DISCUSSION PAPER

April 2009 ■ RFF DP 09-13

Energy Efficiency Economics and Policy

Kenneth Gillingham, Richard G. Newell, and Karen Palmer

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

RESOURCES
FOR THE FUTURE

Energy Efficiency Economics and Policy

Kenneth Gillingham, Richard G. Newell, and Karen Palmer

Abstract

Energy efficiency and conservation are considered key means for reducing greenhouse gas emissions and achieving other energy policy goals, but associated market behavior and policy responses have engendered debates in the economic literature. We review economic concepts underlying consumer decisionmaking in energy efficiency and conservation and examine related empirical literature. In particular, we provide an economic perspective on the range of market barriers, market failures, and behavioral failures that have been cited in the energy efficiency context. We assess the extent to which these conditions provide a motivation for policy intervention in energy-using product markets, including an examination of the evidence on policy effectiveness and cost. While theory and empirical evidence suggest there is potential for welfare-enhancing energy efficiency policies, many open questions remain, particularly relating to the extent of some of the key market and behavioral failures.

Key Words: energy efficiency, appliance standards, energy policy, market failures, behavioral failures

JEL Classification Numbers: Q38, Q41

Contents

Energy Efficiency Economics and Policy

Kenneth Gillingham, Richard G. Newell, and Karen Palmer [*]

1. Introduction

Energy efficiency and conservation have long been critical elements in the energy policy dialogue and have taken on a renewed importance as concerns about global climate change and energy security have intensified. Many advocates and policymakers hold that reducing the demand for energy is essential to meeting these challenges, and analyses tend to find that demand reductions can be a cost-effective means of addressing these concerns. With such great policy interest, a significant literature has developed over the past 30 years that provides an economic framework for addressing energy efficiency and conservation as well as empirical estimates of how consumers respond to policies to reduce the demand for energy.

We begin by defining a few terms to put the literature in context. First, it is important to conceptualize energy as an input into the production of desired energy services (e.g., heating, lighting, motion), rather than as an end in itself. In this framework, energy efficiency is typically defined as the energy services provided per unit of energy input. For example, the energy efficiency of an air conditioner is the amount of heat removed from air per kilowatt-hour of electricity input. At the individual product level, energy efficiency can be thought of as one of a bundle of product characteristics, alongside product cost and other attributes (Newell et al. 1999). At a more aggregate level, the energy efficiency of a sector or of the economy as a whole can be measured as the level of Gross Domestic Product per unit of energy consumed in its

---

[*] Kenneth Gillingham, Stanford University, Precourt Energy Efficiency Center, P.O. Box 16336, Stanford, California 94309; e-mail: kgilling@stanford.edu. Richard G. Newell, corresponding author; Duke University, Nicholas School of the Environment, Box 90227, Durham, North Carolina 27708; e-mail: richard.newell@duke.edu. Also, Resources for the Future, 1616 P Street, NW, Washington, DC 20036; and National Bureau of Economic Research, 1050 Massachusetts Avenue, Cambridge, MA 02138. Karen Palmer, Resources for the Future; e-mail: palmer@rff.org. The authors appreciate the very helpful research assistance of Maura Allaire, as well as useful comments from James Sweeney, Timothy Brennan, Maximilian Auffhammer, Richard Howarth, Danny Cullenward, and Sebastien Houde. This research was funded in part by the Resources for the Future Electricity and Environment Program, a special gift from Exelon for work on Energy Efficiency, and the U.S. Environmental Protection Agency STAR Fellowship program.

production (see, e.g., Metcalf [2008] and Sue Wing [2008] for analyses of the determinants of energy intensity at the state and national levels).

In contrast, energy conservation is typically defined as a reduction in the total amount of energy consumed. Thus, energy conservation may or may not be associated with an increase in energy efficiency, depending on how energy services change. That is, energy consumption may be reduced with or without an increase in energy efficiency, and energy consumption may increase alongside an increase in energy efficiency. These distinctions are important when considering issues such as the “rebound effect,” whereby the demand for energy services may increase in response to energy efficiency–induced declines in the marginal cost of energy services. The distinction is also important in understanding the short- versus long-run price elasticity of energy demand, whereby short-run changes may depend principally on changes in consumption of energy services, while longer-run changes include greater changes in the energy efficiency of the equipment stock.

One must also distinguish between energy efficiency and economic efficiency. Maximizing economic efficiency—typically operationalized as maximizing net benefits to society—is generally not going to imply maximizing energy efficiency, which is a physical concept and comes at a cost. An important issue arises, however, regarding whether private economic decisions about the level of energy efficiency chosen for products are economically efficient. This will depend on both the economic efficiency of the market conditions the consumer faces (e.g., energy prices, information availability) as well as the economic behavior of the individual decisionmaker (e.g., cost-minimization).

Market conditions may depart from efficiency if there are market failures, such as environmental externalities or imperfect information. Aside from such market failures, most economic analysis of energy efficiency has taken cost-minimizing (or utility/profit maximizing) behavior by households and firms as a point of departure in analysis. Some literature, however, has focused more closely on the decisionmaking behavior of economic actors, identifying potential “behavioral failures” that lead to deviations from cost-minimization; this literature is motivated at least partly by results from the field of behavioral economics. Much of the economic literature on energy efficiency therefore seeks to conceptualize energy efficiency decisionmaking, identify the degree to which market or behavioral failures may present an opportunity for net-beneficial policy interventions, and evaluate the realized effectiveness and cost of actual policies.

This line of research has important implications both for assessing the cost of correcting market failures—such as environmental externalities—as well as clarifying the role of policies that are oriented to correcting behavioral failures. For example, if behavioral failures lead to underinvestment in energy efficiency, then a degree of reductions in energy-related emissions could be available at low or even negative cost. At the same time, policies that provide an efficient means of correcting environmental externalities—such as an emissions price—may not be well-suited to inducing these relatively low-cost energy and emission reductions. In principle, a set of policies addressing both market and behavioral failures could therefore potentially provide a more efficient overall response. In practice, the value of individual policy components will depend on the extent of existing market problems and the ability of specific policies to correct these problems in a net beneficial manner.

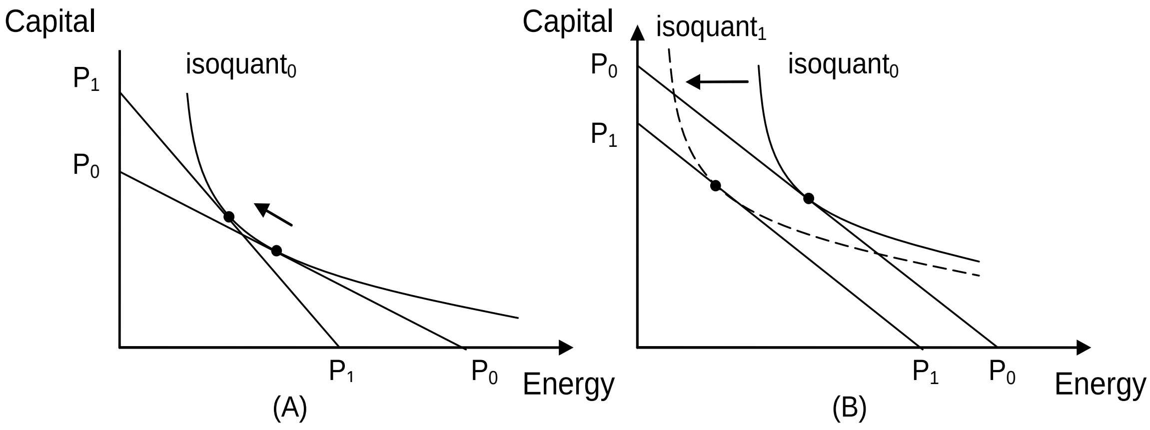
This article views the literature through this perspective, and begins by introducing the notion of energy efficiency as an investment in producing energy services. After presenting evidence of energy market influences on energy efficiency, we turn to identifying and examining empirical evidence on a range of market and behavioral failures that have been discussed in the energy efficiency literature. We then address the implications of this evidence for policy interventions and briefly review the empirical evidence on the effectiveness and cost of policy, including price policies and information policies. Finally, we provide overall conclusions. We limit the scope of this study primarily to energy efficiency and conservation in buildings and appliances and do not address transportation in detail. Nonetheless, most of the same conceptual and empirical issues carry over to transportation as well.

