.

Standard with Carbon tax case and Reduced cost with Carbon tax case are a combination of the case settings above.

We excluded Energy Sales tax case from the model cases, because a couple of energy taxes have been already implemented in Japan and therefore this case has little policy implication.

Results of Model Analysis

(1) Reference Case

Figure 5 and Figure 6 show forecasted sectoral final energy toward 2030 by energy source and by end use for REF case. The share of natural gas increases over time because the fuel source for heating switches from LPG and fuel oil to natural gas due to the expansion of the domestic natural gas network. Total energy demand becomes saturated after 2015–2020 because of decreasing population in Japan. The share of energy by end use changes little over time.

(2) Policy Cases other than Reference Case

Figure 7 shows retail energy prices for Reference case and Carbon Tax case. A solid line is REF case, while a dotted line is Carbon Tax case. Introduction of carbon tax raises retail energy prices by 14% for electricity, 16% for natural gas, 27% for fuel oil and 18% for LPG in 2030. Here we suppose 360g-CO2/kWh as a carbon emission factor of grid electricity.

Figure 8 shows total energy demand trajectories for seven cases. The figure indicates that introduction of carbon tax has very little impact on sectoral energy demand trajectory. This is because Japanese retail energy price is high

Figure 5: Forecasted Sectoral Final Energy by Energy Sources for REF Case

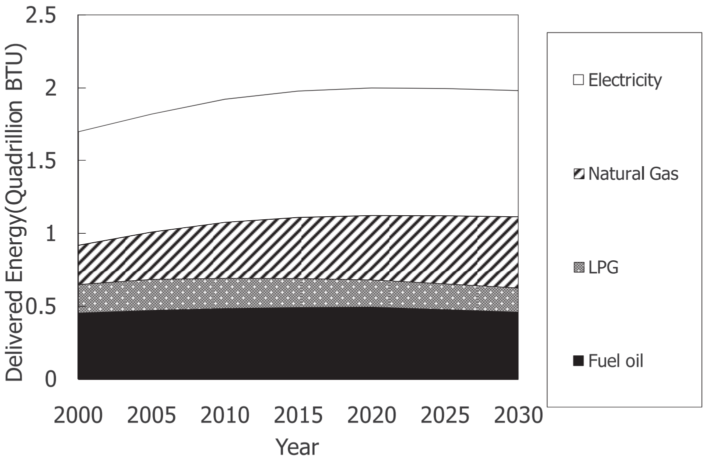
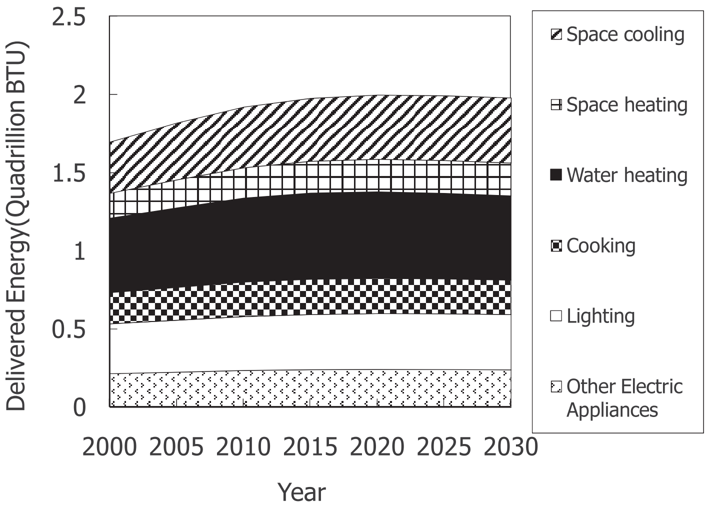


Figure 6: Forecasted Sectoral Final Energy by End Use for REF Case



enough to encourage energy efficiency investment even at present. An additional tax on energy consumption might have little impact on energy efficiency investments. The figure also shows that strengthening standard and equipment cost reduction change the energy demand trajectory. For example, total energy demand in Standard case and Reduced equipment cost case decreases by 5% and 3%, respectively from Reference case in 2030. Increasing equipment energy efficiency

