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Assessing the Energy-Efficiency Gap[†]

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Energy-efficient technologies offer considerable promise for reducing the financial costs and environmental damages associated with energy use, but it has long been observed that these technologies may not be adopted by individuals and firms to the degree that might be justified, even on a purely financial basis. We survey the relevant literature on this "energy-efficiency gap" by presenting two complementary frameworks. First, we divide potential explanations for the energy-efficiency gap into three categories: market failures, behavioral explanations, and model and measurement errors. Second, we organize previous research in terms of the fundamental elements of cost-minimizing energy-efficiency decisions. This provides a decomposition that organizes thinking around four questions. First, are product offerings and pricing economically efficient? Second, are energy operating costs inefficiently priced and/or understood? Third, are product choices cost minimizing in present value terms? Fourth, do other costs inhibit more energy-efficient decisions? We synthesize academic research on these questions, with an emphasis on recent empirical findings, and offer suggestions for future research. (*JEL* D24, D82, L94, L98, O33, Q41, Q48)

1. *Introduction*

Global energy consumption is on a path to grow 30–50 percent over the next twenty-five years, bringing with it, in many countries, increased local air pollution and greenhouse gas emissions. Adoption of energy-efficient technologies could potentially reap both private and social returns, in the form of economic, environmental, and other social benefits from reduced energy consumption. In response, governments and firms around the world have adopted policies and programs to increase energy efficiency and capture these benefits. Still, there is a broadly held view that various barriers to the adoption of energy-efficient technologies have prevented the realization of

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TABLE 1
PRIVATE AND SOCIAL CONCEPTIONS OF THE ENERGY-EFFICIENCY GAP

Potential explanations	Private gap	Public gap	Social gap
Innovation/adoption spillovers, market power, imperfect information		X	X
Too-low energy prices due to unpriced externalities		X	X
Biased beliefs about energy prices and energy usage	X		X
Inattention to operating costs, myopia, and cognitive limitations	X		X

a substantial portion of these benefits. Our purpose is to survey, synthesize, and advance understanding of economics research on this "energy-efficiency gap."

We distinguish between two closely related notions of the energy-efficiency gap based on whether they are defined relative to private or social optima. We designate the "private energy-efficiency gap" as the apparent reality that some energy-efficiency technologies that would pay off for adopters are, nevertheless, not adopted. This basic definition highlights potential deviations from private optimality, and has often been referred to as the "energy paradox" in prior work. More broadly, we use the term "social energy-efficiency gap" to encompass energy-efficiency decisions where technologies that would be socially efficient are not adopted.

The private energy-efficiency gap is nested within the scope of the social energy-efficiency gap (table 1). We view the broader social energy-efficiency gap as the appropriate lens through which to evaluate the potential net benefits of government policy, and therefore use the broader definition to define the scope of this review. Hence, we follow the convention from previous literature of using the phrase "energy-efficiency gap" to refer to deviations from either private or social optimality.

Over the last several decades, a number of scholars have observed that cost-effective energy-conservation technologies appear to diffuse at suboptimal rates. Shama (1983) and the US Department of Energy (1991/1992) noted the paradoxically slow rate of penetration of various energy-conservation technologies, and Jaffe and Stavins (1994a) provided a conceptual framework for thinking about possible explanations. Noting this phenomenon, some analysts and advocates have argued that government intervention to promote energy efficiency could produce environmental benefits at little or even negative economic cost. At the same time, the US federal government, states, and other countries have implemented policies to promote energy efficiency. But the veracity of this argument and economically efficient public-policy responses depend crucially on the underlying causes of the energy-efficiency gap.

Why do decision makers underinvest—or at least appear to underinvest—in energy-efficient technologies, relative to the predictions of some engineering and economic models? Explanations fall into three broad categories: (1) market failures, (2) behavioral explanations, and (3) modeling flaws.

Potential market-failure explanations include: information problems (such as principal–agent issues affecting decisions about the adoption of energy-efficiency technologies in renter-occupied commercial and residential properties, and asymmetric information); energy market failures (including environmental and national-security externalities, and average-cost electricity pricing); capital-market failures (such as liquidity constraints); and innovation market failures (such as information spillovers from research and development).

Potential behavioral explanations include: inattentiveness and salience issues; myopia or short sightedness; bounded rationality and heuristic decision making; prospect theory and reference-point phenomena; and systematically biased beliefs.

Finally, modeling-flaw explanations refer to reasons why the observed rate of diffusion of energy-saving technology may not be as paradoxical as it may at first appear. Evidence for the gap typically involves assumptions about the economic costs and energy use of alternative product choices, the usage profile and characteristics of consumers, and interactions among these factors. Predictions founded on incorrect assumptions could misstate the size of the energy-efficiency gap. These are model and measurement explanations and include: unobserved or understated costs of adoption; ignored product attributes; heterogeneity in benefits and costs of adoption across potential adopters; use of incorrect discount rates; and uncertainty, irreversibility, and option value.[1] In the context of Joseph Schumpeter's classic trio of invention, innovation, and diffusion, our investigation focuses primarily—but not exclusively—on diffusion (adoption).[2]

To provide structure to the many economic elements that enter into adoption decisions related to energy efficiency, we find it useful to think in terms of the fundamental elements of cost-minimizing energy-efficiency decisions. This decomposition is deliberately simple in order to highlight the main features of the issue, and does not explicitly account for all of the factors we consider in our analysis, such as uncertainty, the dynamic nature of decisions (and resulting option value), and heterogeneity:

$$\begin{aligned}\underbrace{\text{min Total Cost}}_{\text{objective}} &= \underbrace{K(E)}_{\text{equipment purchase cost}} \\ &\quad + \underbrace{O(E, P_E) \times D(r, T)}_{\text{discounted operating costs}} \\ &\quad + \text{other costs}\end{aligned}$$

Where
$K(E)$ = equipment purchase cost;
E = annual energy use;
$O(E, P_E)$ = annual operating cost;
P_E = price of energy;
$D(r, T)$ = present-value factor;
r = discount rate; and
T = time horizon.

Based on this decomposition of cost-minimizing energy-efficiency adoption decisions, we organize our synthesis of existing literature around four fundamental questions and a total of twenty-three sub-questions. Referring to the first term of the above equation, we ask whether product offerings and pricing are economically efficient. This question is examined in section 2 of the paper.

Then, in section 3 of the paper, we ask whether energy operating costs are inefficiently priced and/or understood. In section 4, referring to the entire equation, we ask whether product choices are cost minimizing in present-value terms. Finally, in section 5,

[1] For additional discussion of the energy-efficiency gap using this taxonomy of market failures, behavioral effects, and measurement flaws, see Gillingham, Newell, and Palmer (2009) and Gillingham and Palmer (2014). Allcott and Greenstone (2012) suggest the energy-efficiency gap is substantially smaller than it appears to be, emphasizing the role of model and measurement errors.

[2] On innovation, see Newell, Jaffe, and Stavins (1999) and Hall and Rosenberg (2010). For a review of technological change and the environment more generally, of which energy-efficiency technological change is one component, see Jaffe, Newell, and Stavins (2002); Jaffe, Newell, and Stavins (2005); and Popp, Newell, and Jaffe (2010).

we focus on the final term in the above equation and ask whether other costs inhibit more energy-efficient decisions. Alternative explanations of the energy-efficiency gap become parts of sub-questions in these four sections of the paper. In section 6, we offer some conclusions and suggestions for future research priorities.[3]

2. *Do Spillovers, Market Power, or Informational Market Failures Prevent the Energy Efficiency and Associated Pricing of Products on the Market from Being Economically Efficient?*

One set of possible explanations for the energy-efficiency gap is related to the potential economic inefficiencies associated with the first element of the cost-minimization framework—namely, the variety of energy-efficient products on the market, their energy-efficiency levels, and their pricing. Although the theory is clear, empirical evidence is limited. Going forward, more data are becoming available that can facilitate empirical research, although firm-level data are less available than data on consumer decision making.

Given the range of existing public policies in this realm (such as energy-efficiency standards, labeling, utility demand-side management programs, and public funding of research), it is unclear whether there are specific issues related to the variety, availability, and pricing of energy-efficient products, as distinct from other products. Partly because of this, we do not see this area as meriting a high priority for future research specifically in the domain of energy efficiency. Two exceptions are empirical work on whether consumers have adequate information regarding energy-efficient products, and research evaluating and improving the efficacy and efficiency of current information policies.

2.1 *Do Product Developers Invest Too Little in Energy Efficiency Due to Technology Spillovers via Research and Development and Learning-by-Doing?*

Spillovers in the energy-efficiency invention and innovation processes can contribute to the energy-efficiency gap if they lead to underinvestment in the development of new energy-efficient innovations. These spillovers are possible both in basic research and development (R&D) and in subsequent commercialization.

R&D Spillovers.—In theory, firms will invest too little effort in research when the resulting knowledge benefits not only them, but other firms as well. A firm does not reap the full rewards of its investment when knowledge is non-appropriable. This effect is probably most pronounced for early stages of research, because firms cannot capture the knowledge generated in the process perfectly, whereas firms can reduce spillovers in later stages of research through intellectual-property protections (Nordhaus 2011).

While there is little direct empirical evidence of R&D spillovers associated with energy efficiency (Popp, Newell, and Jaffe 2010; Howell 2017), there is substantial evidence of these spillovers in other industries, with empirical estimates of such spillovers ranging from close to zero to 100 percent, with most estimates between 20 and 50 percent (Griliches 1992; Hall, Mairesse, and Mohnen 2010).

Many countries have policies to address generic R&D spillovers. Research grants are widely used to encourage basic research, and tax incentives are used to encourage applied R&D. In addition, intellectual-property protections ameliorate the problem of

[3] The vast majority of the literature is focused on consumer decision making, although where applicable and available we also discuss energy efficiency decision making by firms.

non-appropriability for innovations at the stage of commercialization.

Learning-by-Doing Spillovers.—Learning-by-doing (LBD) refers to productivity improvements that come with experience. The learning effect can be so strong that firms may be willing to operate at a loss when manufacturing a new product to improve productivity and become more competitive (Benkard 2004). But knowledge from such learning can spill over to other firms, creating a free-rider problem. Firms may then under-invest or delay investment to capture knowledge from other firms, rather than incur the cost of generating the knowledge themselves (Arrow 1962; Spence 1981).

Empirical evidence suggests LBD spillovers are present in many industries, with learning spilling over even to firms that are separated by national borders (Lieberman 1984; Irwin and Klenow 1994), although other research suggests that while learning spillovers within a firm can be significant, learning spillovers across firms can be small (Thornton and Thompson 2001).

We are not aware of any direct empirical evidence of LBD in energy efficiency, and none about the extent of any learning *spillovers*. One possible route for research would be to study the engineering pathways by which LBD spillovers occur, building on recent efforts to understand LBD mechanisms (Levitt, List, and Syverson 2013) and utilizing plant-level production data and dynamic structural models of firm production functions.

2.2 *Does Market Power Generate Distortions in the Number of Product Alternatives, Their Level of Energy Efficiency, or Their Prices?*

It is conceivable that the socially optimal diversity of products may not be offered on the market. This could occur, for example, under monopolistic competition. Two forces contribute to this outcome. First, not all welfare-improving products are offered if firms are unable to capture the consumer surplus associated with a given product, due to the difficulty of perfect price discrimination. Second, firms introducing a new product may not internalize the impact of their product's entry on other firms' profits, which can lead to too many products on the market.[4] Despite the soundness of this theory, there is no empirical evidence on the effect of these factors in the energy-efficiency domain.