2. Energy Efficiency as an Investment in Producing Energy Services

From an economic perspective, energy efficiency choices fundamentally involve investment decisions that trade off higher initial capital costs and uncertain lower future energy operating costs. In the simplest case, the initial cost is the difference between the purchase and installation cost of a relatively energy-efficient product and the cost of an otherwise equivalent product that provides the same energy services but uses more energy. The decision of whether to make the energy-efficient investment requires weighing this initial capital cost against the expected future savings. Assessing the future savings requires forming expectations of future energy prices, changes in other operating costs related to the energy use (e.g., pollution charges), intensity of use of the product, and equipment lifetime. Comparing these expected future cash flows to the initial cost requires discounting the future cash flows to present values. Holding consumption of energy services constant, a privately optimal decision would entail choosing the level of energy efficiency to minimize the present value of private costs, while economic efficiency at a societal level would entail minimizing social costs. This makes energy efficiency different in character from many other product attributes for which there may not be a well-defined notion of what constitutes optimal or "rational" behavior on the part of the individual.

This conceptualization of the problem maps directly into a production function framework in which capital and energy are viewed as inputs into the production of energy services. Along an isoquant describing a given level of energy services, the cost-minimizing level of energy use (and thus energy efficiency) is found at the point of tangency where the marginal increase in capital cost with respect to energy reduction is equal to their relative price (in present value terms) (Figure 1). As described above, the relative price will depend on the capital cost of efficiency improvements, the discount rate, expected energy prices, equipment utilization, and decision time horizon. This framework applies at the household level as well as at a broad sectoral or multisectoral level where energy and capital are used to produce energy services.[1]

Figure 1. (A) Energy Efficiency Improving Substitution versus (B) Energy Saving Technological Change



---

[1] Understanding the economic forces governing the rate and direction of energy-related technological change at the product, sectoral, and aggregate levels has been an important area of research, particularly in the context of climate change modeling. For a review of the literature devoted to this topic, which is beyond the scope of this paper, see Gillingham et al. (2008).

Focusing on the household level as an example, greater energy efficiency can be driven by market forces in two ways within this production function framework. First, households may move along the energy services isoquant by substituting capital for energy in response to a change in relative prices (Figure 1A, with relative prices changing from P_0 to P_1). Or, second, technological change that shifts the isoquant in a way favoring (i.e., biased toward) greater energy efficiency (Figure 1B, with isoquant_0 shifting to isoquant_1) could change the production possibilities available to households. In contrast, energy conservation not driven by energy efficiency improvements would be associated with a lower level of energy services (i.e., a lesser isoquant).

Market failures can be represented within this framework as a divergence of the relative prices used for private decisions from the economically efficient prices. For example, unpriced environmental externalities and missing information on the energy intensity of product use would both tend to lower the relative price of energy, leading to choices of inefficiently low energy efficiency (e.g., P_0 compared to P_1 in Figure 1A). Note that this framework presupposes optimizing behavior by the consumer, given available information—an assumption subject to debate within the behavioral economics literature, as discussed in other sections.

The next section further explores the role of energy markets in governing energy efficiency decisions, while the subsequent section identifies potential market and behavioral failures that may lead to suboptimal decisions.

3. Energy Market Influences on Energy Efficiency

Energy markets and market prices influence consumer decisions regarding how much energy to consume and whether to invest in more energy-efficient products and equipment. An increase in energy prices will result in some energy conservation in the short run; however, short-run changes in energy efficiency tend to be limited due to the long lifetimes and slow turnover of energy-using appliances and capital equipment. However, if an energy price increase is persistent, it also is more likely to significantly affect energy efficiency adoption, as consumers replace older capital equipment and firms have time to develop new products and processes.

The extent of demand responsiveness to changes in price is captured in the price elasticity of energy demand. Table 1 presents the ranges of energy own-price elasticity estimates in the literature. Long-run price elasticities are larger than short-run, corresponding to more energy efficiency improvements as capital turns over. On average, natural gas price elasticities are greater than electricity or fuel oil elasticities. Note that, because they are based on actual consumer behavior, these price elasticity estimates include any increase in consumption of energy services that might occur in response to a lower unit cost of energy services resulting from increased energy efficiency (i.e., the rebound effect).

Table 1. Ranges of Estimates of Energy Own-Price Elasticities (absolute values shown; all values are negative)

	Short-run		Long-run	
	Range	Sources	Range	Sources
Residential				
Electricity	0.14–0.44	Dahl (1993)	0.32–1.89	Bernstein & Griffin (2005), Hsing (1994)
Natural gas	0.03–0.76	Bohi & Zimmerman (1984), Dahl (1993)	0.26–1.47[a]	Bohi & Zimmerman (1984), Dahl(1993)
Fuel oil	0.15–0.34	Wade (2003)	0.53–0.75	Dahl (1993), Wade (2003)
Commercial				
Electricity	0–0.46	Dahl (1993)	0.24–1.36	Wade (2003), Dahl (1993)
Natural gas	0.14–0.29	Dahl (1993), Wade (2003)	0.40–1.38	Wade (2003), Bohi & Zimmerman (1984)
Fuel oil	0.13–0.49	Dahl (1993), Wade (2003)	0.39–3.5	Wade (2003), Newell & Pizer (2008)
Industrial				
Electricity	0.11–0.28	Bohi & Zimmerman (1984), Dahl (1993)	0.22–3.26	Bohi & Zimmerman (1984), Dahl (1993)
Natural gas[a]	0.51–0.62	Bohi & Zimmerman (1984)	0.89–2.92	Dahl (1993), Bohi & Zimmerman (1984)
Fuel oil	0.11	Dahl (1993)	0.5–1.57[b]	Bohi & Zimmerman (1984)

[a] Estimates drawn largely from regional studies.
[b] Estimates for 19 states

Other studies that have focused specifically on factors influencing technology adoption find that higher energy prices are associated with significantly greater adoption of energy-efficient equipment (Anderson and Newell 2004, Hassett and Metcalf 1995, Jaffe et al. 1995). Further upstream in the technology development process, Newell et al. (1999) and Popp (2002) find energy-efficient innovation is also significantly determined by energy prices (see Popp et al. [2009] for a review). Empirical estimates therefore demonstrate a substantial degree of responsiveness of energy utilization and energy-efficient technology adoption and innovation to changes in energy price.

4. Potential Market and Behavioral Failures

Much of the literature on energy efficiency focuses on elucidating the potential rationales for policy intervention and evaluating the effectiveness and cost of such interventions in practice. Within this literature there is a long-standing debate surrounding the commonly cited “energy efficiency gap.” There are several ways to view this gap. At its core, the gap refers to a significant difference between observed levels of energy efficiency and some notion of optimal energy use (Jaffe et al. 2004). That notion of optimal energy use has at times focused on maximizing physical energy efficiency, which will not generally coincide with maximal economic efficiency because energy efficiency comes at a cost. Within the investment framework described above, the energy efficiency gap takes the form of underinvestment in energy efficiency relative to a description of the socially optimal level of energy efficiency. Such underinvestment is also sometimes described as an observed rate or probability of adoption of energy-efficient technologies that is “too slow.”

Often the efficiency gap is illustrated by a comparison of the market discount rate and relatively high “implicit discount rates” that are implied by consumer choices over appliances with different costs and energy efficiencies (Hausman 1979). The empirical evidence is relatively well-established; in a number of studies published primarily in the late 1970s and early 1980s, analysts using a variety of methodologies found implicit discount rates ranging from 25 percent to over 100 percent (Sanstad et al. 2006, Train 1985).

Economists have posited a number of explanations to account for part or all of the apparent gap: hidden costs not accounted for by the analyst, including search costs as well as reductions in other product attributes (e.g., lighting quality) (Jaffe et al. 2004); lower energy savings than assumed by the analyst, due in part to heterogeneity of consumers (Hausman and Joskow 1982); uncertain future energy savings, implying rational consumers should put more weight on the initial cost (Sutherland 1991); the irreversibility of energy efficiency investments and the associated option value of waiting to invest later (Hassett and Metcalf 1993, Hassett and Metcalf 1995, van Soest and Bulte 2000); and the possibility that consumers are appropriately forming expectations about future energy prices but energy analysts are using incorrect proxies for these expectations (Jaffe et al. 2004). For example, studies have found that actual savings from past utility-sponsored programs achieved 50 percent to 80 percent of predicted savings (Hirst 1986, Sebold and Fox 1985), although a more recent study by Auffhammer et al. (2008) suggests that utilities have improved their ability to predict savings. Similarly, Metcalf and Hassett (1999) find that once all costs are accounted for, the realized return to attic insulation is much below the returns promised by engineers and manufacturers, and at 9.7 percent is consistent with the interest rate suggested by standard investment theory. Others have argued that the energy efficiency gap must not exist because rational optimizing consumers would not be willing to ignore large benefits—the proverbial $20 bill on the sidewalk (Sutherland 1996).

