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BACKGROUNDER

Energy Efficiency in the Residential and Commercial Sectors

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Abstract

Public policies to promote the diffusion of energy-efficient technology for providing energy services in residential and commercial buildings, which were introduced in the United States in the 1970s, are receiving new attention as a means of reducing carbon dioxide (CO_2) emissions. Energy efficiency (EE) is currently undergoing a dramatic resurgence, stimulated by its potential contribution to CO_2 emissions reduction. In 2009, prior to the U.S. House of Representative's approval of the American Clean Energy and Security Act (H.R. 2454, often referred to as Waxman-Markey after its two primary sponsors) in June, the combined increase in federal EE funding—in the administration's 2010 budget and in the American Recovery and Reinvestment Act—was approximately an order of magnitude above the funding amount in the years immediately prior. The renewed focus on energy efficiency is further reflected in its central role in the Waxman-Markey bill. Concurrently, efficiency programs—particularly utility demand-side management programs and building codes—are continuing to expand in California and other states. Whether or not the specific provisions of the Waxman-Markey bill are ultimately adopted into law, we see little reason to doubt that energy efficiency in buildings will continue to be promoted as part of large-scale CO_2 policy.

In this paper, we review the history and results of these policies and of prospective estimates of future energy consumption reductions that might result from their expansion. We further discuss several key methodological issues underlying the rationale for technology-focused efficiency policies. We summarize key details of the National Energy Modeling System (NEMS) Residential and Commercial modules, and discuss the results of a series of simulations—using a modified version of NEMS referred to as NEMS-RFF—aimed at accelerating energy-efficient technology penetration.

We present the results of a set of runs of the NEMS-RFF model that separately incorporate the EE components of the Waxman-Markey bill, which we later augment with the research and development (R&D)–motivated "High-Tech" scenario composed by the Energy Information Administration. Consistent with the literature, we find that using NEMS-RFF and adding these High-Tech EE policies to a status quo baseline results in negative costs of CO_2 abatement. Once we add these policies to a baseline that contains either a carbon tax or cap-and-trade, we find that the EE policies reduce the abatement costs per ton. We note that about 50 percent of the reduction from our runs come from the EE provisions in Waxman-Markey (building codes, retrofit and lighting standards, and rebates), with the other half being due to the High-Tech assumptions. We show evidence that, for the residential sector, building codes over the 2010–2050 horizon are a potentially cost-effective way to reduce carbon emissions. As other studies have shown as well, these cost estimates are very sensitive to the chosen discount rate and discounting horizon. We also suggest that, based on NEMS-RFF, R&D policies targeting accelerating improvements in appliance energy efficiency and lowering their installed price further drive down these abatement costs and are a promising policy tool.

This background paper is one in a series developed as part of the Resources for the Future and National Energy Policy Institute project entitled "Toward a New National Energy Policy: Assessing the Options." This project was made possible through the support of the George Kaiser Family Foundation.

Contents

Energy Efficiency in the Residential and Commercial Sectors

Maximilian Auffhammer and Alan H. Sanstad*

1. Introduction and Background

From the late 1940s until the middle of the past decade, the United States was the world's leading emitter of carbon dioxide (CO_2), which is the main greenhouse gas (GHG) responsible for anthropogenic climate change. Currently, approximately 86 percent of U.S. CO_2 emissions are related to energy production and consumption, with the remaining emissions due to industrial processes, land use, agriculture, and waste (U.S. Environmental Protection Agency [EPA] 2009). Of the energy consumed in the United States in 2007, 85 percent was produced through the combustion of fossil fuels. Power generation is responsible for 34.2 percent of total emissions, the residential sector for 5.7 percent, and the commercial sector for 4.9 percent. If one attributes the emissions from the power-generating sector to end-use sectors, the commercial and residential sectors account for 17.5 percent and 17.2 percent, respectively, of total emissions. These two sectors are therefore responsible for one-third of U.S. emissions, and approximately 70 percent of the sectors' emissions are due to indirect emissions from power use.

Aggregate U.S. energy consumption has been rising steadily since 1949, as Figure 1 indicates. Overall growth in energy consumption displays a slowing trend over time. Per capita energy use, which is a commonly cited measure of the energy intensity of the economy, displays no growth since the mid-1970s. An alternative measure of energy intensity of the economy is the energy use per real dollar of gross domestic product. The energy intensity of the U.S. economy, according to this statistic, has dropped by an average of 1.4 percent per year. Cumulatively, it takes 56 percent less energy to produce a dollar's worth of goods and services today than it took to produce a dollar's worth of goods produced in 1949. This trend has accelerated over time. If we only look at the time period since 1980, the gains are 1.76 percent per year. The dashed red line indicates the carbon intensity of the U.S. economy (for which data are available only since 1980). The carbon intensity of the U.S. economy has dropped slightly faster than the energy intensity, at 1.97 percent per year.

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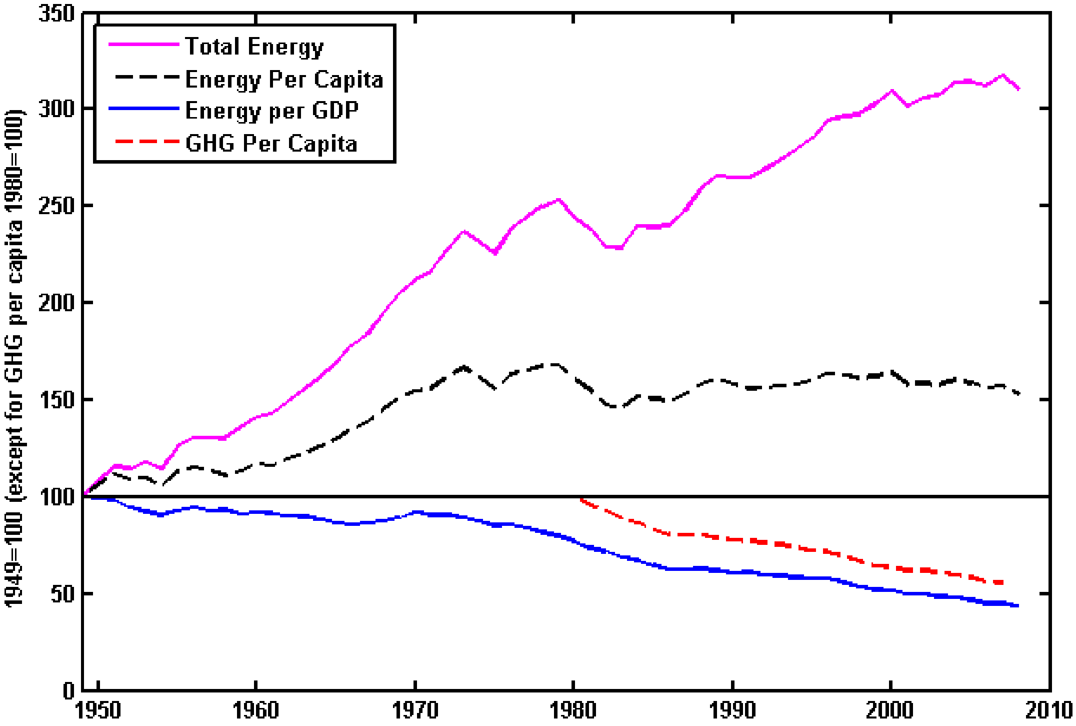
Figure 1. U.S. Energy Consumption, Energy Intensity, and GHG Intensity



Note: GDP, gross domestic product.
Source: EPA 2009.

A variety of explanations have been proposed for the constant drop in the energy intensity of the U.S. economy. First, over the past six decades, the U.S. economy has undergone massive structural change. The economy has undergone a significant shift from an energy-intensive manufacturing economy toward a less energy-intensive service-based economy. Second, in the 1970s and early 1980s and over the recent past, intervals of rapid and significant energy price spikes have occurred. Third, since the 1970s, state- and federal-level policies have been adopted for the purpose of decreasing the amount of energy per unit of service produced—that is, to improve the technical or engineering energy efficiency (EE) of energy-using durable goods, vehicles, industrial equipment and processes, and buildings. From a policy perspective, energy efficiency began receiving serious consideration in the United States with the emergence of the contemporary environmental movement in the late 1960s and early 1970s, particularly following the disruptions in natural gas markets in that period and after the Organization of the

Petroleum Exporting Countries oil embargo of 1973. High energy prices combined with worries about supply security led to state and federal efforts to improve the energy efficiency of every sector of the economy. Currently, EE programs are being significantly and rapidly expanded in the United States as a core policy approach to reducing CO_2 emissions, and we have every reason to believe that this trend will continue and possibly accelerate.

A number of studies over the past two decades have found that expanded public policies to promote the diffusion of efficient end-use energy technology in residential and commercial buildings could slow the growth rates of U.S. electricity and natural gas consumption and their associated CO_2 emissions at low cost or at a net savings (e.g., Carlsmith et al. 1990; Interlaboratory Working Group 2000; and Prindle et al. 2006). The pace of this type of analysis has accelerated in the past several years as global climate change has become a central focus of U.S. environmental policy and savings estimates have tended to increase (NAPEE 2007a, 2007b; Creyts et al. 2007; Granade et al. 2009).

The current study differs from these bottom-up engineering models in two significant ways. First, we examine the savings and costs from a set of proposed federal building-related EE policies (Waxman–Markey, or H.R. 2454) using a modified version of the National Energy Modeling System (NEMS) of the Energy Information Administration (EIA) for the commercial and residential sector. (This modified version is referred to as NEMS-RFF.) In this paper, we specifically look at the two major classes of EE policies proposed in Waxman–Markey, which are building codes and policies to improve the energy efficiency of retrofits, furnaces, boilers, and some outdoor lighting. We conduct this analysis using the baseline conservative assumptions about the efficiency and the cost of available capital as well as a set of aggressive assumptions that make more efficient capital available earlier at a lower cost. The advantage of using NEMS is that the model explicitly reflects how individual households and firms make choices about the adoption of energy-consuming capital and how much to use it based on optimizing behavior and taking market prices and characteristics of available capital as given. The model has a great deal of technological detail at the sector level and allows for general equilibrium–type effects on, for example, prices of complementary and substitute fuels. Because of the great level of detail, NEMS lends itself to the modeling of the very detailed proposed EE policies examined. The drawback of using any model of this type is that the results rest on the assumption regarding how to implement the policies in the model as much as on model-specific assumptions about the values of the thousands of parameters in the model.

As its second contribution, this paper addresses the fact that most of the existing efficiency potential studies have used engineering methods that are designed for strictly incremental analysis and that separate technology and economic influences on the deployment of energy efficiency—in particular, energy prices—are typically held constant. Emerging energy and CO_2 abatement policy architectures (e.g., Waxman–Markey and Kerry–Boxer, S. 1733), by contrast, combine technology-focused EE regulation with large-scale market mechanisms—emissions cap-and-trade systems or emissions taxes. Conversely, currently available analytical tools for studying the economywide dynamics of these market-based environmental policies—particularly *computable general equilibrium* models—do not incorporate the degree of resolution needed to fully represent the details of policies focused on end-use technology. This study therefore aims to advance the understanding of the joint effects of technology-based EE regulation and market-based energy and CO_2 policy. We use runs of the NEMS-RFF model, which contain the cap-and-trade program proposed in Waxman–Markey as well as a run of a largely equivalent carbon tax, and augment them by adding the proposed EE policies. We then estimate the incremental savings as well as the cost of these policies solely under the price-based instruments. This last part is of particular interest because basic economic theory, in the absence of market failures in the EE market, would argue for either a price-based policy or a technical standard, but not both as is currently proposed.

This paper is organized as follows. The next section provides an overview of (a) historical policies to increase end-use energy efficiency in buildings and (b) what is known about the results of these policies in the United States since the 1970s. Section 3 reviews key aspects of the NEMS Residential and Commercial modules, emphasizing details related to their representation of energy efficiency. In section 4, we describe the policy portfolio for this analysis and, in section 5, we provide the details of how this portfolio is represented in NEMS. Section 6 summarizes the numerical results, which we discuss in section 7. In section 8, we present our policy conclusions.

2. EE Policies: Approaches, History, and Effectiveness

The literature on energy efficiency in buildings can be divided into two components. The first component has overwhelmingly emphasized the prospective effects of future policies to promote energy efficiency—*potential* studies such as those cited above. The second component explores the underinvestment in efficiency end-use technology that justifies such policies—termed the *EE gap*—and the sources of this underinvestment. In this section, by contrast, we focus on the track record of efficiency policies and regulations. We first briefly survey the main policy and regulatory approaches to promoting energy efficiency, and then review selected retrospective findings on the results of specific programs or general policy approaches at the national level and for California. Both parts are based substantially on Gillingham et al. (2006), who conducted a unique survey and meta-evaluation of the available ex post evidence on efficiency policy and program outcomes. We then describe the very recent and promising econometric program evaluation literature, much of which is unpublished to date. Finally, we describe the main behavioral explanations for the EE gap, which may be responsible for what are often low estimates of program effectiveness.

Overview of Approaches

EE policies and programs can be divided into five general categories: technical standards, financial incentive programs, information and voluntary programs, management of government energy use, and technology research and development (R&D; Gillingham et al. 2006). All types have been administered at both the state and national levels and often at both levels sequentially.

Technical Standards

Technical standards are regulations that either prescribe the degree of energy efficiency of a specific item (e.g., an appliance) or require that a certain technology or material be used (e.g., insulation in buildings). The two major types of technical standards that have been implemented historically are appliance standards and building codes.

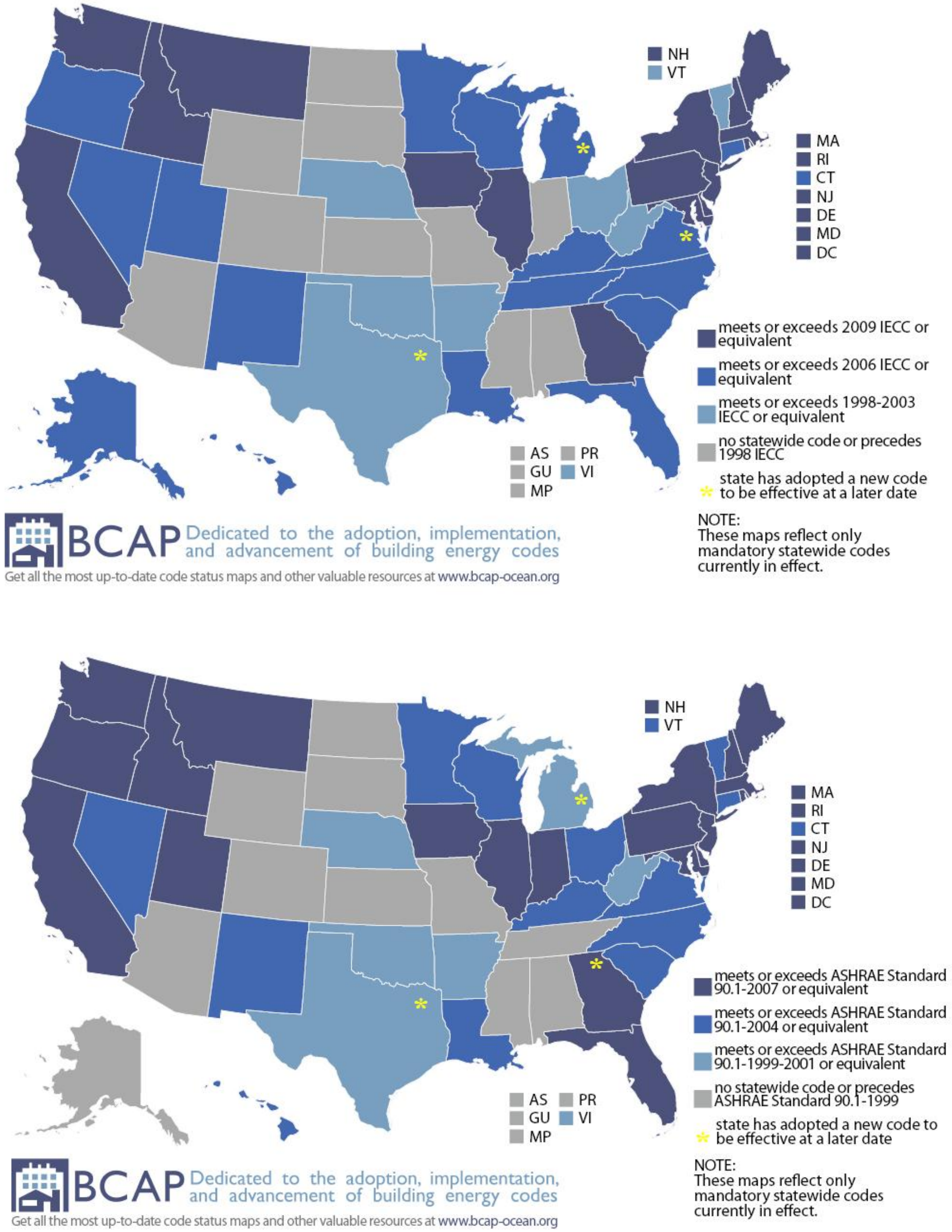
Appliance standards were first proposed and implemented by the state of California; several other states quickly followed suit. Fearing a patchwork of regulations, with each state potentially prescribing its own standards for refrigerators and air conditioners, manufacturers of these appliances pushed for federal appliance standards. This resulted in the 1987 National Alliance Energy Conservation Act, which established specific standards for 15 common types of appliances used in households (e.g., washers, driers, water heaters, and air conditioners). The federal standards were updated twice (in 1988 and 1992), resulting in a longer list of covered appliances and the inclusion of commercial cooling and heating appliances. According to a 2001 household energy consumption survey, appliances are the largest users of electricity in the average U.S. household, consuming approximately two-thirds of all residential electricity (EIA 2001). As such, the energy efficiency of these appliances, defined as the units of energy per unit of service provided, is a major factor determining household and aggregate electricity consumption.

Building energy codes provide minimum building requirements for heating and cooling systems and for the housing envelope that lead to energy savings. For example, with careful building envelope design, good insulation, and appropriate window glazing selection, builders can significantly downsize or even eliminate heating and cooling equipment or reduce the frequency and/or intensity of its use.