Economists generally consider energy-efficient products to be of higher quality than less efficient, but otherwise comparable, products. The theory of vertical differentiation suggests that for a single product offering, firms will under supply product quality (including energy efficiency) relative to the social optimum if the marginal consumer values efficiency less than the average consumer. Firms respond to marginal quality valuation, while the social optimum is achieved by setting quality according to average quality valuation (Spence 1975).[5] However, in the case of multiproduct firms, theory does not provide clear guidance on quality distortion. Indeed, for any given product, the anticipated effect is ambiguous: a firm could supply too much or too little energy efficiency relative to the social optimum, due to demand interactions with the firm's other products.

Calibrations of a theoretical model of the automobile market suggest that multiproduct manufacturers would consider these

[4] In the case of complementary products, these two forces push in the same direction, leading firms to introduce too few products with too little differentiation. With substitutes, the two forces push in opposite directions, in which case, the net effect on product variety (relative to the social optimum) is ambiguous (Spence 1976).

[5] This is not limited to firms with market power. It holds for any profit-maximizing firm that is unable to perfectly price discriminate (Spence 1975).

interactions when choosing fuel efficiency for each vehicle, but manufacturers may over or under supply energy efficiency in different products in response to heterogeneity in consumer valuation of fuel efficiency (Fischer 2010). This is reminiscent of quality distortion arising in models of price discrimination: manufacturers provide too much fuel efficiency in vehicle classes demanded by consumers who value fuel efficiency highly, and too little fuel efficiency in vehicle classes demanded by consumers who value fuel efficiency less. This allows manufacturers to extract surplus from consumers according to consumers' tastes, while reducing the likelihood that consumers defect to other vehicle classes. But theory does not offer clear predictions about welfare impacts, and empirical analysis is lacking in the energy-efficiency context.

Other research on automobiles has explored the responsiveness of suppliers to changes in energy costs. Increases in fuel prices should (weakly) increase demand for more efficient vehicles relative to demand for inefficient vehicles by creating differential variation in operating costs for vehicles with different fuel efficiencies. As a result, equilibrium prices and product characteristics could change. Indeed, automobile manufacturers appear to respond to short-run fluctuations in fuel prices by offering cash incentives (Langer and Miller 2013). The responsiveness of product offerings to long-run trends in energy prices is less clear because it is confounded by simultaneous fuel-economy mandates. Fuel economy increased significantly following increases in oil prices and coincident with the introduction of Corporate Average Fuel Economy (CAFE) standards in the 1970s (Pakes, Berry, and Levinsohn 1993; Berry, Kortum, and Pakes 1996).

Changes in market structure can also affect producer incentives, but anticipated effects on product variety are ambiguous. In the case of firm mergers, the ambiguity is due to countervailing forces of cost reduction, leading to lower prices; and reduced competition, leading to higher prices (Berry and Waldfogel 2001). Changes in the demand side of the market can also affect product quality and variety. In particular, variation in market size can alter incentives for suppliers, leading to changes in the variety and quality of products available.[6]

Public policies may also interact with and influence energy-efficient product market offerings, possibly in unanticipated ways. Recent empirical evidence from the appliance industry suggests that firms employ the Energy Star logo as a price discrimination tool, as some consumers have a high willingness to pay for this certification. This allows firms to extract surplus from consumers, and may have distributional impacts that were not widely anticipated (Houde 2014a). Engineering–economic analysis of CAFE standards highlights the quantitative importance of considering firm compliance decisions to change product characteristics—not just prices—when estimating the net benefits of regulations (Whitefoot, Fowlie, and Skerlos 2017). Another example of unanticipated consequences is found in the response of automobile manufacturers to the "notched" Gas Guzzler Tax, which distorts manufacturer incentives and is less efficient than a smooth linear tax (Sallee and Slemrod 2012).[7] Attribute-based

[6] In the presence of horizontal differentiation but no vertical differentiation, market concentration will decrease with market size and a greater variety of products will be offered. In a market with both horizontal and vertical differentiation, this result no longer holds. If increases in product quality require an increase in fixed costs, the highest quality offered will increase with market size, while the market will remain concentrated (Shaked and Sutton 1987).

[7] This comparison of notched and smooth taxes hinges on the assumption of consumer rationality. Under alternative assumptions (see below), the choice between notched and smooth policies becomes considerably less clear. For example, the benefits of certifications may outweigh these

regulations—regulations designed conditional on product attributes other than the target of regulations—generate similar supply distortions (Ito and Sallee 2014).

A tension can exist between optimal innovation and product offerings, on the one hand, and optimal adoption of energy-efficient products, on the other hand. Firms incur fixed costs to generate energy-efficiency improvements in their products, and firms may not invest if they do not expect to recover these costs. However, innovators pricing above marginal cost, which is necessary to recoup fixed costs, could hamper rapid adoption of new products offering significant reductions in energy consumption. Optimal policy would seek to balance these two forces to encourage both innovation and adoption of energy-efficient products (Kamien and Schwartz 1982).

This tension, as with much of the preceding discussion, is generic; that is, the issues are not specific to energy efficiency. In other domains, R&D support and intellectual property protections are the primary tools used to encourage innovation, while antitrust regulation is intended to ameliorate problems associated with market concentration. There is no existing evidence to suggest that energy-efficiency markets exhibit unique market failures that call for tools beyond these traditional policies.

The limitations of theoretical results and the small quantity of empirical evidence in this realm are striking. While empirical evidence from some sectors generally supports theoretical findings,[8] relevance for energy efficiency is unclear. Hence, empirical analysis is needed to assess the role of these factors for energy-efficient product markets. In particular, empirical research with structural models is needed to understand and predict impacts of energy-efficiency policy, particularly in industries that are highly concentrated and highly regulated.

2.3 *Are There Too Few New Energy-Efficient Product Offerings Due to Demand Spillovers?*

Product offerings may be suboptimal in number due to demand spillovers. Product innovations may exhibit information asymmetries between consumers and producers, with consumers needing to be convinced to try a new product. Firms try to generate demand with advertising and/or promotional pricing, the cost of which must be recouped through sales. The consequent learning by consumers can spill over to other consumers, benefiting the innovating firm. Importantly, however, the firm's competitors can also capture these demand spillovers—without paying the costs to educate consumers. The net effect of these two forces is ambiguous. If the latter effect dominates, firms will introduce too few new products.

Existing research provides little insight into the contributions of such demand spillovers to the energy-efficiency gap, possibly due to the empirical challenge of identifying demand spillovers.[9] Hybrid vehicles are a rare example of an energy-efficient technology that has been well studied and that may be associated with learning spillovers among consumers. Empirical evidence that market penetration rates of hybrid vehicles affect future purchases is consistent with this hypothesis. Furthermore, these learning spillovers may not be fully appropriated by the original producer; higher penetration rates for the Toyota Prius have led to greater

supply distortions if consumers are inattentive to energy efficiency (Sallee 2014).

[8] For example, in the restaurant industry, increasing market size is associated with lower concentration, greater variety, and more quality differentiation. In the newspaper industry, where improving quality requires higher fixed costs, larger markets remain concentrated and average quality improves (Berry and Waldfogel 2010).

[9] See the section on learning-by-using spillovers for discussion of the difficulty of identifying demand spillovers.

purchases of hybrids of all makes (Heutel and Muehlegger 2015).[10]

The impact of demand spillovers on product offerings is inherently difficult to study, because researchers do not observe potentially innovative energy-efficient products that firms decide not to introduce. In the absence of such data, researchers can study the impact of learning spillovers across products that *are* introduced, which can serve as a guide for whether these spillovers appear to be significant enough to prevent the introduction of candidate products. Such research could follow the approach of research on the pharmaceutical industry (Crawford and Shum 2005; Coscelli and Shum 2004; Berndt, Pindyck, and Azoulay 2003).[11] The existence and magnitude of spillovers across products appear to be correlated with the degree of substitutability of the products (Janakiraman, Sismeiro, and Dutta 2009). This finding accords with theory and provides a useful guide for evaluating the importance of learning spillovers among energy-efficient products. Implementing government or utility programs that educate consumers about innovative energy-saving technologies is one possible response to significant demand spillovers.

2.4 *Does Adverse Selection Due to Asymmetric Information Inhibit Energy-Efficient Product Offerings?*

In theory, asymmetric information could lead to adverse selection in the marketplace, which in turn might lead to underinvestment in energy efficiency. Such underinvestment would occur if buyers cannot observe perfectly the energy efficiency of products, and as a result are unwilling to pay for its true expected value. If sellers have private information they cannot credibly communicate, some energy-efficient products may not be offered in the market (Akerlof 1970). This problem of asymmetric information tends to be more pronounced in the secondary market, as consumers who invest in energy-efficient capital, such as home weatherization, may have difficulty capitalizing on these investments when reselling. But adverse selection in secondary markets can affect incentives for adoption of efficient technologies in primary markets. Asymmetric information is sometimes cited as a justification for disclosure policies and standards—such as energy-efficiency testing and labels.[12]

Despite widespread acceptance of the theoretical argument for adverse selection due to information asymmetries, there is little empirical evidence of this phenomenon in the context of energy efficiency, particularly in the period since energy-efficiency product testing and labeling became the norm for many energy-using appliances. By its very nature, adverse selection is difficult to study. Like an uninformed buyer, researchers are often unable to observe perfectly the energy-efficiency characteristics of a product. Unobserved heterogeneity among buyers and sellers, particularly in buyers' demand functions, complicates analysis. It is also challenging to separate, in practice, adverse selection from moral hazard. One model research design is the use of randomized experiments to isolate adverse selection from moral hazard in energy consumption (for example, Munley, Taylor, and Formby

[10] Of course, just as learning spillovers can increase demand for similar products, such spillovers can also dampen demand. Heutel and Muehlegger (2015) found that higher market penetration by the Honda Insight led to fewer purchases of all hybrid models, consistent with anecdotal evidence that the Insight was of lower quality.

[11] Research in pharmaceuticals examines both competition between branded and generic drugs following patent expiration and competition among branded drugs. The latter is more relevant to energy-efficient technologies.

[12] For example, the US government cited asymmetric information as a justification for its recent medium- and heavy-duty vehicle fuel economy standards, projecting that these standards will save industry money after accounting for both up-front costs and fuel savings (US Environmental Protection Agency and US Department of Transportation National Highway Traffic Safety Administration 2011).

1990). In the absence of relevant experiments, theory does provide some qualitative guidance for policy and research efforts: outcomes depend on disclosure technology; in markets where disclosure is low-cost and effective, there may be less rationale for policy intervention.[13]

2.5 *Do Consumers Have Inadequate Information Regarding Energy-Efficient Products?*

Lack of information could lead to private decisions to invest less in energy-efficient technologies than would otherwise be the case. Such a lack of information is one of the most commonly cited justifications for policy intervention in this realm (Palmer et al. 2013; Sanstad, Hanemann, and Auffhammer 2006). Two alternative interpretations fit the available evidence: consumers may be inattentive to, or have difficulty using, readily available information; or they may have imperfect information on product availability or product characteristics. We focus here on the classic market failure of imperfect information. We turn to inattention, bounded rationality, and heuristic decision making in later sections.

Information provision has been documented to affect consumer decisions. In a recent artefactual field experiment, provision of information about the energy use of alternative light bulbs increases consumer willingness-to-pay for efficient bulbs (Allcott and Taubinsky 2015). However, these effects were attenuated in the context of a parallel natural field experiment, possibly due to information already available in the marketplace.

Furthermore, few studies disentangle the effects of imperfect information from competing explanations of consumer behavior (e.g., inattention). One recent study attempts to do this using a stated-choice experiment to understand the relative importance of various elements of information labels—including the EnergyGuide, Energy Star, and European Union (EU)-style labels—while controlling for other relevant factors, such as discounting behavior (Newell and Siikamäki 2014). This research finds that a lack of relevant information can lead to significant undervaluation of energy efficiency, and that providing simple information on the economic value of saving energy was the most important element guiding more cost-effective energy-efficiency decisions.