Some authors examine these explanations for why there may not be a gap and find some of them lacking. Metcalf (1994) finds that the uncertainty of future energy savings described in Sutherland (1991) should actually lead a rational investor to require a rate-of-return that is lower than the market discount rate, since energy efficiency investments will tend to serve as a hedge against other risks. Sanstad et al. (1995) show that the option value analysis of Hassett and Metcalf (1993, 1995) implies an implicit discount rate much lower than observed implicit discount rates, even when taking irreversibility into account. Howarth and Sanstad (1995) discuss heterogeneity and hidden costs as a possible concern, but suggest that analysts are cognizant of these issues and are careful to take them into account. For example, Koomey and Sanstad (1994) pay close attention to confounding factors such as heterogeneity and hidden costs and still find high implicit discount rates for efficient ballasts for commercial lighting and consumer purchases of refrigerators.

Other papers focus on distinguishing “market barriers” to the adoption of energy-efficient technologies from market failures. Market barriers can be defined as any disincentives to the adoption or use of a good (Jaffe et al. 2004). Market barriers may or may not be market failures in the traditional welfare economic sense. Potential market barriers described in the broader energy efficiency literature occasionally include such factors as low energy prices, fluctuating energy prices, or high technology costs, which are clearly not market failures on their own. Systematic biases in consumer decisionmaking that lead to underinvestment in energy efficiency relative to the cost-minimizing level are also often included among market barriers. Following the Shogren and Taylor (2008) review of behavioral economics, however, we classify these biases as “behavioral failures.” In the present context, we consider behavioral failures to represent consumer behavior that is inconsistent with utility maximization, or in the current context, energy service cost-minimization. In contrast, market failure analysis is distinct in presupposing individual rationality and focusing on the conditions surrounding interactions among economic agents and society.

There is an economic rationale for policies to correct market barriers if they represent market or behavioral failures (Shogren and Taylor 2008). Table 2 provides a summary of potential market and behavioral failures relating to energy efficiency and conservation along with policy responses that have been implemented, or could be implemented, to address these problems in cases where they are found to be significant. We focus on the most commonly raised market and behavioral failures, but do not prejudge whether they are empirically significant problems for energy efficiency and conservation.[2] The remainder of this section discusses each of these potential concerns in turn, while the subsequent section reviews experience with policies that have been proposed and implemented, in part, as a response to these concerns.

Table 2. Commonly Cited Market and Behavioral Failures Relevant to Energy Efficiency Along with Potential Policy Responses

Potential Market Failures	**Potential Policy Options**
Energy market failures	
Environmental externalities	Emissions pricing (tax, cap-and-trade)
Average-cost electricity pricing	Real-time pricing; market pricing
Energy security	Energy taxation; strategic reserves
Capital market failures	
Liquidity constraints	Financing/loan programs
Innovation market failures	
Research and development (R&D) spillovers	R&D tax credits; public funding
Learning-by-doing spillovers	Incentives for early market adoption
Information problems	
Lack of information; asymmetric information	Information programs
Principal–agent problems	Information programs
Learning-by-using	Information programs
Potential Behavioral Failures	
Prospect theory	Education; information; product standards
Bounded rationality	Education; information; product standards
Heuristic decisionmaking	Education; information; product standards

4.1 Energy Market Failures

The common theme in energy market failures is that energy prices do not reflect the true marginal social cost of energy consumption, either through environmental externalities, average-cost pricing, or national security.

---

[2] In addition to the issues discussed below, Fischer (2005) develops an economic theory supporting a role of price discrimination in imperfectly competitive markets in diminishing producers' incentives to improve energy efficiency of low-end products. The effects of inseparability of product features on markets for energy efficiency is discussed by Ruderman et al. (1987), although in competitive markets associated inefficiencies should be minimal.

Environmental externalities associated with the production and consumption of many sources of energy lead to emissions of greenhouse gases and other air pollutants resulting in costs that are borne by others—that is, they are not internalized by the energy consumer. Absent policy, an environmental externality leads to an overuse of energy relative to the social optimum, and hence, underinvestment in energy efficiency and conservation. Although there is no debate over the existence of environmental externalities, the magnitude of such externalities and their degree of internalization is uncertain and hard to measure. Gillingham et al. (2006) review the literature on environmental externalities from the production of electricity and find that past policies to reduce electricity use provided monetized benefits from the reduction in CO_2, nitrous oxides (NO_x), sulfur dioxide (SO_2), and fine particulate matter (PM_{10}) that were about 10 percent of the direct value of the electricity savings. Environmental externalities, largely in the form of air emissions, also exist with other fossil fuels, such as home heating oil or propane. To the extent that energy prices do not currently internalize these externalities (which varies by pollution type), the market will provide a level of energy efficiency that is too low from a societal point of view. The economically optimal policy response is to price emissions, which will indirectly stimulate greater energy efficiency.

Prices faced by consumers in electricity markets also may not reflect marginal social costs due to the common use of average-cost pricing under utility regulation. Average-cost pricing could lead to under- or overuse of electricity relative to the economic optimum. On one hand, to the extent that average costs are above marginal costs due to amortized fixed costs, consumers face a price above the economically optimal price, thus encouraging underuse of electricity.

On the other hand, average-cost prices depend on the average cost of the mix of generators used to produce electricity. Market-based pricing produces daily or hourly wholesale prices that reflect the cost of the marginal generator and retail prices that typically reflect the average of these marginal costs over a period of months. Time-of-use (TOU) prices vary in a pre-set manner by time of day or season, while real-time-pricing (RTP) directly conveys information about the current marginal cost of generation and transmission in the price, updated at an hourly or even more frequent basis. If consumers are facing prices that are at times too low (peak times) and at other times too high (off-peak), they will be overusing electricity during the peak and underusing during the off-peak relative to the social optimum (Joskow and Tirole 2007).

RTP, and to a lesser degree, TOU pricing, can partly alleviate this market failure (which could alternatively be described as a policy failure). Of course, the cost of implementing TOU pricing or RTP may exceed the benefits, and there may be other market failures related to the adoption of real-time meters (Brennan 2004). However, recent evidence from the Anaheim Critical Peak pricing experiment suggests that with recent technology advances, a variation of RTP implemented during peak periods has significant potential to improve social welfare, with little effect on use in off-peak periods (Wolak 2006). Whether there would be conservation of total energy use with a comprehensive RTP scheme during all time periods is less clear. Similarly, the effect of TOU pricing or RTP on energy efficiency investments is unclear, and would depend on the pricing existing during the time those investments would be used.

Some authors have suggested that there are national security external costs from the United States' dependence on certain energy sources, particularly oil, from unstable regions of the world, that consumers do not face in energy prices or therefore take into account in their energy use decisions (Bohi and Toman 1996, Bohi and Zimmerman 1984). While these concerns are associated primarily with transportation-related consumption of oil, they are relevant to building-related energy consumption of fuel oil for heating and the association between the natural gas and oil markets. Economic and other analysis of the national security risks of energy consumption is not entirely satisfying, in part due to the lumpiness of the problem. On the margin, reducing oil consumption would not likely change the associated security risks, nor the military and diplomatic expenditures undertaken in response. Nonetheless, a long-term larger reduction may reduce these risks, and to the extent these risks are not fully reflected in the price of relevant energy resources, there will be a resulting underinvestment in energy efficiency.

4.2 Information Problems

Information problems are consistently raised in the energy efficiency literature and, along with behavioral failures, are often given as the primary explanation for the energy efficiency gap (Sanstad et al. 2006). Specific information problems cited include consumers' lack of information about the availability of and savings from energy-efficient products, asymmetric information, principal–agent or split-incentive problems, and externalities associated with learning-by-using. The following descriptions take the consumers' perspective, but several of these same information problems have been studied in the context of decisionmaking by firms (DeCanio 1993, 1994a, 1994b, DeCanio and Watkins 1998, Stein 2003). As discussed in the next section, if such problems are significant and correctable they may warrant labeling and other information programs.

Lack of information and asymmetric information are often given as reasons why consumers systematically underinvest in energy efficiency. The idea is that consumers often lack sufficient information about the difference in future operating costs between more-efficient and less-efficient goods necessary to make proper investment decisions (Howarth and Sanstad 1995). This argument can be consistent with cost-minimizing behavior if we assume that under perfect information consumers would reach a privately optimal outcome. Alternatively, information problems may occur when there are behavioral failures, so that consumers are not appropriately taking future reductions in energy costs into account in making present investments in energy efficiency. We discuss information problems in the context of behavioral failures in the next section.