California's Warren–Alquist Act, enacted in 1974, established the California Energy Commission and granted it authority to introduce and enforce environmental criteria in the production and consumption of energy. EE standards for residential and nonresidential buildings were enacted in 1978 through Title 24 of the California Code of Regulations. At the federal level, the 1975 Energy Policy and Conservation Act was amended in 1978 to include, as a condition of receiving federal funding, requirements for state conservation and efficiency programs, including building energy codes. Through the 1980s, a number of states adopted codes based on the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) code 90-1075. Other states adopted the Model Energy Code (MEC) developed by the Council of American Building Officials (Bion and Prindle 1991). In 1992, the enactment of the federal Energy Policy Act included a provision for states to review and/or revise their residential building codes regarding EE to meet the MEC. The MEC has since been revised and updated; its successor is the International Energy Conservation Code (IECC).

In contrast to appliance standards, building codes vary greatly across states for both the commercial and the residential sectors. Figure 2 outlines the patchwork of regulations across states, showing the significant heterogeneity in building codes. The differences in building codes can be only partially explained by variation in climate. California, for example, is divided into 16 climate zones, among which the slight variations in the types of requirements are due solely to differences in climate. The more distinct differences—such as whether a state has a building code at all—are more likely determined by the willingness of state and local regulators to adopt such standards.

Figure 2. Residential and Commercial Building Code Status, January 2011



Note: EPCA, Energy Policy and Conservation Act.
Source: BCAP (Building Codes Assistance Project), http://bcap-ocean.org/code-status

Financial Incentive Programs

Financial incentive programs provide either a price signal or an equipment purchase subsidy to consumers to encourage the adoption of EE technology. The two most important financial incentive programs are utility-based *demand-side management* (DSM) programs and *income tax credits*.

Utility DSM programs for energy efficiency promote the adoption by residential, commercial, and industrial customers of efficient equipment to moderate electricity demand, as an alternative to constructing new generation facilities or otherwise procuring new supply. In addition, many DSM programs aim to manage load profiles by, for example, reducing demand at peak times. Utility DSM originated in a small number of jurisdictions (including California and New York) in the mid-1970s, and was further encouraged by the passage of the 1978 Public Utility Regulatory Policies Act. DSM program types include:

- combined information and loan programs, which simultaneously inform firms and households about potential savings from EE investments and provide them with loans for the purchase of efficient devices;
- rebate programs that directly defray some portion of the cost of selected energy-efficient devices;
- comprehensive DSM, in which utilities provide audits of customers' facilities or homes and help identify long-term potential sources of savings, and then offset the cost of recommended EE improvements through direct rebates or other cost-sharing agreements; and
- market transformation programs, which provide incentives "upstream" to equipment manufacturers or distributors to encourage the development or marketing of energy-efficient technologies (an example is the Golden Carrot Super-Efficient Refrigerator Program).

The funding of DSM programs has varied over time; when utility ratepayer funding attenuated following deregulation of electricity markets in 1990, regulators attempted to offset this decrease by establishing public benefit funds. Most states with public benefit funds have implemented *wire charges* on the electricity distribution system under the state's purview. These fees are set at a level such that the total sum collected equals some historic average of the public benefits program. The fees are distributed to DSM programs, low-income subsidy programs, and renewable programs to name but a few.

Income tax credits, the other major financial incentive program, are sometimes used by regulators to incentivize consumers to improve their energy efficiency. The first income tax credits were mandated by the Energy Tax Act of 1978, which encouraged EE improvements in new building by investing in renewable sources of energy. This program resulted in $5 billion in forgone tax revenue during the seven-year period of its existence. The Energy Policy Act of 2005 reestablished tax incentives for hybrid vehicles and home improvements in energy efficiency and extended them to manufacturers of energy-efficient appliances. At the state level, such tax credits have a longer history. From 1979 to 1985, six states offered tax credits and another three offered deductions. Six states still offer tax credits or deductions to this day.

Information and Voluntary Programs

A variety of federal- and state-level programs are designed to increase the information available to firms and consumers about the energy efficiency of production processes and products. In some cases, these are “pure” information programs, with no financial element; in others, some form of information provision is combined with a financial incentive. And, in some voluntary programs, participants commit to certain actions that may include undertaking EE measures. The following examples, from Gillingham et al. (2006), are partly or wholly directed toward residential and/or commercial buildings.

- The Energy Policy Act of 1992 resulted in the creation of a voluntary national registry of GHG emissions and reductions, designated “1605b.” Participating companies committed to reductions relative to a baseline; in many cases, EE investments were the means of meeting the commitments.
- The Climate Challenge program of the U.S. Department of Energy (DOE), which operated during the 1990s, involved partnerships between DOE and national industry trade associations. The trade associations committed to specific GHG emissions reductions and, in many cases, met these commitments through energy efficiency.
- EPA’s Energy Star program is an information program that rates more than 35 different types of energy-using durable goods and other equipment as well as homes and commercial buildings according to their energy use. Units that meet certain efficiency thresholds qualify for an “Energy Star” designation. The goal is to encourage (a) consumers to buy more energy-efficient equipment and (b) producers to improve the energy efficiency of their products.

- Several DOE programs are informational or include major informational components. These programs include Building America, which provides technical support to home builders regarding energy efficiency; Rebuild America, which establishes partnerships between local communities, state governments, and private companies to improve energy efficiency; High Performance Buildings, designed to improve the EE of commercial buildings; and Zero Energy Buildings, a program targeted at designing and building zero net–energy homes.
- The Partnership for Advanced Technology in Housing (PATH) is a collaboration between the U.S. Department of Housing and Urban Development and home construction companies, manufacturers, insurers, and financial companies with the goal of improving the energy efficiency of residential housing, as well as its price, life span, sustainability, and safety.
- DOE also runs several programs targeting low-income households: the Weatherization Assistance Program, which promotes and finances the weatherization of homes, and the Low-Income Home Energy Assistance Program (LIHEAP), which provides a direct subsidy to the fuel costs of participating households.

Technology R&D

In a thoughtful discussion of the federal role in energy technology development, Fri (2006) points out that "…technological innovation is more than R&D." Particularly because of the nature of the complex process of bringing purely technical advances in energy to fruition as products in commercial markets, he suggests that "…innovation in energy technology happens almost entirely in the private sector." Nevertheless, he argues that government energy R&D is, in principle, warranted when directed toward well-defined public policy goals and the solution of specific market failures and when it is implemented so as to complement the activities of the private sector, including private R&D.

Reviewing U.S. federal energy R&D expenditures from 1961 to 2008, Dooley (2008) points out that the federal government's support of energy R&D—efficiency and renewables, fossil energy, nuclear energy, and basic energy sciences—has historically accounted for a relatively small proportion of total federal spending on all R&D, even when including defense-related spending. The peak share of energy R&D spending during this period occurred in 1977–1981, when it exceeded 10 percent of the total. Federal R&D spending on end-use efficiency specifically began in the mid-1970s. A federal R&D program on efficient end-use energy technology was one component of the Energy Research & Development Administration, which was created by President Ford in 1975 and was then absorbed by DOE upon the latter's creation by President Carter in 1977.

The DOE's efficiency R&D includes programs on buildings, industry, and transportation. The National Research Council (NRC) reported that, from 1978 to 2000, the share of total cumulative spending on buildings fell between the shares of transportation (the largest) and industry (the smallest)—about 32 percent of the total, approximately $2 billion (cumulative, in 1999$; NRC 2001).

Federal support for efficiency research has contributed to or resulted in a number of key efficient technologies for buildings, including high-efficiency refrigerators, compact fluorescent and electronic ballast lighting technologies, and low-emissivity windows.

Though on a considerably smaller scale than that of DOE, the state of California has supported R&D for building energy efficiency since the mid-1990s. The state legislation enacting electric utility industry restructuring in 1996 also created the Public Interest Energy Research (PIER) program to promote energy-related research, development, and demonstration. This program, funded by a tax collected through California's three large investor-owned (and publicly regulated) electric utilities, is managed by the California Energy Commission. In 2004, a parallel program for natural gas research was introduced. From 1997 through 2007, PIER funded $540 million of research, of which 34 percent was for R&D in energy efficiency and demand response (CEC 2009).

Estimates of Policy and Program Effectiveness

National Aggregate Estimates

Gillingham et al. (2006) reported numerical estimates of outcomes from several of the policies and programs summarized above, while noting that data for other examples are in many cases incomplete or unavailable. Their survey did not include building codes. Nadel (2004) reported an estimate of energy savings from building codes enacted in the 1980s and early 1990s. These estimates are presented in Table 1, which shows, for example, cumulative national energy savings of approximately 4 percent of national consumption circa the early 2000s. That is, the combined effect of these policies over time, as reflected in aggregate U.S. consumption in that year, was approximately a 4 percent reduction relative to what consumption would have been in their absence. Aggregate primary energy consumption in the United States was approximately 99 quadrillion British thermal units (*quads*) in the year 2000. The table also shows Nadel's finding of approximately one-half of one quad, which is approximately 0.5 percent of total energy consumption, as of the year 2000, from the building codes he examined.

Table 1. Efficiency Policy and Program Results

Program	**Date**	**Energy Savings (quadrillion btu ("quads")**	**Costs (billion $2002)**	**Cost- Effectiveness (billion $2002 per quad)**	**Carbon EmissionsSavings (MMtCE)**
Appliance Standards	2000	1.2	$2.51	$3.28	17.75
Financial Incentives					
Utility DSM	2000	0.62	$1.78	$2.89(high $19.64)	10.02
Information and Voluntary Programs					
1605b registry	2000	<0.41	$0.0004	-	<6.08
DOE Climate Challenge	2000	<0.81	-	-	<12.04
Energy Star	2001	<0.93	$0.05	-	<13.80
DOE Rebuild America	2002	0.01	-	-	0.21
PATH	2000	-	$0.00	-	-
Weatherization Assistance Program	2003	0.09	$0.14	-	1.35
LIHEAP	2002	-	$0.20	-	-
Total Appliance standards and information and voluntary		**<4.1**			**<61.25**
Building Codes					
Residential	2000	0.31	-	-	-
Commercial	2000	0.23	-	-	-
Total Building Codes		**0.54**			

Notes: Quad, quadrillion British thermal units; MMtCE, million metrics tons of carbon equivalent
Sources: Gillingham et al. 2006; Nadel 2004.

California Results

The contemporary technology-oriented approach to EE policy and regulation originated, and is generally recognized as having been pursued most aggressively, in California. Moreover, long-term quantitative estimates of these results, distinguishing among program types, are available only for California. A widely cited benchmark of sorts is the so-called *Rosenfeld Effect*, the contribution of state efficiency policy to holding per capita California electricity consumption flat since the mid-1970s while per capita U.S. consumption steadily increased. The California Energy Commission estimates that the cumulative effect (in the sense described in the previous paragraph) of its utility DSM programs, appliance standards, and building energy codes applied to the residential and commercial sectors was 7.5 percent of statewide electricity consumption in 2000 (CEC 2007). Combined with national energy data and state and national population data, this implies that these policies and programs account for roughly one-fifth of the Rosenfeld Effect gauged in that year.

More detailed results for California, by sector, utility, and program type, are shown in Table 2. The five utilities addressed in Table 2 include the three large investor-owned utilities, Pacific Gas & Electric Company (PG&E), San Diego Gas & Electric Company (SDG&E), and Southern California Edison (SCE), and two major municipal utilities, the Sacramento Municipal Utility District (SMUD) and the Los Angeles Department of Water and Power (LADWP). These results for the year 2000 again show the cumulative impact, on that year's electricity consumption, of all efficiency policies and programs undertaken starting in the mid-1970s; in other words, the results after a quarter-century. As Table 2 shows, the savings vary widely, from approximately 6 percent (LADWP commercial) to nearly 25 percent (SMUD residential). In addition, in both sectors, the technology standards are estimated to have had a greater impact than utility DSM and other programs, with appliance standards having the largest effect in the residential sector and building codes in the commercial sector. The combined savings for the two sectors in 2000 were approximately 11 percent.1

Ex Post Econometric Identification of Program Impacts

The estimates of policy effectiveness have been derived almost exclusively using bottom-up accounting models. Although these models can provide estimates for the extent to which reduced energy consumption is due to behaviors consistent with those intended by the various policies, it is impossible to argue that the results should be interpreted as a causal effect of policy on energy consumption. For example, estimates of utility DSM outcomes have been criticized as being biased downward regarding costs and upward regarding energy savings (Joskow and Marron 1992). Although specific evaluation practices vary widely, in some jurisdictions, the methodological issues behind these critiques have long been recognized and efforts have been made to address them. Following the emergence of utility DSM in the 1970s and 1980s, regulators recognized characteristic biases in utilities' ex ante savings estimates in the direction of overestimation of savings. This led in the 1990s to the development and implementation in California of a requirement for ex post evaluation of program outcomes and correction for self-selection (the *free rider* problem) in these measurements (Sanstad 2007). This resulted both in some general lowering of reported net benefits from the state's regulated DSM programs and in some degree of increased reliability of these reports.

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[1] This is higher than the 7.5 percent cited in the preceding paragraph because the latter is a percentage of total statewide electricity consumption, not just the residential and commercial sectors.

Table 2. Policy-Induced Electricity Savings as of 2000: Estimates for Five California Utilities

	Residential Sector				Commercial Sector			
Utility	Savings from building codes (GWh)	Savings from appliance standards (GWh)	Savings from utility and public agency programs (GWh)	Total consumption (GWh)	Savings from building codes (GWh)	Savings from appliance standards (GWh)	Savings from utility and public agency programs (GWh)	Total consumption (GWh)
PG&E	1,919	2,728	1,014	31,646	1,277	884	612	34,503
SDG&E	166	587	19	6,513	437	268	287	8,628
SCE	1,393	2,386	168	27,980	1,585	1,109	443	34,798
SMUD	609	386	259	4,135	207	115	56	3,596
LADWP	253	505	53	7,519	355	233	8	10,105
Total	**4,341**	**6,592**	**1,513**	**77,793**	**3,861**	**2,609**	**1,406**	**91,630**

	Residential Sector				Commercial Sector			
Utility	Savings from building codes	Savings from appliance standards	Savings from utility and public agency programs	Total savings	Savings from building codes	Savings from appliance standards	Savings from utility and public agency programs	Total savings
PG&E	5.14%	7.31%	2.72%	15.17%	3.43%	2.37%	1.64%	7.44%
SDG&E	2.28%	8.06%	0.26%	10.60%	4.54%	2.79%	2.98%	10.31%
SCE	4.36%	7.47%	0.53%	12.36%	4.18%	2.92%	1.17%	8.27%
SMUD	11.31%	7.17%	4.81%	23.28%	5.21%	2.89%	1.41%	9.51%
LADWP	3.04%	6.06%	0.64%	9.74%	3.32%	2.18%	0.07%	5.57%
Total	**4.81%**	**7.31%**	**1.68%**	**13.79%**	**3.88%**	**2.62%**	**1.41%**	**7.92%**

Note: GWh, gigawatt-hours.
Source: CEC 2007.

The ideal way to minimize selection bias in ex post DSM or other efficiency program evaluation is to randomize participation, as is standard in experimental trials for medical drug testing. Although randomization remains extremely difficult to accomplish in practice in EE programs, there is nonetheless growing interest in program evaluation using econometric methods to provide unbiased estimates of the treatment effect on energy consumption from these programs.

The core problem for ex post measurement of program outcomes is that of possible unobserved factors—factors other than program effects—that may affect energy consumption. Estimates of program effects may be confounded by such factors, with the direction and magnitude of the bias depending on the sign and magnitude of the partial correlation between energy consumption and the unobservable, and the unobservable and the program participation indicator. A partial solution to this problem is to examine the energy consumption of program participants before and after they receive the program "treatment." An alternative strategy is to compare the energy consumption of program participants with that of nonparticipants. If the program is assigned randomly across individuals, one can arrive at estimates of program effectiveness by comparing characteristics of the distribution of energy consumption in the two groups. However, EE programs are characteristically subject to nonrandom program participation. Deciding to participate in an energy audit or choosing to purchase a more efficient refrigerator in response to a utility program, for example, may be correlated with characteristics of individuals such as education and income. If one simply compares the energy consumption of individuals who have taken up a program to that of individuals who have not, one will confound the estimate of treatment with the effect of socioeconomic characteristics and will therefore overestimate program effectiveness.

Difference-in-difference methods can be used to address this problem given repeated cross-sections of energy consumption during a period in which some individuals participated in a program and others did not. Such a method compares the energy consumption of treated individuals to that of untreated individuals, while controlling for time-invariant unobservable confounders and for changes in energy consumption affecting both treated and untreated individuals before and after the implementation of the program. However, this approach still may not allow for the unbiased estimation of a program's effectiveness. If energy consumption trends are due to unobservable factors that vary across individuals, and if program implementation (or take-up) is correlated with this trend, the difference-in-difference methods of program effectiveness may still be confounded. For example, imagine two communities. One is a "green community" whose residents have, over time, continuously decreased their energy consumption independently of any interventions. In the second community, residents have held their energy consumption constant. If an ineffective program were assigned by a hopeful regulator only to the green community and we compared its before and after consumption to that of the other community, we would be led to believe that the policy was effective because of preexisting trends in consumption that have nothing to do with the policy.

It is possible to overcome these problems in practice. Davis (2008) provides the first example of such an econometric study in the EE context. Using household-level data from a field trial in which participants received free high-efficiency clothes washers, he shows that treated households increased clothes washing on average by 5.6 percent after receiving a high-efficiency washer. He then uses the results to evaluate the cost-effectiveness of recent changes in minimum efficiency standards for clothes washers.

Jacobsen and Kotchen (2010) provide one of the first evaluations of energy building codes. They exploit an energy code change and access to residential billing data on electricity and natural gas consumption to identify the effect on consumption. They find that Florida's 2002 energy code change is associated with a 4 percent decrease in electricity consumption and a 6 percent decrease in natural gas consumption. Examining day-to-day and within-day variation, they show that savings are consistent with reduced consumption of electricity for air conditioning and reduced consumption of natural gas for heating. They further find that the private payback period for the average new residence is 7.5 years.

Aggregate Econometric Studies

Even when identification problems cannot be fully overcome, econometric methods have advantages over model-based and engineering approaches in that they use observed data on energy consumption, require minimal behavioral and other assumptions, and provide for rigorous, if not always conclusive, ways to deal with errors of measurement and inference. Cross-section time series methods have long been used in the EE literature; Dahl (1992) contains a good account of the papers and methods used in earlier studies. Most of these studies attempt to examine energy demand more generally, without claiming to estimate the causal impact of a specific EE program. More recently, several authors have paid more careful attention to research design in serious attempts to estimate causal treatment effects.