Past evidence in the United States and recent evidence from India suggests that imperfect information also exists among firms (as consumers of energy-efficiency technology), and that firms may fail to undertake profitable investments because they are simply unaware of them (Anderson and Newell 2004; Bloom et al. 2013). Anderson and Newell (2004) examine industrial energy audits and find that while plants accept only half of recommended projects, most plants respond to the costs and benefits presented in energy audits and, with the additional information, adopt investments that meet hurdle rates consistent with standard investment criteria.

In theory and in practice, an informed third party can fill the information gap, as many government and private labeling programs seek to do. Examples include EnergyGuide labels, Energy Star logos, automobile fuel economy labels, and Leadership in Energy and Environmental Design (LEED) certification.[14] A number of studies have analyzed

[13] See Jovanovic (1982) for an analysis of how disclosure costs affect welfare. Recent empirical evidence on the impact of disclosure costs on equilibrium prices comes from online automobile sales (Lewis 2011). Several companies have recently faced sanctions by the US Department of Energy (DOE) for overstating the efficiency of their products, failing to meet minimum efficiency standards, or both.

[14] LEED is a building rating system designed by the US Green Building Council, a non-governmental organization. See: www.usgbc.org/leed.

the effect of such information policies. For example, Davis and Metcalf (2014) use a stated-choice experiment to quantify the welfare gains of using tailored, state-specific EnergyGuide labels rather than one label based on nationwide averages. Sallee (2014) highlights the possible supply distortions caused by coarse energy-efficiency certifications, such as the binary certification employed in the Energy Star program. But the benefits of coarse certifications may outweigh supply distortions, given limits on consumer attention to detail about performance. Houde (2014b) evaluated the welfare effects of the Energy Star certification program and found that consumers rely heavily on the certification, indicating that the program does provide new information to the market. However, he also found that some consumers *over-rely* on the binary label, as opposed to considering actual energy savings. This induces suppliers to bunch at the certification point and could crowd out some efficiency investments (Houde 2014a).

Hedonic analyses of two building certifications, LEED and Energy Star, suggest that certifications provide information to the market, as certification status explains some of the residual variation in rental and sales prices after conditioning on prominent property characteristics (Eichholtz, Kok, and Quigley 2010, 2013). Residential certifications are associated with higher sales prices in both the Netherlands and the United States (Brounen and Kok 2011; Kahn and Kok 2014; Walls et al. 2013).

Experimental research on point-of-sale interventions for energy-consuming products has found heterogeneity in consumer beliefs about possible energy-cost savings. Providing information to consumers could, in theory, lead some consumers to increase energy use—or invest in inefficient technology—in response to information, in a mean-reverting pattern. Carefully designed information provision may eliminate this effect (Schultz et al. 2007). In practice, some information provision interventions may generate negligible demand effects (Allcott and Sweeney 2014).

Further research is needed to distinguish the effects of incomplete information from competing explanations of the energy-efficiency gap, such as inattention and heuristic decision making. Randomized control trials, including both revealed- and stated-choice experiments, may be the most promising method to isolate and test these mechanisms. Likewise, targeted, randomized research designs could provide practical guidance for existing and potential new policy interventions. In particular, research on the effects of online information provision is merited, because consumers increasingly obtain information about and purchase energy-consuming (and other) products online.

3. *Are Energy Operating Costs Inefficiently Priced, Understood, and/or Analyzed?*

Even if energy-consuming durable goods are available on the market and appropriately priced, energy operating costs could be inefficiently priced, understood, or analyzed. In fact, even if consumers make privately optimal decisions, energy-saving technology could—in the absence of corrective policy—diffuse more slowly than the socially optimal rate, due to negative externalities from energy production and use. In other words, even if the private energy-efficiency gap is not present, a social energy-efficiency gap might exist.

For example, the combustion of fossil fuels is associated with numerous environmental pollutants, including greenhouse gases, sulfur dioxide, oxides of nitrogen, and particulate matter, and the environmental and human health effects of these pollutants are not fully incorporated into the price of fossil fuels (and electricity generation). Such unpriced externalities and/or utility regulation can, in principle, lead to a divergence between the energy prices consumers face and the prices that would guide efficient decisions.

In addition, regardless of whether energy prices are set at efficient levels, consumers who hold biased beliefs about energy prices or their expected energy use will make decisions that do not appear optimal, given observed prices. On the other hand, analysts who overestimate the savings associated with efficiency investments or ignore consumer heterogeneity will identify an energy-efficiency gap even where none exists.

As in the previously examined realm, the theoretical arguments in this area are robust. However, unlike in the previous case, here the empirical evidence is considerable, and in some cases quite compelling. In most cases, data are likely to be available for additional research, with the exception of those sub-questions below (3.4 and 3.5) that refer to beliefs, which are challenging to recover with a sufficient degree of reliability. Furthermore, in several cases, existing policies (for example, gasoline taxes, carbon pricing, and electricity price structures) appear not to provide sufficient incentives for energy efficiency from an economic perspective, suggesting that further research is warranted. We view further research in this realm as a relatively high priority; specifically, empirical estimates of the incremental monetized social damages from energy production and use, and the degree to which such damages are already accounted for in energy prices. Where appropriate, it is useful for such estimates to be location and time-specific.

3.1 *Are Retail Electricity or Natural Gas Prices Too Low (or High) Due to Regulation?*

Evidence is mixed regarding whether the regulation of electricity and natural gas prices helps to explain the energy-efficiency gap, due to a divergence of prices from marginal cost. On the one hand, a lack of time-varying electricity pricing suggests that prices are sometimes too low and sometimes too high. On the other hand, average-cost pricing and other features of electricity and gas price regulation could lead to prices that exceed marginal cost systematically. The net effect of these different factors is unclear.

The dynamics of electricity markets can cause prices to be below marginal cost, particularly during peak periods. The marginal cost of electricity generation varies over time, and many pricing schemes do not reflect this variation, leading to inefficient utilization decisions (Joskow and Wolfram 2012). Real-time electricity pricing could correct this, particularly if consumers have access to real-time feedback on consumption (Jessoe and Rapson 2014), which could yield large efficiency gains (Borenstein 2005), but the impact of time-of-use pricing and associated load shifting on energy-efficiency investment is ambiguous (Gillingham, Newell, and Palmer 2009).

Many utilities use multipart tariffs to recover fixed costs while preserving marginal incentives (Coase 1946). But marginal (or usage) prices are typically set above marginal costs. Natural gas customers in the United States face prices inclusive of fixed distribution costs that are well above marginal cost, with one study estimating that these additional costs are comparable to a tax of over \$50 per ton of carbon dioxide (Davis and Muehlegger 2010). Pricing above short-run marginal cost is also present in the electricity sector (Naughton 1986; Borenstein 2012). Equity considerations are one explanation for these markups in regulated industries (Borenstein and Davis 2012), but this issue is not restricted to regulated firms; utilities in restructured markets facing imperfect retail competition also diverge from optimal two-part tariffs (Puller and West 2013).

A second possible reason for inefficiently *high* prices of energy for regulated utilities comes from a principal–agent problem—regulated utilities may not minimize capital costs on behalf of consumers, and these costs cannot be perfectly observed by regulators. Under rate-of-return regulation, utilities may overcapitalize in order to increase profits (Averch and Johnson 1962), a phenomenon that has been confirmed empirically (Spann 1974). Comparisons of electricity generators subject to different regulatory regimes following deregulation have validated this phenomenon (Fowlie 2010; Cicala 2015).

Other research, however, has not supported the theory that utilities overinvest to increase profits (Boyes 1976), and recasting this problem in a dynamic framework highlights the possibility of "regulatory hold-up" (Gilbert and Newbery 1994), where firms may strategically limit investment if they expect regulators to refuse to allow a fair rate of return after the investment is sunk. There is empirical evidence that, due to such regulatory hold-up, utilities underinvest in infrastructure that improves reliability (Lim and Yurukoglu 2015); this could lead to inefficiently low prices.

Inattention, rational or otherwise, may also influence consumer decisions. Recent empirical research provides evidence that retail electricity customers respond to average prices rather than marginal prices (Ito 2014), and that feedback about electricity consumption influences the price elasticity of demand (Jessoe and Rapson 2014). Further empirical research directed at understanding how alternative pricing schemes affect investment in energy efficiency would be valuable.

3.2 *Are Electricity Prices Too Low Due to Unpriced Externalities?*

Electric power production is also associated with environmental externalities. Quantitative estimates of the magnitude of these externalities are limited, and only a subset of these account for marginal emissions and damages being both location and time specific (Muller and Mendelsohn 2009; Graff Zivin, Kotchen, and Mansur 2014).

Coal and natural gas combustion for electric power production have received the most attention, with estimates suggesting the (non-carbon) damages from coal-powered electricity cost society about three to four cents per kilowatt-hour (kWh), and those from natural gas-powered electricity cost society much less than 1 cent per kWh on average (National Research Council 2010). Carbon dioxide emissions from these sources approximately double these cost estimates, depending on choices of the social cost of carbon and the discount rate.[15]

In general, the full incorporation of environmental externalities into the price of electricity would likely raise electricity prices in most US regions. However, many of these externalities are already regulated and thereby indirectly—and sometimes directly—priced. But other market distortions—such as electricity price regulation—make it difficult to judge overall whether electricity prices are too low, and the answer seems certain to vary by region (and time of day). More research is needed to quantify and monetize electricity generation externalities, including comprehensive assessments of which externalities are currently unpriced or underpriced and which are effectively addressed by existing policy.

3.3 *Are Gasoline Prices Too Low Due to Unpriced Externalities?*

Some unpriced transportation-related externalities are a direct function of gasoline

[15] Other fuel sources (for example, nuclear and renewable energy) and stages of production (for example, fuel extraction) produce externalities that are more difficult to quantify, but also potentially important. Qualitative discussions of these impacts abound, but there is little knowledge of the economic magnitudes of the externalities. See, for example, National Research Council (2010). Table 2-2 on page 70 summarizes the discussion.

consumption. These include the effects of greenhouse gas emissions and oil dependency (National Research Council 2010). Available estimates place these external costs at about thirty to forty cents per gallon (Parry, Walls, and Harrington 2007). Local pollution, congestion, and accident externalities can be approximated as mileage-related costs, and converted to per gallon costs; estimates for these are as great as $2.40 per gallon (Parry, Walls, and Harrington 2007; Anderson and Auffhammer 2014). These externality estimates are more than five times larger than current gasoline taxes in the United States.[16] Furthermore, complementarities between gasoline consumption and leisure justify a gasoline tax significantly larger than marginal damages from externalities, due to interactions with labor taxes (West and Williams III 2007). These inefficiencies are exacerbated by fuel subsidies in some countries (Clements et al. 2013), while in others, prices may actually be inefficiently high due to existing taxes (Parry and Small 2005).

Raising gasoline prices (whether through taxation or reduction of subsidies) is not necessarily the optimal policy response to all of these externalities. For example, the damages created by congestion are both location and time dependent and would optimally be priced accordingly. Accident externalities may be best regulated by weight-specific mileage taxes, although this could be approximated by a simpler gasoline tax (Anderson and Auffhammer 2014).

Competing goals present another complication. Due to the rebound effect,[17] improvements in energy efficiency could lead to more vehicle miles traveled, resulting in larger external costs due to congestion and accidents. Addressing congestion and accidents through gasoline taxes would provide an incentive for energy-efficiency improvements to vehicles, but would fail to satisfy economic efficiency due to interactions with other externalities.

On net, economists agree that the price of gasoline in the United States is inefficiently low, and that this contributes to the divergence between observed and socially optimal adoption of energy-efficient technology.

3.4 *Are Beliefs about Current and Future Fuel Prices and/or Usage Systematically Uninformed or Biased Downward?*

Imperfect understanding of energy operating costs on the part of consumers is another possible contributor to the energy-efficiency gap, but biased beliefs about fuel prices do not seem to be a major factor.