Asymmetric information, where one party involved in a transaction has more information than another, may lead to adverse selection (Akerlof 1970). In the context of energy efficiency, adverse selection could imply that sellers of energy-efficient technologies that would provide clear *ex post* benefits to consumers are unable to perfectly transfer this information to buyers since the energy efficiency is unobserved (Howarth and Sanstad 1995). The sellers of every product would have an incentive to suggest that the energy efficiency of the product is high, but because the buyers cannot observe the energy efficiency, they may ignore it in their decision. The Howarth and Andersson (1993) model, which incorporates explicit transaction costs of transferring information, formally describes how this circumstance could lead to an underinvestment in energy efficiency. While in this context transaction costs may be a source of market failure, in general transaction costs may be legitimate costs and not a reason for intervening in markets.

The principal–agent or split-incentive problem describes a situation where one party (the agent), such as a builder or landlord, decides the level of energy efficiency in a building, while a second party (the principal), such as the purchaser or tenant, pays the energy bills. When the principal has incomplete information about the energy efficiency of the building, the first party may not be able to recoup the costs of energy efficiency investments in the purchase price or rent charged for the building. The agent will then underinvest in energy efficiency relative to the social optimum, creating a market failure (Jaffe and Stavins 1994). Murtishaw and Sathaye (2006) attempt to quantify the magnitude of the principal–agent problem for four end uses: space heating, refrigerators, water heating, and lighting. They find that the principal–agent problem is potentially relevant to 25 percent of refrigerator energy use, 66 percent of water heating energy use, 48 percent of space heating energy use, and 2 percent of lighting energy use, although they do not quantify the degree to which energy efficiency decisions in these cases have actually been inefficient. Levinson and Niemann (2004) find that tenants whose electric bills are included in their rental contracts consume significantly greater energy than tenants who pay their own electric bills.

Positive externalities associated with learning-by-using can exist where the adopter of a new energy-efficient product creates knowledge about the product through its use, and others freely benefit from the information generated about the existence, characteristics, and performance of the product. This phenomenon is not unique to energy efficiency (Jaffe et al. 2004). In the context of demand-side management programs, some studies have distinguished learning-by-using spillovers into “free-drivers” and program spillovers (Blumstein and Harris 1993, Eto et al. 1996). Free-drivers are nonparticipants who install energy-efficient products due to hearing about them from program participants. Program spillovers occur when the participating household installs additional energy-efficient products, without rebates, due to the information they learned through participation in the program.

4.3 Liquidity Constraints in Capital Markets

Blumstein et al. (1980) first described liquidity constraints that hinder access to financing for energy-efficient investments as a market barrier. Some purchasers of equipment may choose the less energy-efficient product due to lack of access to credit, resulting in underinvestment in energy efficiency and reflected in an implicit discount rate that is above typical market levels. This effect is a variation of a market failure associated with a lack of access to capital that is widely discussed in the development economics literature, and applies to any capital-intensive investment, not just energy-efficient products (Ray 1998). The extent to which liquidity constraints are an issue in energy efficiency has yet to be established empirically. Some evidence indicates that only a small percentage of home improvements are funded by loans, which could imply liquidity constraints are only important for a small fraction of energy efficiency investments or that liquidity constraints effectively force most energy efficiency investments to be self-financed (Berry 1984).

In industry and government, a common financing constraint is the institutional disconnect between capital and operating budgets, but energy services performance contracts have developed to fill this niche. In some cases, such as for industrial customers, energy service providers pay the capital cost and receive a share of the resulting savings. In other cases, such as for government and institutional customers, the customer can borrow at a lower interest rate than the energy service provider, so it makes greater financial sense for the customer to make the investment. In such cases, the energy service providers recommend energy efficiency improvements, guarantee the operating cost savings, and pay the difference if those savings are not realized—often allowing for the repayment of the capital cost to be treated as an operating expense (Zobler and Hatcher 2003). In addition, if liquidity constraints are an issue for energy efficiency investments then they will also constrain other types of investments, and any potential solution would have to reach well beyond energy efficiency policy.

Golove and Eto (1996) describe a case of asymmetric information where consumers are unable to transfer information to their lenders about the relative certainty of operating cost savings from an efficiency investment, and thus likelihood of repayment. Golove and Eto claim the resulting credit constraints imply that consumers should be given a lower interest rate than lenders are willing to offer, and thus consumers faced with the higher interest rate may underinvest in energy efficiency. The extent of this potential problem has not been measured empirically to our knowledge, and this problem of information transfer may apply to other costs as well, possibly altering the result. Energy-efficient mortgages from some lenders address this problem by crediting a home's energy efficiency in determining the interest rate or the size of the mortgage. Warranties may also address this problem privately.

4.4 Innovation Market Failures

R&D spillovers may lead to underinvestment in energy-efficient technology innovation due to the public good nature of knowledge, whereby individual firms are unable to fully capture the benefits from their innovation efforts, which instead accrue partly to other firms and consumers. This is not particular to energy-efficient innovation; rather, it is a general feature of technological innovation, which manifests empirically as an approximately two to four times higher social rate of return to R&D compared to the private rate of return (Griliches 1995, Hall 1996, Nadiri 1993). If energy is underpriced relative to the social optimum this innovation problem will nonetheless be magnified in the context of energy-saving technologies (Goulder and Schneider 1999, Jaffe et al. 2005, Schneider and Goulder 1997).

Learning-by-doing (LBD) refers to the empirical observation that as cumulative production of new technologies increases, the cost of production tends to decline as the firm learns from experience how to reduce its costs (Arrow 1962). LBD may be associated with a market failure if the learning creates knowledge that spills over to other firms in the industry, lowering the costs for others without compensation (Fischer and Newell 2008, van Benthem et al. 2008). In the energy context, LBD processes have been empirically investigated and applied primarily to fledgling low-carbon electricity-generation technologies in the context of energy and climate policy modeling. The empirical evidence on learning in energy-using equipment is very limited, and what there is focuses generally on product cost reductions rather than learning specifically with respect to improving energy efficiency (see, e.g., Bass [1980]). It is also difficult to empirically distinguish learning from other factors that affect product costs and prices. Further research would be needed to more closely examine learning in energy-efficient technologies and ascertain the degree to which the learning spills over to other firms. The potential for positive externalities from LBD is not unique to energy, but may occur with any new technology that displays nonappropriable learning characteristics.

4.5 Behavioral Failures

The behavioral economics literature has drawn attention to several systematic biases in consumer decisionmaking that may be relevant to decisions regarding investment in energy efficiency. Similar insights can be gained from the literature on energy decisionmaking in psychology and sociology (e.g., see Stern [1985], Lutzenhiser [1992, 1993]). Frameworks incorporating such departures from perfect rationality have intuitive psychological appeal as well as an empirical basis from behavioral economic and psychological studies. The crucial question is whether these deviations from perfect rationality lead to significant systematic biases in energy efficiency decisionmaking, and if so, whether these biases lead to under- or overinvestment in energy efficiency. Due to the limited economics literature in this area, in many cases we reference literature from other social sciences that bears directly on energy consumption–related behavior.

The behavioral economics literature draws upon cognitive psychology and other disciplines to inform experimental and theoretical analyses aimed at understanding how consumers make decisions. Behavioral economists tend to relax the classic microeconomic assumption of rational choice and replace it with bounded rationality or other heuristic decisionmaking methods (McFadden 1999). Behavioral economics has been motivated by evidence that consumers are not perfectly rational—even if they are given perfect information—and has developed a positive theory designed to understand how consumers make decisions in practice. In the energy efficiency context, the most relevant and common rationality assumption is that of behavior that minimizes present value costs for a given level of energy service provision.

The evidence that consumer decisions are not always perfectly rational is quite strong, beginning with Tversky and Kahneman's research indicating that both sophisticated and naïve respondents will consistently violate axioms of rational choice in certain situations (Tversky and Kahneman 1974, Kahneman and Tversky 1979). Since then, an entire literature has developed examining when and how people violate the axioms of rational choice. Surveys of this literature of behavioral decision theory include Camerer (1997), McFadden (1999), Machina (1989), Rabin (1997), and Thaler (1991). Shogren and Taylor (2008) and List and Price (2009) provide reviews specifically in the context of resource and environmental economics. This review follows the primary theme of behavioral economics by focusing on consumer decisions. Firms may also face some of the same issues, although competitive forces serve to moderate the significance of behavioral failures for firms (Shogren and Taylor 2008).