Loughran and Kulick (2004) estimate the effect of DSM programs on household energy consumption. They exploit time series and cross-sectional variation in utility-level energy demand and DSM spending to arrive at estimates of energy savings and dollars per unit of energy saved. They claim that actual savings from utility-level DSM savings are significantly smaller than the savings claimed by the utilities themselves. Auffhammer et al. (2008) show that (a) a more careful examination of the provided estimates does not support the findings of Loughran and Kulick (2004) and (b) one cannot reject the utility-based estimates based on the work by Loughran and Kulick (2004). Further, the econometric strategy that Loughran and Kulick employ to control for the endogeneity of DSM spending lacks a strong exogenous instrument; admittedly, this is difficult to come by.

Horowitz (2004, 2007) provides two estimates of program effectiveness based on panel data. The 2004 paper quantifies the impact of DSM programs on commercial sector energy intensity at the state level. The 2007 paper exploits differences in EE program intensity across states to estimate their impact using a split-sample research design. Both papers provide estimates of significant savings due to these programs. The drawback to the identification, which Horowitz acknowledges, is that selection into such programs is endogenous, and therefore the estimates are likely to be upper bounds of program effectiveness.

Aroonruengsawat et al. (2009) study the impacts of state-level residential building codes on per capita residential electricity consumption. They construct a timeline indicating when individual states first implemented residential building codes. Using panel data for 48 U.S. states from 1970 to 2006, they exploit the temporal and spatial variation of building code implementation and the issuance of building permits to identify the effect of the regulation on residential electricity consumption. Controlling for the effect of prices, income, and weather, they show that, in states that adopted building codes and then experienced a significant amount of new construction, per capita residential electricity consumption has decreased noticeably, ranging from 3 to 5 percent in 2006. Once they allow for heterogeneity in enforcement and code stringency, they find large population-weighted effects.

DOE Technology R&D

NRC has evaluated DOE's technology development programs as well as the agency's own evaluation methods for these programs (NRC 2001, 2005). NRC's 2001 study encompassed both the EE and fossil energy programs, with the efficiency component examining 17 cases (specific technologies), of which 7 were for building technologies (with the rest for industry and transportation). Among all efficiency and fossil programs, NRC singled out the results of one fossil program and the energy cost savings of the building efficiency programs as yielding, "[b]y an order of magnitude, the largest apparent benefits…" (NRC 2001, 6). Fri (2006) highlighted this outcome as an example of both the possibilities and the risks of federal energy R&D, noting that three efficiency programs—refrigerators, electronic ballasts for fluorescent lighting, and low-emissivity windows—received 0.1 percent of the total cumulative R&D spending reviewed by NRC while accounting for three-quarters of the estimated benefits. NRC (2001) further notes that three-quarters of the overall spending resulted in no quantifiable economic benefit. These findings lend support to the view that government R&D on efficient end-use technology can be a relatively low-cost, high-payoff investment. Table 3 summarizes the NRC (2001) estimates for the three efficient technologies.

California's PIER program does not report cost–benefit estimates for its individual projects. An evaluation of 33 products resulting from PIER R&D and defined as having been successfully commercialized as of 2003 included 11 products in the category of residential and commercial end-use efficiency (Pine et al. 2004). The gross benefits of these 11 products in their first five years of commercialization were projected to be between $200 and $500 million, accounting for roughly three-quarters of projected gross benefits from the entire portfolio of projects. These estimates were compared to overall PIER program expenditures over the review period (1997–2003) of $200 million, for a reported net benefit ratio of between 1.3:1 and 3.4:1. Further, according to the NRC (2001) review, these R&D activities resulted in sizable CO_2 emissions reductions.

Table 3. Results of DOE EE Programs

	Cumulative net energy savings (1978-2008)		**Cost of DOE and private R&D**	**Net cost savings**	**Cumulative CO_2 reduction**
Program	*Fuel*	*Electricity (primary energy)*	*(billions of 1999$)*	*(billions of 1999$)*	*(million metric tons)*
Advanced refrigerator/freezer compressors		1.00	~0.002	7.00	20.00
Electronic ballast for fluorescent lamps		2.50	>0.006	15.00	40.00
Low-e glass	0.70	0.50	>0.004	8.00	20.00
Totals	0.70	4.00	0.01	~30	80.00

Source: NRC 2001, Table 3-4.

Market Barriers, Market Failures, and the EE Gap

Having reviewed the types, characteristics, and history of EE policies and programs, methods for their evaluation, and evidence of their effects in practice, we now turn to the underlying policy rationale for these approaches to promoting efficiency adoption. The justification for these approaches, particularly from an economic standpoint, has been the subject of a long-running but still inconclusive debate. Broadly speaking, many energy economists have questioned the theoretical and empirical grounds for the engineering-based framework within which EE policies are commonly conceived and implemented, as well as this framework's practical applications. Much of this debate hinges on what is colloquially known as the "$20 bill on the sidewalk" problem: if, as efficiency proponents claim, significant gains are to be had for consumers and firms from investments in end-use efficiency, why are public policies needed to compel the adoption of efficient technologies? In this section, we summarize the main themes of this debate.

Efficiency Cost-Effectiveness Methodology

The best-known type of end-use efficiency analysis is the *potential* study, which addresses one or more variations on the question, if existing installed energy-using equipment is replaced by equipment that produces equivalent energy services—such as lighting, refrigeration, heating, and cooling—with lower fuel (electricity or natural gas) inputs, what are the resulting reductions in fuel consumption and costs?

The standard, engineering economics–based methodology for this type of analysis originated nearly four decades ago and continues to be refined and applied. It is a form of deterministic discounted cash-flow or lifecycle cost minimization analysis focused on the trade-off between the higher initial capital cost of more efficient equipment and the lower future costs of the energy needed to operate such equipment. Thus, the choice of efficiency levels takes the form of an investment decision, where the initial outlay is the incremental equipment cost and the future return is in operating cost savings. It is assumed that the energy service level and quality is unchanged. That is, a substitution is made between fuel and technology inputs, but their joint output of, for example, refrigeration, lighting, or space cooling, is constant, as are any relevant "hedonic" characteristics, such as lighting quality or nonenergy refrigerator features. In addition, the parameters of efficiency potential analysis, in practice, include scope and scale—ranging from specific end uses in individual utility service territories to all end uses in national sectors or the entire economy—as well as the length of the planning horizon. With these assumptions, two key types of calculations can be made. The first is the net present value (NPV) of the efficiency investment, or the NPVs of the set of available investments across end uses (and possibly sectors) in more comprehensive studies. The finding of potential then takes the characteristic form of a positive NPV from increased efficiency, showing that the incremental investment is cost-effective. The second type of calculation is the internal rate-of-return (IRR) of a prospective efficiency investment—in other words, the discount rate at which its NPV will be zero. This in turn enables the application of the decision criterion that investments with IRRs greater than the decisionmaker's actual discount rate should be undertaken.

Discount Rates and the Efficiency Gap

All else being equal, the choice of discount rate is critical in these procedures. For given values of other inputs, the value of the discount rate will determine the sign of the NPV and thus the presence or absence of the efficiency potential, as well as the benchmark for the IRR comparison. In applications with multiple end uses and multiple possible efficiency levels for each (represented by *engineering cost curves*)—for example, in studies of potential in an entire sector such as residential buildings—the maintained value of the discount rate will be a critical factor in the estimate of the overall magnitude of potential. From the emergence of this analytical approach in the 1970s, standard practice has been to use real discount rates on the order of 5 to

10 percent, generally corresponding to aggregate estimates of consumers' and firms' (including energy utilities') average costs of capital.

The characteristic finding of the existence of cost-effective but unexploited EE investments (or, equivalently, nonadoption of investments with IRRs exceeding consumers' or firms' observed or estimated discount rates for borrowing) is often referred to as the EE gap. Another way to characterize this phenomenon is in terms of consumers' *implicit discount rates* or hurdle rates inferred from observing the estimated rates-of-return to efficiency that they forgo. For example, if consumers do not adopt an available efficiency technology or measure with an IRR of, say, 30 percent, then they are said to have an implicit discount rate of at least this magnitude. In many studies over several decades, ranging from single technologies in particular utility service territories to multiple end-use and technology types across national sectors, it has been found that rate, scope, and scale of energy-efficient technology adoption is less than warranted by the cost-effectiveness criterion. Such estimates of positive efficiency potential have, in turn, been the basis for promulgating most of the types of policies we review above (the notable exception being technology R&D).

The Crux of the Debate

This brings us to the aforementioned debate on the justification for such policies. We first note that, in this context as in others, economists generally take exception to the use of technology regulation rather than price incentives. Here, however, a more fundamental issue is in play. In principle, the use of "low" discount rates, as described above, might be interpreted as representing a social perspective, analogous with standard cost–benefit analysis. From this perspective, one could imagine a variation on the Kaldor–Hicks criterion, with net lifecycle cost gains and losses to different consumer or firm cohorts compared. However, the fundamental claim made for EE policies, implicitly or explicitly, is that they yield *private* benefits to all end users, not simply social benefits. This underlying conflation of public and private criteria is the ultimate source of the "$20 bill on the sidewalk" critique: if the technologies are already available and are privately cost-effective, why aren't they already being adopted, and why are public policies and regulations needed to promote them?

Market Barriers and Failures

This question has been raised in various forms since technology-focused efficiency policies were first implemented in the 1970s. The following synopsis is in partially chronological form, as the evolution of the debate over the efficiency gap provides insight into the substantive issues.

With the development and first applications of the basic end-use analysis and cost-effectiveness methodology, efficiency investment opportunities began to be identified in practice, and it was clear that their nonadoption in the status quo required an explanation. In addition, because the original justification of the policies had largely derived from environmental and energy supply concerns, energy economists argued that the appropriate reflection of such externalities in energy prices, not direct regulation, was the appropriate policy response.

Both issues were addressed in a seminal paper by Blumstein et al. (1980). Drawing on the findings of a series of case studies, these researchers made the case that even incorporating externalities into energy prices would not result in fully "optimal" or cost-effective adoption of energy efficiency. Several of the "barriers" they posited as inhibiting such adoption continue to be cited today—as, for example, in the influential recent McKinsey & Company study of U.S. EE potential (Granade et al. 2009)—including a lack of information about energy efficiency on the part of consumers, insufficient capital or a lack of financing options for efficiency investments, and *split incentives* situations (such as rental housing or leased office space) in which the returns to an efficiency investment would not accrue to the party who actually made it.

In subsequent years, through the 1980s, a few economists addressed the relationship between such barriers and the standard market failures recognized by economists (e.g., Fisher and Rothkopf 1989). The contemporary debate was stimulated in part by an influential paper by Sutherland (1991), critiquing a national potential study. He argued that, with the partial exception of information problems, none of the standard barriers cited by efficiency proponents was actually a market failure and that these barriers were therefore not legitimate grounds for public policy.

Sutherland's critique was one catalyst for a number of studies in the early- to mid-1990s that analyzed the energy gap from various perspectives. Jaffe and Stavins (1994) presented an integrated framework for relating public and private criteria for EE investments and their implications for public policy. They concurred with Sutherland and others that the possible market failures underlying the efficiency gap were only a subset of market barriers to efficiency, and that the grounds for public policies promoting efficiency adoption were therefore narrower than those claimed by efficiency proponents. They also concluded that, in principle, these policy-relevant market failures had to do with information problems in markets for energy efficiency, but that further research would be needed to clarify and quantify the exact nature and extent of these problems as well as the degree to which they might be ameliorated by public policy.

Until recently, little theoretical or empirical progress had been made in understanding efficiency market failures and the gap since the work of Jaffe and Stavins and other researchers during the same period in the 1990s. However, new research, the benefit of additional hindsight, and the further record of efficiency policies in practice since then does allow several general conclusions to be drawn, as follows.

Lack of information. There is little doubt that, in the absence of public policies and regulations, consumers and firms typically lack the kinds of engineering and cost data generated and used by efficiency specialists.[2] However, both research and applied program outcomes have repeatedly and consistently demonstrated that simply providing this information has very weak effects on efficiency adoption or investment. This was among the main findings of several National Academy of Sciences studies in the 1980s that reviewed a decade or more of both extensive research on consumer energy behavior and the results of the first generation of efficiency policies implemented during the same period (Stern and Aronson 1984; Stern 1985). A more recent survey of research on residential energy interventions to induce conservation reached essentially the same conclusion (Abrahamse et al. 2005). An important theme that emerges in this research is that the concepts of *information* and *informativeness* in the engineering-based efficiency paradigm are not grounded in psychology, decisionmaking research, marketing, or other relevant disciplines. Some evidence suggests that behavioral science–based approaches can be more effective, but not that their results support the "lack of information" hypothesis as it is framed in the efficiency gap literature.[3] That is, this evidence does not show or imply that better-designed information delivery will lead significant numbers of consumers to adopt energy-efficient technology at the cost-effective potential level estimated by engineering models.

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[2] The direct provision to customers of residential and commercial building energy consumption, demand, and cost information is one of the main avowed purposes of emerging energy applications of information technology, such as "smart meters." Abrahamse et al. (2005) review the existing evidence on previous interventions of this type (among others), and find it to be both limited and subject to problems with experimental design and measurement. It remains to be seen how current, more widespread deployment will affect energy consumption and efficiency investment decisions on a broader scale.

[3] The experience of utility DSM programs in California also provides indirect evidence of the weakness of the lack-of-information hypothesis. California's extensive evaluation requirements for these programs—including ex post measurement and controlling for selection effects—do not extend to information-only programs because the effects of these are regarded as too small to be reliably evaluated with this level of rigor (Sanstad 2007).

“Split incentives” and other principal-agent effects. There are several variants of the hypothesis that asymmetric information in one or more markets is an important factor behind the efficiency gap. Most commonly, this is claimed for residential multifamily dwellings, non-owner-occupied single-family dwellings, and commercial real estate. Very limited empirical evidence on this question in the residential sector is available, and those studies that have examined it and found evidence for a principal-agent effect have also noted that its actual magnitude appears to be very small relative to aggregate consumption (Levinson and Niemann 2004; Davis 2010; Gillingham et al. 2010). We are not aware of any corresponding empirical analysis in the commercial sector. Reed et al. (2004) point out, however, that commonly used leasing arrangements in the commercial real estate market allow for the correct assignment of incentives relating to energy consumption and efficiency, so that the “splitting” may be present in principle in only 15 percent of the market. Similarly, the recent McKinsey & Company EE study notes that

> agency issues, in the sense of landlord–tenant issues, are not as widespread as often thought . . . [Their] effect is only somewhat prevalent in the residential sectors, with 8 percent of residential potential affected. Impact varies in the commercial sector, with roughly 5 to 25 percent of the potential impact in most commercial subsectors . . . In total, approximately 9 percent of potential across all sectors is affected by this type of agency issue. (Granade et al. 2009, 26)

Lack of capital and other financing problems. Dating to the Blumstein et al. (1980) work, some economists have claimed, and continue to claim, that consumers’—and possibly firms’—adoption of energy-efficient technology is impeded by problems in affording or financing the initial purchase increment. It may be somewhat surprising, therefore, that with the important possible exception of low-income households, little or no evidence supports the notion that financing or affordability, per se, are significant, systematic contributors to the efficiency gap across customer or market segments. This was noted as long ago as the 1970s; in particular, a 1979 study of residential energy conservation found that most households undertaking EE retrofits paid for them out of cash, savings, or short-term credit, and that those households that did require financing did not have problems obtaining it (Office of Technology Assessment 1979). Hirst et al. (1981) reached similar conclusions in a nationwide review of utility energy audit and retrofit programs. Although such findings might appear to be at odds with research showing increased adoption of efficiency investments relative to programs providing only information, it has also been reported that, in utility DSM programs, the primary use of program-provided financing was to substitute for other financing already available to program participants (Berry 1984). In any case, even with financing, the ultimate penetration of technologies and measures from a range of EE programs has generally been bounded at roughly 5 percent of potential adopters (Walker et al. 1985). All in all, one can infer that, although efficiency demand responds to incentives (like most products or services), the absence of incentives in the status quo is not the reason for limited adoption of efficient technology, and providing incentives—like providing information—does not close the efficiency gap to the degree implied by engineering studies.

That this conclusion does not apply, as such, to low-income households is one reason that this market segment has been, and continues to be, the focus of targeted policies and programs. Even in this cohort, however, it has not been shown that financing alone is the primary impediment to greater adoption of efficient technologies.

Counterhypotheses

While questioning market barriers and other aspects of the efficient technology paradigm, a number of economists have also acknowledged, at least implicitly, the possibly anomalous nature of evidence on the efficiency gap and the need to account for it. The two most prominent such counterhypotheses are as follows.

Uncertainty. Several researchers have proposed models of decisionmaking under uncertainty to rationalize the efficiency gap evidence—that is, to show that seemingly "high" implicit discount rates may actually reflect rational behavior in the face of uncertainty about energy prices and potential returns to efficiency investments. In the paper cited above, Sutherland (1991) applied the logic of the Capital Asset Pricing Model (CAPM) to argue that the pattern of correlation between returns to efficiency investments and those to other assets implied a positive risk premium to the former. However, Metcalf (1994) pointed out that the CAPM framework in fact implied the opposite conclusion: because EE investments would tend to earn higher returns when energy prices were higher than usual and the returns to other assets were concurrently lower, the "premium" on these investments should actually be negative, and consumers' efficiency hurdle rates should be lower than market interest rates. Instead, Metcalf (1994), as well as Hassett and Metcalf (1993), proposed an alternate model, in which uncertain energy price paths create an option value associated with delaying efficiency investments, and rational investors demand a premium for undertaking these investments that is not reflected in the standard NPV rule. One shortcoming of this approach is that it does not account for the fact that energy-using technologies are required to provide the energy services that consumers value. Because a certain fraction of purchases are made to replace defective units, a loss of service is associated with any replacement delay. An offsetting cost of delay would also be present in cases of equipment purchases that are constrained by other factors—for example, the timing of a home remodel. This issue notwithstanding, however, a more basic problem with the option value model is that it does not necessarily account for the quantitative evidence. Sanstad et al. (1995) showed that the model and data used by Hassett and Metcalf did not actually explain implicit discount rates of the magnitudes reported in the literature. On the contrary, with their option value model and estimates of uncertain parameters, underlying discount rates (i.e., exclusive of the option value premium) would still need to be anomalously high for the model's predictions to match these magnitudes.