Consumer Beliefs about Fuel Prices.—Downward-biased beliefs about fuel prices would tend to lead to underinvestment in energy-efficient technology. Qualitative interviews suggest that people may know current gasoline prices, but lack other essential inputs to valuing vehicle fuel economy (Turrentine and Kurani 2007). Quantitative survey evidence suggests that, on average, consumers forecast future gasoline prices using current prices (Allcott 2011a; Anderson, Kellogg, and Sallee 2013).[18]

Is the current price an unbiased predictor of future prices? It is crucial to compare ex ante consumer beliefs with other

[16] As of July 1, 2015, the federal excise tax on gasoline was 18.4 cents per gallon and the average state excise tax was 26.49 cents per gallon (www.eia.gov/tools/faqs/faq.cfm?id=10&t=5).

[17] The rebound (or take-back) effect refers to the reduction in energy savings from the adoption of an energy-efficiency technology that is due to behavioral response, such as raising the temperature setting on a home thermostat after installing better thermal insulation in the home.

[18] Allcott (2011a) compares survey respondents' fuel-price forecasts to futures prices, not current prices. However, futures prices at the time of the survey were almost identical to a scenario of constant real prices.

possible ex ante beliefs, rather than using outcomes to judge the beliefs of consumers ex post, because beliefs can turn out to be mistaken after the fact, even when they are unbiased in expectation. Some empirical evidence suggests that this no-change forecast is a better predictor of future prices than predictions derived from econometric models, professional survey forecasts, and oil futures (Alquist and Kilian 2010). Together, these two findings—that consumers forecast using current prices, and that current prices are more accurate than other conventional forecasting techniques—do not support the argument that downwardly biased beliefs about fuel prices contribute to the energy-efficiency gap.[19]

Consumer Beliefs about Fuel Usage.—There is little evidence on gasoline usage forecasts or the contribution of inaccurate usage forecasts to the energy-efficiency gap. There is evidence from other settings, however. For example, consumer decisions about mobile phone and health club contracts suggest biased beliefs about product usage (DellaVigna and Malmendier 2006; Grubb 2009). But in the context of automobile purchases, consumers may be less likely to misestimate future fuel usage, due to the salience of gasoline expenditures and relative stability of driving patterns for a given individual.

Future research to understand the impact of fuel-price beliefs on investments in energy-efficient technology outside the transportation sector could be valuable. Likewise, studies of the beliefs of firms, or of key decision makers within firms, could aid understanding of the energy-efficiency gap. Little research has been carried out on consumers' predictions of future usage. Without eliciting or recovering these beliefs, assessing the optimality of consumer purchases requires strong assumptions. A research design that combines elicited price and usage forecasts with choice data could possibly recover preferences without bias from heterogeneity in beliefs among consumers.

3.5 *Are Beliefs about Current and Future Electricity Prices and/or Usage Systematically Uninformed or Biased Downward?*

Consumer Beliefs about Electricity Prices.—Limited evidence suggests that consumers may be misinformed about current electricity prices, but there is no evidence of systematic bias. Consumers respond to average, rather than marginal price (Ito 2014), but in one study appear to *reduce* consumption in response to a reduction in price, in contrast to theoretical predictions (Jessoe, Rapson, and Smith 2014). This could be a product of consumer inattentiveness, but research is needed to distinguish this from competing explanations (Faruqui and Sergici 2011; Ito, Ida, and Tanaka 2015). In contrast, other research has provided evidence that consumers value changes in physical energy use (for example, kWh of electricity and therms of natural gas) at close to their price (Newell and Siikamäki 2014).

Consumer Beliefs about Electricity Usage.—Experimental-choice data suggest that consumers are also misinformed about electricity usage or how daily activities translate into usage; consumers provided with real-time usage feedback become significantly more price responsive than consumers

[19] Although average beliefs about prices may not be biased, consumer forecasts of future gasoline prices display substantial heterogeneity (Allcott 2011a; Anderson, Kellogg, and Sallee 2013). One survey elicited upper and lower bounds on future fuel prices, with responses exhibiting significant uncertainty. The spread between the mean response for each bound was almost two dollars, or 45 percent of the midpoint between these means (Greene, Evans, and Hiestand 2013). These findings could explain underinvestment by some consumers.

without such feedback (Jessoe and Rapson 2014).[20] In consumer surveys, respondents systematically overestimate the energy costs of low-usage goods (for example, computers) and underestimate the energy costs of high-usage goods (for example, water heaters) (Attari et al. 2010).

Separately identifying beliefs and preferences is certainly challenging. Economic research in this area typically makes assumptions—sometimes quite strong assumptions—about beliefs in order to recover preferences. Future research could begin by eliciting beliefs from economic agents, and then using these beliefs to recover preferences (Manski 2004). In some contexts, this approach could enable the researcher to isolate multiple effects of information policies (for example, isolate the effect of salience from the effect of information that alters beliefs).

3.6 *Do Analysts Systematically Overestimate Energy Savings from Efficiency Investments?*

Incomplete understanding of energy operating costs on the part of analysts—rather than consumers—can also help reconcile conflicting estimates of the magnitude of the energy-efficiency gap. In the past, analysts' predictions of energy savings from efficiency investments have tended to overstate the magnitude of the energy-efficiency gap. We distinguish between ex ante engineering–economic analyses,[21] which rely primarily on physical models to predict energy savings, and ex post impact evaluations, which typically rely on observed energy consumption to estimate net savings associated with energy-efficiency investments. Hybrid models combine the technological detail of engineering models with economic evaluations (Murphy and Jaccard 2011).

Ex post economic evaluations, using actual energy usage, are generally thought to be more credible than ex ante engineering–economic analyses,[22] and comparisons provide evidence of a seemingly systematic bias in ex ante predictions (Nadel and Keating 1991). Several explanations for the divergence between engineering models and impact evaluations have been offered: erroneous assumptions about usage; complex interactions omitted from engineering estimates (for example, the rebound effect in some cases); quality control problems (for example, problems with equipment installation); and adoption of energy-saving measures by nonparticipants (which lowers net savings attributable to utility programs).

A meta-analysis of forty-two utility conservation programs in the residential, commercial, and industrial sectors found that actual energy-savings estimates for residential retrofit programs ranged from 15 to 117 percent of ex ante

[20] In this experiment, the treatment and control groups received the same day-ahead notifications of price changes. This research design isolates the effect of usage feedback and eliminates the potentially confounding effect of salience.

[21] These are also called "bottom-up" or "technology-based" approaches. They typically utilize detailed information about the relative efficiency of various types of energy-using equipment, existing deployment, and assumptions about usage patterns, in order to estimate how energy usage, expenditures, and pollutant emissions would change in response to changes in the mix of capital goods. By making assumptions about opportunities for substitution, switching costs, and infra-marginal behavioral responses, these studies have been used to predict the effects of policies. For an early critique of these studies, see Joskow and Marron (1993). In a particularly influential engineering–economic study, McKinsey & Company estimated a supply curve of carbon-emission reductions in the United States (Granade et al. 2009) and concluded that a substantial amount of reductions could be achieved at negative cost by investing in greater energy efficiency. This result generated considerable interest, and also substantial criticism, partly on the grounds that some costs of adoption were not included in the analysis.

[22] However, ex ante studies offer something ex post approaches do not, namely predictions, which are critical for evaluating proposed energy-efficiency investments on cost-effectiveness grounds, as well as for projecting energy savings associated with a given policy.

engineering–economic estimates (Nadel and Keating 1991). Commercial retrofit programs exhibited energy savings ranging from 36 to 248 percent of engineering predictions, while a majority of programs failed to meet savings benchmarks from ex ante analysis (Nadel and Keating 1991). These direct comparisons suggest that caution is warranted when interpreting ex ante engineering–economic evidence of the energy-efficiency gap, although this research has documented some cases in which ex ante analyses underestimated energy savings.

Home energy auditors use engineering-based tools to predict energy savings. These tools are one potential source of systematically biased energy-savings estimates, for reasons that include user error (for example, incorrect inputs or inaccurate assumptions about post-audit thermostat settings) and improper accounting for residents' behavioral responses, even when the underlying engineering models are correct.

In empirical research, two groups of participants in a utility-weatherization program in the 1980s achieved 47 and 78 percent of predicted savings on average (Hirst 1986),[23] while realized savings from another utility program ranged from 50 to 81 percent of predicted electricity savings, and 14 to 42 percent of predicted natural gas savings (Sebold and Fox 1985). In another study, a tool used for weatherization home audits overpredicted savings by 186 percent, despite accurate engineering calculations (Ternes and Gettings 2008). Likewise, weatherization projects in New York State achieved only 57 to 69 percent of the savings predicted by the National Energy Audit Tool, and studies from other states have reached qualitatively similar conclusions (Berry and Gettings 1998). In a randomized-utility experiment providing insulation and HVAC appliances to certain households, ex ante engineering estimates overstated actual conservation by 13 percent (Dubin, Miedema, and Chandran 1986).

Analyses that significantly overestimate energy savings persist, despite substantial improvements in ex ante engineering–economic methods over time. For example, ex post analysis of the "Cash for Coolers" program in Mexico, which provided subsidies for the replacement of inefficient household appliances, indicates that refrigerator replacement achieved only one-quarter of the annual savings predicted by the World Bank. Replacement of air conditioners led to increased electricity consumption, in stark contrast to engineering predictions of energy savings (Davis, Fuchs, and Gertler 2014). A randomized evaluation of the Weatherization Assistance Program in the United States found model projections exceeded realized savings by a factor of 2.5 (Fowlie, Greenstone, and Wolfram 2015b). Nonetheless, care must be taken in generalizing these findings, as weatherization may not be representative of other energy-efficiency programs, which have been found to vary significantly in cost effectiveness (Hoffman et al. 2015).

Scrutiny of the rates of return predicted by ex ante engineering–economic analyses also provides evidence of bias in energy-savings estimates. Econometric analysis of home energy-efficiency investments by Metcalf and Hassett (1999) suggests the median rate of return for insulation improvements was 9.7 percent, consistent with reasonable discount rates, but far below the ex ante estimates of Blasnik (1990). A combined engineering/econometric approach to estimating these rates of return finds broadly similar results: Dubin and Henson (1988) estimate average rates of return of

[23] Hirst (1986) reviews possible causes of differences between predicted and actual energy savings, including errors in audit methodology, data collection and interpretation, installation of inappropriate retrofit measures, use of poor materials, low-quality installation work, changes in occupant behavior, errors in electricity usage data, and errors in analysis of electricity-billing data.

4.9 percent for ceiling insulation and 8.3 percent for wall insulation.[24]

There are significant opportunities for research in this area. First, more attention is needed to ex post analysis in the transportation, commercial, and industrial sectors. The preponderance of evidence brought to bear on this question of accuracy in ex ante energy-savings predictions has come from the residential sector, presumably because of the large number of government and utility programs that provide existing engineering analysis and rich data for ex post assessment. More ex post analyses of model predictions are needed to better judge whether ex ante engineering–economic analyses continue to systematically overstate the savings associated with energy-efficiency investments, or whether these approaches have truly improved over time.[25] It is at least conceivable that selection bias has come about through researchers having chosen to evaluate engineering–economic analyses that have most exaggerated the savings potential of efficiency investments.

3.7 *Do Analysts Insufficiently Account for Consumer Heterogeneity?*

For any energy-efficiency technology, the benefits and costs of adoption can vary substantially across potential adopters (Jaffe and Stavins 1994a, 1994b, 1995; Metcalf and Hassett 1999; Alberini, Gans, and Towe 2013). Even when engineering predictions correctly find that, on average, the benefits of adoption exceed the costs of adoption, this will not be true for some potential adopters.