The three primary themes that emerge from behavioral economics and have been applied in the context of energy efficiency are prospect theory, bounded rationality, and heuristic decisionmaking. The prospect theory of decisionmaking under uncertainty posits that the welfare change from gains and losses is evaluated with respect to a reference point, usually the status quo. In addition, consumers are risk averse with respect to gains and risk seeking with respect to losses, so that the welfare change is much greater from a loss than from an expected gain of the same magnitude (Kahneman and Tversky 1979). This can lead to loss aversion, anchoring, status quo bias, and other anomalous behavior (Shogren and Taylor 2008).

Bounded rationality suggests that consumers are rational, but face cognitive constraints in processing information that lead to deviations from rationality in certain circumstances (Simon 1959, 1986). Heuristic decisionmaking is related closely to bounded rationality and encompasses a variety of decision strategies that differ in some critical way from conventional utility maximization in order to reduce the cognitive burden of decisionmaking. For example, Tversky (1972) develops the theory of “elimination-by-aspects,” wherein consumers use a sequential decisionmaking process where they first narrow their full choice set to a smaller set by eliminating products that do not have some desired feature or aspect (e.g., cost above a certain level), and then they optimize among the smaller choice set, possibly after eliminating further products.

Not much economic literature empirically tests these behavioral hypotheses to uncover whether there is a systematic bias, either negative or positive, in decisionmaking related to energy consumption. Hartman et al. (1991) empirically examine whether the status quo effect posited in prospect theory holds in the consumer valuation of reliable electric service (but not directly energy efficiency). They find that the status quo effect is significant, suggesting in this case that consumers are irrationally reluctant to move from the status quo and accept more likely interruptions in electricity service.

Empirically testing bounded rationality is even more difficult for there is no single consensus model of bounded rationality in energy decisionmaking (Sanstad and Howarth 1994). Friedman and Hausker (1988) develop a theoretical model by using a particular structure of bounded rationality where consumers do not have the ability to optimize their energy consumption in response to a tiered-rate structure of electricity prices. The model indicates that consumers will overconsume energy if the rate structure is increasing and underconsume if it is decreasing. Friedman (2002) tests this theoretical model by using electric utility data and exploits the increasing block structure of electricity rates to find that the empirical specification consistent with bounded rationality (and leading consumers to overconsume electricity) has more predictive power than one based on utility maximization.

Heuristic decisionmaking in energy is similarly difficult to test empirically, although several papers in psychology have done so. Kempton and Montgomery (1982) use a survey technique to find that consumers use simple heuristic techniques to determine their energy consumption and that these techniques systematically lead to underinvestment in energy efficiency. For example, for decisions regarding energy-efficient investments consumers tend to use a simple payback measure where the total investment cost is divided by the future savings calculated by using the energy price today, rather than the price at the time of the savings—effectively ignoring future increases in real fuel prices (Kempton and Montgomery 1982). Kempton et al. (1992), using similar methods, find that consumers systematically miscalculate payback for air conditioner investments, again leading to overconsumption of energy.

Yates and Aronson (1983) find that consumers attach disproportionate weight to the most psychologically vivid and observable factors, often called the “salience effect.” The salience effect may influence energy efficiency decisions, potentially contributing to an overemphasis on the initial cost of an energy-efficient purchase, leading to an underinvestment in energy efficiency (Wilson and Dowlatabadi 2007). This may be related to evidence suggesting that decisionmakers are more sensitive to up-front investment costs than energy operating costs, although this evidence may also be the result of inappropriate measures of expectations of future energy use and prices (Anderson and Newell 2004, Hassett and Metcalf 1995, Jaffe et al. 1995).

Loewenstein and Prelec (1993) develop a theoretical model of intertemporal choice that replaces the utility function with a value function that is more elastic for outcomes with large absolute magnitudes than for outcomes with small magnitudes, consistent with evidence in Thaler (1981) and Holcomb and Nelson (1992). Thus, in this value function framework, discounting depends on the magnitude of the outcome. Applying this to the case of energy efficiency investments, flows of electricity savings are typically smaller than the annual returns from other types of investments and thus would be subject to higher rates of discount. Loewenstein and Prelec (1993) posit that their model may capture a behavioral bias that implies a systematic underinvestment in energy efficiency relative to the consumers' cost-minimizing choice. To our knowledge the model has not been empirically tested in the context of energy efficiency.

This review reveals that the empirical literature testing behavioral failures specifically in the context of energy decisionmaking is very limited. The literature in psychology and sociology discusses these biases further and provides some additional evidence of such biases (e.g., see Wilson and Dowlatabadi [2007] for a review of the approaches in the different fields as applied to energy). The available evidence suggests that systematic biases may exist in consumer decisionmaking that could lead to overconsumption of energy and underinvestment in energy efficiency. However, more fully understanding the magnitude of these biases, disentangling them from informational and other market failures, and measuring the ability of practicable policies to address these behavioral failures remains an important area for future research.

5. Energy Efficiency Policy

While the literature has identified a number of potential market and behavioral failures that are relevant to energy efficiency, for policy responses to improve economic efficiency they must successfully reduce these failures and the associated benefits must exceed the cost of implementing the policy.

In the previous section we identified a number of relevant market failures, several of which are, however, not unique to energy efficiency and conservation. For example, R&D spillovers exist throughout the economy and motivate general policies such as patent protection, R&D tax credits, and basic research funding. Policy decisions specific to energy efficiency R&D arise mainly in the context of determining the level and allocation of public research spending among different purposes (see Newell [2008] for a related discussion). LBD spillovers are similar in that any emerging technology may exhibit nonappropriable gains from learning, raising questions over the appropriate bounds on policy.

The environmental externalities avoided by energy efficiency and conservation largely result from emissions associated with burning fossil fuels. Economic theory suggests that if consumers are optimizing and there are no other market imperfections, a first-best policy to address the environmental externalities would ensure that the external cost from emissions is added to the energy price, such as through a Pigouvian tax or cap-and-trade system. The resulting internalization of the externality would lead to reduced energy demand (more conservation) and more energy efficiency investment. To assess the amount of energy savings from such an emissions price policy, one can examine the price elasticity of energy demand discussed earlier, which is typically done in the context of a computable general equilibrium model or other aggregate energy-economic model. In the context of climate policy, such modeling typically finds that a significant portion of cost-effective emissions reductions are achieved through energy efficiency and conservation, alongside renewable energy, nuclear power, and carbon capture and storage applied to coal (Clarke et al. 2006, Weyant et al. 2006). Policies to directly promote energy efficiency are second-best responses to environmental externalities, however, because they do not discriminate among the emissions intensities of different energy sources, do not provide an incentive for reducing consumption of energy services, and tend to apply only to a subset of sources. Instead, policies to promote energy efficiency may be the appropriate response to demonstrated behavioral failures, particularly in contexts where that behavior has broader societal implications (e.g., environmental externalities).

The remaining discussion focuses on the economic rationale, effectiveness, and cost of policies that are specifically targeted to energy efficiency grouped into three broad categories: information programs, incentives, and product standards. Before turning our attention to these issues, we briefly review some generic issues that arise in measuring the effectiveness and cost of energy efficiency policies. For a more detailed review of these issues see Gillingham et al. (2006).

5.1 Issues in Measuring Energy Efficiency Policy Effectiveness and Cost

The literature on energy efficiency and conservation policy evaluation is extensive and has become more sophisticated with time. There are a few critical issues common to energy efficiency policies. First, *ex ante* studies dominate much of energy efficiency policy literature, particularly for evaluating product standards. These studies formed a valuable starting point for understanding future policy, but they do not demonstrate that policies have been effective or net-beneficial in actual implementation. As more energy efficiency and conservation policies have been implemented, the literature is shifting to *ex post* studies that examine the historical effectiveness and cost of energy efficiency and conservation policies in order to improve future policy making.

One of the major criticisms of the energy efficiency and conservation policy evaluation literature is that “free-riders” are not always properly accounted for. Free-riders are consumers who would have invested in energy efficiency or conserved energy absent the policy, but receive additional benefits from the policy (Joskow and Marron 1992). Benefits from free-riders should not be counted in the benefits from the policy, but costs (that are not simply transfers) should be included in the costs of the policy. As discussed above, on the other hand, papers in the broader energy efficiency literature point to an offsetting effect of "free-drivers," where nonparticipants in the program are induced to invest in energy efficiency or conserve energy due to observing program participants (Blumstein and Harris 1993, Eto et al. 1996, Geller and Attali 2005).

Another common criticism of energy efficiency policy evaluations is that they either ignore or inappropriately account for the rebound effect, whereby energy efficiency improvements decrease the marginal cost of energy services, thereby increasing demand and inducing less-than-proportional reductions in energy use. There is an extensive debate in the literature about the importance of the rebound effect in the context of energy efficiency standards (see Gillingham et al. [2006] for a review), but some empirical evidence suggests it may be numerically small in the case of energy efficiency standards (Dumagan and Mount 1993). For example, Davis (2008) examines the case of clothes washers, and finds a relatively small, but not insignificant, rebound effect of –6 percent. For recent evidence in the household transportation context, see Small and Van Dender (2007).