Although these models are not persuasive, risk and uncertainty associated with EE investments still may be important factors in consumers' and firms' adoption decisions. Single-family energy retrofits are an example: although many retrofit programs have yielded energy and cost savings on average (across participants), these savings often display very high variance—that is, it is quite difficult to accurately predict the results for individual dwellings (Friedan and Baker 1983; Goldman 1985). In commercial buildings, the problem of predicting the outcomes of efficiency investments on an individual structure basis has recently drawn considerable attention because of wide variation in the measured energy consumption in buildings rated by the Leadership in Energy and Environmental Design program (Newsham et al. 2009). Although it should hardly be controversial that, like all investments, efficiency investments contain an element of risk, the detailed quantitative aspects of this risk and its relationship to the efficiency gap have yet to be systematically analyzed.

Unmeasured factors and hidden costs. It has frequently been suggested that the standard EE lifecycle cost calculations omit factors that bear on the investment decision to the extent that they account for the efficiency gap in whole or in part. Such factors may take the form of *hidden costs* associated with more efficient equipment that result in a nonequivalence of the underlying energy service across efficiency levels—specifically, a degradation of service with an increase in efficiency. A salient example is that of compact fluorescent light bulbs (CFLs), which have long had problems with color, temperature, reliability, size, and configuration (with respect to standard fixtures) and a lack of such features as dimmability (Sandahl et al. 2006). Because of the typically large share of efficiency potential accounted for by residential lighting—for example, in the recent McKinsey & Company study—CFLs are probably the most important example of hidden costs, although we are not aware of any work quantifying these costs in terms of consumer utility losses.

Beyond this example, the prevalence and magnitude of hidden costs of efficiency—specifically with respect to technology characteristics or energy service quality—and their relationship to the efficiency gap are unclear. In some cases, such as standard types of heating and cooling equipment, no obvious significant or systematic product amenity shortcomings are associated with more energy-efficient models. In others, notably refrigerators, evidence suggests that increased efficiency coincides with increased features: analyzing the relationship between EE standards and refrigerator features and characteristics, Greening et al. (1997) found that the historical pattern of improving hedonic quality was maintained through the introduction of U.S. federal standards in 1990. Although these researchers could not rule out the possibility that the rate of such improvements was slowed by the regulation, their results illustrate that possible hidden costs should be considered on a case-by-case (end-use by end-use) basis.

Another interpretation of hidden costs is that they have to do with disruptions associated with the installation of efficient equipment. The analogy is to production processes in industry, in which replacing or upgrading machinery—whether for increased efficiency or other reasons—involves a temporary loss of output. There are some examples in the residential and commercial sectors in which this analogy may be valid, such as the replacement of central heating or cooling equipment. Even in these cases, however, the existence of such disruption costs does not completely account for the observed reluctance of consumers and firms to make efficiency investments when the decision to replace equipment has already been made for other reasons. Examples include the use of commercial fluorescent lighting, single-family dwelling energy retrofitting at the time of a nonenergy-related remodel, and the replacement of nonfunctioning appliances. Thus, as with the costs associated with hedonic quality losses, the extent to which *disruption costs* impede efficiency adoption requires case-by-case empirical analysis.

Microeconometric Studies of Equipment Purchases

The preceding discussion departs from the well-known engineering estimation approach to energy efficiency. Another body of evidence, though now dated and limited in scope, provides important insights into individuals' and households' EE decisions. Primarily in the 1970s and early 1980s, a number of ex post studies of consumer purchases of energy-using equipment in the market used so-called *discrete choice* econometric modeling and estimation methods. Among other elements of this research was the empirical estimation of consumers' revealed trade-offs between initial costs and future savings when making their equipment choices. Moreover, several of these studies incorporated income and demographic data on purchasers. As reviewed by Train (1985), the consistent finding, across several end-use categories, was of a pronounced inverse relationship between implied discount rates and income. That is, higher-income purchasers discounted future savings at a lower rate than lower-income purchasers in cases where the average revealed discount rate was “high.” For example, in Hausman’s (1979) well-known analysis of room air conditioner purchases, the average implicit discount rate in the sample was estimated to be 29 percent, but the range was from 89 percent in the lowest income bracket to 5 percent in the highest. Similar results were found for thermal shell improvements and central space conditioning (heating and cooling) equipment as well as for automobile purchases.

Unfortunately, as with other subfields of energy demand research during the same era, this line of inquiry did not persist long enough to conclusively determine the reason for this pattern, such as the extent to which capital constraints, education levels, and other factors might have been at work. However, despite their vintage, these results indicate the clear importance of nontechnological factors—in this case, decisionmaker features—in EE adoption.

Behavioral and Other Nontechnological Aspects of Efficiency Decisions

Applications to energy demand analysis of what is now called behavioral economics date back to the 1980s. Magat et al. (1986), for example, examined reference point effects in a study of energy and cost information format and household energy retrofit decisions. Loewenstein and Prelec (1992) proposed an intertemporal choice model incorporating hyperbolic discounting and reference point effects and noted that it might account qualitatively for a decisionmaker’s reluctance to adopt efficient technology. Interest in behavioral models of energy consumption, including efficiency adoption decisions, has increased markedly in recent years, in part reflecting active progress in behavioral modeling and the analysis of intertemporal choice, such as deviations from exponentially discounted utility maximization (Frederick et al. 2002). To date, however, behavioral energy modeling has been primarily focused on fuel economy choice in passenger vehicle purchases, reflecting, in our judgement, the greater availability of the relevant data on vehicle markets than on markets for energy efficiency in residential and commercial buildings. Several recent empirical studies on vehicle choice have found evidence of decision anomalies relating to fuel economy (Greene et al. 2009; Allcott and Wozny 2010).

Complementing research on the details of individual choice processes has been work on the influence on energy consumption of social, demographic, cultural, and other nontechnological and not-strictly-economic factors. A robust finding in this field has been the nonpredictability of household energy use as a function of engineering and technical characteristics, including energy efficiency, of thermal shells and installed equipment; measured energy consumption among residential houses in the same location of very similar design, size, and thermal characteristics has been found to vary by up to several hundred percent (Lutzenhiser 1993). As with the previously noted finding of wide variations in implicit discount rates as a function of purchaser income, this result shows that engineering and technical information alone cannot accurately predict patterns of end-use energy consumption.

Interpreting the Evidence and Its Implications

This review of the main themes and findings of the literature on the EE gap indicates that the empirical evidence and theoretical modeling are, overall, inconclusive. In a sense, both more and less is known about this phenomenon than is commonly appreciated. On one hand, the available evidence does not generally support the standard and oft-cited barriers to efficiency in the sense of their systematically and significantly retarding the adoption of efficient technologies that would yield private net benefits. We emphasize the word *significantly*; for example, the very recent work on split-incentives in the residential sector finds evidence for the effect but, taken at face value, implies a small aggregate impact on energy consumption. In the case of information and financing barriers, in addition to research findings, we believe that a now-extensive record of the results of programs based on these hypotheses shows quite clearly that other explanations are required.

On the other hand, the extent to which hidden costs and/or uncertainty account for the efficiency gap remains to be determined. As we noted, residential lighting is a clear and significant example of the hidden cost problem. By contrast, in the case of refrigerators—which are important because of the wealth of hedonic, nonenergy features associated with the product—the evidence does not support the hidden cost hypothesis. With regard to uncertainty, we find that several attempts to rationalize the efficiency gap via stochastic investment models have not been successful. However, known uncertainties are associated with some types of efficiency investments—particularly those involving building thermal shells—that have not been effectively analyzed for their effects on technology investment decisions. Overall, the evidence does not support either the hidden cost or the uncertainty hypothesis as general, robust explanations of the efficiency gap.

We view empirically grounded behavioral models of EE decisions as a very promising direction, and think it likely that, with further research, behavioral factors will be shown to play an important role in these decisions and their implications for aggregate adoption patterns. However, this is not to say that decisionmaking anomalies should be expected to explain the efficiency gap in the sense of supporting engineering potential calculations per se. The standard evidence on the efficiency gap, including implicit discount rates, is inextricably tied to the deterministic lifecycle cost model or, in the older microeconometric literature, to utility maximization models that describe the outcomes, but not the processes, of individual choice. In both methodologies, as Sanstad et al. (2006) point out, this “as if” mode of explanation is part of the problem, as it were, in understanding EE decisions. That consumers are “implicitly discounting” at excess rates when choices are represented by the discounted cash-flow model does not mean that their underlying decision procedures are correctly described by this model, nor does it mean that the effects of efficiency-promoting policies can accurately be analyzed by manipulating the discount rate within it. Similarly, although hidden costs play a role in at least some end uses, such costs are not a matter of incorrect discounting and, in strict modeling terms, they cannot be represented by the magnitude of discount rates in engineering models; the extent to which this indirect approach serves as an acceptable quantitative approximation has not been analyzed in the literature.

These limitations of the standard engineering model in understanding the efficiency gap are of a piece with the results noted in previous subsections on the relationship between income and efficiency investment, and on the weakness of technology and engineering information, alone, as predictors of household energy consumption. For the present study, these issues are especially important for (a) understanding how the NEMS model generally represents EE choices, (b) understanding how these choices are affected by policies, and (c) interpreting quantitative NEMS-RFF output on these topics. We return to this point in subsequent sections.

3. Energy Efficiency in the NEMS Residential and Commercial Modules

End-use energy efficiency in U.S. residential and commercial buildings is determined in the NEMS Residential and Commercial Modules as part of a complex set of input assumptions and model computations. Because a full description of either module is quite complicated, we will, in this section, summarize only some general features in addition to key details directly relevant to energy efficiency. The representation of consumer’s and firms’ decisionmaking in the NEMS Residential and Commercial Modules, including the implications for modeling EE adoption, is discussed in Sanstad and McMahon (2008).[4]

Both modules embody a technology-oriented modeling philosophy in the sense that end-use energy consumption is presumed to be determined primarily by observable physical and engineering characteristics of building stocks and shells and energy-using equipment. Thus, the

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[4] The modules’ complete documentation is contained in EIA 2008a (for the Commercial Module) and EIA 2008b (Residential).

modules contain a relatively high level of detail on individual technology types. Although the two modules differ in the details of internal structure as well as those of the economic decision rules applied to technology choices, both contain multiple components corresponding to decisions, including building shells, technology or fuel types, and the use of distributed generation. Both modules disaggregate according to the nine U.S. Census regions.

Residential Module

The Residential Module distinguishes among 3 housing types (single-family, multifamily, and mobile), 16 energy service categories (including space heating and cooling, lighting, water heating, and refrigeration), and 18 technology types. Within each service category, several combinations of equipment cost and EE characteristics are available. The module calculates end-use energy consumption to 2030 according to the following schematic series of steps.

Housing stock projection → Technology choices → Appliance stock projections → Building shell thermal integrity → Distributed generation → End-use energy consumption by service category.

The market shares of technologies and equipment types, and their energy efficiencies, are determined by logit functions of either lifecycle costs (the sum of purchase prices and discounted operating costs) or linearly weighted sums of purchase prices and operating costs. The module distinguishes among choices for new construction and for equipment replacement, including fuel switching. These calculations are one pathway through which energy prices (and, in some policy simulations, technology subsidies) affect decisions. In addition, the formulae for energy consumption contain short-term price elasticity parameters as well as other specific parameters determining *rebound* effects, the offsetting changes in energy use resulting from increases (or decreases) in energy efficiency. More generally, these short-term elasticities allow for changes in fuel use in response to price changes.

Characteristically, the representation of EE choice in NEMS conforms to the engineering–economic framework described in the previous section. More efficient technologies have higher purchase prices and lower operating costs than less efficient versions and deliver equivalent energy services. Therefore, all else being equal, the decision to purchase and operate a more efficient device takes the form of an investment (the initial cost differential) yielding a return (the stream of reduced operating costs). Thus, as in efficiency potential analysis, the discount rates applied to future operating costs are key parameters that are determined either explicitly, in lifecycle cost formulae, or indirectly, in logit functions of purchase prices and operating costs. In the latter case, the implied discount rate is a function of the ratio of the weights on the two factors; this is a standard technique in the microeconometric modeling of technology choice (Train 1985). In the calculations of energy use in new housing, the lifecycle cost evaluation is made with a seven-year horizon. Heating, ventilating, and air conditioning (HVAC) equipment lifetimes (for all fuel types) are on the order of 15 years. The discount rate for these decisions is 20 percent (real, annual). Equipment replacement occurs at fixed intervals determined by equipment lifetimes, so the timing of replacement is not affected by, for example, changes in energy prices or in policies. Fuel or technology switching at replacement is allowed only for single-family homes and is subject both to a ceiling on the proportion of eligible homes and to a penalty; the discount rate for this decision is also 20 percent. Finally, the discount rate entering the determination of energy efficiencies of specific end-use technologies—such as cooking or refrigeration—is also 20 percent.

The numerical values of discount and hurdle rates in the Residential Module reflect the empirical regularity of revealed hurdle rates for efficiency investments exceeding market interest rates for borrowing or saving, as described in the preceding section on the efficiency gap. However, EIA does not endorse the view that these hurdle rates are evidence that consumers are forgoing cost-effective investments. Instead, to the extent that NEMS discount rates exceed market interest rates, they are interpreted by EIA simply as calibration parameters, chosen to reflect evidence on observed consumer choices and market outcomes. The empirical evidence that informs these choices includes engineering or “bottom-up” estimates for appliances (Koomey et al. 1991). For HVAC equipment, the parameters governing hurdle rates are partly determined in a calibration step to reproduce estimates of market shares among technology types and efficiency levels; the seven-year lifetime corresponds to average tenancies (Cymbalsky, pers. comm., 2009).

Several other parameters also affect the uptake of efficient technology in the Residential Module. A bound of 20 percent is placed on the proportion of single-family dwellings that can switch fuels and technology types for HVAC and several appliance categories in a given year; replacements in multifamily and mobile homes are always with the same technology, although efficiency levels may increase. In addition, switching costs are imposed (above and beyond equipment and installation costs) on changes to either air-source or ground-source heat pumps.

These parameters are based on existing data on cost and market trends; the limitations on switching behavior, for example, are intended to ensure that rates of change in technology market shares in NEMS-RFF projections are consistent with those observed historically.

Together with the fixed replacement timing, these constraints and costs place overall limits on both the rate and the degree to which energy-efficient technology can penetrate in the NEMS Residential Module.

Commercial Module

The NEMS Commercial Module distinguishes among 10 building types, 13 energy service categories, and 20 technology types. As in the Residential Module, different equipment cost and performance combinations are available within each end use. The Commercial Module also calculates end-use consumption to 2030 in a sequential fashion, as follows.

Commercial floorspace projection → Energy end-use service projections → Distributed generation/combined heat and power → Technology choices → End-use energy consumption by service category.

Technology market shares and equipment efficiencies are determined by lifecycle cost minimization. The details of this process, however, differ considerably from those in the Residential Module. The Commercial Module represents three decision types and three decision rules. The decision types are (a) purchase equipment for newly constructed buildings; (b) replace equipment at the end of its useful lifetime; and (c) retrofit—that is, replace existing equipment prior to the end of its useful lifetime. (Retrofits in this sense are not allowed in the Residential Module.) The decision rules are (a) least cost (choose the technology with the minimum annualized cost), (b) choose the least-cost technology with the same fuel type as the equipment it is replacing, and (c) choose the least-cost technology of the same type that is being replaced. The combination of decision types and rules results in a total of nine combinations, each of which is possible in the module.

As in the Residential Module, the discount rates in the Commercial Module are adjusted upward so that investment hurdle rates exceed average costs-of-capital. EIA's explanation of these adjustments is ambiguous: the agency describes both as "risk premia" but also as reflecting ". . . all factors, both financial and non-financial, that affect an equipment purchase decision;" and the documentation refers to the efficiency gap debate (EIA 2008a, 51). Different distributions of these premia or *wedges* are assumed to apply to different segments of the commercial building sector, with magnitudes ranging from 0 to 1,000 percent, so that effective discount rates accordingly range widely. The discount rates can be extremely high—effectively infinite in the highest-risk-premium category. These parameter settings are based in part on five empirical studies of commercial customer investment criteria for EE investments.[5] (To our knowledge, these studies did not conclusively identify "risk" as the source of differences between the observed or inferred hurdle rates and market interest rates.)

As in the Residential Module, the Commercial Module features fixed constraints on the flexibility with which fuel and technology can be selected or changed. The Commercial module assigns all fuel and equipment choices to one of three categories: (a) unrestricted (all fuels and technologies are considered); (b) the fuel cannot change, but a shift to different technology is allowed; or (c) both the same fuel and same technology are stipulated. Different fractions are assigned to each choice type in the three decision types of new construction, equipment replacement (at the end of the lifetime of the equipment), and retrofit (in contrast to the Residential Module, the Commercial Module does allow, within these constraints, some retrofitting prior to the end of the useful lifetimes of equipment). No additional direct switching costs are imposed.

Technology Inputs

The purchase costs and performance characteristics (capacities, efficiencies, and lifetimes) of all end-use energy service technologies are exogenous inputs to NEMS-RFF that are determined by the modeler. In addition to the inputs for the existing installed stocks of equipment, two sets of inputs reflect projections of future technology improvements (within the NEMS-RFF 20-year forecast horizon). The standard assumptions are the so-called *Reference* technology inputs, which reflect what are deemed business-as-usual improvements in cost and efficiency. The other is the set of so-called *Advanced* inputs reflecting accelerated technical progress that might come about from changes in market trends or from increased government-sponsored R&D on high-efficiency technologies, an increase in the effectiveness of such R&D, or both, or from other influences. In this set of inputs, efficiency levels are higher, and purchase costs the same or lower, than those in the reference inputs. In some scenarios, these advanced technologies become available earlier. The Reference and Advanced input sets each contain thousands of individual parameters.

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[5] One study is Koomey (1990), and the other four are described in DAC and SAIC (1992).

For several years, EIA has included, as one of its side cases to the *Annual Energy Outlook*, a "High-Tech" case in which the Advanced inputs are substituted and other Reference input assumptions are maintained. In the High-Tech case, the menu of EE choices available to households and firms is enlarged, and the discount or hurdle rates, decision rules, and other parameters governing these choices are unchanged. In general, end-use energy consumption is lower in High-Tech cases, although not for every fuel in every end-use category.

For example, residential "typical" gas-fired water heaters are assumed to be 37 percent more efficient by 2030 under the High-Tech assumptions than in the Reference input set. The installed costs, however, almost double. For high-efficiency water heaters, efficiency increases by 62 percent, whereas prices increase by only 41 percent. For some technologies, similar improvements arrive at constant or lower costs. Navigant Consulting supplies EIA with the specific technology assumptions, and these reports are not in the public domain.