Differences in benefits and costs across agents generate variation in adoption patterns. These differences can explain low adoption rates for technologies that appear cost effective (Griliches 1957), especially if benefits and costs are correlated (Suri 2011). Similarly, heterogeneity across consumers may explain variation in the adoption of energy-efficient technology. For example, Hausman and Joskow (1982) pointed out that heterogeneity in usage profiles, capital stock, or consumer preferences could result in realized savings below average predicted savings. Failure to model heterogeneity correctly can introduce bias in estimates of the size of the energy-efficiency gap.

If the bias due to heterogeneity is systematic, analyses ignoring heterogeneity could overstate the magnitude of the energy-efficiency gap. The sign of the bias is ambiguous, but can be identified. Neglecting consumer heterogeneity appears to have produced empirical estimates that overstate the extent to which vehicle purchasers undervalue fuel economy (Bento, Li, and Roth 2012). Ignoring heterogeneity can bias energy-savings estimates upward: systematic differences between past and future adopters can drive a wedge between observed and potential returns for a given investment. This wedge is likely positive in a context where consumers and firms have selected the most profitable projects first, as prospective returns will likely be below

[24] Simulation-based studies, which use energy-market models to trace out energy-efficiency supply curves, improve on simpler ex ante analyses. These models explicitly model complex adoption decisions, consumer heterogeneity, uncertainty, and feedback effects. As a result, even if these models begin with the same technology assumptions as simpler engineering–economic models, the general equilibrium effects of these interrelationships lead to different, typically lower, predicted levels of end-use energy efficiency. One study (Huntington 2011) found that incorporating these factors reduces by three-quarters the size of the energy-efficiency gap identified in the McKinsey & Company study (Granade et al. 2009).

[25] Some assessments have been improved by accounting for "free riders" (i.e., inframarginal consumers) that would have adopted technologies even in the absence of certain programs, and by incorporating a utilization elasticity termed the "rebound effect" (Davis, Fuchs, and Gertler 2014; Dubin and Henson 1988; Gillingham and Palmer 2014; Greening, Greene, and Difiglio 2000; Houde and Aldy 2014; Sorrell, Dimitropoulos, and Sommerville 2009).

historical average returns. Heterogeneity in individual time preferences will also alter the estimated attractiveness of energy-efficiency investments, which will tend to be more problematic for analyses where a larger share of benefits are estimated to come from households with relatively high discount rates (Newell and Siikamäki 2015).

One potential area for future research involves using randomized experiments to better understand the distribution of energy savings associated with given investments by comparing the distribution of energy outcomes for treated and control groups. This could help improve ex ante predictions for future decision making. Wider use of techniques from industrial organization (for example, random coefficient logit models) could improve predictions by modeling heterogeneity explicitly.

4. *Are Product Choices Cost Minimizing in Present-Value Terms?*

The framework we posited in part 1 is one of cost-minimizing energy-efficiency decisions, and so it is natural to ask whether market failures and/or behavioral phenomena inhibit cost minimization in present-value terms.

Here the empirical evidence ranges from strong (split incentives/agency issues and inattention/salience phenomena) to moderate (heuristic decision making/bounded rationality, systematic risk, myopia/shortsightedness, and option value) to weak (learning-by-using, loss aversion, and capital-market failures). And here, as elsewhere in our review, we find that most previous work has focused on the residential sector, with much less attention given to the commercial and industrial sectors—presumably because of lack of available data. That said, the availability of data for further research varies by subtopic, with split incentives/agency issues and effects of myopia offering the most promising opportunities for further investigation.

Given the wide use of building codes and energy-efficiency standards, split incentives/agency problems in the residential, commercial, and industrial sectors may not be as severe as one would expect in the absence of interventions. Some areas merit priority for future research, such as empirical analysis of split incentives/agency issues in markets for technologies that are not subject to efficiency standards. Much more work can be done in the behavioral realm on issues such as inattention/salience, loss aversion/reference points, heuristic decision making, and myopia.

4.1 *Do Split Incentives/Agency Issues Due to Asymmetric Information Inhibit Energy-Efficient Decisions?*

Differences in interests between economic agents frequently arise, causing problems of agency or split incentives. In the energy-efficiency realm, prominent examples include landlord–tenant and builder–buyer problems, in which capital investors may make decisions that are not optimal from the perspective of the end user. Similarly, agency conflicts are possible within firms when investment and operating decisions are divided among individuals or business units (Tietenberg 2009). Research has long cited these conflicts as potential explanations for the energy-efficiency gap (Blumstein et al. 1980; Fisher and Rothkopf 1989; DeCanio 1993; Jaffe and Stavins 1994a; Jaffe and Stavins 1994b; Gillingham, Newell, and Palmer 2009; Tietenberg 2009; Gillingham and Palmer 2014).

Empirical evidence has confirmed the existence of the principal–agent problem, and comprehensive accounting exercises have sought to estimate the potential importance of this market failure by quantifying the amount of energy consumption subject to incentive conflicts (IEA 2007). As much as 35 percent of US residential energy use may be affected (Murtishaw and Sathaye 2006). Some research has compared owner-occupied and rental properties to estimate directly the impacts of split incentives. Results are compelling: even after controlling for household income and other household characteristics, renters are significantly less likely to have energy-efficient refrigerators, clothes washers, and dishwashers, based on data from the Residential Energy Consumption Survey (Davis 2012). Owner-occupied dwellings in California are 13 to 20 percent more likely to have exterior wall and ceiling insulation (Gillingham, Harding, and Rapson 2012).[26]

Other evidence supports the hypothesis that information asymmetries exist in housing markets. Data from the United States show that landlords frequently include utility costs in rental prices even when units are individually metered. This may be because landlords with energy-efficient units cannot credibly communicate this information and instead include utilities as a signal of the units' efficiency (Levinson and Niemann 2004). Landlords may even use utility-included rental contracts to attract renters or as a signal of other unobservable forms of quality unrelated to energy efficiency. The empirical correlation between how well-maintained a unit is and the inclusion of utilities in rent provides some support for this hypothesis (Choi and Kim 2012).

Further insight can be gleaned by assessing the link between information asymmetries and new investment in energy efficiency. Recent work on residential housing markets finds that patterns of investment in conversion from inefficient oil heating to more efficient natural gas heating are consistent with the hypothesis of asymmetric information between landlords and tenants. The potential gains from these missed investments are not trivial: back-of-the-envelope calculations suggest the annualized cost savings from converting from oil to gas heating are 12 to 24 percent of annual heating expenditure on average (Myers 2015).

More support for the hypothesis of asymmetric information comes from stated preferences. Responding to a survey, New Zealand tenants stated that they would be willing to pay higher rents in exchange for improved energy efficiency and, in many cases, respondents' willingness to pay appears to justify landlord investments in energy-efficiency improvements. Asymmetric information could explain why landlords do not make such seemingly profitable efficiency investments (Phillips 2012). In contrast, recent research on commercial buildings finds little evidence of asymmetric information between building owners and prospective buyers or tenants (Papineau 2015).

Although such studies provide evidence regarding the hypothesis of asymmetric information, they do not provide direct estimates of the impact of information asymmetries on investments in energy efficiency. While a market failure exists, the magnitude may be small, because the energy impacts of inefficient appliances and less insulation only amount to a few percent of total energy consumption in rental units (Davis 2012; Gillingham, Harding, and Rapson 2012).

Alternative contract structures can contribute to another, less cited outcome: moral hazard. Tenants who sign energy-inclusive rental agreements face zero marginal cost from energy consumption, and therefore may use too much energy, relative to the social optimum. Indeed, tenants appear to keep indoor temperatures higher during winter months and when their homes are unoccupied when utilities are included in their leases (Maruejols and Young 2011; Levinson and Niemann 2004). Likewise, tenants who

[26] In contrast, a hedonic regression analysis of survey data in Australia failed to find evidence of split incentives in rental housing (Wood, Ong, and McMurray 2012).

pay for utilities are more likely to adjust heating temperatures at night than tenants who face zero marginal cost (Gillingham, Harding, and Rapson 2012). Such findings do not relate directly to investment in energy efficiency, except to the degree that landlords respond strategically to such behavior. However, even if landlords do respond strategically, they are more likely to invest in high-efficiency appliances or decouple rental agreements and energy use than they are to underinvest in energy efficiency. Thus, moral hazard is unlikely to contribute to the energy-efficiency gap.

The best available evidence is from the residential sector, but agency problems due to information asymmetries could also play a role in commercial and industrial-sector energy-efficiency decisions. Indeed, research confirms that firms are susceptible to internal principal–agent problems. Green Lights, a program that provides technical assistance to (voluntarily) participating firms, enabled cost-saving lighting upgrades that these firms had not installed independently. Program experience suggests that firms failed to install these cost-effective measures before the program due to internal principal–agent conflicts: capital rationing by managers and split incentives across divisions (Howarth, Haddad, and Paton 2000). Likewise, case studies of the electric-motor market in Europe identified split incentives as a barrier to investments in energy efficiency (de Almeida 1998; Ostertag 2003).

Despite the frequency with which the principal–agent problem is named as a contributor to the energy-efficiency gap, there are few formal agency models adapted to this setting. Experimental work is difficult in many settings, since researchers cannot randomly assign landlords and tenants to properties. Therefore, creative empirical strategies (e.g., Myers 2015) and new data sources may be needed.

The structure of the principal–agent problem may also create opportunities for creative policy responses. Eliminating information asymmetries or innovation in the form of contracts could allow private markets to overcome misaligned incentives. For example, Japan requires vending-machine operators—rather than owners of properties where machines are installed—to pay for the machines' energy use (IEA 2007). Despite this, vending machines are also subject to minimum efficiency standards in Japan.

4.2 *Do Learning-By-Using Spillovers Inhibit More Energy-Efficient Decisions?*

In many cases, consumers learn about the benefits of a given technology by adopting and experiencing it. In some cases, other consumers benefit from this information without having to adopt the technology. A positive information spillover could slow the rate of technology adoption relative to the social optimum, as each consumer has an incentive to delay adoption in order to learn from others. Put another way, the opportunity for individuals to substitute their peers' experiences for their own creates an incentive to free ride (Foster and Rosenzweig 2010). At least in theory, this phenomenon could contribute to the energy-efficiency gap.[27]

Empirical research in other domains emphasizes the prevalence of social learning and peer effects (Case and Katz 1991; Ammermueller and Pischke 2009; Duflo and Saez 2002; Foster and Rosenzweig 1995; Emerick 2014; Conley and Udry 2010), but there is limited evidence regarding how information spillovers affect energy-efficient technology, and—if positive spillovers exist—whether consumers respond by free

[27] These spillovers are related to the effects of demand spillovers on innovation by firms, discussed above, in that they also affect product offerings.

riding. The bulk of the evidence on information spillovers comes from the introduction of hybrid vehicles, drawing on both stated-preference (Mau et al. 2008) and revealed-preference studies (Axsen, Mountain, and Jaccard 2009; Narayanan and Nair 2013).[28] In the residential sector, a study of thermal insulation choices by homebuilders found no evidence of large knowledge externalities among builders, suggesting builders do not learn from the adoption of these technologies by competitors (Jaffe and Stavins 1995).[29]

Theoretical research from other fields highlights the potential importance of social learning and peer effects (Manski 1993a), and underscores the potential for social learning to lead to inefficient technology-adoption decisions, even irrespective of free ridership. Information spillovers in the context of irreversible technology choice with network externalities can result in proven technologies being chosen over alternatives with higher expected value (Choi 1997). Similarly, a model in which it is rational to adopt technology based on the adoption decisions of others (for example, because the decisions of others may reflect information the agent lacks) predicts herd behavior in which agents make decisions that depart from the decision they would make using only private information. This can lead to inefficient outcomes, as agents collectively undermine the benefits of learning by taking cues from others, rather than relying on private information (Banerjee 1992).

