

# Advances in Evaluating Energy Efficiency Policies and Programs

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## Abstract

This paper reviews the recent evidence on the effectiveness and cost-effectiveness of energy efficiency interventions. After a brief review of explanations for the energy efficiency gap, we explore key issues in energy efficiency evaluation, including the use of randomized controlled trials and incentives faced by those performing evaluations. We provide a summary table of energy savings results by type of efficiency intervention. We also develop an updated aggregate estimate of 2.8 cents per kilowatt hour (kWh) of net savings from utility energy efficiency programs, but note that this estimate is based on aggregate utility-reported energy savings. Our review of the economics literature suggests that energy savings are often smaller than implied by utility-reported results, but some interventions appear to be cost-effective relative to the marginal cost of electricity supply.

**Key Words:** energy efficiency, evaluation, energy savings, cost-effectiveness

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# Motivating and Evaluating Energy Efficiency Policy

Kenneth Gillingham, Amelia Keyes, and Karen Palmer\*

## 1. Introduction

As global interest in mitigating climate change continues to increase, there is an ever-growing demand for policies aimed at improving the energy efficiency of the economy. Policymakers have largely been reluctant to directly impose caps or prices on CO<sub>2</sub> emissions, and with the adoption of the Paris Agreement in 2015, international climate negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) have shifted from a focus on an international emissions cap-and-trade approach—as was envisioned under the Kyoto Protocol—to more decentralized national commitments to emissions reductions with a collection of strategies or mechanisms to achieve those reductions. Energy efficiency not only typically has more political support than policies to limit emissions directly, but also is often perceived by policymakers as a low-cost approach to reducing carbon emissions that can save consumers money through lower energy costs, even after accounting for the costs of the necessary investments in more efficient technology and the policies to bring those investments about. The cost-saving potential of energy efficiency policies is due to a phenomenon called the energy efficiency gap, a deviation between the level of energy efficiency that appears to make economic sense and the level that we observe. Indeed, if the market does not elicit efficient levels of investment in energy efficiency, there may be economic justification for policies to promote efficiency investments even if externalities from carbon emissions are internalized.

To help policymakers identify the energy savings, emissions reduction potential, and costs associated with energy efficiency policies, analysts from federal and state governments, industry, and nonprofits have conducted hundreds of studies over the past several decades (e.g., Wilson et al. 2017; Holmes & Mullen-Trento 2017). There is a large and growing body of energy efficiency impact evaluations, often performed by professional evaluators at the request of policymakers, utilities, and regulators. More recently, there has been an explosion of economic literature on energy efficiency policy, aiming both to improve our theoretical understanding of when, where, and why the market

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fails to deliver economically efficient levels of energy efficiency investment and to evaluate selected energy efficiency programs to assess their cost-effectiveness. Despite this plethora of studies, there is still much we do not know about energy efficiency, in particular about the role of policy and market interventions in delivering energy savings and emissions reductions. However, the evidence is growing, and this literature can offer insights for policy design and future policy evaluations.

In this paper, we review the academic literature on energy efficiency, with a focus on recent peer-reviewed empirical studies that seek to identify the roles of various theoretical explanations for the energy efficiency gap and that look at the effectiveness and cost-effectiveness of different types of policies. Our review differs from the existing set of energy efficiency reviews in four primary ways.<sup>1</sup>

First, we focus on estimates of effectiveness and cost-effectiveness in recent peer-reviewed studies that use experimental and quasi-experimental approaches to evaluate specific energy efficiency policies and draw out useful estimates for policymakers. Second, this review of estimates highlights a major thread of the recent literature that draws on behavioral economics to assess the relevance of potential behavioral failures that could justify policy interventions to address these failures. Third, we use utility-reported data through 2016 to update the aggregate estimates of the cost-effectiveness of utility energy efficiency programs from Gillingham et al. (2006), finding an aggregate estimate of 2.8 cents per kilowatt hour (kWh) net savings, or 1.9 cents per kWh gross savings. This result is based on utility-reported data using a variety of methodologies, but it suggests that these programs are relatively cost-effective in comparison to the marginal social cost of electricity generation, which we estimate to average over 5.6 cents per kWh in 2015, incorporating both private and environmental costs of generation.<sup>2</sup> Fourth, we discuss the benefits and challenges of using experimental and quasi-experimental approaches in energy efficiency evaluation, as well as incentive problems that may currently afflict evaluations.