NEMS Hurdle Rates and the Model's Use in Efficiency Policy Analysis

As we have sketched, in both building modules, equipment investment decisions are represented by lifecycle cost (or logit) models in which discount rates are adjusted to approximately reflect observed choices by consumers and firms. Notwithstanding EIA's official agnosticism on the topic, this parameterization approach has been viewed by different NEMS users in terms of the two standard views on the efficiency gap evidence—that is, that it shows either (a) the existence of *market barriers* to cost-effective investments that can be lowered or removed by policies and regulations or (b) the presence of factors such as hidden costs and uncertainty that prevent rational decisionmakers from adopting more efficient technology. Under interpretation (a), NEMS has been used with lowered hurdle rates with the justification that these would correspond to private efficiency decisions with barriers removed.[6] By contrast, under interpretation (b) this use of NEMS amounts to removing real costs from efficiency decisions, and therefore yields distorted model output pertaining to policy costs and outcomes.

The discussion of EE market barriers and failure, and the efficiency gap, applies directly to these issues in applying NEMS. First, the evidence is incomplete and is sufficiently fragmented that, in using the model, neither the "pro" nor the "con" interpretation can be conclusively defended. For example, as previously noted, the evidence supports the hidden cost

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[6] This was done, for example, in the Clean Energy Future efficiency potential study (Interlaboratory Working Group 2000).

argument in the case of residential lighting, so that, for this end use, lowering hurdle rates to reflect reduced market barriers would not be justified. But the opposite may be true for commercial lighting. Similarly, uncertainty has not been shown to be a robust general explanation for the efficiency gap. (And, to elaborate on a point made above, no body of evidence supports the interpretation of extremely high hurdle rates across commercial market cohorts as risk premia.) At the same time, the extent to which risk and uncertainty account for slow adoption of specific efficient technologies and measures—such as residential thermal shell energy retrofits—is unquantified.

A more fundamental issue is that of underlying model specification. We noted at the beginning of this section that NEMS is based on the assumption that energy consumption and technology decisions can be well-represented by information on the physical and engineering characteristics of equipment, thermal shells, and building stocks as well as on equipment initial and operating costs given energy prices and lifecycle cost parameters. As we concluded in section 2, this assumption is broadly unsupported by empirical evidence. Narrowly, evidence suggests that omitted factors, such as household income and demographic characteristics, have first-order effects on consumption and efficiency decisions. Broadly, at least preliminary evidence suggests that consumers' actual decision rules systematically deviate from lifecycle cost minimization, even allowing for an "as if" interpretation of the latter. To the extent that such factors contribute significantly to observed efficiency investment patterns, no rigorous, established theoretical or empirical grounds exist for assuming that a technology and engineering–economic model can accurately approximate the drivers of the efficiency gap and their implications for public policy or the aggregate effects of policies and regulations. More specifically, the use of NEMS hurdle rates as "tunable" parameters to represent different explanations of efficiency investment behavior is, at best, a crude and indirect technique, and the results of model simulations using this approach must be interpreted and used with caution.

In addition to these considerations regarding hurdle rates, the Residential and Commercial Modules summary overview in this section also illustrates our observation that NEMS-RFF estimates of building energy efficiency are a function of many assumptions, a very large number of specific parameters, and a complex system of calculations. Therefore, we emphasize that, in general, no one assumption or parameter can be singled out when attempting to interpret NEMS-RFF simulations and that this interpretation can be quite challenging. In the context of a review of NEMS-based and other methods for evaluating DOE technology programs, NRC (2005, 25) highlighted the problem of ". . . the lack of transparency—the difficulty of identifying the critical assumptions on which . . . [the] NEMS calculation is based."

Although this problem is by no means unique to NEMS, it does indicate another reason why care and caution are needed in drawing economic and policy inferences from the outputs of NEMS-RFF.

4. EE Policies in the American Clean Energy and Security Act (Waxman–Markey)

Background and Motivation

Technology-oriented EE policies, such as building codes and appliance standards, as well as direct subsidy approaches, such as utility DSM, have traditionally been conceived, analyzed, and promoted independently of, or as an alternative to, market-based policies that use the price mechanism to achieve environmental goals. One of the most important recent developments in national energy and environmental policy is that the two policy and regulatory paradigms are being actively considered for joint implementation, and the rationale for this two-fold approach, as well as its possible outcomes, are matters of considerable interest.

By way of recent background, the past several years have seen an expansion of U.S. EE regulation and policymaking at both national and subnational levels. The Energy Independence and Security Act of 2007, for example, stipulated significant increases in efficiency levels of lighting (and in the fuel economy of vehicles). In 2009, this expansion has been dramatic, as Congress and the Obama administration have moved quickly to emphasize end-use efficiency in national energy and economic policy. The American Recovery and Reinvestment Act (ARRA) of 2009, for example, provides for substantial increases in funding for EE measures and programs.

The American Clean Energy and Security Act, referred to as the Waxman-Markey bill (H.R. 2454), was approved by the U.S. House of Representatives in June 2009 and contains EE provisions whose scope and scale are unprecedented in federal legislation. The building efficiency components of Waxman-Markey include aggressive national building energy codes, increased efficiency standards for lighting, a national building energy performance labeling requirement, new federal grants for efficiency investments, and other provisions, which we discuss in more detail below. These are complemented by numerous other policies for efficiency in transportation and industry, and for renewable energy supply. All of these elements are proposed to be implemented in addition to a national CO_2 emissions cap-and-trade system.

To an economist, this would seem to be a "doubling up" on regulation. In theory, a cap-and-trade system would achieve the desired level of emissions in the presence or absence of additional EE standards. Further, in a world of perfect information, a cap-and-trade system would achieve the desired emissions reductions at least cost without the need for such additional standards. By contrast, efficiency advocates hold that, not only are the technology policies justified because of various market barriers or failures, but also that these policies will serve to cushion the consumer energy price impacts of the cap-and-trade system by reducing consumers' use of fuels relative to technology. Although, if realized, the latter effect would tend to blunt the otherwise desirable (by economic efficiency criteria) consequences of the price changes, it nevertheless has powerful political appeal.

At the request of the bill's cosponsors, Representatives Waxman (D-CA) and Markey (D-Mass), EIA (2009) conducted an analysis, using NEMS, of the potential energy, economic, and CO_2 emissions effects of key provisions in the bill—including both technology regulations and the CO_2 cap-and-trade system. The EIA modeling implemented all of the policies, the EE components and the cap and trade, jointly. Although this approach enables an understanding of the overall savings from the policy portfolio, it does not allow one to answer three fundamental questions.

- How much do the individual components of the policy contribute to overall reductions in energy use and emissions from the residential and commercial sectors?
- What are the NEMS-RFF-based costs of implementing the individual EE components of the Waxman-Markey bill alone and under a cap-and-trade system or an equivalent carbon tax?
- How sensitive are the estimated costs and savings to assumptions about the evolution of technology?

Below, we separate out the new building code provisions from the remaining EE components of the Waxman-Markey bill and estimate their impacts and costs as if they were implemented without any pricing policy. We then add the remaining EE policies in the Waxman-Markey bill and, in a third run, change the technology assumptions from the Reference case[7] assumptions to the High-Tech case and compare savings and cost estimates to the previous scenarios. Finally, we examine the consequences of including this full portfolio of policies, with

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[7] The Reference case is equivalent to that used in Krupnick et al. (2010), and is basically the Energy Information Administration's "*Annual Energy Outlook 2009* with Stimulus" scenario (EIA 2009), with enhanced Corporate Average Fuel Economy standards for vehicles.

the High-Tech assumptions, with the Central Cap-and-Trade and Carbon Tax policies as defined in Krupnick et al. (2010).

We have taken this approach, rather than attempt to design a new set of policies and generate new NEMS-RFF inputs and simulations de novo, for the following reasons. As we document in section 1, there are existing estimates of the potential of EE policies, covering a wide range of possible outcomes. Given the paucity of studies with any estimates regarding the costs of building codes and their central importance in the proposed policy, we study them separately. To arrive at a savings and cost estimate of the EE policies alone, we study the portfolio of EE policies, which will allow policymakers to compare the cost of this portfolio per ton of CO_2 avoided to the costs of alternate policy measures. Finally, we are interested in the joint effects of technology-focused and market-based policies, an important topic that has received surprisingly little attention.

Overview of the Waxman-Markey EE Provisions

According to a statement from the bill's sponsors, the Waxman-Markey bill would "create millions of new clean energy jobs, save consumers hundreds of billions of dollars in energy costs, enhance America's energy independence, and cut global warming pollution" (Office of Representative Edward Markey, 2009). The bill is split into five titles, with EE provisions in Titles II and III.

- Title I (Clean Energy) contains standards for conventional and renewable energy technologies and provides funds in support of the development of clean energy technologies and projects.
- Title II (Energy Efficiency) contains a collection of new mandates in terms of *EE standards for appliances, buildings, transportation, and industry*. It further provides funds to support EE projects and technologies.
- Title III (Reducing Global Warming Pollution) *creates a national cap-and-trade scheme designed to reduce GHG emissions* from major sources by 17 percent (2020) and 83 percent (2050) relative to 2005 levels.
- Title IV (Clean Energy Economy) provides financial support to industries and persons negatively affected by the provisions of the Waxman-Markey bill and protects consumers from increases in energy prices.

- Title V (Offsets) provides opportunities for domestic emissions from the forestry and agricultural sectors.

Title II contains eight subtitles targeted at improving the energy efficiency of the U.S. economy in the buildings, transportation, industrial, and public sectors. Following EIA, we model the following EE provisions contained in Waxman-Markey.

Building EE Programs (Subtitle A)

- Section 201, which amends section 304 of the Energy Conservation and Production Act, sets EE targets for residential and commercial buildings. The provisions specify reductions of energy use from buildings built to code relative to a baseline standard. The ASHRAE Standard 90.1-2004 serves as the baseline code for commercial buildings, and the 2006 IECC standard serves as the baseline code for residential buildings. After enactment, compliant buildings will meet a 30 percent reduction in energy use. By 2014 (residential) and 2015 (commercial), buildings will be required to meet a 50 percent reduction. The reduction requirements are tightened by 5 percent at three-year intervals thereafter until 2029 and 2030, respectively. The secretary of energy is charged with developing these annual standards. States can either certify that they have adopted the standard or prove that they have raised their state-specific standards to meet or exceed the national standards. Compliance is achieved if at least 90 percent of new construction and renovated construction in the year prior meets the code. States are given an incentive to adopt the standards by being eligible for allowance allocations and other DOE funds.
- Section 202 requires EPA to develop building retrofit policies for both residential and nonresidential buildings. These retrofit policies are designed to achieve the utmost cost-effective energy efficiency and water use improvements. The programs will be administered through states, which again receive allowances as incentives.

Lighting and Appliance EE Programs (Subtitle B)

- Section 211 amends the Energy Policy and Conservation Act by creating new standards for outdoor lighting. The standards begin in 2016 and are tightened in 2018 and 2022. The section further sets standards for portable light fixtures by 2012 and incandescent reflector lamps.
- Section 212 amends the Energy Policy and Conservation Act by requiring testing procedures for water dispensers, portable electric spas, and hot food–holding cabinets; it

sets efficiency standards for these appliances as of 2012. The section further sets standards for commercial furnaces as of 2011.

- **Oil and Gas Customer Rebates**
- Title III, “reducing Global Warming Pollution,” subtitle B section 782 deals with the allocation of emissions allowances by purpose. Appendix A, Allocation of Emissions Allowances, specifies the use of the allowances as percentages of the total number of allowances. Sections 782b and 782c provide a very small share of emissions allowances to oil and gas consumers to improve energy efficiency (starting at less than 5 percent initially and ramping down to less than 0.7 percent by 2030).

Policy Cases Modeled

Although it would be instructive to model each of the minor provisions separately, because of the high degree of complexity of the NEMS-RFF model, the resources required for a single policy run in NEMS-RFF are significant. OnLocation, a Virginia based consulting firm, conducted the NEMS runs according to our specifications. Based on our available budget, we have therefore designed the following set of “policy bundles,” which allow us to provide NEMS-RFF-based answers as to the effectiveness and costs of these combinations of policies compared to their baseline.

- Case 1: Reference case + Building Codes for New Construction (Subtitle A, section 201).
- Case 2: Reference case + All Title II and Title III EE Provisions
- Case 3: Reference case + case 2 augmented by the High-Tech assumptions.
- Case 4: Central Cap-and-Trade + case 2 augmented by the High-Tech assumptions.
- Case 5: Carbon Tax + case 2 augmented by the High-Tech assumptions.

Case 1 is designed to determine the effectiveness and cost of implementing the most stringent nationwide building codes for new construction in history. As section 1 showed, not all states have building codes and only a handful currently satisfy the reference standard.

Case 2, which is designed to determine the effectiveness and cost of implementing the remainder of the EE programs jointly, allows for a direct comparison to the New Construction Building Codes case.

Case 3 augments case 2 by adopting the more optimistic High-Tech assumptions. In this analysis we treat the High-Tech equipment characteristics in principle as an outcome of R&D

policy and combine these assumptions with the Waxman-Markey policy provisions into a single efficiency policy portfolio. Existing policy includes, for example, DOE's programs for developing energy-efficient technology, as reviewed by NRC (2001). Funding for these programs is currently increasing, as is funding for other programs to stimulate the deployment of efficiency. Although explicitly connecting these developments to specific future outcomes is not possible in general, we believe that this approach is well-justified given the history of, and current trends in, policy-driven energy end-use R&D, including the heightened interest in such research for potential CO_2 reduction.

We compare cases 1–3 to the Reference case, which allows for a more traditional analysis of the effectiveness of these programs in the absence of a price policy.

Case 4 augments the Central Cap-and-Trade model run, which is discussed in detail in Krupnick et al. (2010), by adding the EE provisions under the High-Tech assumptions. With this run, we hope to show the degree of emissions savings and costs achieved by these efficiency standards. Importantly, under a binding cap, these additional reductions would be offset by higher emissions from other sectors. Because of modeling issues specific to NEMS, the total emissions in case 4 and Central Cap-and-Trade run differ, resulting in a "cap" that is not directly comparable.

Case 5 augments the Carbon Tax run of the NEMS-RFF model, which is discussed in detail in Krupnick et al. (2010), by adding the EE provisions under the High-Tech assumptions. With this run, we hope to show the degree of emissions savings and costs achieved by these efficiency standards on top of a carbon tax.

Calculation of Costs

In their report summarizing the results of an overall National Energy Policy Institute–Resources for the Future (RFF) study and integrating the findings from the sector-specific analyses, Krupnick et al. (2010) develop a cost calculation method and welfare metric for estimating the economic effects of the policies, including the residential and commercial EE policies discussed in this paper. Here, we use a simpler method for calculating these costs, described in this section. Although not yielding welfare impacts per se, our calculations complement those of Krupnick et al. and may provide additional insight into how different assumptions and the mechanisms of NEMS-RFF translate into cost estimates of EE policies. For all of our cost and CO_2 savings estimates, the Reference case is the "baseline" against which the incremental effects are computed. For each run of NEMS-RFF, we observe expenditure on fuels by sector and by end use. Further, by sector, fuel, and end use we observe capital expenditures. We therefore calculate a present value cost estimate by adding the discounted stream of fuel savings relative to baseline to the discounted stream of change in capital expenditures from the baseline policy.

$$Cost = \sum_{t=2010}^{2050} \rho^{(t-2010)} (\Delta FuelExpenditures_t) + \sum_{t=2010}^{2030} \rho^{(t-2010)} (\Delta CapitalExpenditures_t) \quad (1)$$

As we discuss below in more detail, NEMS-RFF forecasts end in 2030[8]. If a new, more energy-efficient home is built in 2029, for example, the model provides only one year of savings if we let our discounting horizon end in 2030. To circumvent this issue, we assume that expenditure savings continue at the value for 2030 until 2050, accounting for the fact that not all buildings survive year to year using type-specific survival rates. We test the sensitivity of the estimated cost figures to the discounting horizon assumptions when we discuss costs below.

One limitation of NEMS constrains this calculation. Although NEMS provides fuel expenditures and corresponding energy use for all technologies, sectors, and end uses, it does not report investment costs for all end uses—that is, the costs of purchasing and installing energy-using technologies—whether in the baseline or in policy cases. Broadly speaking, the end uses for which these investment costs are unavailable are in the "miscellaneous electricity use" category in both the Residential and Commercial Modules.

The delivered energy, fuel expenditures, and associated CO_2 emissions for which equipment investment costs *are* available are summarized in Table 4 as a percentage of the in-sector totals for each of these three variables, averaged over the period 2010–2030.

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[8] Newer versions of EIA's Annual Energy Outlook include forecasts out to 2035.

Table 4. Percentage of Delivered Energy, Fuel Expenditures, and CO_2 Emissions with Associated Equipment Costs in NEMS-RFF for Baseline Cases and Cases 3, 4, and 5 (Averages 2010–2030)

	Reference Case		Reference + WMEEHT	
	Residential	**Commercial**	**Residential**	**Commercial**
Delivered energy	85.93%	61.29%	86.56%	61.42%
Fuel expenditures	80.43%	59.87%	81.32%	60.51%
CO_2	75.70%	55.67%	76.63%	56.33%
	Central Cap-and-Trade		**Central Cap-and-Trade+ WMEEHT**	
	Residential	**Commercial**	**Residential**	**Commercial**
Delivered energy	86.07%	60.38%	86.69%	60.41%
Fuel expenditures	80.28%	58.66%	81.13%	59.27%
CO_2	76.95%	54.76%	77.67%	55.23%
	Carbon Tax		**Carbon Tax + WMEEHT**	
	Residential	**Commercial**	**Residential**	**Commercial**
Delivered energy	86.06%	60.37%	86.68%	60.36%
Fuel expenditures	80.25%	58.66%	81.10%	59.18%
CO_2	76.91%	54.74%	77.75%	55.17%

Note: WMEEHT, Waxman-Markey Energy Efficiency + High Tech

For the cost calculation summarized above, we omit energy use for which investment costs are unavailable; that is, we only compute the costs and associated CO_2 savings for which these investment costs can be included. As Table 4 shows, this represents a nontrivial share of energy use, expenditure, and CO_2 and therefore cannot be counted as rounding error in our cost calculation. This approach allows for unbiased estimates of the costs of the uses for which we have data. If emissions reductions from these nonpriced uses have higher or lower costs per unit, our estimates will be biased. To obtain the discounted present value of costs per ton of CO_2 avoided, we divide the total avoided CO_2 emissions for end uses with available costs by the costs for these uses calculated using equation (1). To obtain the discounted present value of costs per barrel of oil avoided, we divide the total avoided distillate fuel oil for end uses with available costs by the costs for these uses calculated using equation (1). Note that, for the commercial sector, distillate fuel oil in 2010 is responsible for only 62 percent of liquid fuels. For the remaining liquid fuels, the only fuel separated out by end use is liquid propane gas, which is derived from natural gas. For the residential sector, distillate fuel oil is responsible for only 58 percent of all liquid fuels. The savings of liquid fuels from EE policies are expected to be minor; therefore, we would expect high costs per ton of distillate saved.