Previous research illustrates the challenge of credibly identifying spillovers using observational data (Narayanan and Nair 2013; Manski 1993b). The challenge is to disentangle spillover effects from unobservables (Foster and Rosenzweig 2010). Even then, empirically testing for the presence of learning spillovers does not indicate whether the spillovers contribute to the energy-efficiency gap, such as through individuals free riding and thus slowing the overall rate of technology adoption. Further research will be needed to determine the effect of learning spillovers on the adoption of energy-efficient technology, potentially through the use of experimental techniques (Baird et al. 2014).

4.3 *Does Inattention to and/or a Lack of Salience of Energy Operating Costs Inhibit Energy-Efficient Decisions?*

Broadly speaking, there is considerable evidence that consumer inattention to non-salient costs affects decisions. Experiments and observational data reveal that consumers are inattentive to sales taxes (Chetty, Looney, and Kroft 2009), shipping charges (Hossain and Morgan 2006), and out-of-pocket costs for health care (Abaluck and Gruber 2011). Conceptually, inattention may contribute to the energy-efficiency gap to the degree that energy costs are not salient for the investment decision. In some markets, this contribution could be substantial. Almost half of surveyed vehicle buyers report making their decisions without considering fuel costs (Allcott 2011a), which is consistent with research that found that consumers largely ignored replacement ink prices when making printer purchase decisions (Hall 1997).

There are two fundamental ways to frame research on inattention. One is a reduced-form approach, empirically estimating an attentiveness parameter without taking a stance on the underlying structural model of inattention (DellaVigna 2009). This

[28] Learning spillovers from hybrid technology are not always positive. Analysis of both the Toyota Prius and the Honda Insight suggests that while higher market penetration by the Prius has led to increased adoption of all hybrids, higher market penetration by the Insight has led to *reduced* adoption (Heutel and Muehlegger 2015).

[29] An alternative explanation acknowledged by Jaffe and Stavins (1995) is that builders have complete (or close to complete) information, so there is little or no scope for learning from the adoption decisions of others.

approach can produce credible estimates of the relative importance of inattention in a given context, but it falls short of identifying the mechanisms that underlie inattention. The other approach is to develop a model of the decision process itself, making explicit the underlying factors at play.[30]

Intuition suggests that consumers will only allocate attention to an attribute if the cognitive costs of doing so are less than the expected utility gains. Thus, the level of inattentiveness should vary across individuals and decision environments. Modeling inattention to energy efficiency as a result of costly information acquisition offers one way to explain decisions that are *apparently* privately suboptimal (Howarth and Andersson 1993; Sallee 2014).

There are two leading methods for testing for inattention to energy efficiency in empirical research. First, the reduced form of attentiveness suggests comparing demand elasticities with respect to prices and energy costs from market data, the empirical approach taken in many studies of discrete choice, which assess the trade-off consumers make between purchase price and future energy operating costs (Hausman 1979; Dubin and McFadden 1984; Jaffe and Stavins 1995; Goldberg 1998; Anderson and Newell 2004; Sallee, West, and Fan 2015; Busse, Knittel, and Zettelmeyer 2013; Allcott and Wozny 2014).[31] The primary shortcoming of this method—which these researchers acknowledge—is that price and energy-cost elasticities can diverge for multiple reasons, including discounting behavior.

Experimental manipulations of salience provide an alternative means of studying inattention to energy efficiency. Field experiments designed to study lightbulb choice provide mixed evidence on the impact of an intervention that targets both salience and information: an online intervention increased average willingness to pay for compact fluorescent lightbulbs (CFLs) by over two dollars, while an in-store intervention had no statistically significant effect on CFL demand (Allcott and Taubinsky 2015).[32] Stated-choice experiments that vary the type of information available to consumers, be it economic, physical energy, or environmental, can also help assess which of these is most salient to consumers. However, experimental studies are limited by concerns about distinguishing inattention from incomplete information, demand effects, and external validity. Complementary use of experimental and nonexperimental techniques can ameliorate the shortcomings of each approach (Chetty, Looney, and Kroft 2009).

Economic theory and empirical research provide some guidance for policies to address inattention to energy efficiency. Targeting inattentive consumers could enhance policy cost effectiveness. Information disclosure could target consumers with biased beliefs and those inattentive to future energy costs. The success of information disclosure policies depends crucially on salience, as well as on other context-specific factors. In contrast to information disclosure, subsidies may be poorly targeted for combating inattention if the consumers who know about them also tend to be attentive to future energy costs

[30] Research following this approach from other domains could provide guidance for future work on energy efficiency. For example, one common approach is to model inattention as a result of costly information acquisition and processing (see Conlisk 1996 for background and Gabaix et al. 2006 for experimental evidence), while other strands of research describe how salience affects consumer decisions (e.g., Bordalo, Gennaioli, and Shleifer 2013), and formulate alternative frameworks for consumer optimization (e.g., Gabaix 2014).

[31] We discuss these and other studies in more detail later, in the context of consumer discount rates.

[32] Recent field experiments demonstrate the potential for experimental research to advance knowledge of the energy-efficiency gap in additional markets. See Price (2015) for a summary of this literature.

(Allcott, Knittel, and Taubinsky 2015).[33] That said, there is an alternative argument for poorly targeted taxes and subsidies if these interventions do raise salience or otherwise reduce inattention; such interventions can generate first-order welfare gains for inattentive consumers and only second-order distortions for attentive consumers (O'Donoghue and Rabin 2006).

Public policies can also lower the cost of attention, and even fairly blunt policies could be justified if they lower the cost of attention sufficiently (Sallee 2014). Several recent studies investigate firm responses to coarse policy designs, and attempt to quantify the welfare impacts of these policies (Sallee and Slemrod 2012; and Houde 2014a, 2014b).

Debates over price and information interventions to address inattention highlight a broader question of instrument choice. A number of recent studies provide evidence on the effects of different policy instruments on welfare and energy-efficiency outcomes. Pigouvian taxes on fuels are a natural economic response to the externalities associated with energy use. There may also be a case for product-market price interventions if consumers are inattentive to energy costs (Allcott, Mullainathan, and Taubinsky 2014). Minimum efficiency standards are another alternative used by regulators; in some cases, such standards can lead to an effective ban on certain classes of products (Allcott and Taubinsky 2015). In addition to regulatory mandates for disclosure and product certification, information interventions by utilities and, in particular, peer comparisons, have been successful in reducing residential energy use and may be applicable elsewhere (Allcott 2011b; Ayres, Raseman, and Shih 2013; Allcott and Rogers 2014).[34]

Experimental techniques, including belief elicitation, offer promising opportunities for future research. Researchers can also directly test models of inattention, where they offer testable predictions that are unlikely to be confounded by alternative explanations (Sallee 2014).

4.4 *Does Myopia/Short-Sightedness Inhibit More Energy-Efficient Decisions?*

A key issue surrounding the question of whether myopia contributes to the energy-efficiency gap involves identifying the discount rates used by consumers and analyzing whether these discount rates are consistent with maximizing present-value net benefits. There is a long history of observing consumers' choices of energy-consuming durable goods to examine the trade-off between upfront capital costs and operating costs. If consumers are seeking to minimize discounted lifecycle costs, it becomes possible to estimate implicit discount rates.[35]

The seminal study of this kind was by Hausman (1979), which found average implicit discount rates in excess of 20 percent. Many other researchers subsequently found implicit discount rates much higher than market interest rates (Dubin and McFadden 1984; Gately 1980).[36] Such findings have been interpreted as evidence of myopia, the existence of other behavioral issues or

[33] The literature on retirement savings also speaks to this problem of targeting: for example, Chetty et al. (2014) conclude that automatic retirement account contributions are more effective than subsidies in promoting retirement savings, because subsidies only affect the savings of attentive workers.

[34] These interventions may operate through multiple channels other than raising salience (e.g., providing new information, changing reference points, etc.). Allcott and Rogers (2014) estimate how the effects of these treatments change over time and discuss multiple mechanisms consistent with the estimates.

[35] Of course, it is also possible that consumers are not minimizing aggregate costs because of errors regarding time horizons, their beliefs, or due to inattention, in which case such studies would not reveal true consumer discount rates (Allcott and Wozny 2014).

[36] Train (1985) and Sanstad, Hanemann, and Auffhammer (2006) review other examples.

market failures, or alternatively as evidence of rational discounting subject to liquidity constraints. Studies that identify a discount rate while assuming cost-minimizing behavior cannot, however, distinguish myopia as an underlying cause of the energy-efficiency gap from other possible causes. For example, high implicit discount rates for home energy investments could also be rationalized by moral hazard: contractors may provide low-quality services, and consumers may use high hurdle rates to insulate themselves from this risk (Giraudet and Houde 2014).[37]

Automobile purchases provide a good setting to study these questions because such purchases are major decisions, about which consumers presumably think carefully, and because the cost of gasoline has varied substantially over time. Yet the evidence on consumer valuation of fuel economy is mixed (Greene 2010; Helfand and Wolverton 2011). One study has found that consumers are indifferent between $0.76 now and $1.00 of discounted future gasoline expenditures, suggesting mild undervaluation of fuel economy that could be due to myopia (Allcott and Wozny 2014). On the other hand, other studies have found that market outcomes are consistent with dynamically cost-minimizing behavior (Busse, Knittel, and Zettelmeyer 2013; Sallee, West, and Fan 2015). Evidence from gasoline and diesel car purchases in Europe in the early 1990s suggests an implicit discount rate of about 11.5 percent, only slightly above automobile loan rates at the time (Verboven 2002). However, research has not always taken into account the fact that automobile markets have been subject to fuel economy regulation for many years, which tends to reduce the possibility for high implicit discount rates by constraining consumers' choice sets.

To assess the implications of these studies for the energy-efficiency gap, it is necessary to identify a benchmark discount rate, which depends on the cost of capital. One structured-choice experiment found that—conditional on information labeling—elicited discount rates rationalized participant decision making on average, but the use of a common discount rate of five percent for all subjects tended to lead to a conclusion that consumers significantly undervalued energy efficiency (Newell and Siikamäki 2014). In related work, Newell and Siikamäki (2015) found considerable heterogeneity in individual discount rates and also found that individual time preferences systematically influence willingness to invest in energy efficiency, as measured through product choices, required payback periods, and energy efficiency tax credit claims.

Direct research on intertemporal tradeoffs in energy-efficiency investment decisions might clarify the contribution of myopia to the energy-efficiency gap. For example, researchers could manipulate intertemporal trade-offs through information provision and pricing interventions, and examine decision making. Another approach may be to combine elicitation of time preferences with choice data and compare choices observed across multiple domains (Bradford et al. 2014).

Strategic responses by firms to consumer myopia present another area for potential research. If firms believe consumers are myopic and therefore undervalue energy efficiency, product offerings will not be optimal from a social perspective, even if firms hold incorrect beliefs about consumer preferences. Studies of the automotive industry

[37] An alternative way to frame the consideration of myopia is with experimental research and alternative theories at the intersection of psychology and economics. Research on intertemporal decision making from other contexts provides robust evidence that individuals are dynamically inconsistent (Loewenstein and Thaler 1989), and delay costly up-front action even when they acknowledge that it is in their long-run interest (Akerlof 1991). Quasi-hyperbolic discounting provides a theoretical alternative to exponential discounting to explain these empirical anomalies (Laibson 1997).

posit several explanations for the apparently suboptimal level of fuel economy that manufacturers provide (Helfand and Wolverton 2011).