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<sup>1</sup> Previous reviews include Gillingham et al. (2006, 2009), Gillingham & Palmer (2014), Allcott & Greenstone (2012), Allcott (2016), and Gerarden et al. (2017).

<sup>2</sup> We calculate the marginal social cost of electricity by summing the wholesale price of electricity and the social cost of electricity generation. The wholesale price, 3.6 cents per kWh, is the volume-weighted annual average of daily wholesale price data collected by EIA. These daily data are the volume-weighted average price of each transaction that occurs on a given day. The environmental cost, 2 cents per kWh, is the annual emissions factor of CO<sub>2</sub> estimated by EIA, multiplied by the IWG (2016) estimate of the social cost of carbon using the central 3% discount rate. We use the 2015 marginal cost of electricity because of the unavailability of 2016 emissions factor data. We recognize that there are other environmental costs associated with electricity production using fossil fuels but these vary greatly by location, so we focus on carbon.

The empirical studies by economists that seek to evaluate energy efficiency interventions consider several types of interventions including behavioral programs, subsidies for efficient appliances and energy savings, building codes, and weatherization programs. These studies typically find that the empirically estimated savings fall short of ex ante engineering estimates of savings, when available, although the size of the difference varies across studies and programs. The heterogeneity in experimental results, due to various factors including the time period of evaluation and consumer characteristics, provides insights into the specific mechanisms behind energy savings (e.g., changes in energy conservation habits versus investments in more efficient durable goods) and lessons for improving the cost-effectiveness of policies, such as targeting the most responsive consumers.

The rest of the paper is organized as follows. In Section 2, we briefly review the key concepts in energy efficiency economics, including several recent insights from behavioral economics. In Section 3, we discuss methods for evaluation of energy efficiency policy and programs. In Section 4, we review recent empirical evidence testing economic theory and evaluating the results of energy efficiency programs. In Section 5, we discuss the results of our analysis quantifying the cost-effectiveness of energy efficiency in aggregate. Section 6 concludes.

## **2. Brief Review of Key Concepts in Energy Efficiency Economics**

Much of the discussion around energy efficiency policy cites the “energy efficiency gap.” This refers to a significant difference between observed levels of energy efficiency and some notion of optimal energy use (Jaffe et al. 2004). In the context of climate change mitigation, this notion has been used to identify potential upgrades to energy-using capital that might yield low- or negative-cost CO<sub>2</sub> emissions reductions when the upfront cost of the upgrades appears lower than the value of the anticipated energy savings (Granade et al. 2009). Gillingham et al. (2009), Gillingham & Palmer (2014), and Gerarden et al. (2017) outline the range of explanations that economists have posited for this phenomenon. These potential explanations include a range of classic market failures, behavioral failures rooted in behavioral economics, and analyst miscalculations of energy savings or costs of achieving those savings or both, with the final explanation suggesting that there is no energy efficiency gap at all.

An economic rationale for energy efficiency policy exists when market barriers that slow the diffusion of energy-efficient technologies can be demonstrated to stem from market or behavioral failures. Market failures assume that consumers are rational and are defined as a deviation between socially optimal and privately optimal decisions. Market failures are sometimes described as contributing to the “social energy efficiency gap” because the private

market does not provide the socially optimal level of energy efficiency, even if consumers are fully rational (see Gerarden et al. 2017). For example, negative externalities from pollution and landlord-tenant principal-agent issues (e.g., the tenant chooses how much energy to use, while the landlord pays for it) are classic market failures relevant to energy efficiency. Innovation market failures leading to an underinvestment in research and development (R&D) and capital market liquidity constraints leading to an underinvestment in more expensive energy-efficient technologies are additional market failures that may apply to energy efficiency (Palmer et al. 2012). These market failures, and others not mentioned here, are discussed at much greater length in Gillingham et al. (2009) and Gillingham & Palmer (2014).

Information problems represent a type of market failure that is an often-cited contributor to the energy efficiency gap. Information problems take a variety of forms, and in addition to causing systematic underinvestment in energy efficiency, they can also undermine the effectiveness of certain policies. One important form is simply a lack of information. Palmer et al. (2012) argue that a lack of credible information about actual energy savings from investment in efficient equipment may limit demand for efficiency improvements. Another information problem is asymmetric information, in which one agent in an economic transaction possesses information that another agent does not. This can lead to principal-agent problems, also commonly described as split incentives. These problems are particularly relevant for energy efficiency outcomes when consumers do not pay for their own energy consumption or make energy efficiency investments whose energy savings are imperfectly observed.