To obtain the annual cost figures for 2020 and 2030 reported in the metrics table at the end of this paper, we simply report the total cost savings and costs per ton of avoided carbon and distillate fuel oil for that year. These figures provide a limited amount of insight because they do not account for the persistence of savings due to a dollar's worth of investment in more energy-efficient capital.

We conclude this subsection by summarizing the rationale for our cost calculations. First, in two reports on the retrospective and prospective evaluation of DOE's technology programs, NRC discusses the question of using the NEMS model for calculating economic welfare benefits (or costs) of these programs (NRC 2001, 2005). NRC concludes that NEMS does not calculate these outcomes according to standard microeconomic measures (e.g., of compensated or equivalent variation) and describes a procedure for using information from NEMS to carry out the appropriate calculations "offline," using a hypothetical simplified model. However, this procedure requires that demand for energy service, rather than energy (fuel), be the quantity on which welfare estimates are based. Although the NEMS Commercial Module projects energy service demands, the NEMS Residential Module does not; thus, welfare measures of efficiency policies cannot be estimated consistently between the two sectors, or estimated at all for the sectors combined.

Second, for the reasons discussed in sections 2 and 3, we believe that the use of discount rates as tunable parameters to represent different assumptions about the role of market failures in observed efficiency adoption is difficult to justify and interpret. However, in section 6 we show the results of different discounting assumptions for our cost estimates.

5. Implementing the Waxman-Markey EE Provisions in NEMS-RFF

In this section, we summarize the mechanics of how the cases and assumptions were represented in NEMS-RFF.

Case 1: Building Codes for New Construction (Waxman-Markey Title II, Subtitle A, Section 201)

Among the standard input files to the NEMS Residential Module is a set of shell efficiency combinations or "packages," which specify various levels of thermal efficiency for housing of the three different types by Census region and technology or fuel for HVAC. These are categorized in terms of criteria including the IECC code and the EPA Energy Star threshold. They were changed to reflect the specific improvements required by Waxman-Markey, which are defined in terms of the IECC 2006 code.

The Commercial Module standard inputs include a set of building shell efficiency indices, which specify shell efficiencies by building type, year of construction, and Census region (EIA 2008a, 113). These indices have been developed to correspond to existing code requirements, including the reference code for commercial buildings in the Waxman-Markey bill—ASHRAE Standard 90.1-2004—so that the new requirements were represented by adjustments in these indices.

Each improvement in the code was assumed to take five years to achieve compliance by all states. There is variation across the nine Census divisions in compliance, which were modeled according to a historical compliance score taken from the American Council for an Energy-Efficient Economy (see ACEEE 2007).

Case 2: Retrofits, Lighting, and Rebates

- **Retrofits to Existing Buildings (Waxman-Markey bill, Title II, Subtitle A, Section 202)** As EIA has noted, there is considerable uncertainty in the possible energy and CO_2 effects of this provision, arising from uncertainty both in the amount and timing of revenue that will be available to fund it and in how this revenue will be allocated by the states. For representation in NEMS-RFF, we assumed that $2 billion was available annually for residential buildings, and energy savings were estimated by the method that EIA applied to model the retrofit (weatherization) provision of the ARRA. For the commercial sector, it was assumed that building shell efficiencies would improve by 1 percent relative to the baseline by 2030. The commercial sector module simply assumes that the shell efficiency of buildings improves by an additional 1 percent relative to the Reference case by 2030; no funding level, or cost, was assigned to this change.
- **Standards (Waxman-Markey bill, Title II, Subtitle B, Sections 211 and 212)** Because individual lighting technology types are represented in both the Residential and Commercial Modules, these new requirements were incorporated by changing the lighting input assumptions directly to ensure that the affected lamp types would comply.
- **Rebates (Waxman-Markey bill, Title III, Subtitle B, Sections 782b and 782c)** Sections 782b and 782c allocate a relatively small portion of the overall emissions allowances to oil and natural gas customers specifically for EE programs. In the buildings

sector, these provisions are assumed to take the form of rebate programs for the purchase of energy-efficient furnaces and boilers; this adjusts the prices of these devices by making them less expensive.

Case 3: High-Tech Inputs

As discussed in section 2, these inputs reflect assumptions of—depending on the specific technology—higher efficiencies, lower initial costs, and/or earlier availability than those assumed in the Reference, Central Cap-and-Trade, or Carbon Tax cases. For this study, they are combined with the Waxman-Markey inputs described above. An extremely important consequence of the manner in which the High-Tech efficiencies are represented in NEMS is that they are likely to carry *negative incremental costs relative to the baseline case.* One can think of the High-Tech assumptions as *exogenous technical change*—in this case, increases in energy efficiency that originate outside the economy and energy system as they are represented in NEMS; the result is that lower fuel inputs are required to meet the projected energy or energy service demands, and therefore fuel expenditures will also decrease. These more efficient technologies enlarge the menu of options available to the abstract consumers and firms in NEMS, rather than prescribing minimum efficiency levels. However, if High-Tech inputs reflect lower operating costs, lower purchase prices, or both, in this case the incremental costs will necessarily be negative because of the cost-minimization assumption. A finding of negative costs here is therefore fundamentally different from the finding of negative costs due to the traditional EE gap literature. Within NEMS, the proverbial $20 bill found on the ground does not exist because it does not explicitly model market failures related to the EE gap. Here, negative costs relative to a Reference case arise by exogenously introducing a slightly less expensive set of more energy-efficient technologies without accounting for the cost of R&D to obtain these technologies in the model.

6. Simulated Impacts and Costs of the Waxman-Markey EE Provisions

Energy Consumption Impacts

Table 5 (panel a) lists the absolute fuel consumption for the year 2030 in quads for each of our 5 runs (cases 1–5) and the three baseline runs (Reference, Central Cap-and-Trade, and Carbon Tax) for the residential sector using NEMS-RFF. The first column displays baseline consumption by fuel, showing that 41 percent of energy consumed comes from natural gas, 46 percent from electricity, and the remainder from liquid fuels and renewables. Coal is no longer consumed directly by households, yet a significant share of electricity is produced using coal.

The second column displays the impact of the New Construction Building Codes run (case 1). Total consumption goes from 12.28 quads to 11.97 quads, a 2.51 percent decrease in consumption by 2030. Table 5 (panel b) shows the percentage decrease in consumption by fuel relative to the Reference case run. We show that kerosene, natural gas, and renewables see the biggest decreases in consumption. However, because kerosene and renewables supply only a small share of overall energy, these reductions are minor in absolute scale. Table 5 (panel c) displays the share of reductions by each fuel in total reduction. It is not surprising that more than 60 percent of the reductions come from decreases in natural gas use and another 20 percent from electricity use because these are the two main sources of energy for heating and cooling services in new construction. This relatively modest reduction in energy use from the stringent new national building codes is not surprising given the slow turnover of housing stock. Table 6 displays the heating shell index, which reflects the efficiency of the housing envelope by building type. We can see that, in 2030 in the absence of regulation, a new building shell would be 29 percent more efficient than the 2005 version. The new building codes drive this index down to 0.34, which is a 66 percent improvement over 2005. Pre-2005 buildings will become more efficient in the absence of policy because retrofits are rational for some consumers. The baseline improvement in pre-2005 homes is 9 percent, which is the same in our Case 1 building codes run. The bottom panel of Table 6 indicates that the average home in the United States in 2030 would have a 14 percent more efficient shell in the absence of building codes. Once we add the new construction building codes, this average index will be driven up to only 20 percent.

The third column of Table 6 (Case 2) displays energy consumption once we add the complete EE portfolio embedded in Waxman–Markey to the Reference case run. The total reductions in energy consumption rise by 0.74 to 3.26 percent overall reductions. Because this policy bundle includes significant retrofits of existing buildings combined with minor lighting programs and the rebates for furnaces and boilers, it is not surprising that the distribution of reductions does not change significantly. There is a slightly higher reduction in fuel oil and a proportionally smaller reduction in electricity use because older homes are more likely to be heated with fuel oil. The retrofits, as Table 6 indicates, result in minor improvements in the thermal efficiency of existing homes—a 2 percent reduction over baseline by 2030.

Table 5. Residential Sector Fuel Consumption by Fuel Type in 2030

(a) Total consumption (quads)	**Ref. case**	**Case 1**	**Case 2**	**Case 3**	**Central C&T**	**Case 4**	**Carbon Tax**	**Case 5**
Price policy	*Reference*	*Reference*	*Reference*	*Reference*	*Cap*	*Cap*	*Tax*	*Tax*
EE Policy	*None*	*Building codes*	*WM*	*WM*	*None*	*WM*	*None*	*WM*
Technology assumptions	*Reference*	*Reference*	*Reference*	*High-Tech*	*Reference*	*High-Tech*	*Reference*	*High-Tech*
Liquefied petroleum gases	0.51	0.50	0.49	0.47	0.50	0.46	0.50	0.46
Kerosene	0.07	0.07	0.07	0.06	0.07	0.06	0.07	0.06
Distillate fuel oil	0.50	0.50	0.49	0.47	0.49	0.46	0.49	0.46
Liquid fuels subtotal	1.09	1.06	1.05	1.01	1.06	0.98	1.06	0.98
Natural gas	5.01	4.81	4.75	4.69	4.81	4.50	4.81	4.48
Coal	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Renewable energy	0.50	0.48	0.47	0.46	0.53	0.48	0.53	0.48
Electricity	5.67	5.61	5.60	5.32	5.24	4.89	5.25	4.87
Total	12.28	11.97	11.88	11.49	11.65	10.87	11.66	10.82

(b) % change (see note)	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Liquefied petroleum gases	0.00	-3%	-3%	-8%	0.00	-8%	0.00	-8%
Kerosene	0.00	-11%	-12%	-13%	0.00	-14%	0.00	-14%
Distillate fuel oil	0.00	-1%	-3%	-6%	0.00	-6%	0.00	-6%
Liquid fuels subtotal	0.00	-3%	-4%	-7%	0.00	-7%	0.00	-7%
Natural gas	0.00	-4%	-5%	-6%	0.00	-6%	0.00	-7%
Coal	0.00	0%	-2%	-5%	0.00	-5%	0.00	-5%
Renewable energy	0.00	-4%	-6%	-8%	0.00	-9%	0.00	-8%
Electricity	0.00	-1%	-1%	-6%	0.00	-7%	0.00	-7%
Total			-3.26%	-6.44%		-6.77%		-7.19%

(c) Share of total savings	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Liquefied petroleum gases		4%	4%	5%		5%		5%
Kerosene		3%	2%	1%		1%		1%
Distillate fuel oil		2%	4%	4%		3%		3%
Liquid fuels subtotal								
Natural gas		64%	65%	40%		39%		39%
Coal		0%	0%	0%		0%		0%
Renewable energy		7%	7%	5%		6%		5%
Electricity		20%	18%	45%		45%		46%

Note: * Relative to Reference case. ** Relative to Central Cap-and-Trade (C&T) case. *** Relative to Carbon Tax case. WM, Waxman-Markey.

Table 6. Heating Shell Efficiency Index of New and Existing Buildings

Pre-2005 homes		2005	2010	2020	2030
	Reference case	1.00	0.97	0.94	0.91
	Case 1	1.00	0.97	0.94	0.91
	Case 2	1.00	0.97	0.93	0.89
	Case 3	1.00	0.97	0.91	0.87
	Central Cap-and-Trade	1.00	0.97	0.93	0.90
	Case 4	1.00	0.97	0.91	0.86
	Carbon Tax	1.00	0.97	0.93	0.90
	Case 5	1.00	0.97	0.91	0.86
New construction					
	Reference case	1.00	0.78	0.73	0.71
	Case 1	1.00	0.78	0.43	0.34
	Case 2	1.00	0.78	0.43	0.34
	Case 3	1.00	0.78	0.43	0.34
	Central Cap-and-Trade	1.00	0.78	0.73	0.70
	Case 4	1.00	0.78	0.43	0.34
	Carbon Tax	1.00	0.78	0.73	0.71
	Case 5	1.00	0.78	0.43	0.34
All Buildings					
	Reference case	1.00	0.96	0.90	0.86
	Case 1	1.00	0.96	0.89	0.80
	Case 2	1.00	0.96	0.88	0.79
	Case 3	1.00	0.96	0.87	0.78
	Central Cap-and-Trade	1.00	0.96	0.90	0.85
	Case 4	1.00	0.96	0.87	0.77
	Carbon Tax	1.00	0.96	0.90	0.85
	Case 5	1.00	0.96	0.87	0.77

For the case 3 run, we assume policies identical to those of the case 2 run, but impose the High-Tech assumptions, which result in many cases in an earlier arrival of more efficient, and sometimes cheaper, technology. Again, this is not endogenous to NEMS, but these technologies appear in the choice set without reflecting the cost of developing them and bringing them to market. What we see is approximately a doubling in the overall reductions from 3.25 to 6.44 percent relative to the Reference case. In this scenario, interestingly, 85 percent of the reductions are due to electricity and natural gas, but the split between the two is different. Although for the case 2 scenario, 65 percent of the reductions came from natural gas and 18 percent from electricity, under the High-Tech scenario, 40 percent of the reductions are due to natural gas and 45 percent are due to changes in electricity use, a finding that we explore further below.

We turn to the price policies next. First, under the Central Cap-and-Trade and the Carbon Tax policies, the shell efficiency of buildings does not change much compared to the Reference case, which is surprising. Also, interestingly, under both types of price regulation, the distribution of reductions across fuels in percentage terms is almost identical to that under the baseline (Table 5). *This suggests that these EE provisions in NEMS have the same marginal impact on fuels in the presence and absence of price policies.*

To better understand how these savings are achieved in the residential sector, we now consider these results by end-use category. Table 7 shows total residential consumption by end use. The top panel (a) again displays consumption in quads, panel b displays the percentage reduction by fuel relative to baseline, and panel c displays the share of each end use in total reductions, which is the most interesting metric from a policy perspective. In the baseline, 40 percent of energy goes to heating, 9 percent to cooling, and 16 percent to water heating, accounting for roughly two-thirds of total consumption.

The New Construction Building Codes (case 1) affect heating and cooling. Because heating is responsible for a larger share of consumption, almost 90 percent of the overall reductions are due to reductions in energy consumption from heating. This is consistent with the findings on electricity and natural gas in Table 5. By adding the retrofit, lighting standards, and rebates under case 2, the end-use impacts picture does not change significantly. The majority of savings come from space heating. The lighting savings over baseline due to these policies are less than 0.5 percent. Overall, this suggests that, given the Reference technology assumptions, *the largest reductions from the EE provisions in Waxman–Markey come from changes in heating and cooling in new housing and retrofits.*

Once we add the High-Tech assumptions, the distribution of savings changes significantly toward end uses fueled fully or partially by electricity. Space cooling has a bigger reduction as a result of more efficient cooling equipment. Personal computers and color televisions become significantly more efficient, as does water heating equipment. There is also a significant increase in savings from the “other uses” category. As in the fuels discussion above, the *shares of reductions by end use are almost identical when we add the full High-Tech Waxman–Markey portfolio to the Central Cap-and-Trade and Carbon Tax scenarios.*

Table 7. Residential Delivered Energy Consumption by End Use (2030)

(a) Total consumption (quads)	**Ref. case**	**Case 1**	**Case 2**	**Case 3**	**Central C&T**	**Case 4**	**Carbon Tax**	**Case 5**
Price policy	*Reference*	*Reference*	*Reference*	*Reference*	*Cap*	*Cap*	*Tax*	*Tax*
EE Policy	*None*	*Building codes*	*WM*	*WM*	*None*	*WM*	*None*	*WM*
Technology assumptions	*Reference*	*Reference*	*Reference*	*High-Tech*	*Reference*	*High-Tech*	*Reference*	*High-Tech*
Space heating	4.91	4.64	4.56	4.46	4.76	4.33	4.76	4.32
Space cooling	1.06	1.01	1.01	0.97	0.97	0.89	0.97	0.88
Water heating	1.92	1.92	1.92	1.86	1.74	1.65	1.73	1.64
Refrigeration	0.43	0.43	0.43	0.43	0.42	0.42	0.42	0.42
Cooking	0.41	0.41	0.41	0.41	0.40	0.40	0.40	0.40
Clothes dryers	0.39	0.39	0.39	0.39	0.37	0.37	0.37	0.37
Freezers	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Lighting	0.53	0.53	0.52	0.53	0.49	0.49	0.49	0.49
Clothes washers	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Dishwashers	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Color televisions and set-top boxes	0.56	0.56	0.56	0.50	0.52	0.47	0.52	0.47
Personal computers and related equipment	0.23	0.23	0.23	0.17	0.23	0.17	0.23	0.17
Furnace fans and boiler circulation pumps	0.17	0.17	0.17	0.17	0.16	0.16	0.16	0.16
Other uses	1.45	1.46	1.46	1.37	1.36	1.27	1.37	1.27
Total	12.28	11.97	11.88	11.49	11.65	10.87	11.66	10.82

(b) % change	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Space heating		-6%	-7%	-9%		-9%		-9%
Space cooling		-4%	-5%	-9%		-9%		-10%
Water heating		0%	0%	-3%		-5%		-6%
Refrigeration		0%	0%	0%		0%		0%
Cooking		0%	0%	0%		0%		0%
Clothes dryers		0%	0%	1%		1%		0%
Freezers		0%	0%	0%		0%		0%
Lighting		0%	0%	0%		1%		0%
Clothes washers		0%	0%	0%		0%		0%
Dishwashers		0%	0%	0%		0%		0%
Color televisions and set-top boxes		0%	0%	-9%		-9%		-10%
Personal computers and related equipment		0%	0%	-27%		-27%		-27%
Furnace fans and boiler circulation pumps		0%	0%	0%		0%		0%
Other uses		0%	0%	-6%		-7%		-7%
Total			-3.25%	-6.44%		-6.77%		-7.19%

(c) Share of total savings	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Space heating		88%	89%	57%		54%		53%
Space cooling		15%	13%	12%		11%		11%
Water heating		-1%	-1%	7%		10%		12%
Refrigeration		0%	0%	0%		0%		0%
Cooking		0%	0%	0%		0%		0%
Clothes dryers		0%	0%	0%		0%		0%
Freezers		0%	0%	0%		0%		0%
Lighting		-1%	0%	0%		0%		0%
Clothes washers		0%	0%	0%		0%		0%
Dishwashers		0%	0%	0%		0%		0%
Color televisions and set-top boxes		0%	0%	7%		6%		6%
Personal computers and related equipment		0%	0%	8%		8%		7%
Furnace fans and boiler circulation pumps		0%	0%	0%		0%		0%
Other uses		-1%	-1%	11%		11%		11%
Total		100.00%	100.00%	100.00%		100.00%		100.00%

Note: * Relative to Reference case. ** Relative to Central Cap-and-Trade (C&T) case. *** Relative to Carbon Tax case. WM, Waxman-Markey.