Figure 7: Retail Energy Prices for REF Case and Carbon Tax Case

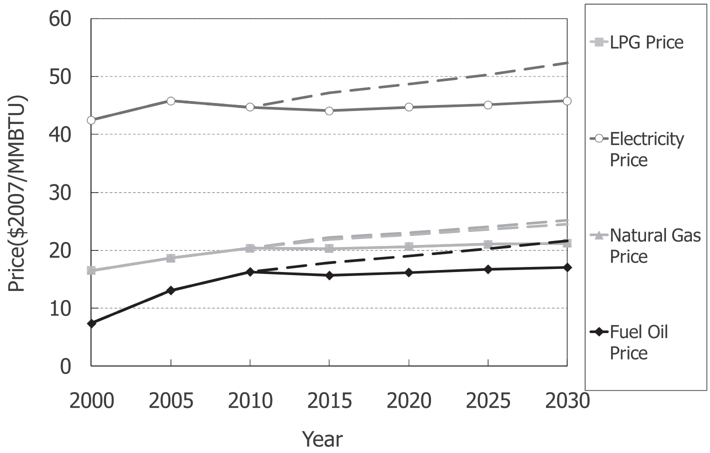
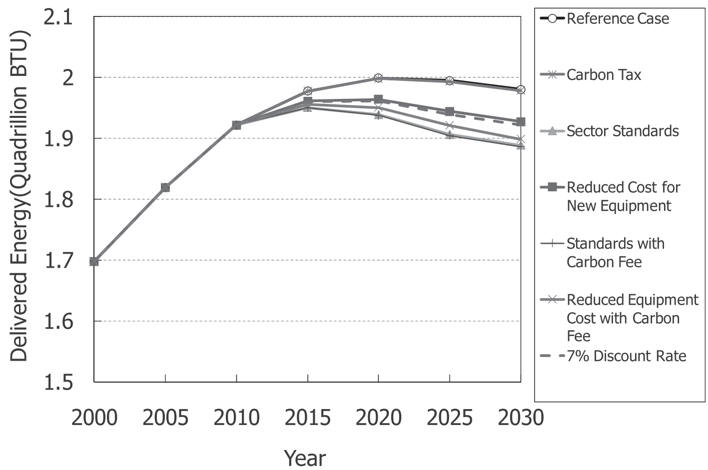


Figure 8: Sectoral Delivered Energy Demand for Seven Cases



and equipment cost reduction lower the life cycle cost of energy efficiency equipments for customers and raises the customer's adoption.

Figure 9-1, 9-2 and 9-3 show energy demand trajectories at end use levels, that is for space cooling and heating, water heating and lighting. Revision of efficiency standards for air conditioners reduces space cooling and heating demand by 15% in 2030 (Figure 9-1). Figure 9-2 shows equipment cost reduction of heat pump water heater decreases heating demand. This is the same as LED lighting as well (Figure 9-3).

Figure 9-1: Sectoral Delivered Energy Demand for Space Cooling

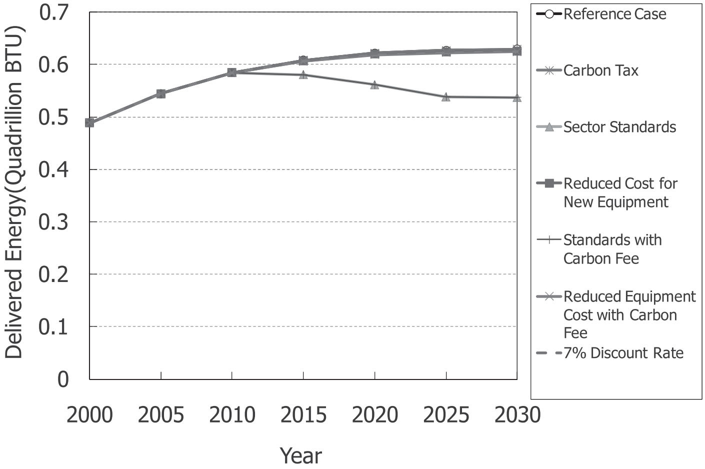
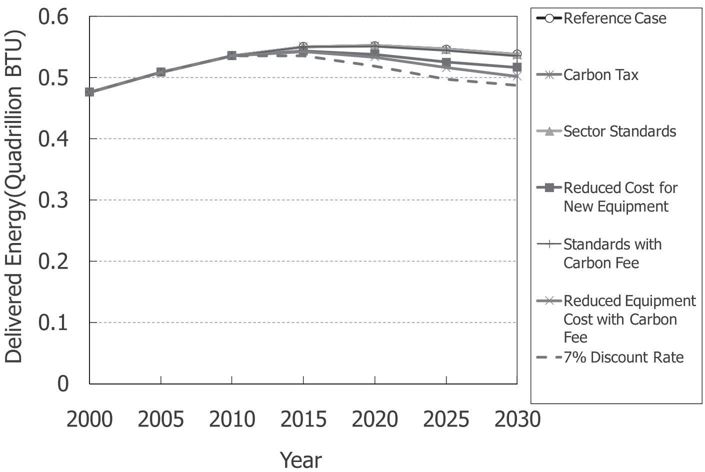