The recent energy efficiency literature has become increasingly focused on the possibility of behavioral failures, and these phenomena are often cited as major drivers behind the energy efficiency gap. Behavioral failures can be defined as any feature of decision-making that leads the consumer to exhibit a deviation between the utility at the time of the decision—decision utility—and the utility at the time when the consequences of the decision occur. In contrast to market failures, which create externalities and contribute to a social energy efficiency gap, behavioral failures create internalities and can contribute to a private energy efficiency gap (Gerarden et al. 2017). These anomalies in decision-making may stem from cognitive biases such as status quo bias, loss and risk aversion, sunk-cost effects, temporal and spatial discounting, and availability bias (see Frederiks et al. 2015). Energy efficiency decisions have also been linked to prospect theory, in which consumers have reference-dependent preferences, exhibit loss aversion, and subjectively weight probabilities when faced with uncertainty (see Heutel 2017). Much of the literature has focused on how consumers implicitly discount future

fuel savings from energy-efficient investments and whether they appear to undervalue future fuel savings relative to what would be expected based on how consumers discount in other contexts.

Whether cognitive biases are actual behavioral failures, however, has not gone unchallenged. Brennan (2013) questions the assumption that consumers fail to make utility-maximizing choices when investing in energy efficiency. Smith & Moore (2010) suggest a consumer choice model that incorporates additional choice constraints such as cognitive needs, providing an alternative theory for consumer behavior that does not require irrationality. Sallee (2014) furthers this point and argues that observed behavioral failures may be explained at least in part by rational inattention, in which consumers choose to act based on incomplete information if information is costly to acquire. In these cases, what may appear to the analyst as an undervaluation of future fuel savings may simply be unobserved costs.

If behavioral failures cause systematic bias in energy efficiency decision-making, then they clearly contribute to the energy efficiency gap and motivate a role for policy to correct the bias. Additionally, policies designed to address market failures would not sufficiently correct for the biases created by behavioral failures. Tsvetanov & Segerson (2013) use a theoretical model that incorporates temptation to show that product standards can have better welfare outcomes than price-based policies like externality taxes because they reduce consumers' opportunities to give in to the temptation of purchasing low-cost products that are less energy-efficient. Additionally, their findings suggest that a policy combining product standards with externality taxes can yield higher welfare outcomes.

In a similar vein, Allcott & Mullainathan (2010) suggest that policies designed specifically to address behavioral failures can have as much of an effect on behavior as price-based policies. Behavioral-based policies, often referred to as "nudges," are low-cost interventions designed to persuade consumers to change their behavior. Nudges generally incorporate strategies such as invoking social approval, providing energy consumption feedback, and encouraging goal setting and commitments on energy conservation. A commonly used nudge, for example, is the provision of feedback to homeowners or renters on their energy usage and their peers' usage. Allcott et al. (2014) argue that in the presence of market and behavioral failures, an optimal policy would involve an energy tax set below marginal damages in conjunction with policies that target behavioral failures. This conclusion follows from their finding that consumers who have the greatest undervaluation of energy costs are also the least sensitive to energy taxes, so the optimal policy would target more biased customers while limiting distortions to less biased customers.



Policy interventions to address the energy efficiency gap lead to behavioral responses that can affect optimal policy design. For example, there is evidence of a rebound effect, in which consumers increase their energy use in response to obtaining a more efficient product (Gillingham et al. 2016). Such behavioral responses inform not only policy design but also accurate evaluation of policy impacts.

### 3. From Theory to Evaluating Policies and Programs

There are many possible explanations for the energy efficiency gap, but what really matters from a policy perspective is the effectiveness, cost-effectiveness, and welfare implications of policies or programs. From a theoretical perspective, if the apparent energy efficiency gap can be entirely attributed to hidden costs and mismeasurement by the analyst, then there is no actual gap. In this case, interventions are not likely to yield greater benefits than costs, and evaluations that appropriately account for hidden costs and correct for mismeasurement would tend to bear this out.

However, if there are market failures or behavioral failures underpinning the apparent energy efficiency gap, then it is possible for an evaluation that accounts for all hidden costs and corrects for any mismeasurement to reveal that a program not only is cost-effective relative to other approaches but also yields savings that exceed costs. The presence of market or behavioral failures is a necessary but not sufficient condition for evaluations to reveal a program with positive net benefits. Programs to promote energy savings in such a setting could be poorly designed, poorly implemented, or not targeted appropriately to the relevant market or behavioral failure, thereby leading to non-cost-effective outcomes. The real challenge for policy design and evaluation lies in developing accurate evaluations under real-world constraints.