4.5 *Do Other Cognitive Limitations Inhibit More Energy-Efficient Decisions?*

Cognitive limitations other than inattention and myopia could conceivably contribute to the energy-efficiency gap by preventing individuals (or possibly firms) from properly balancing present-value benefits and costs when investing in energy-using capital goods (Gillingham, Newell, and Palmer 2009). This could manifest itself in the use of heuristics or simple optimization errors. Many empirical studies are consistent with these explanations (Sanstad and Howarth 1994). However, it is difficult to disentangle the role of heuristics and bounded rationality from competing explanations, because consumers' decision processes cannot be observed directly and because there is no unified theory of decision making subject to cognitive limitations from which to draw testable hypotheses (Conlisk 1996).

That said, studies of vehicle fuel economy provide some support for the hypothesis of bounded rationality. First, experimental evidence has revealed that consumers systematically misperceive the information contained in fuel economy ratings, due to the inverse relationship between gasoline consumption and miles per gallon ("the MPG illusion") (Larrick and Soll 2008; Allcott 2013). Other research has shown that stated preferences for cars of various efficiencies depend on the metric and scale of information provided on energy labels (Camilleri and Larrick 2014). Translations of fuel economy into multiple perfectly correlated metrics (that is, gallons per mile, estimated annual fuel cost, and greenhouse gas rating) alter stated preferences (Ungemach et al. forthcoming).

This research may provide guidance for regulatory changes that would encourage greater energy efficiency. The findings suggest that tailoring the scale of energy labels based on the expected lifetime of a given product or providing multiple translations of energy-efficiency metrics could help guide decisions (Camilleri and Larrick 2014; Ungemach et al. forthcoming). To some extent, this is already happening: the US Environmental Protection Agency recently redesigned new vehicle labels to include gallons per miles, multiple cost estimates, comparisons with other vehicles in the same class, and environmental ratings (US Environmental Protection Agency 2015).

There are numerous opportunities to study the effects of cognitive limitations on energy-efficiency decisions. Most direct evidence is from laboratory studies of stated preferences. More research on revealed preferences in real decision environments could complement these studies, but—as noted above—the key research-design challenge, particularly in revealed-preference studies, is credibly distinguishing the effects of heuristic decision making and bounded rationality from other explanations of behavior.

4.6 *Do Loss Aversion or Reference Points Inhibit More Energy-Efficient Decisions?*

Research in psychology has highlighted the importance of reference points and loss aversion (i.e., people's tendency to strongly prefer avoiding losses to acquiring gains) in economic decision making. Empirical insights have been formalized in prospect theory and other alternatives to expected-utility theory (Kahneman and Tversky 1979; Thaler 1985; Tversky and Kahneman 1991; Kőszegi and Rabin 2006).[38] Yet despite

[38] See also Tversky and Kahneman (1981) and (1992). More recent theoretical and experimental work in psychology also highlights the importance of reference dependence. Query theory hypothesizes that consumers consider discrete arguments for or against a given alternative, and that the number of considerations and the order in which

strong evidence in other decision environments and general theoretical frameworks for analysis, very little is known about the impacts of loss aversion and reference points on energy-efficiency investments.

The most relevant evidence comes from an electric utility that offered residential consumers the opportunity to enroll in a nonbinding goal-setting program to reduce energy consumption (Harding and Hsiaw 2014). Two findings from this study are consistent with reference-dependent preferences: consumers voluntarily enrolled in the program, setting personal conservation goals, and many of these consumers reduced energy use to meet their own goals.

If the importance of goal-based reference points holds in practice, governments and businesses could stimulate investments in energy efficiency by encouraging personal goal-setting or otherwise influencing reference points (Heath, Larrick, and Wu 1999). Two experiments have attempted to affect reference points by providing tailored information, goals, and personalized feedback about energy consumption (Abrahamse et al. 2007; Carrico and Riemer 2011). These studies suggest that providing goals can lead to reductions in energy use, but further research is needed to determine whether goals or tailored information drove observed energy use reductions and to extend this approach to interventions that encourage investment in energy-efficiency technology.

Consumers and firms considering energy-efficiency improvements are almost certainly susceptible to reference points and loss aversion, but empirical research would be needed to better quantify the importance of these phenomena. Research focused on assessing the importance of loss aversion in the context of energy-efficiency decisions has received virtually no attention, so some initial research would be of value. Such research could help determine, for example, whether evidence that consumers value energy savings less than the investment costs of energy efficiency is due to inattention, myopia, or loss aversion. Future work could synthesize previous experimental techniques to study how different types of information displayed on energy labels influence reference points. Challenges to implementing policy based on existing research include heterogeneity—that no one level of energy efficiency is right for every consumer—and concerns over paternalism, which is a valid concern if reference points can be manipulated. Research on policy interventions (such as energy labels) could inform the design of uniform interventions that minimize the welfare cost of providing blunt guidance. Carefully targeted interventions could shift reference points for some consumers without creating incentives for other consumers to alter their behavior.

4.7 *Do Capital-Market Failures Influence Consumer Discount Rates for Energy-Efficiency Investments?*

Capital-market failures could in principle help explain a divergence between estimated implicit discount rates and typical market interest rates. Prospective investors facing capital constraints may be unable to finance energy-efficiency investments, even if future returns would justify the up-front cost. This could result in an estimated implicit discount rate that is above normal market rates. Information asymmetries could prevent efficient lending even for collateralized investments; firms that possess private information about future cost savings from a particular investment may be unable to convince

they come to mind affects decision making (Weber and Johnson 2009; Weber et al. 2007). This theory underscores the importance of defaults. As another example, Hardisty, Appelt, and Weber (2013) study the combination of loss aversion and intertemporal decision making. In general, this work highlights the need to strive for a comprehensive understanding of decision making to explain the energy-efficiency gap.

lenders of its financial potential if such savings are costly for the lender to evaluate.

In the future, theoretical and empirical findings from consumer-finance research may shed light on specific capital-market failures that are most important for energy efficiency. The actual distribution of market interest rates faced by consumers and firms through various lending mechanisms is critical to identifying the appropriate benchmark market interest rate (or range of rates) in order to quantify its impact on energy-efficiency investments. However, it may be difficult to distinguish empirically between capital-market failures leading to high discount rates and lack of underlying demand for energy-saving technology (Palmer, Walls, and Gerarden 2012). While we encourage research on capital markets generally, we do not assign a high priority to future research on the impact of capital-market failures on energy-efficiency investments. Where capital-market failures do exist, it seems unlikely that policies specific to energy efficiency would be the best response, given the broad set of financial decisions that would be affected.

4.8 *Does Systematic Risk Affect the Appropriate Discount Rate for Energy-Efficiency Analysis?*

The capital asset pricing model (CAPM) presents one way to frame debate about the "correct" discount rate to use for energy-efficiency analysis (Fama and French 2004). The CAPM provides a static optimization framework for determining the appropriate hurdle rate for an investment, based on the risk-free rate of interest, expected returns from a diversified portfolio of assets, and the normalized covariance (β) between the investment's returns and that of the diversified portfolio. Optimal investment depends on the *opportunity cost* of capital, not simply the nominal cost of capital.

Under the CAPM, a positive (negative) correlation between energy prices and the rest of the economy would suggest hurdle rates for energy-efficiency investments that are higher (lower) than the returns on a diversified portfolio. A negative relationship between energy prices and the greater economy ($\beta < 0$) supports the use of low hurdle rates, because energy-efficient investments can serve as a hedge. One study found such a negative correlation between the consumer price index for fuels and the S&P 500 index (Metcalf 1994). Likewise, more recent research argues that applying the CAPM to an analysis of vehicle purchases would lower the discount rate due to the low correlation between annual changes in gasoline prices and market returns (Allcott and Wozny 2014). For some end uses, the correlation between fuel prices and market returns is artificially low due to regulation. This could also lead to a lower discount rate under the CAPM.

However, the CAPM may fail as an appropriate benchmark for discount rates for energy-efficiency investment for two reasons. First, the model is not ideal for many energy-efficiency investments because of the CAPM's static nature, meaning that the investment choice set, expected investment returns, and covariances among investments are treated as fixed over time. In contrast, energy-efficiency investment opportunities, expected returns, and risk relationships likely vary substantially with technological change and other exogenous factors. Second, the CAPM assumes that transaction costs are zero, that the investment can be resold on a secondary market, and that investors already hold diversified portfolios when considering a new investment (Sutherland 1991). These assumptions may be tenable in certain contexts (for example, for sizable businesses), but not in others (for example, for low-income households). Third, the model has failed numerous empirical tests (Fama and French 2004).

On the other hand, the CAPM's simplicity generates useful intuition and sharp, testable predictions that enable researchers to assess its utility for energy-efficiency investments. One possible approach would be to use observational data on similar investments utilizing different fuels. Prices for various fuels covary heterogeneously with the greater economy. As a result, investment hurdle rates should vary across fuel types. Estimating and comparing these hurdle rates could directly test the CAPM in this realm. However, it may be difficult to eliminate correlated unobservables.

4.9 *Can Option Value Help Explain the Energy-Efficiency Gap?*

Option value—the net benefit of delaying an investment even when the investment's net present value is positive—is a general feature of dynamic-optimization problems with uncertainty, irreversible investment, and timing flexibility (Dixit and Pindyck 1994; Kellogg 2014). Consumers and firms commonly face decision problems of this type when investing in energy-consuming durable goods with little or no resale value.

This presents an alternative explanation of the energy-efficiency gap: the difference between *apparently* optimal investment and observed investment may be due to the option value of waiting. Failure to account for this option value could bias estimates of the energy-efficiency gap. In an analysis of irreversible investment in residential energy-efficiency measures under conditions of energy-price uncertainty, Hassett and Metcalf (1993) explained observed technology adoption rates without any reference to market failures.[39] Potential technological innovation, which would reduce future adoption costs, can also yield option value for delaying energy-efficiency investments (Jaffe and Stavins 1995; Ansar and Sparks 2009).

Energy-price uncertainty is important in some industries. Direct computation, reduced form estimation, and simulations have found large hurdle rates due to energy-price volatility based on observed investment decisions (Metcalf and Rosenthal 1995; Diederen, van Tongeren, and van der Veen 2003; Löfgren, Millock, and Nauges 2008).[40] Technological change is the other prominent explanation for investment delay. Evidence from air conditioner purchases indicates that purchase timing depends on expectations about future developments in product efficiency (Rapson 2014). Other relevant sources of uncertainty include future product use, product efficiency, and product life.

The option value of waiting due to uncertainty regarding future energy prices or technological change may explain part of the apparently suboptimal investment in energy-efficient technologies, but probably not a large part, in most cases (Baker 2012). The option-value explanation hinges on four assumptions: irreversibility, uncertainty, flexible timing, and lumpiness of investment (McDonald and Siegel 1986). In practice, one or more of these conditions can fail. Not all energy-efficient investments are irreversible. There are active resale markets for many types of consumer goods and producer capital. Uncertainty may be irrelevant, as in the case of firms that have long-term energy-procurement contracts in place, which provide price certainty. In other cases, energy-price

[39] Sanstad, Blumstein, and Stoft (1995) maintained that the option value analysis of Hassett and Metcalf (1993) suggested an implicit discount rate much lower than actually observed, even when taking irreversibility into account.

[40] In this context, the hurdle rate is the multiplier on the cost of capital that corresponds to the minimum acceptable rate of return for a project to be undertaken. Diederen, van Tongeren, and van der Veen (2003) find hurdle rates of 1.76 for Dutch greenhouses based on simulation, and Löfgren, Millock, and Nauges (2008) econometrically estimate hurdle rates of 3.4 to 3.6 for the Swedish energy and heating sector.

uncertainty may be relatively unimportant, as in the case of energy-consuming goods with relatively short lifetimes or in the face of other, dominant sources of uncertainty (Abadie, Chamorro, and González-Eguino 2013). Finally, the timing of investments in energy-consuming durables is not always flexible (for example, replacement of a broken water heater).