We now turn to the commercial sector results. Table 8 displays energy consumption by fuel for the commercial sector. The table is set up in the same fashion as the residential tables, and the policy run designations are identical. In the Reference case run, note that, compared to the residential sector, the commercial sector has a larger electricity share (60 percent) in total energy than in natural gas (33 percent), which is not surprising. When the building codes for new commercial construction are implemented (case 1), we see a significantly smaller reduction (1.33 percent) in this sector than in the residential sector. Almost all of the savings from commercial building codes in new construction come from savings in natural gas (82 percent), with the remaining savings split between distillate fuel oil and electricity (8 percent each). The retrofits, lighting provisions, and rebates add little in terms of savings, leading to total reduction in energy consumption of 1.55 percent. Once the High-Tech assumptions are added, total savings increase to 4.55 percent. There is a significant shift in the share of savings by fuel toward electricity from the High-Tech assumptions; this is consistent with the results from the residential sector and is not surprising considering the large share of electricity in total consumption. As in the residential sector results, imposing the case 3 assumptions onto the cap and trade or the carbon tax yields almost identical total savings with a very similar distribution of reductions across fuels. There is a slight shift toward higher reductions in electricity use under those scenarios, which may have to do with the relative change in prices across fuels under the price policies and the sector’s very high electricity intensity.

Table 8. Commercial Sector Fuel Consumption by Fuel Type

(a) Total consumption (quads)	**Ref. case**	**Case 1**	**Case 2**	**Case 3**	**Central C&T**	**Case 4**	**Carbon Tax**	**Case 5**
Price policy	*Reference*	*Reference*	*Reference*	*Reference*	*Cap*	*Cap*	*Tax*	*Tax*
EE Policy	*None*	*Building codes*	*WM*	*WM*	*None*	*WM*	*None*	*WM*
Technology assumptions	*Reference*	*Reference*	*Reference*	*High-Tech*	*Reference*	*High-Tech*	*Reference*	*High-Tech*
Liquefied petroleum gases	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Motor gasoline	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Kerosene	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Distillate fuel oil	0.33	0.32	0.32	0.31	0.31	0.30	0.31	0.30
Residual fuel oil	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Liquid fuels subtotal	0.58	0.57	0.57	0.56	0.56	0.54	0.56	0.54
Natural gas	3.53	3.40	3.39	3.37	3.38	3.28	3.39	3.27
Coal	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Renewable energy	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Electricity	6.36	6.36	6.35	6.05	5.96	5.63	5.97	5.61
Total	10.66	10.51	10.49	10.17	10.09	9.64	10.10	9.61

(b) % change	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Liquefied petroleum gases		0%	0%	0%		0%		0%
Motor gasoline		0%	0%	0%		0%		0%
Kerosene		0%	0%	0%		0%		0%
Distillate fuel oil		-4%	-4%	-6%		-5%		-6%
Residual fuel oil		0%	0%	0%		0%		0%
Liquid fuels subtotal		-2%	-2%	-3%		-3%		-3%
Natural gas		-4%	-4%	-4%		-3%		-3%
Coal		0%	0%	0%		0%		0%
Renewable energy		0%	0%	0%		0%		0%
Electricity		0%	0%	-5%		-6%		-6%
Total		-1.33%	-1.55%	-4.55%		-4.40%		-4.87%

(c) Share of total savings	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Liquefied petroleum gases		0%	0%	0%		0%		0%
Motor gasoline		0%	0%	0%		0%		0%
Kerosene		0%	0%	0%		0%		0%
Distillate fuel oil		9%	8%	4%		4%		4%
Residual fuel oil		0%	0%	0%		0%		0%
Liquid fuels subtotal								
Natural gas		90%	82%	31%		22%		23%
Coal		0%	0%	0%		0%		0%
Renewable energy		0%	0%	0%		0%		0%
Electricity		1%	10%	65%		74%		73%
Total		100%	100%	100%		100%		100%

Note: * Relative to Reference case. ** Relative to Central Cap-and-Trade (C&T) case. *** Relative to Carbon Tax case. WM, Waxman-Markey.

Table 9 splits the commercial sector results out by end use. From the Reference case run, we see that space heating and cooling account for only 23 percent of total energy consumed, and lighting is responsible for another 11 percent. The "other uses" category is responsible for 38 percent in this sector.[9] The case 1 run shows that almost all reductions from the building codes

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[9] This is important later because the "other uses" category is not associated with any investment costs.

are due to reductions in space heating. Space cooling consumption increases very slightly under the building codes scenario, which is counterintuitive.

Table 9. Commercial Delivered Energy Consumption by End Use

(a) Total consumption (quads)	**Ref. case**	**Case 1**	**Case 2**	**Case 3**	**Central C&T**	**Case 4**	**Carbon Tax**	**Case 5**
Price policy	*Reference*	*Reference*	*Reference*	*Reference*	*Cap*	*Cap*	*Tax*	*Tax*
EE Policy	*None*	*Building codes*	*WM*	*WM*	*None*	*WM*	*None*	*WM*
Technology assumptions	*Reference*	*Reference*	*Reference*	*High-Tech*	*Reference*	*High-Tech*	*Reference*	*High-Tech*
Space heating	1.84	1.68	1.67	1.58	1.69	1.45	1.69	1.44
Space cooling	0.68	0.70	0.70	0.70	0.63	0.64	0.63	0.64
Water heating	0.68	0.68	0.68	0.68	0.63	0.62	0.63	0.62
Ventilation	0.72	0.71	0.72	0.71	0.61	0.61	0.61	0.60
Cooking	0.25	0.25	0.25	0.25	0.23	0.23	0.23	0.23
Lighting	1.21	1.21	1.21	1.18	1.09	1.05	1.09	1.04
Refrigeration	0.40	0.40	0.40	0.39	0.39	0.37	0.39	0.37
Office equipment (PC)	0.34	0.34	0.34	0.22	0.33	0.21	0.33	0.21
Office equipment (non-PC)	0.44	0.44	0.44	0.41	0.43	0.41	0.43	0.41
Other uses	4.09	4.09	4.08	4.06	4.05	4.06	4.06	4.06
Total	10.66	10.51	10.49	10.17	10.09	9.64	10.10	9.61

(b) % change	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Space heating		-9%	-9%	-14%		-14%		-15%
Space cooling		2%	2%	2%		2%		1%
Water heating		0%	0%	-1%		-1%		-2%
Ventilation		0%	0%	-1%		-1%		-2%
Cooking		0%	0%	0%		1%		0%
Lighting		0%	0%	-3%		-4%		-5%
Refrigeration		0%	0%	-3%		-5%		-5%
Office equipment (PC)		0%	0%	-36%		-37%		-37%
Office equipment (non-PC)		0%	0%	-5%		-5%		-5%
Other uses		0%	0%	-1%		0%		0%
Total		-1.33%	-1.55%	-4.55%		-4.40%		-4.87%

(c) Share of total savings	**Ref. case**	**Case 1***	**Case 2***	**Case 3***	**Central C&T**	**Case 4****	**Carbon Tax**	**Case 5*****
Space heating		111%	102%	54%		55%		52%
Space cooling		-11%	-10%	-3%		-2%		-1%
Water heating		0%	-1%	2%		2%		3%
Ventilation		0%	0%	1%		1%		2%
Cooking		0%	0%	0%		-1%		0%
Lighting		0%	-1%	7%		10%		11%
Refrigeration		0%	0%	3%		4%		4%
Office equipment (PC)		0%	0%	26%		28%		25%
Office equipment (non-PC)		0%	0%	4%		5%		5%
Other uses		0%	10%	6%		-2%		0%
Total		100.00%	100.00%	100.00%		100.00%		100.00%

Note: * Relative to Reference case. ** Relative to Central Cap-and-Trade (C&T) case. *** Relative to Carbon Tax case. PC, personal computer; WM, Waxman-Markey.

Once we add the other efficiency policies, we see some very small additional reductions in lighting and other uses as well as water heating. The most noteworthy changes here come from improvements in the efficiency of personal computers, lighting, and other office equipment, which are responsible for roughly 30 percent of the significant 4.55 percent reduction in consumption relative to baseline. The distribution of savings is again almost identical once we add the price policies and compare them to their respective baselines.

The reductions reported above count all uses, regardless of whether NEMS reports capital costs for them, in terms of delivered energy. The delivered energy measure ignores what EIA (year) calls electricity-related losses. Conversion of heat energy into steam at steam-electric power plants results in thermodynamically predetermined losses. Most of these losses occur at steam-electric power plants (conventional and nuclear) in the conversion of heat energy into mechanical energy to turn electric generators. The loss is a thermodynamically necessary feature of the steam-electric cycle. Further losses include the electricity used at power plants, transmission and distribution losses, and unaccounted-for losses. EIA allocates these losses to end-use sectors proportionally to their share of total electricity sales. About 65 percent of all energy is lost in conversion, 5 percent is used by the plants themselves, and transmission losses account for 7 percent. Table 10 compares the sectoral savings from the different policies over the relevant baseline scenario for total and delivered energy. Not surprisingly, the cap-and-trade policy and the tax policy see larger percentage decreases in total energy compared to delivered energy. Electricity production in the United States has a large share of coal, which is a high-carbon fuel. Therefore, this probably reflects the greater decrease in delivered electricity compared with delivered natural gas because the reduction in delivered electricity also brings down the associated energy (in "total") that goes toward generating it.

Table 10. Policy Impacts on Delivered and Total Energy by Sector

Total consumption (quads)	**Ref. case**	**Case 1**	**Case 2**	**Case 3**	**Central C&T**	**Case 4**	**Carbon Tax**	**Case 5**
Price policy	*Reference*	*Reference*	*Reference*	*Reference*	*Cap*	*Cap*	*Tax*	*Tax*
EE Policy	*None*	*Building codes*	*WM*	*WM*	*None*	*WM*	*None*	*WM*
Technology assumptions	*Reference*	*Reference*	*Reference*	*High-Tech*	*Reference*	*High-Tech*	*Reference*	*High-Tech*
Residential delivered	12.28	11.97	11.88	11.49	11.65	10.87	11.66	10.82
Residential total	24.02	23.59	23.48	22.65	22.24	20.94	22.27	20.71
Commercial delivered	10.66	10.51	10.49	10.17	10.09	9.64	10.10	9.61
Commercial total	23.82	23.68	23.63	22.80	22.12	21.18	22.15	20.93
Sum delivered	22.94	22.48	22.37	21.66	21.74	20.51	21.76	20.43
Sum total	47.85	47.26	47.12	45.45	44.36	42.12	44.42	41.64
% change delivered		-1.96%	-2.47%	-5.56%		-5.67%		-6.11%
% change total		-1.23%	-1.53%	-5.01%		-5.05%		-6.24%

Note: WM, Waxman-Markey

Costs of Emissions Reductions

The previous section describes the savings in energy consumption from the price policies and the additional savings from the two sectors gained by introducing three versions of the energy EE programs. Although it is instructive to discuss the potential savings from each of the policies, the cost at which these savings are ultimately achieved will heavily influence whether these policies should and will be adopted. In this section, we discuss the costs of reducing CO_2 emissions via the EE programs studied in this paper. The metrics table at the end of this paper contains the complete set of cost estimates for this study.

The main measure of interest is the total discounted present value of these programs over the baseline case. For cases 1, 2, and 3, the relevant comparison is the Reference case run of the NEMS–RFF model. For the New Construction Building Codes and adopting an arbitrary discount rate of 10 percent, we arrive at an estimated present discounted value of costs for the residential sector in the amount of $4 billion (2007$), which translates into a cost per ton of CO_2 abated of $6.[10] If we add the whole set of EE provisions from Waxman–Markey (case 2), the costs increase to $13 dollars per ton of CO_2. Once we add the High-Tech assumptions, costs become negative at –$21 per ton. As noted in section 5, these negative costs are a consequence of the input assumptions and the design of the numerical simulations. In addition, in the NEMS model, whatever rebound is computed by the model will offset to some extent how much energy is really saved relative to a straight engineering estimate, but this is not sufficient to offset all of the gains.

If we compare the costs of adding the High-Tech EE provisions to the pure Central Cap-and-Trade policy, the present discounted value for the residential sector rises from a –$25 billion NPV under the equivalent Reference case comparison to –$44 billion. This increase in NPV is consistent with the higher costs of energy under cap and trade and the fact that, for example, the building shell investments are not conducted without mandating them under the baseline cap-and-trade setting as we discuss above. Given that our measure of costs is the discounted sum of the difference over baseline in capital flows and the sum of the difference over baseline in fuel expenditures for costed uses, this result is not surprising. Fuel expenditures rise drastically under

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[10] The NEMS-RFF forecasting horizon ends in 2030. Current investments in energy-efficient buildings will result in fuels expenditure savings beyond 2030. Because NEMS-RFF does not project fuel prices beyond 2030, one cannot explicitly calculate the NPV using a horizon beyond 2030. We assume that expenditure savings and CO_2 reductions continue at the 2030 value, adjusted for the “death of buildings” according to NEMS-RFF’ specific survival rates by building type.

the Central Cap-and-Trade scenario because of the pricing of carbon. The corresponding figures for the carbon tax are similar. PDV costs for the residential sector are –$32 billion; this is less negative than the costs for the cap-and-trade scenario. The Central Cap-and-Trade and Carbon Tax cases are consistent with the view that combining EE programs with the price-mechanism policies will lower costs, although we emphasize that the comparison is only approximate because we are not holding constant the level of CO_2 abatement. This is a consequence of the NEMS-RFF-specific implementation of the efficiency policies.

As discussed above, NEMS is not a model uniquely suited to calculating the welfare effects of policies. Capital costs are not tracked for a large number of end uses and investments. In our case, this is especially relevant for the commercial sector. The metrics table at the end of this paper displays negative cost estimates across the board for the commercial sector for all five policy cases. Although for the residential sector, NEMS records costs of new building shell investments, costs of retrofits are not tracked. For the commercial sector, the cost of building shells, new and retrofit, are not tracked. Although we have obtained estimates of the costs of retrofit building shells from EIA, we do not have estimates of the costs for commercial buildings. Therefore, these energy-saving innovations arrive free of cost and result in significant savings. The cost numbers presented for the commercial sector in the metrics table should therefore be interpreted as the present discounted value of expenditure savings, not the net present discounted value. We will therefore not discuss these cost estimates in any form.

Sensitivity to Choice of Discount Rate and Discounting Horizon

As we point out above, the choice of discount rate used and the considered horizon over which one discounts the savings of capital investments made in NEMS-RFF until 2030 is expected to have a significant impact on the estimated cost per ton of avoided CO_2. At discount rates near zero, the cost per avoided ton of CO_2 is a sizable negative number often exceeding multiple hundreds of dollars. For what we consider to be reasonable values of the discount rate (at least 5 percent), the costs per ton of CO_2 avoided are small and in some cases negative. Table 11 indicates these numbers for 5 percent, 10 percent, and 20 percent.

Table 11 varies not only the discount rate, but also the discounting horizon. By not allowing the savings from the considered policies to continue beyond 2030, one biases the cost estimates in favor of artificially high costs—and in many cases this bias is sizable. If we had to choose a preferred combination, we would subjectively choose the horizon to 2050 and a discount rate of 10 percent. Yet it is clear that, by choosing the appropriate discount rate and discounting horizon, one can essentially obtain any cost number one wishes, which is a problem not unique to our study.

Table 11. Cost per Ton of CO$_2$ by Discount Rate and Discounting Horizon

Ending year	Discount rate	Case 1	Case 2	Case 3	Case 4	Case 5
2030	0	$264	$246	-$49	-$239	-$74
2030	5	$135	$138	-$22	-$116	-$34
2030	10	$72	$84	-$11	-$62	-$17
2030	15	$40	$55	-$6	-$37	-$10
2030	20	$23	$38	-$3	-$23	-$6
2040	0	-$62	-$47	-$230	-$922	-$274
2040	5	$7	$18	-$71	-$308	-$87
2040	10	$15	$25	-$24	-$118	-$31
2040	15	$12	$21	-$9	-$53	-$13
2040	20	$8	$16	-$4	-$28	-$6
2050	0	-$148	-$135	-$288	-$1,392	-$351
2050	5	-$15	-$7	-$72	-$373	-$90
2050	10	$6	$13	-$21	-$123	-$28
2050	15	$7	$13	-$7	-$50	-$10
2050	20	$5	$11	-$3	-$25	-$5

The present discounted value of costs rises as the discount rate rises, but then falls at higher rates (between 20 and 25 percent). Costs eventually fall because the discounting of equipment costs at a higher rate tends to offset the discounting of energy savings at a higher rate. We point out that our estimates differ from those in Krupnick et al. (2010) as those authors only discount energy savings while holding equipment cost discounting at the social rate of 5 percent.[11] Krupnick et al. (2010) find that costs rise continuously as the discount rate rises.

Comparison with Retrospective and Potential Estimates

The energy consumption reductions in the case 3 run are greater than, but approximately comparable to, those estimated by Gillingham et al. (2006) and Nadel (2004), as summarized in section 2. This could be interpreted as implying that a nationwide technology-focused efficiency policy could achieve, over the coming two decades, further energy savings of a magnitude generally equivalent to that realized during the first quarter-century of these policies' more limited deployment.

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[11] Our estimates are the same for a discount rate of 5 percent.