5.2 Information Programs

Information programs typically aim to induce energy efficiency investments by providing information about potential energy savings or examples of energy savings. Some programs attempt to promote energy conservation, particularly for electricity during times when the electricity grid is stressed. Historically, many information programs have been part of utility demand-side management (DSM) programs, and others have been federal programs such as EnergyStar, appliance labels, and Home Energy Ratings for new homes. Information programs also include programs to provide feedback to consumers about their energy consumption.

Information programs are motivated by the informational problems and behavioral failures noted earlier. The intention is that by providing greater and more reliable information, issues of uncertain future returns and asymmetric information may be lessened. Additional information may also lower the cognitive cost of energy decisionmaking or help guide consumers toward better decisions.

Information programs vary greatly, both in their method and implementation, and evidence of their effectiveness is mixed. Weil and McMahon (2003) offer anecdotal evidence that product labeling requirements can be successful in increasing energy-efficient investments, but Levine et al. (1995) find that the EnergyGuide product labeling requirements were fairly ineffective. The EnergyGuide label has been revised in a recent rulemaking to improve its effectiveness. According to some studies, voluntary EnergyStar labels appear to have achieved significant savings by inducing greater energy efficiency (Webber et al. 2000). For example, Howarth et al. (2000) present evidence that the voluntary EPA Green Lights program (now part of EnergyStar) and EnergyStar Office products program have been effective in increasing energy efficiency investments by increasing access to information.

Anderson and Newell (2004) examine industrial energy audits and find that while plants only accept about half of the recommended projects, most plants respond to the costs and benefits presented in the energy audits and, with the additional information, adopt investments that meet hurdle rates consistent with standard investment criteria the audited firms say they use. Newell et al. (1999) find that the responsiveness of energy-efficient product innovation to energy prices increased substantially after product labeling was required. Stern (1985) suggests that many early energy conservation information programs (particularly DSM programs) were not very effective. Fischer (2008) examines the psychological literature on feedback programs (i.e., programs that provide consumers real-time information about their electricity consumption) and finds feedback induces energy conservation with typical savings of 5 percent to 12 percent. Reiss and White (2008) examine data from the 2000–2001 California electricity crisis and find that in times of crisis, conservation appeals and information programs can produce sustained reductions in energy demand. Data indicating the cost-effectiveness of these programs are not readily available.

5.3 Financial Incentives

Incentive programs provide financial motivation for energy efficiency investments through direct subsidies, tax credits, tax deductions, rebates, or loan subsides. Financial incentives have also been used to promote energy conservation in the electricity market during times of peak load. In addition, financial incentives have been used to encourage the development of new energy technologies, such as through prizes for highly energy-efficient products (Gillingham et al. 2006). Incentive programs have been primarily implemented as part of utility DSM programs. These programs are broadly motivated by the concerns mentioned above, in effect responding to the perceived underinvestment in energy efficiency by subsidizing such investment.

The empirical evidence on the effectiveness of financial incentives is also somewhat mixed. Stern (1985) suggests financial incentives are not very effective in inducing initial interest in energy efficiency improvement programs, but may help induce energy efficiency investments by those already participating in the programs. Carpenter and Chester (1984) use a survey about the conservation tax credits of the early 1980s and find that although 86 percent of those surveyed were aware of the credit, only 35 percent used it, and of those who used it, 94 percent would have invested anyway. Several studies econometrically estimate the effect of state tax incentives on all conservation investments and find mixed results. Hasset and Metcalf (1995) attempt to correct previous methodological errors and estimate that a 10 percentage point change in the tax price for energy investment increases the probability of making an energy efficiency investment by 24 percent. Using data on the 1980s tax credit, Williams and Poyer (1996) also find that despite the free-rider issue, tax credits increased the probability of an energy efficiency investment.

These results suggest that financial incentives may be effective, but further research is needed to determine their cost-effectiveness. There is a fairly extensive literature examining the cost-effectiveness of utility DSM programs, which typically contain financial incentives along with information programs. Common values in the literature of the “negawatt cost” or the full life cycle cost (i.e., total expense of running the program and installing equipment) per kilowatt-hour saved as a result of a DSM program range from below $0.01/kWh to above $0.20/kWh saved (in real 2002 dollars). For comparison, the U.S. average residential electricity price has been in the range of $0.08–0.09/kWh (in real 2002 dollars) over the past 10 years (EIA 2008). A debate in the literature is still continuing regarding negawatt costs, with recent econometric evidence by Loughran and Kulick (2004) suggesting utilities are overestimating energy savings, leading to costs on the high end. An analysis of the same data by Auffhammer et al. (2008) points out, however, that the savings summary statistic used by Loughran and Kulick (2004) was unweighted, and thus in this case underestimates the national average electricity saved per dollar spent on DSM programs. Auffhammer et al. (2008) find a weighted average negawatt cost in the range of $0.05–0.13/kWh based on the Loughran and Kulick (2004) model and fail to reject the null hypothesis that the utility-reported savings estimates are correct on average. These figures only include costs to the utilities, however, not to the energy end user; consumer costs may be in the range of 60 percent to 70 percent of utility costs (Nadel and Geller 1996). Taking utility estimates of costs and effectiveness as given, Gillingham et al. (2004) calculate a cost-effectiveness for all DSM programs of $(2002) 0.034/kWh saved in 2000 by using only utility costs and utility self-reported savings.

5.4 Product Standards

Product standards set a minimum level of energy efficiency that all covered products on the market must meet. In some cases, standards may be differentiated by size and type of the product, such as refrigerator standards that may be different for mini-fridges than full-sized refrigerators. Energy efficiency standards are politically motivated by the full range of concerns noted earlier. From an economic perspective, other policy responses would tend to be more direct, efficient responses to the market failures described. For example, if consumers are making rational decisions and there is heterogeneity in their preferences for energy efficiency, product standards could lead to a loss in economic efficiency by forcing behavior change on those who gain relatively little from energy efficiency (e.g., those who do not use the product often) (Hausman and Joskow 1982). On the other hand, verified behavioral failures could provide an economic rationale for product standards.

The literature on product standards primarily focuses on appliance standards, for which there are primarily *ex ante* estimates of cost and effectiveness based on government regulatory analysis. Using engineering estimates of the energy savings and energy prices, Meyers et al. (2003) find a cumulative net benefit of US$(2003) 17.4 billion over 1987–2000 for the 1987–2000 appliance standards. With projections of future energy savings added, they find a cumulative net benefit of the current standards of US$(2003) 154 billion for 1987–2050. Taking the Meyers et al. (2003) estimates as given, Gillingham et al. (2004) calculate an implied cost-effectiveness of $0.028/kWh saved in 2000.

These net benefit estimates have to our knowledge not been subject to independent verification in the economic literature. Because these analyses do not include a valuation of environmental or security externalities, their net benefits are arising solely from implicit modeling assumptions that are different from the way consumers are behaving in the absence of the standards (i.e., implicitly modeling behavioral failures). The implication is that either consumers are not minimizing costs or that the model is making incorrect assumptions. Further empirical research evaluating the degree to which each of these cases is more correct would be valuable.

6. Conclusion

The literature on the economics of energy efficiency and conservation has embodied significant debate over the past few decades, yet there remain many outstanding issues. The heart of the debate centers on the issue of identifying the economically efficient level of energy efficiency and determining whether policy directed specifically to energy efficiency is necessary to bring us to this level, and if so, determining its net benefits in practice. We identify potential market and behavioral failures that may help to explain this gap, although quantitative evidence on the magnitude of many of these potential failures is limited.

Many of the commonly cited market failures are not unique to energy efficiency, and addressing them tends to call for a much broader policy response, such as an economywide price on greenhouse gases to address climate change, comprehensive innovation policy to increase innovative effort, and electricity market reforms moving toward marginal cost pricing. On the other hand, information and behavioral failures—to the extent they are substantial—tend to motivate more specific energy efficiency policies, provided that the benefits of the policies exceed the costs. Further research in this vein is essential to better clarify the potential for energy efficiency policies to increase economic efficiency.