Figure 9-2: Sectoral Delivered Energy Demand for Water Heating



The estimated carbon emission trajectories shown in Figure 10 have a similar feature to the trajectories for energy demand of Figure 8. Here the carbon emission in the figure include carbon emissions from grid electricity and we assumed that carbon emission factor of grid electricity is 360g-CO2/kWh. Introduction of carbon tax has very little impact on the carbon emission trajectory; however, enhanced standard and equipment cost reduction have impacts on it. In the Standard and Reduced cost cases, the carbon emission is reduced by 6% and 3%, respectively, from the Reference case in 2030.

Figure 9-3: Sectoral Delivered Energy Demand for Lighting

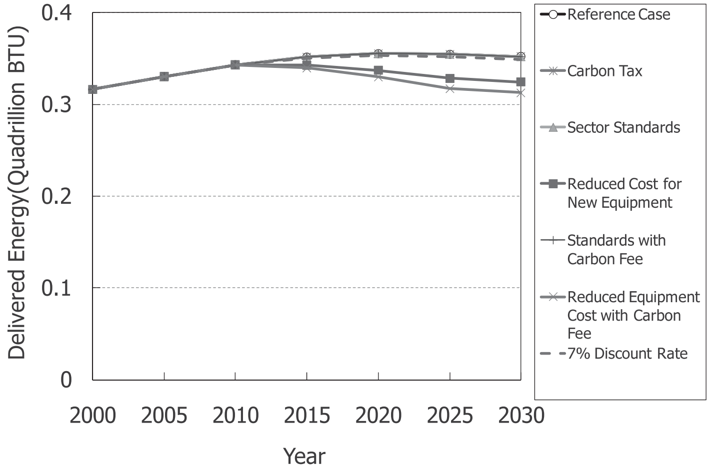
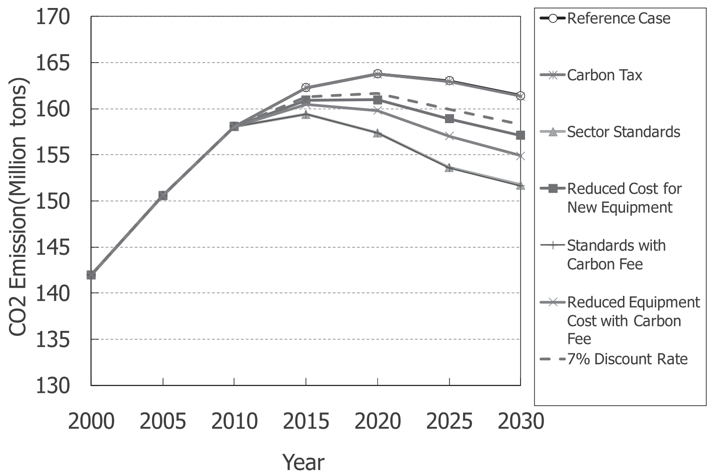


Figure 10: Carbon Emission Trajectories for Seven Cases (incl. electricity)



6. CONCLUSION

This study shows model analysis results of energy efficiency policy impacts on Japanese commercial buildings sector, using the CRIEPI's sectoral bottom-up energy model. The policy cases we analyzed in this study are consistent with those of other EMF25 model teams, but Energy Sales Tax case was excluded in the list of policy cases because a couple of energy taxed have already implemented in Japan and it gives little policy implication. The model results indicate the following.

