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

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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.

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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

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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 timeframe 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]

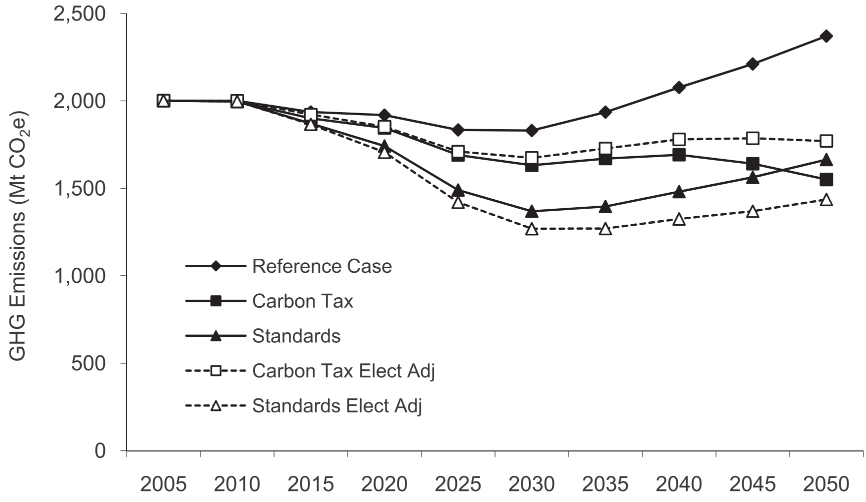
4. IMPACTS ON THE TARGETED END-USE SECTORS

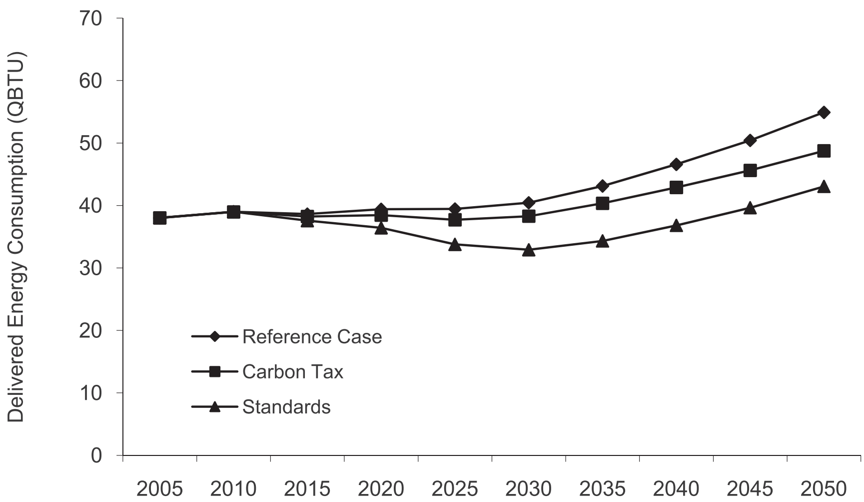
The energy efficiency standards described in the previous sub-section are forecast to reduce annual GHG emissions from the buildings and personal transportation sectors by 25% from reference case levels in 2030 and by 30% in 2050 (Figure 1). Emissions are also reduced from 2005 levels, with the maximum 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.