One possible way to assess the relative importance of the option value of waiting due to energy-price uncertainty would be to survey consumers and firms directly. The evidence here is mixed. Energy-price uncertainty ranked fourth out of fifteen reported reasons firms did not undertake energy-efficiency investments recommended by auditors in a survey of small- and medium-sized businesses (Fleiter, Schleich, and Ravivanpong 2012). On the other hand, a stated-choice experiment in the residential sector revealed a correlation between energy-price uncertainty and a preference for the status quo over energy-efficiency improvements (Alberini, Banfi, and Ramseier 2013). This result is consistent with the basic prediction of the option-value model, but does not quantify its relative importance.

5. *Do Other Unobserved Costs Inhibit Energy-Efficient Decisions?*

We turn to the final term in the cost-minimization equation described above in section 1, and ask whether other costs inhibit more energy-efficient decisions. We find that the empirical evidence in this realm is generally sound, and that data for additional research are available. We assign a relatively high priority to research in this area, particularly research aimed at better understanding of consumer demand (willingness to pay) for product attributes, which can be useful for improving regulatory design.

5.1 *Do Analysts Take Sufficient Account of Product Attributes?*

Products of varying efficiencies differ from each other in ways that are often omitted from engineering and econometric analysis, potentially contributing to the misidentification of an energy-efficiency gap. Producers may generate efficiency improvements by trading off other product attributes for enhanced energy efficiency. For example, the color, sound, and start-up time of fluorescent lights differ from those of incandescent lights. In such a case, consumers may face opportunity costs of decreased product quality, in addition to any price change, when considering energy-efficient products. Ignoring these opportunity costs would bias estimates of consumer choice and welfare, and also bias estimates of the magnitude of the energy-efficiency gap.

The fundamental challenge to inference is omitted-variable bias. Analyses can be classified in terms of information sets: (1) attributes observed by both the analyst and the consumer; (2) attributes observed by the consumer, but not by the analyst; (3) attributes observed by the analyst, but not the consumer; and (4) attributes observed by neither the analyst nor the consumer. Engineering techniques can recover unbiased estimates unless the consumer observes attributes that the engineer does not. In contrast, appropriate econometric techniques can succeed in all four cases. Thus, the second and arguably most important case necessitates the use of econometric techniques.

Early engineering–economic studies compared capital investment and lifetime operating costs to identify cost-effective investments or infer consumer discount rates, disregarding or only partially correcting for nonenergy attributes. The prominent McKinsey & Company study treated compact fluorescent lightbulbs as interchangeable with other forms of lighting (Granade et al. 2009), thus ignoring a potentially important source of (unobserved) opportunity costs.

In principle, econometric methods can improve on such engineering methods by including product attributes in analyses of choice data. In practice, however, econometric analysis has been limited by the impracticality of observing and accurately measuring all product characteristics. These characteristics are typically subsumed into error terms. Instrumental variables provide researchers an opportunity to weaken identifying assumptions needed for work with cross-sectional data by isolating variation in energy-efficiency characteristics that are uncorrelated with the error term.[41]

Modern econometric techniques improve on previous work by explicitly accounting for product attributes unobserved by the econometrician in discrete-choice models. These models can be estimated using either cross-sectional or panel data. Studies employing the random-coefficients model provide examples of this type of cross-sectional estimation. An early application found significant heterogeneity in demand for automobile fuel economy, suggesting small negative willingness to pay for fuel economy improvements in relatively inefficient vehicles (Berry, Levinsohn, and Pakes 1995), reflecting heterogeneity in the distribution of consumer preferences.

Subsequent research incorporating micro data in the random-coefficients estimation strategy confirmed the importance of heterogeneity, but also found that consumers have a negative willingness to pay for fuel economy, on average (Petrin 2002). However, the primary focus of these early studies using random coefficients was on modeling unobserved consumer heterogeneity, rather than quantifying fuel economy valuation. These studies did not instrument for fuel economy, so these coefficients are likely biased. More recent estimation strategies that focused on identifying average demand for fuel economy have used alternative instruments and have not found a negative willingness to pay for fuel economy (Verboven 2002; Klier and Linn 2012; Whitefoot, Fowlie, and Skerlos 2017). One study of appliance purchases using transactions data and geographic variation in operating costs (that is, electricity prices) found that consumers undervalue operating costs, on average (Houde 2014b).

Panel data provide another credible way to account for unobserved product attributes. Researchers using panel data can effectively condition on all unobserved product attributes that are time-invariant using differencing or fixed-effects models. Recent studies of this type provide limited evidence for an energy-efficiency gap (Allcott and Wozny 2014; Busse, Knittel, and Zettelmeyer 2013; Sallee, West, and Fan 2015).[42]

Choice experiments offer another possible way to control for unobserved product characteristics. One approach in a stated-preference context would be to ask subjects to treat all products they consider as identical in nonenergy attributes. This holds promise for stated-preference studies but is infeasible for revealed-preference analysis. Analyses that assess the correlation between energy and nonenergy attributes for different

[41] Instruments have been employed in models of energy-efficiency technology adoption for decades to address concerns about price endogeneity and selection on expected usage that could generate a correlation between product efficiency and the error term in a discrete-choice model (for example, Hausman 1979; Dubin and McFadden 1984). However, these early studies did not directly address the possibility of additional product characteristics that are observed by the consumer, but not the econometrician, and could therefore generate omitted variable bias.

[42] The earlier section on myopia contains a more detailed discussion of the findings of these three papers. Also, see Bento et al. (2009), Greene (2010), and Helfand and Wolverton (2011) for more detailed discussions of automobile choice models and consumer valuation of fuel economy.

products could help identify where the bias from ignoring nonenergy attributes is most likely to be present.

5.2 *Do Analysts Take Sufficient Account of the Costs of Implementing Energy-Efficient Options?*

Omitting any (opportunity) cost of adoption from a comparison of the benefits and costs associated with a given energy-efficiency technology will contribute to the impression of an energy-efficiency gap. Such omitted costs can take many forms, including time spent researching investment alternatives, unobserved implementation costs, and reallocation of resources within a firm. In particular, costs that are less easily quantified are more likely to be omitted by analysts (Granade et al. 2009; Huntington 2011). But these costs may serve as real barriers to investment—not optimization errors or market failures—and should be included in an unbiased analysis of the energy-efficiency gap. This has been a key criticism of the McKinsey study (Granade et al. 2009).

Consumers face a set of adoption costs beyond the most obvious costs of a technology's purchase price and direct installation charges. For example, homeowners have attributed the decision not to install or upgrade attic insulation to the hassle of clearing stored items from the attic space (Caird, Roy, and Herring 2008). A policy experiment in the United Kingdom found that lowering such costs by offering attic cleaning would increase insulation investments (UK Department of Energy and Climate Change 2013). Another study estimated opportunity costs for adopting thermal insulation to be more than twice the costs of materials and labor (Sharma 2011). One possible interpretation of low participation rates in subsidized weatherization programs is that there are high nonmonetary costs associated with these improvements (Fowlie, Greenstone, and Wolfram 2015a).

In the commercial and industrial sectors, case studies and survey evidence provide the bulk of the empirical evidence (Fleiter, Schleich, and Ravivanpong 2012), with firms indicating that production disruptions and inconvenience can preclude investment in energy efficiency (Rohdin and Thollander 2006, Thollander and Ottosson 2008). Survey respondents also cite lack of time as a barrier, highlighting the role of opportunity cost in simply considering investments (Sorrell et al. 2004; Thollander, Danestig, and Rohdin 2007; Schleich 2009; Trianni and Cagno 2012). Furthermore, recipients of industrial energy audits who failed to undertake recommended investments attributed their decisions to unmeasured costs and risks not considered in the audit analysis (Anderson and Newell 2004).

In principle, there is no reason analysts cannot incorporate these additional costs, but in practice, data and measurement challenges often inhibit their ability to do so. One route forward may be to treat such costs as unobservables to be recovered using structural, experimental, and quasi-experimental research designs.

6. *Conclusion*

Energy-efficient technologies offer promise for reducing the costs and environmental damages associated with energy use, but these technologies appear not to be used by consumers and businesses to the degree that would be justified, even on the basis of their private financial net benefits. With this in mind, we have examined the private energy-efficiency gap, the apparent reality that some energy-efficiency technologies that would pay off for adopters are nevertheless not adopted, as well as the broader phenomenon we characterize as the social energy-efficiency gap, the apparent reality that some energy-efficiency technologies that would be socially efficient are not adopted.

The economic literature on explanations of the energy-efficiency gap continues to evolve from its origins in Hausman's 1979 article in the *Bell Journal of Economics*. Concerns about energy conservation and independence in the 1980s brought more attention to the existence of the apparent gap, with the mid-1990s seeing greatly renewed interest, due in part to economists' attention to the issue of global climate change. In this century, concerns about energy security and climate change have combined with developments in behavioral economics, as well as increasing numbers of environmental economists, to produce a massive increase in research on the energy-efficiency gap.

We began our review and assessment of this literature by decomposing cost-minimizing energy-efficiency decisions into their fundamental elements, which allowed us to identify four major questions, the answers to which are germane to sorting out the causes (and reality or lack thereof) of the energy-efficiency gap. First, we asked whether the energy efficiency and associated pricing of products on the market are economically efficient. To answer this question, we examined the variety of energy-efficient products on the market, their energy-efficiency levels, and their pricing. Although the theory is clear, empirical evidence is quite limited. More data that could facilitate potential future empirical research are becoming available, although firm-level data are much less plentiful than data on consumers. We do not see this area as meriting high priority for future research, with the exception of research that evaluates the effectiveness and efficiency of existing energy-efficiency information policies and examines options for improving these policies.

Second, we asked whether energy operating costs are inefficiently priced and/or understood. Even if consumers make privately optimal decisions, energy-saving technology may diffuse more slowly than the socially optimal rate, because of negative externalities. So, even if the private energy-efficiency gap is not present, the social energy-efficiency gap may be. As in the first realm, the theoretical arguments are strong. Empirical evidence is considerable, and in many cases data are likely to be available for additional research. Existing policies appear not to be sufficient from an economic perspective, suggesting that further research is warranted. Indeed, we assign high priority to the pursuit of research in this realm.

Third, we asked whether product choices are cost-minimizing in present-value terms, or whether various market failures and/or behavioral phenomena inhibit such cost-minimization. We found that the empirical evidence ranges from strong (split incentives/agency issues and inattention/salience phenomena) to moderate (heuristic decision making/bounded rationality, systematic risk, myopia/shortsightedness, and option value) to weak (learning-by-using, loss aversion, and capital-market failures). Importantly, here, as elsewhere in our review, the bulk of previous work has focused on the residential sector and much less attention has been given to the commercial and industrial sectors. Much more work can be done in the behavioral realm, and we view this as a priority for future research.

Fourth, we asked whether other unobserved costs may inhibit energy-efficient decisions. We found that the empirical evidence is generally sound, and that data needed for more research are available. We assign a relatively high priority to future research, particularly to aid understanding of consumer demand for product attributes that are correlated with energy efficiency, thereby informing policy and product-development decisions.

Finally, we can ask what these findings suggest about our three categories of explanations for the apparent underinvestment in energy-efficient technologies, relative to the predictions of some engineering and economic models: (1) market failures, (2) behavioral explanations, and (3) modeling flaws. It turns out that all three categories of explanations are theoretically sound and that limited empirical evidence exists for each category as well, although the empirical research is by no means consistently strong across all of the specific explanations, as we highlight above.

The validity of each of these explanations—and the degree to which each contributes to the energy-efficiency gap—are relevant for crafting sensible policies, so we hope this review can help inform both future research and future policy. Given the many energy-efficiency policies and programs that are already in place, we also place a high priority on research that evaluates the effectiveness, cost effectiveness, and overall economic efficiency of existing energy-efficiency policies, as well as options for their improvement.

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