References

Akerlof G. 1970. The Market for Lemons: Quality Uncertainty and the Market Mechanism. *Quarterly Journal of Economics* 84: 488–500

Anderson S, Newell R. 2004. Information Programs for Technology Adoption: The Case of Energy-Efficiency Audits. *Resource and Energy Economics* 26: 27–50

Arrow K. 1962. The Economic Implications of Learning by Doing. *Review of Economic Studies* 29: 155–73

Auffhammer M, Blumstein C, Fowlie M. 2008. Demand-Side Management and Energy Efficiency Revisited. *The Energy Journal* 29: 91–104

Bass F. 1980. The Relationship Between Diffusion Rates, Experience Curves, and Demand Elasticities for Consumer Durable Technological Innovations. *Journal of Business* 53: 51–67

Bernstein M, Griffin J. 2005. *Regional Differences in the Price-Elasticity of Demand for Energy*. Santa Monica, CA: RAND Corporation

Berry L. 1984. The Role of Financial Incentives in Utility-Sponsored Residential Conservation Programs: A Review of Customer Surveys. *Evaluation and Program Planning* 7: 131–41

Blumstein C, Harris J. 1993. The Cost of Energy Efficiency. *Science* 261: 970

Blumstein C, Kreig B, Schipper L, York C. 1980. Overcoming Social and Institutional Barriers to Energy Efficiency. *Energy* 5: 355–72

Bohi D, Toman M. 1996. *Economics of Energy Security*. Norwell, MA: Kluwer Academic Publishers

Bohi D, Zimmerman M. 1984. An Update on Econometric Studies of Energy Demand Behavior. *Annual Review of Energy* 9: 105–54

Brennan T. 2004. Market Failures in Real-Time Metering. *Journal of Regulatory Economics* 26: 119–39

Camerer C. 1997. Progress in Behavioral Game Theory. *Journal of Economic Perspectives* 11: 167–88

Carpenter EH, Chester TS. 1984. Are Federal Energy Tax Credits Effective? A Western United States Survey. *The Energy Journal* 5: 139–49

Clarke L, Wise M, Placet M, Izaurralde C, Lurz J, et al. 2006. *Climate Change Mitigation: An Analysis of Advanced Technology Scenarios.* Pacific Northwest National Laboratory, PNNL-16078, Richland, WA

Dahl C. 1993. *A Survey of Energy Demand Elasticities in Support of the Development of the NEMS.* Colorado School of Mines; United States Department of Energy

Davis L. 2008. Durable Goods and Residential Demand for Energy and Water: Evidence from a Field Trial. *RAND Journal of Economics* 39: 530–46

DeCanio SJ. 1993. Barriers within Firms to Energy-Efficient Investments. *Energy Policy* 21: 906–14

DeCanio SJ. 1994a. Agency and Control Problems in U.S. Corporations: The Case of Energy-Efficient Investment Projects. *Journal of the Economics of Business* 1(1): 105–123

DeCanio SJ. 1994b. Why Do Profitable Energy-Saving Investment Projects Languish? *Journal of General Management* 20(1): 62–71.

DeCanio SJ, Watkins W. 1998. Investment in Energy Efficiency: Do the Characteristics of Firms Matter? *Review of Economics and Statistics* 80: 95–107

Dumagan JC, Mount TD. 1993. Welfare Effects of Improving End-Use Efficiency: Theory and Application to Residential Electricity Demand. *Resource and Energy Economics* 15(2): 175–201

EIA. 2008. *Electric Power Monthly with Data for September 2008.* U.S. Department of Energy, Energy Information Administration, Washington, DC.

Eto J, Vine E, Shown L, Sonnenblick R, Payne C. 1996. The Total Cost and Measured Performance of Utility-Sponsored Energy-Efficiency Programs. *The Energy Journal* 17: 31–52

Fischer C. 2005. On the Importance of the Supply Side in Demand-side Management. *Energy Economics* 27: 165-80

Fischer C. 2008. Feedback on Household Electricity Consumption: A Tool for Saving Energy? *Energy Efficiency* 1: 79–104

Fischer C, Newell R. 2008. Environmental and Technology Policies for Climate Mitigation. *Journal of Environmental Economics and Management* 55: 142–62

Friedman L. 2002. Bounded Rationality versus Standard Utility-Maximization: A Test of Energy Price Responsiveness. In *Judgments, Decisions, and Public Policy*, ed. R Gowda, J Fox, pp. 138–73. New York: Cambridge University Press

Friedman L, Hausker K. 1988. Residential Energy Consumption: Models of Consumer Behavior and Their Implications for Rate Design. *Journal of Consumer Policy* 11: 287–313

Geller H, Attali S. 2005. *The Experience with Energy Efficiency Policies and Programmes in IEA Countries: Learning from the Critics.* Paris: International Energy Agency

Gillingham K, Newell R, Palmer K. 2004. *Retrospective Examination of Demand-Side Energy Efficiency Policies.* Resources for the Future, Discussion Paper 04-19, Washington, DC

Gillingham K, Newell R, Palmer K. 2006. Energy Efficiency Policies: A Retrospective Examination. *Annual Review of Environment and Resources* 31: 161–92

Gillingham K, Newell R, Pizer W. 2008. Modeling Endogenous Technological Change for Climate Policy Analysis. *Energy Economics* 30: 2734–53

Golove W, Eto J. 1996. *Market Barriers to Energy Efficiency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency.* Lawrence Berkeley National Laboratory, LBL-38059, UC-1322, Berkeley, CA

Goulder L, Schneider S. 1999. Induced Technological Change and the Attractiveness of CO2 Emissions Abatement Policies. *Resource and Energy Economics* 21: 211–53

Griliches Z. 1995. R&D and Productivity: Econometric Results and Measurement Issues. In *Handbook of the Economics of Innovation and Technical Change*, ed. P Stoneman, pp. 52–71. Oxford: Blackwell

Hall B. 1996. The Private and Social Returns to Research and Development. In *Technology, R&D, and the Economy*, ed. LR Smith, CE Barfield, pp. 140–83. Washington, DC: Brookings Institution and American Enterprise Institute

Hartman R, Doane M, Woo C-K. 1991. Consumer Rationality and the Status Quo. *Quarterly Journal of Economics* 106: 141–62

Hassett KA, Metcalf GE. 1993. Energy Conservation Investment: Do Consumers Discount the Future Correctly? *Energy Policy* 21: 710–16

Hassett KA, Metcalf GE. 1995. Energy Tax Credits and Residential Conservation Investment: Evidence from Panel Data. *Journal of Public Economics* 57: 201–17

Hausman J. 1979. Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables. *The Bell Journal of Economics* 10: 33–54

Hausman JA, Joskow PL. 1982. Evaluating the Costs and Benefits of Appliance Efficiency Standards. *American Economic Review* 72: 220–25

Hirst E. 1986. Actual Energy Savings After Retrofit: Electrically Heated Homes in the Pacific Northwest. *Energy* 11: 299–308

Holcomb J, Nelson P. 1992. Another Experimental Look at Individual Time Preference. *Rationality and Society* 4: 199–220

Howarth R, Andersson B. 1993. Market Barriers to Energy Efficiency. *Energy Economics* 15: 262–72

Howarth RB, Haddad BM, Paton B. 2000. The Economics of Energy Efficiency: Insights from Voluntary Participation Programs. *Energy Policy* 28: 477–86

Howarth RB, Sanstad AH. 1995. Discount Rates and Energy Efficiency. *Contemporary Economic Policy* 13: 101–09

Hsing Y. 1994. Estimation of Residential Demand for Electricity with the Cross-Sectionally Correlated and Time-Wise Autoregressive Model. *Resource and Energy Economics* 16: 255–63

Jaffe A, Newell R, Stavins R. 2004. The Economics of Energy Efficiency. In *Encyclopedia of Energy,* ed. C Cleveland, pp. 79–90. Amsterdam: Elsevier

Jaffe A, Newell R, Stavins R. 2005. A Tale of Two Market Failures: Technology and Environmental Policy. *Ecological Economics* 54: 164–74

Jaffe A, Stavins R. 1994. The Energy Efficiency Gap: What Does It Mean? *Energy Policy* 22: 804–10

Jaffe A, Stavins R, Newell R. 1995. Dynamic Incentives of Environmental Regulations: The Effects of Alternative Policy Instruments on Technology Diffusion. *Journal of Environmental Economics and Management* 29(3): S43–S63

Joskow P, Tirole J. 2007. Reliability and Competitive Electricity Markets. *RAND Journal of Economics* 38: 60–84

Joskow PL, Marron DB. 1992. What Does a Negawatt Really Cost? Evidence from Utility Conservation Programs. *The Energy Journal* 13: 41–74

Kahneman D, Tversky A. 1979. Prospect Theory: An Analysis of Decisions Under Risk. *Econometrica* 47: 263–91

Kempton W, Feuermann D, McGarity A. 1992. I Always Turn It on "Super": User Decisions About When and How to Operate Room Air Conditioners. *Energy and Buildings* 18: 177–91