(1) Such a low carbon tax as $30 per t-CO2 from 2010, increasing to $80 by 2030, has very little impact on the final energy demand and carbon emission trajectory of Japanese commercial sector. This is thought because Japanese retail energy prices are high enough even at present to encourage the energy efficiency investment, and therefore the impact of additional low tax on energy consumption is limited from a viewpoint of price effect of tax.

(2) Enhanced energy efficiency standard and reduced equipment cost are very effective on reducing the sectoral energy demand. Additional private R&D activities and governmental subsidies are needed to achieve them, but they raise issues of R&D and investment costs.

REFERENCE

EDMC (2009). "Handbook of Energy & Economic Statistics in Japan", The Energy Data and Modeling Center, Institute of Energy Economics, Japan

Energy Modeling Forum (EMF) (2010). "EMF 25 Scenario Design." Stanford University, Stanford, CA. Document available online at http://emf.stanford.edu/files/res/2372/25design2.pdf.

IEA (2007). "Energy Use in the New Millennium — Trends in IEA Countries", International Energy Agency, OECD

JCCCA (2007). "A Fact Sheet on Energy-Efficient Home Appliances, revised in September 2007" (in Japanese only), Japan Center for Climate Change Actions. http://www.jccca.org/pamphlet_panel/pamphlet/img/pamphlet_green05_data01.pdf

JILPT (2005). "Issues on employment and labor policy in the period facing decreasing population" (in Japanese only), the Japan Institute for Labor Policy and Training. http://www.jil.go.jp/english/index.html

McKinsey & Company (2007). "Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?"

METI (2008). "Long-term Energy Outlook" (in Japanese only), Ministry of Economy, Trade and Industry, Japan. http://www.meti.go.jp/report/data/g80521aj.html

METI (2006). "Final Summary Report by Air Conditioner Evaluation Standard Subcommittee, Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy", Ministry of Economy, Trade and Industry, Japan. http://www.eccj.or.jp/top_runner/

METI (2010). "Top Runner Program, revised edition in March 2010", Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, Japan. http://www.enecho.meti.go.jp/policy/saveenergy/toprunner2010.03en.pdf

Murakami, Shuzo, Mark D. Levine, Hiroshi Yoshino, Takashi Inoue, Toshiharu Ikaga, Yoshiyuki Shimoda, Shuichi Miura, Tomoki Sera, Masahiro Nishio, Yasuhiro Sakamoto and Wataru Fujisaki (2006). "Energy Consumption, Efficiency, Conservation, and Greenhouse Gas Mitigation in Japan's Building Sector", Lawrence Berkeley National Laboratory Paper LBNL-60424.

NIPSSR (2002). "Population Projection by Prefecture for Japan: 2000–2030" (in Japanese only), The National Institute of Population and Social Security Research, Japan. http://www.ipss.go.jp/site-ad/index_english/population-e.html

Vattenfall (2007). "Global Mapping of Greenhouse Gas: Abatement Opportunities up to 2030," Stockholm, Sweden.

IAEE/USAEE CONFERENCE PROCEEDINGS – ORDER FORM

Institutions, Efficiency and Evolving Energy Technologies

34th IAEE International Conference,
Stockholm, Sweden, June 19 to 23, 2011

This CD-Rom includes articles on the following topics:
Markets vs. regulation in the implementation of new energy technologies
The future of world oil markets
The economics of smart grids
Command and control policies vs. economic incentives in demand management
R&D and innovation
Energy storage
Biofuels policy and land-usage
The effect of political institutions on natural resource management
Rebound effects of energy efficiency subsidies
Economic growth
Electrification of developing countries

Energy Economy, Policies and Supply Security: Surviving the Global Economic Crisis