To compare our results to those of recent studies of the potential for U.S. national efficiency and/or CO_2 reductions that used pure engineering methods, we provide here some further background on the efficiency potential methodology described in section 2. In this methodology, distinctions are made among technical, economic, and achievable potentials. *Technical potential* refers to the replacement of equipment by more efficient equipment, subject only to technical feasibility and without regard to economic costs or benefits. For example, all residential incandescent light bulbs might be replaced by CFLs wherever sockets are compatible, or all refrigerators might be replaced by more efficient models of equivalent exterior dimensions and interior volume. Even here, assumptions can vary (among studies) as to the timing of replacement, particularly whether one assumes a schedule based on the end of the useful life of the equipment or one based on "premature" replacement.

Economic potential, a subset of technical potential, results from application of a lifecycle cost-effectiveness criterion, based on the assumption that more efficient equipment costs more to purchase initially but reduces operating costs. Thus, replacement is imagined to occur only when the *marginal* investment in an efficient device, over a "standard" one, has a positive NPV. In practice, the discount rate used in these studies is almost always on the order of 5–7 percent real (per annum).

Finally, *achievable potential,* a subset of economic potential, takes into account various practical constraints. As summarized in NAPEE 2007a (2-5),

> achievable potential . . . is the amount of energy use that efficiency can realistically be expected to displace assuming the most aggressive program scenario possible (e.g., providing end-users with payments for the entire incremental cost of more efficiency [sic] equipment). This is often referred to as maximum achievable potential. Achievable potential takes into account real-world barriers to convincing end-users to adopt efficiency measures, the non-measure costs of delivering programs (for administration, marketing, tracking systems, monitoring and evaluation, etc.), and the capability of programs and administrators to ramp up program activity over time.

As would be expected, technical and achievable potentials can differ considerably. Moreover, the general results of potential estimates with a given criterion have varied over time and continue to vary widely among studies. For example, a 1990 DOE study found a 20-year cost-effective potential in residential and commercial buildings of 14 percent from baseline (Carlsmith et al. 1990), whereas a subsequent DOE study found a 20-year achievable potential of 9 percent from baseline (Interlaboratory Working Group 2000).

A recent EPA review of U.S. state and regional and Canadian provincial potential studies conducted in the past decade found that achievable electricity savings potential estimates ranged from 8 to 23 percent in four studies with a 10-year horizon, and were 6 and 11 percent in two studies with a 20-year horizon (NAPEE 2007b). The same review found achievable natural gas savings estimates from 9 to 25 percent in three studies with a 20-year horizon. The ratios of technical-to-achievable potential in these studies ranged from 2 to over 5.

In the past two years, several new U.S. national efficiency and CO_2 mitigation potential studies have received considerable attention, including a report by the McKinsey & Company consulting firm (Creyts et al. 2007) and a report by the Electric Power Research Institute (EPRI 2009). The EPRI study, which dealt only with electricity but also included the industrial sector, included an additional category of *realistic potential* as a subset of achievable potential. McKinsey & Company analyzed natural gas and CO_2 as well as electricity and included the industrial, transportation, and electric power sectors in addition to the residential and commercial sectors. We emphasize that both studies focused exclusively on EE policies and programs, without a CO_2 cap-and-trade or tax policy.

The McKinsey & Company study's underlying methodology appears to correspond to the economic potential calculation, as described above, with the results then scaled to yield three different penetration cases (Creyts et al. 2007, 80–81). These cases—"low-range," "mid-range," and "high-range"—correspond to "different levels of national commitment" to GHG reduction, reflecting "incremental departures from current practices" (low-range), "concerted action across the country" (mid-range), or "urgent national mobilization" (high-range; Creyts et al. 2007, xi).

Key results of the two studies are presented in Table 12.[12] The magnitude of the EPRI realistic electricity potential is approximately equal to the savings in our Reference case with EE case for both residential and commercial sectors, and the EPRI realistic and maximum achievable estimates together are comparable to the electricity reductions in residential or commercial sectors in the Central Cap-and-Trade and Carbon Tax relative to Reference cases. The McKinsey energy and CO_2 savings estimates, which are considerably greater than ours as well as EPRI's, are for the most part comparable to previous studies' technical potential estimates. As noted above, the McKinsey cases were a function of judgments regarding the

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[12] We are indebted to Dr. Priya Sreedharan of EPA (pers. comm., 2009) for information on these studies and the interpretation of their results.

quantitative influence on energy and CO_2 savings of national political motivation or will; given the assumption of "urgent national mobilization," it is perhaps not surprising that these higher savings were judged to be feasible.

Table 12. Results of Potential Studies—Percentage Reductions in Delivered Energy and CO_2 from Baseline in 2030

Study	Case	Electricity reductions	Natural gas reductions	CO_2 reductions
EPRI (2009)	Technical Economic Max achievable Realistic	27% 11% 8% 5%	N/A	N/A
McKinsey & Company (Creyts et al. 2007)	High-range Mid-range	23% 20%	17% 11%	24% 20%

Notes: The EPRI baseline for these estimates was the EIA *Annual Energy Outlook (AEO) 2008* reference case; and the McKinsey baseline was the *AEO 2007* reference case. In addition to the residential and commercial sectors, electricity and natural gas reduction percentages include industrial (EPRI) and industrial, transportation, and electric power sectors (McKinsey). McKinsey CO_2 reduction percentages are for residential and commercial sectors only.

The table further illustrates the considerable variation that arises in the application of the general potential methodology. This can be interpreted as reflecting substantial uncertainty regarding the future possibilities of end-use efficiency in both energy and GHG policy, even when analyzed solely within the technology-based, engineering economic paradigm.

7. Discussion of Results

As noted at the beginning of the paper, energy efficiency is currently undergoing a dramatic resurgence, stimulated by its potential contribution to CO_2 emissions reduction. In 2009, prior to the House of Representative's approval of the Waxman-Markey bill in June, the combined increase in federal funding of energy efficiency —in the Obama administration's 2010 budget and in the ARRA—was approximately an order of magnitude more than that of the immediate prior years.[13] The renewed focus on efficiency is further reflected in its central role in

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[13] Based on the authors' calculations using information from the Alliance to Save Energy.

Waxman-Markey. Concurrently, efficiency programs—particularly utility DSM—are continuing to expand in California and other states. Whether or not the specific provisions of the Waxman-Markey bill are ultimately placed into law, we see little reason to doubt that energy efficiency in buildings will continue to be promoted as part of large-scale CO_2 policy.

At the same time, of course, the details of how the efficiency element of national carbon policy will be designed and implemented are a work in progress. For many years, the technical and policy analysis of energy efficiency has tended to bifurcate starkly between advocates and skeptics. Although advocates are currently ascendant, a certain degree of caution is in order regarding at least the most expansive claims. For example, although the 2007 McKinsey & Company study described in the preceding section (as well as its successor, released in August 2009) has received a great deal of attention, the fact that its high-range estimates would require an "urgent national mobilization" seems to have been generally overlooked. We see no evidence that such a mobilization is forthcoming.

Within Waxman-Markey, the tension between the goal of significant CO_2 reduction and the practical limits to efficiency policy implementation may be best illustrated by the national building energy code provision in Section 201. Although we do not know the exact origins of the near-term (2015) goal of a 50 percent increase in building efficiencies, this goal does reflect the results of a study by the National Renewable Energy Laboratory on high-efficiency buildings (Anderson et al. 2004). These results, however, were outputs of an optimization model that, as the study acknowledges, included neither the full costs of, nor the practical constraints on, implementation of the measures in question. There are significant compliance problems nationwide with existing building codes, which in many jurisdictions have been in place for years or decades (Building Codes Assistance Project 2008); these problems reflect, among other impediments, the localized, practical challenges of code enforcement (Quigley 1982). It is not clear how these and other challenges might be addressed to an extent that would allow for a significant, enforceable, nationwide increase in building efficiency standards within the next five years.

Of course, such considerations by no means preclude continued expansion of effective efficiency policies and programs. At the same time, the NEMS-RFF results described in the previous section highlight the potential importance of raising the "ceiling" on energy efficiency through technology improvements in addition to raising the "floor" through technology regulation. Although the outputs of technology R&D such as those conducted by DOE are themselves very uncertain, both the historical record and our results support the value of increased resources for this activity.

8. Best-Performing Policies

Importantly, the results summarized in the previous section share with almost all model-based energy or environmental policy outputs the limitation that they are subject to very large uncertainties that have been analyzed in a very restricted fashion, or not at all. These uncertainties encompass virtually all of the NEMS inputs, as well as "model uncertainty" in the economic and other assumptions on which the model is constructed. The relatively high level of detail should not be confused with accuracy. Again, these issues are not unique to NEMS, but are fundamental to this field of quantitative policy analysis. Further, this does not imply that the results are either "optimistic" or "pessimistic," but rather that they are simply uncertain. The problem of understanding the factors that determine energy–economic models' policy outputs is discussed by Fischer and Morgenstern (2006).

This pervasive uncertainty was well-characterized in a report of the Congressional Research Service on the projected economic impacts of the provisions of S. 2191, the Lieberman–Warner Climate Security Act of 2008, according to five energy–economic models (including NEMS; Parker and Yacobucci 2008). As the report states, "long-term cost projections are at best speculative, and should be viewed with attentive skepticism" (Summary). These authors emphasized the importance of the potential insights available from quantitative modeling rather than the precise numerical results, a perspective articulated by Peace and Weyant (2008).

Within this context, we frame our results as follows. To reiterate the point made in sections 5 and 6, the formulation of the inputs and the structure of the analysis are such that the New Construction Building Codes run (case 1) and the full portfolio of EE policies contained in Waxman–Markey (case 2) result in significant savings from the residential sector at relatively low costs. NEMS-RFF outputs lead to estimates that the reductions in NPV terms are roughly one-third to one-half of the price at which carbon is currently traded on the European Carbon Exchange. The portfolio of policies augmented by the High-Tech assumptions looks even better along this dimension—it has negative costs. One must understand that this set of polices necessarily has negative costs compared to the Reference case. That is, the results do not *demonstrate* that these negative costs are attainable; rather, the results estimate the consequences of *assuming* that they are attainable, reflecting this assumption in the inputs, and then propagating it numerically through NEMS-RFF.

With this approach, the results provide insight into the problem we posed in the introduction—understanding the joint effects of technology and market (cap-and-trade and carbon tax) policies. As described in section 6, when applied independently, the technology and the market policies result in reductions of approximately equal magnitude and, when combined, the energy reductions are approximately additive. When combined with the cap-and-trade or carbon tax policy, the technology policies have the effect of lowering the average cost of CO_2 abatement relative to the price policies alone. Conditional on the various assumptions, this result supports the hypothesis that the technology and market approaches are complementary in large-scale CO_2 abatement. At the same time, in these NEMS-RFF simulations, the primary technology policy–driven contribution to both energy and CO_2 reduction is from the High-Tech component of the efficiency portfolio. As noted in the previous section, we draw the conclusion that increased public support of efficient technology R&D should be given high priority in national CO_2 reduction policy.

Metrics Table

		2020						2030					
			Policy Runs					Reference case	Policy Runs				
	2007	Reference case	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5		Policy 1	Policy 2	Policy 3	Policy 4	Policy 5
Key Metrics													
Net Imports (mmbpd)	**12.09**	9.34	9.33	9.32	9.31	~~9.08~~	~~9.09~~	8.17	8.14	8.15	8.17	~~7.49~~	~~7.48~~
Total Petroleum (mmbpd)	**22.02**	17.84	**17.83**	**17.82**	**17.80**	~~**17.53**~~	~~**17.54**~~	17.99	**17.92**	**17.93**	**17.87**	~~**16.94**~~	~~**16.92**~~
Total Energy-CO2 Emissions (mmt)	**5,991**	5,881	5,878	5,871	5,823	~~5,326~~	~~5,300~~	6,193	6,153	6,149	6,076	~~4,869~~	~~4,745~~
Total GHG Emissions (mmt)	**7,282**	7,383	7,380	7,374	7,326	~~6,605~~	~~6,574~~	7,946	7,907	7,903	7,830	~~6,350~~	~~6,221~~
Real GDP, $ billion (2000 $)	**11,524**	15,399	15,400	15,397	15,401	~~15,341~~	~~15,344~~	19,871	19,870	19,872	19,850	~~19,697~~	~~19,702~~
Total cost of policy, $ million Residential*		Baseline	3,710	4,667	415			Baseline	2,154	2,386	-5,534		
Total cost of policy, $ million Commercial*		Baseline	-1,108	-4,668	-31,825			Baseline	-1,379	-4,903	-31,825		
Average cost of reducing CO2, $/ton Residential*		Baseline	728	453	25			Baseline	87	78	-134		
Average cost of reducing CO2, $/ton Commercial*		Baseline	-1,089	4,890	-6,839			Baseline	-1,341	14,656	-7,830		

		2020						2030					
			Policy Runs						Policy Runs				
	2007	Central Cap-and-Trade	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5	Central Cap-and-Trade	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5
Key Metrics													
Net Imports (mmbpd)	**12.09**	9.11	~~9.33~~	~~9.32~~	~~9.31~~	9.08	~~9.09~~	7.40	~~8.14~~	~~8.15~~	~~8.17~~	7.49	~~7.48~~
Total Petroleum (mmbpd)	**22.02**	17.56	~~**17.83**~~	~~**17.82**~~	~~**17.80**~~	**17.53**	~~**17.54**~~	16.94	~~**17.92**~~	~~**17.93**~~	~~**17.87**~~	**16.94**	~~**16.92**~~
Total Energy-CO2 Emissions (mmt)	**5,991**	5,384	~~5,878~~	~~5,871~~	~~5,823~~	5,326	~~5,300~~	4,815	~~6,153~~	~~6,149~~	~~6,076~~	4,869	~~4,745~~
Total GHG Emissions (mmt)	**7,282**	6,658	~~7,380~~	~~7,374~~	~~7,326~~	6,605	~~6,574~~	6,290	~~7,907~~	~~7,903~~	~~7,830~~	6,350	~~6,221~~
Real GDP, $ billion (2000 $)	**11,524**	15,346	~~15,400~~	~~15,397~~	~~15,401~~	15,341	~~15,344~~	19,707	~~19,870~~	~~19,872~~	~~19,850~~	19,697	~~19,702~~
Total cost of policy, $ million Residential*		Baseline				-1,479		Baseline				-12,139	
Total cost of policy, $ million Commercial*		Baseline				-8,420		Baseline				-8,358	
Average cost of reducing CO2, $/ton Residential*		Baseline				-80		Baseline				-2,319	
Average cost of reducing CO2, $/ton Commercial*		Baseline				1,851		Baseline				6,709	

		2020						2030					
			Policy Runs						Policy Runs				
	2007	Carbon Tax	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5	Carbon Tax	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5
Key Metrics													
Net Imports (mmbpd)	**12.09**	9.14	~~9.33~~	~~9.32~~	~~9.31~~	~~9.08~~	9.09	7.43	~~8.14~~	~~8.15~~	~~8.17~~	~~7.49~~	7.48
Total Petroleum (mmbpd)	**22.02**	17.10	~~**17.83**~~	~~**17.82**~~	~~**17.80**~~	~~**17.53**~~	**17.54**	17.00	~~**17.92**~~	~~**17.93**~~	~~**17.87**~~	~~**16.94**~~	**16.92**
Total Energy-CO2 Emissions (mmt)	**5,991**	5,389	~~5,878~~	~~5,871~~	~~5,823~~	~~5,326~~	5,300	4,829	~~6,153~~	~~6,149~~	~~6,076~~	~~4,869~~	4,745
Total GHG Emissions (mmt)	**7,282**	6,663	~~7,380~~	~~7,374~~	~~7,326~~	~~6,605~~	6,574	6,305	~~7,907~~	~~7,903~~	~~7,830~~	~~6,350~~	6,221
Real GDP, $ billion (2000 $)	**11,524**	15,354	~~15,400~~	~~15,397~~	~~15,401~~	~~15,341~~	15,344	19,718	~~19,870~~	~~19,872~~	~~19,850~~	~~19,697~~	19,702
Total cost of policy, $ million Residential*		Baseline					88	Baseline					-8,374
Total cost of policy, $ million Commercial*		Baseline					-7,115	Baseline					-7,275
Average cost of reducing CO2, $/ton Residential*		Baseline					3	Baseline					-234
Average cost of reducing CO2, $/ton Commercial*		Baseline					-11,219	Baseline					-11,341

	Policy Runs						
Residential	Discount rate	Stop at 2030/continue beyond	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5
PDV Costs^{a}	5%	Stop at 2050	-10	-6	-85	-134	-103
PDV Cost-effectiveness ($ per ton of CO2)^{a}	5%	Stop at 2050	-15	-7	-72	-373	-90
PDV Costs^{a}	10%	Stop at 2050	4	11	-25	-44	-32
PDV Cost-effectiveness ($ per ton of CO2)^{a}	10%	Stop at 2050	6	13	-21	-123	-28
PDV Costs^{a}	20%	Stop at 2050	3	9	-3	-9	-5
PDV Cost-effectiveness ($ per ton of CO2)^{a}	20%	Stop at 2050	5	11	-3	-25	-5

	Policy Runs (against Core 1 Baseline)						
Commercial	Discount rate	Stop at 2030/continue beyond	Policy 1	Policy 2	Policy 3	Policy 4	Policy 5
PDV Costs^{a}	5%	Stop at 2050	-26	-63	-410	-144	-125
PDV Cost-effectiveness (CO2 reductions)^{a}	5%	Stop at 2050	-118	-301	-841	1172	-214
PDV Costs^{a}	10%	Stop at 2050	-11	-38	-271	-74	-67
PDV Cost-effectiveness (CO2 reductions)^{a}	10%	Stop at 2050	-48	-181	-555	603	-114
PDV Costs^{a}	20%	Stop at 2050	-3	-20	-156	-33	-31
PDV Cost-effectiveness (CO2 reductions)^{a}	20%	Stop at 2050	-14	-94	-320	266	-53

Notes: All monetary figures are in 2007$ except where noted. Policy 1: Reference case + New Construction Building Codes. Policy 2: Policy 1 + Complete Set of Waxman–Markey Energy Efficiency Policies. Policy 3: Policy 2 + High-Tech Assumptions. Policy 4: Policy 3 + Central Cap-and-Trade. Policy 5: Policy 3 + Carbon Tax. CO_2, carbon dioxide; GDP, gross domestic product; GHG, greenhouse gas; mmbpd, millions of barrels per day; mmt, million metric tons; PDV, present discounted value. ^{a} Only accounts for end uses with reported capital costs in NEMS.

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