Kempton W, Montgomery L. 1982. Folk Quantification of Energy. *Energy* 7: 817–27

Koomey J, Sanstad A. 1994. Technical Evidence for Assessing the Performance of Markets Affecting Energy Efficiency. *Energy Policy* 22: 826–32

Levine M, Koomey J, McMahon J, Sanstad A, Hirst E. 1995. Energy Efficiency Policy and Market Failures. *Annual Review of Energy and the Environment* 20: 535–55

Levinson A, Niemann S. 2004. Energy Use by Apartment Tenants When Landlords Pay for Utilities. *Resource and Energy Economics* 26: 51–75

List J, Price M. 2009. What Do Behavioral and Neural Economics Have to Offer Environmental and Resource Economics? *Annual Review of Resource Economics*, forthcoming

Loewenstein G, Prelec D. 1993. Anomalies in Intertemporal Choice: Evidence and an Interpretation. *Quarterly Journal of Economics* 107: 573–97

Loughran D, Kulick J. 2004. Demand-Side Management and Energy Efficiency in the United States. *The Energy Journal* 25: 19–41

Lutzenhiser L. 1992. A Cultural Model of Household Energy Consumption. *Energy* 17: 47–60

Lutzenhiser L. 1993. Social and Behavioral Aspects of Energy Use. *Annual Review of Energy and the Environment* 18: 247–89

Machina M. 1989. Dynamic Consistency and Non-Expected Utility Models of Choice Under Uncertainty. *Journal of Economic Literature* 32: 1622–68

McFadden D. 1999. Rationality for Economists? *Journal of Risk and Uncertainty* 19: 73–105

Metcalf G. 2008. An Empirical Analysis of Energy Intensity and Its Determinants at the State Level. *The Energy Journal* 29: 1–26

Metcalf GE. 1994. Economics and Rational Conservation Policy. *Energy Policy* 22: 819–25

Metcalf GE, Hassett KA. 1999. Measuring the Energy Savings from Home Improvement Investments: Evidence from Monthly Billing Data. *Review of Economics and Statistics* 81: 516–28

Meyers S, McMahon JE, McNeil M, Liu X. 2003. Impacts of U.S. Federal Energy Efficiency Standards for Residential Appliances. *Energy* 28: 755–67

Murtishaw S, Sathaye J. 2006. *Quantifying the Effect of the Principal-Agent Problem on US Residential Use.* Lawrence Berkeley National Laboratory, LBNL-59773, Berkeley, CA

Nadel S, Geller H. 1996. Utility DSM: What Have We Learned? Where Are We Going? *Energy Policy* 24: 289–302

Nadiri IM. 1993. *Innovations and Technological Spillovers.* National Bureau of Economic Research, Working Paper 4423, Cambridge, MA

Newell R. 2008. *A U.S. Innovation Strategy for Climate Change Mitigation*, Brookings Institution Hamilton Project, Discussion Paper 2008-15, Washington, DC

Newell R, Jaffe A, Stavins R. 1999. The Induced Innovation Hypothesis and Energy-Saving Technological Change. *Quarterly Journal of Economics* 114: 941–75

Newell R, Pizer W. 2008. Carbon Mitigation Costs for the Commercial Building Sector: Discrete-Continuous Choice Analysis of Multifuel Energy Demand. *Resource and Energy Economics* 30: 527–39

Popp D. 2002. Induced Innovation and Energy Prices. *American Economic Review* 92: 160–80

Popp D, Newell R, Jaffe A. 2009. Energy, the Environment, and Technological Change. In *Handbook of Economics of Technical Change*, ed. B Hall, N Rosenberg. Oxford: North-Holland

Rabin M. 1997. Psychology and Economics. *Journal of Economic Literature* 36: 11–46

Ray D. 1998. *Development Economics*. Princeton, NJ: Princeton University Press

Reiss P, White M. 2008. What Changes Energy Consumption? Prices and Public Pressures. *RAND Journal of Economics* 39: 636–63

Ruderman H, Levine M, McMahon J. 1987. The Behavior of the Market for Energy Efficiency in Residential Appliances including Heating and Cooling Equipment. *The Energy Journal* 8: 101-24

Sanstad A, Blumstein C, Stoft S. 1995. How High Are Option Values in Energy Efficiency Investments? *Energy Policy* 23: 739–43

Sanstad A, Hanemann M, Auffhammer M. 2006. *End-use Energy Efficiency in a "Post-Carbon" California Economy: Policy Issues and Research Frontiers.* The California Climate Change Center at UC-Berkeley, Berkeley, CA

Sanstad AH, Howarth RB. 1994. *Consumer Rationality and Energy Efficiency*. Presented at Proceedings of the 1994 Summer Study on Energy Efficiency in Buildings, Berkeley, CA

Schneider S, Goulder L. 1997. Achieving Carbon Dioxide Emissions Reductions at Low Cost. *Nature* 389: 13–14

Sebold FD, Fox EW. 1985. Realized Savings from Residential Conservation Activity. *The Energy Journal* 6: 73–88

Shogren J, Taylor L. 2008. On Behavioral-Environmental Economics. *Review of Environmental Economics and Policy* 2: 26–44

Simon H. 1959. Theories of Decision-Making in Economics and Behavioral Science. *American Economic Review* 49: 253–83

Simon H. 1986. Rationality in Psychology and Economics. *Journal of Business* 59: 209–24

Small K, Van Dender K. 2007. Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect. *The Energy Journal* 28: 25–51

Stein J. 2003. Agency, Information, and Corporate Investment. In *Handbook of the Economics of Finance*, ed. G Constantinides, M Harris, R Stulz. Amsterdam: Elsevier

Stern P, ed. 1985. *Energy Efficiency in Buildings: Behavioral Issues*. Washington, DC: National Academy Press

Sue Wing I. 2008. Explaining the Declining Energy Intensity of the U.S. Economy. *Resource and Energy Economics* 30: 21–49

Sutherland RJ. 1991. Market Barriers to Energy Efficiency Investments. *The Energy Journal* 12: 15–34

Sutherland RJ. 1996. The Economics of Energy Conservation Policy. *Energy Policy* 24: 361–70

Thaler R. 1981. Some Empirical Evidence on Dynamic Inconsistency. *Economics Letters* 8: 201–207

Thaler R. 1991. *Quasi-Rational Economics*. New York: Russell Sage Foundation

Train K. 1985. Discount Rates in Consumers' Energy-Related Decisions: A Review of the Literature. *Energy* 10: 243–53

Tversky A. 1972. Elimination by Aspects: A Theory of Choice. *Psychological Review* 79: 281–99

Tversky A, Kahneman D. 1974. Judgment under Uncertainty: Heuristics and Biases. *Science* 185: 1124–31

van Benthem A, Gillingham K, Sweeney J. 2008. Learning-by-Doing and the Optimal Solar Policy in California. *The Energy Journal* 29: 131–51

van Soest DP, Bulte E. 2000. Does the Energy-Efficiency Paradox Exist? Technological Progress and Uncertainty. *Environmental and Resource Economics* 18: 101–12

Wade S. 2003. *Price Responsiveness in the AEO2003 NEMS Residential and Commercial Buildings Sector Models*. Energy Information Administration, U.S. Department of Energy, Washington, DC

Webber CA, Brown RE, Koomey JG. 2000. Savings Estimates for the ENERGY STAR Voluntary Labeling Program. *Energy Policy* 28: 1137–49

Weil S, McMahon J. 2003. Governments Should Implement Energy-Efficiency Standards and Labels—Cautiously. *Energy Policy* 31: 1403–15

Weyant JP, de la Chesnaye FC, Blanford GJ. 2006. Overview of EMF-21: Multigas Mitigation and Climate Policy. *The Energy Journal* Special Issue on Multi-Greenhouse Gas Mitigation and Climate Policy: 1–32

Williams M, Poyer D. 1996. The Effect of Energy Conservation Tax Credits on Minority Household Housing Improvements. *Review of Black Political Economy* 24: 122–34

Wilson C, Dowlatabadi H. 2007. Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources* 32: 169–203

Wolak F. 2006. *Residential Customer Response to Real-Time Pricing: The Anaheim Critical-Peak Pricing Experiment.* University of California Energy Institute Center for Study of Energy Markets, CSEM Working Paper 151, Berkeley, CA

Yates S, Aronson E. 1983. A Social Psychological Perspective on Energy Conservation in Residential Buildings. *American Psychologist* 38: 435–44

Zobler N, Hatcher K. 2003. Financing Energy Efficiency Projects. *Government Finance Review* February: 14–18