11th IAEE European Conference,
Vilnius, Lithuania, August 25 to 28, 2010

This CD-Rom includes articles on the following topics:
Energy Supply Security (political, economical and technical)
Sustainability of Energy systems, Mitigation of Global Warming
Role of Renewable Energy Sources and Biofules
Energy Demand Forecasting
Energy Sector Analysis and Modeling
Energy Policy
Geopolitics of Energy Supply (gas, oil, nuclear and etc.)
Price of Security
Road Map for Energy Efficiency
Market Integration and Liberalization
Energy Sector Risk Analysis
Specific Energy Sector Problems of CEE Countries
Nuclear Energy: Hopes and Realities
Environment

The Future of Energy: Global Challenges, Diverse Solutions

33rd IAEE International Conference,
Rio de Janeiro, Brazil, June 6–9, 2010

This CD-Rom includes articles on the following topics:
Bioethanol: Production, Use and Trade
Energy and Environment: What Will Come After Kyoto?
Energy Development and Poverty: Key Issues for Energy Access
Energy Efficiency, Electricity Demand and Smart Grids
Geopolitics of Natural Gas
Innovation and the Economics of Nuclear Industry
OPEC'S 50 Years and the Future of Oil Industry
The Challenges of Energy Regulation in the Future
Speculative Activity in Oil Markets
The Future of Energy: New Energy Policies and Technologies
Why Do We Need a New Energy Order?

Energy, Economy, Environment: The Global View

32nd IAEE International Conference,
San Francisco, CA, June 21–24, 2009

This CD-Rom includes articles on the following topics:
Electricity Pricing and Cost Discovery
Economics of Wind Energy
Climate Change and Economics
Modeling Energy Demand in Transport
Renewable Energy Economics and Policy
Issues in Global LNG Markets
State and Regional Climate Action Plans: Implications for Energy and the Economy
Energy Demand Modeling in the Residential Sector
De-carbonizing Electricity Generation
Economics of Petroleum Exploration and Development

Unveiling the Future of Energy Frontiers

28th USAEE/IAEE North American Conference,
New Orleans, Louisiana, December 3–5, 2008

This CD-Rom includes articles on the following topics:
Gulf Coast Energy Renaissance - Reviving Production, Expanding Infrastructure
Global Warming and Carbon Management - Timing, Costs, Priorities
Ratcheting Down Demand - Ratcheting Up Renewables
Challenges and Plans for Hydrocarbon Extraction from the Gulf
Toward Rational Energy Policies for 2009
Oil and Gas Resource Development Outlook
Global Liquefied Natural Gas (LNG) Market
Energy Modeling in a Carbon-Constrained Economy
Non-Conventional Fossil Fuel Economics and Risks
Future Electric Generation Capacity Expansion

Bridging Energy Supply and Demand: Logistics, Competition and Environment

31st IAEE International Conference, Istanbul, Turkey, June 18–20, 2008

This CD-Rom includes articles on the following topics:
Geopolitics of Oil & Gas
Climate Change & Post Kyoto
Integration of Renewable Energy Sources into the Electricity Grid
Energy Governance in Asia
Investment Oriented Turkish Electricity Market Modeling
The Petroleum Paper Trail: Petroleum Agreements and Supply Security
Interconnection versus Integration: The Challenge of Transit Regimes and Jurisdictions for Eurasian Gas
Energy and CO_2 Policies in the individual Transport Sector
Energy Market Modeling
Large Scale Integration of Intermittent Energy Sources as PV and Wind-Energy for Meeting the RES Targets of Countries in 2020

continued on next page

Information for Authors

The Energy Journal publishes theoretical and empirical papers devoted to the advancement and dissemination of knowledge concerning energy and related topics. Content and editorial board composition are international in scope. Although most articles published will emphasize the economic aspects of their subjects, coverage is interdisciplinary. *The Energy Journal* quarterly issues include:

- Major, refereed articles (25–35 pages) that deal with theoretical or applied problems of continuing interest in energy economics and related disciplines.
- Shorter, refereed papers and notes (10–15 pages) that are more topical and focus on the theory and practice of economics as related to current energy policy problems.
- An 'Energy Perspectives' section which provides current readable (and refereed) papers on important issues.
- A review section examining books and topical government reports, national and international, which assess issues in energy policy and prospects.