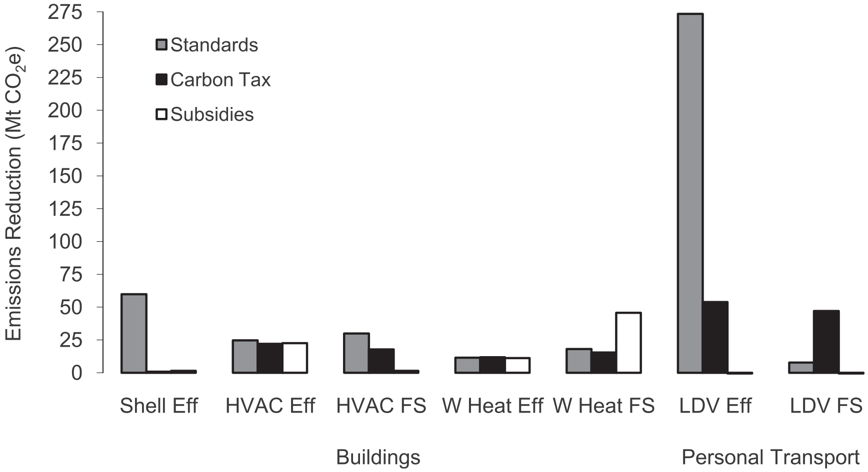
5. EMISSIONS REDUCTIONS BY ACTION

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

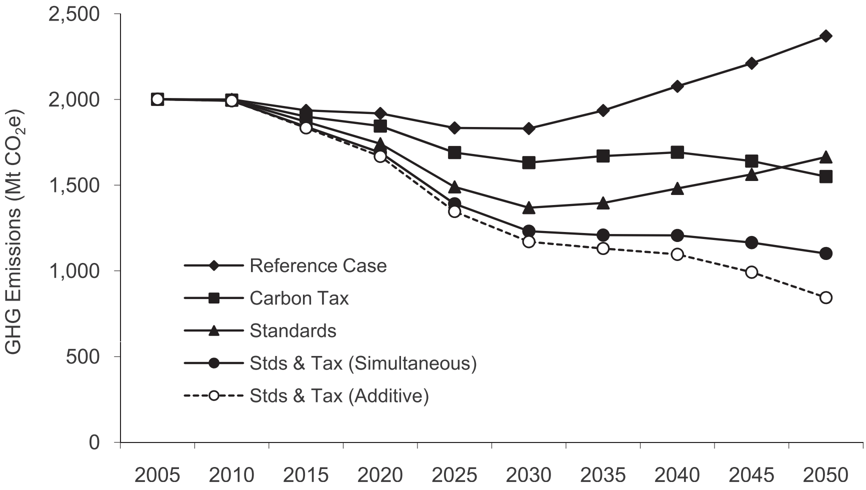
When the efficiency standards and the carbon tax are run simultaneously, as shown in Figure 3, annual direct emissions from the buildings and personal transportation sectors are reduced by about 35% from reference case levels in 2030 and by about 55% in 2050. These emissions reductions are substantially 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

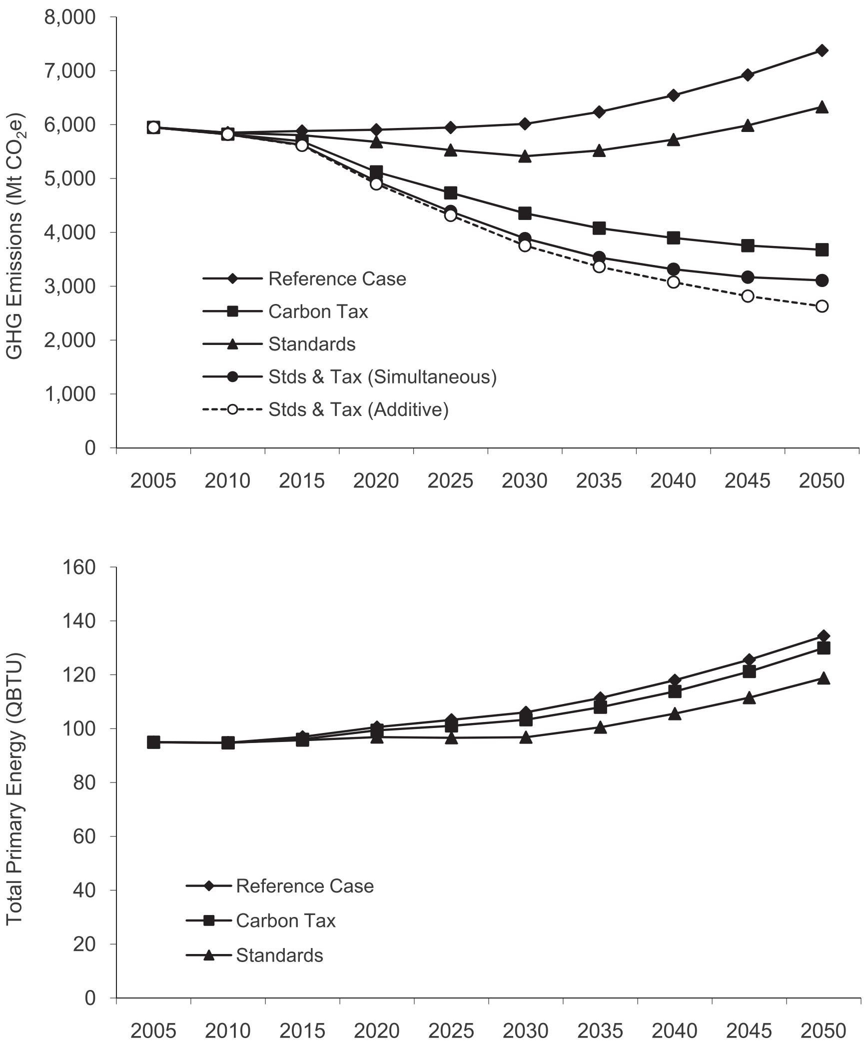


effect than the efficiency-based standards (Figure 4).[6] Indirect emissions are associated with an increase in electricity generation due to fuel switching under the carbon tax; however, the increase in output is accompanied by a dramatic reduction in the emissions intensity of generation. Carbon capture 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.

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