Submissions: Authors please submit online at http://www.iaee.org/en/publications/submit.aspx two electronic copies of your paper in PDF format; one with the authors' names included and one with authors' names removed. Articles will not be considered if multiple files are submitted – e.g., text files along with separate files with graphics, tables, equations, etc. Each of the two electronic files must incorporate all text, tables, equations and graphics. Assurance should be made that the paper has not been submitted elsewhere for publication. The submission fee for articles submitted to *The Energy Journal* is $100. Members may submit articles complimentary.

Revised articles should be emailed directly to the Associate Editor at geoffrey.pearce@utoronto.ca

Authors submitting a manuscript do so on the understanding that if it is accepted for publication, copyright in the article, including the right to reproduce the article in all forms and media, shall be assigned exclusively to *The Energy Journal. The Energy Journal* will not refuse any reasonable request by the author for permission to reproduce any of his or her contributions to the journal. Manuscripts should be prepared according to the following style rules which are based on *The Chicago Manual of Style.*

Form. Manuscripts should be double-spaced on one side of 8.5 x 11 inch (or similar) white paper. The first page should contain the article title, author(s) name(s) and complete affiliation(s), title(s), and complete mailing address of the person to whom all correspondence should be addressed. An abstract of no more than 150 words must be included. The manuscript with the names removed will be sent to anonymous referees for double-blind peer review.

Math. Mathematical expressions should be set in *italic* type with all equations numbered consecutively on the right hand side of the page.

Tables. Tables should be numbered consecutively. All tables should have concise titles.

Footnotes. Footnotes should be numbered consecutively with superscript Arabic numerals. Footnotes are placed at the bottom of each page.

Figures. All figures should be numbered consecutively throughout the text. Figures must be submitted as camera-ready copy or high resolution PDF format in a form suitable for reproduction.

References. Please use the author-date citation system and include an alphabetical reference list of all works cited. Examples of reference list style are as follows:

Chandler, Alfred (1977). *The Visible Hand.* Cambridge: Belknap Press.

Federal Trade Commission, Bureau of Economics (1979). *The Economic Structure and Behavior of the Natural Gas Production Industry.* Staff Report.

Henderson, J.S. (1986). "Price Determination Limits in Relation to the Death Spiral." *The Energy Journal* 7(3): 150–200.

Proofs. Page proofs will be sent to the corresponding author for approval before publication.

Offprints. One set of 10 offprints without covers will be provided free of charge to the corresponding author. Additional article reprints may be purchased from IAEE.

Book Reviews: Books for review should be sent to
Professor Peter J.G. Pearson, Welsh School of Architecture, Cardiff University, Bute Building, King Edward VII Avenue, Wales CF10 3NB. Email: pearsonpj@cardiff.ac.uk

ISSN 0195-6574

Energy Economics Education Foundation, Inc.
28790 Chagrin Blvd, Suite 350
Cleveland, OH 44122
USA

PERIODICAL

IAEE International Association for Energy Economics
WWW.IAEE.ORG

INSTITUTIONAL MEMBERSHIP

IAEE is very grateful for the support and involvement of our Institutional Members listed below. Institutional membership carries with it many special benefits.

For a full listing of benefits and services please visit
http://www.iaee.org/en/membership/institutional.aspx

Administración del Mercado Eléctrico, Uruguay
Aramco Services Co., USA
Berlin University of Technology, Germany
BKW FMB Energie AG, Switzerland
BP Plc., UK
ConocoPhillips, USA
CRA International, USA
Curtin Business School, Australia
Energy Information Administration, USA
GDF SUEZ, France
Institute for Economics, Transport & Energy, Czech Republic
Institute for Energy Strategy, Moscow
Institut Francais Du Petrole, France
Institute of Energy Economics, Japan
National Energy Board, Alberta, Canada
Norwegian School of Economics, Norway
Platts, USA
QED Research, Inc.
Rice University, Baker Institute, USA
Shell International, UK
Talisman Energy, Canada
UCL SERAus, Australia
University of Alberta, Canada
University of Auckland Business School, New Zealand
University of Stavanger