To understand the challenges inherent in evaluations, it is instructive to first consider energy efficiency evaluation in an ideal world. In this ideal world, unlimited resources could be brought to bear, and the intervention could be rolled out as a large-scale, well-designed randomized controlled trial (RCT). An RCT will randomly pre-assign entities to a treatment or control group, allowing for a comparison between these two groups on completion of the experimental treatment (List & Metcalfe 2014). Depending on the scale and scope of the policy or program, the randomization may be possible at different levels—household, neighborhood, or even city—as long as the sample size is sufficiently large. This ideal vision is well understood by many, if not most, in the economics and energy efficiency evaluation profession (e.g., see Vine et al. 2014 for a perspective from the energy efficiency evaluation community).

Unfortunately, this ideal is often far from reality. While energy efficiency RCTs are being run by many analysts, the number is small relative to the very large number of evaluations being performed every year. For example, in the California Measurement Advisory Council database of energy efficiency impact evaluations, only 13 of the 467 evaluations of California energy efficiency programs in the past 10 years used an RCT methodology. Rather than RCTs, it is more common for evaluations to be simple comparisons of energy use before and after an intervention (which may be subject to bias if there are any confounding trends or other factors that occurred before or after the intervention) or “deemed-savings” approaches that use engineering estimates for the energy savings of individual actions taken in response to the intervention and may not account for behavioral responses or implementation challenges.<sup>3</sup> “Deemed savings” approaches usually involve some “ex ante” calculations, whereby energy savings are in part determined by calculations made prior to the program, rather than measurements from the program (i.e., ex post evaluations).

One of the major challenges limiting the use of RCTs is simply the resource intensity they entail; RCTs are typically much more expensive and time-consuming to develop than the other common types of evaluations. Policymakers are often unwilling to earmark a high percentage of the cost of a program to evaluation, limiting the possibility of RCTs. In some cases, the entire budget for an efficiency program may not be large enough to fund a single RCT with a sufficiently large sample size to permit an analysis with adequate statistical significance (the sufficient sample size can be determined based on the expected treatment effect using power calculations).

A related challenge is that implementing an RCT often requires substantial upfront investment in program design, which may not be possible for programs with tight deadlines. A further challenge is the possibility of spillovers and the difficulty of ensuring that the control group is not contaminated by the treatment.<sup>4</sup> This issue may be particularly problematic for large-scale marketing campaigns, such as radio or other media campaigns, which inherently

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<sup>3</sup> For instance, there may be a rebound effect. Alternatively, it may be that in real-world conditions, the energy efficiency improvement is not installed correctly, reducing the energy savings. Challenges may also occur if the deemed savings estimates were developed in a different setting (e.g., different climate zone) than where the program takes place. See Jayaweera et al. (2013) for more details on standard practices for calculating energy savings associated with a host of specific energy efficiency measures.

<sup>4</sup> In some cases, spillovers or “treatment externalities” are the object of interest of an RCT (e.g., Miguel & Kremer 2004). These RCTs typically require very careful research design.

cover large geographic areas. It may also be problematic for “market transformation” energy efficiency programs (defined by the American Council for an Energy-Efficient Economy [ACEEE] as programs that “remove barriers or exploit opportunities”), which usually include a bundle of measures targeted marketwide.<sup>5</sup> Finally, some seemingly promising treatments may simply be difficult to implement in an RCT setting. For instance, Allcott & Sweeney (2017) found that a randomized information treatment implemented by home appliance sales agents had little effect, a result attributed to the limited incentive agents had under the experiment to deviate from their standard sales pitch.

Thus, while RCTs may be the “gold standard” for credible evaluation, most studies by economists and evaluators are not RCTs. Other modern empirical methods are available to evaluate policies and programs, however. A common theme of these approaches is that they attempt to isolate sources of variation in the data that can be considered plausibly random (Angrist & Pischke 2008). For example, many studies exploit a boundary between two regions that is arguably arbitrarily defined, and thus entities on either side of the boundary are plausibly the same except for the treatment (i.e., as good as randomly assigned). These difference-in-difference studies assume common trends on either side of the border. Other studies exploit an unexpected dramatic change that occurs at a certain time, through a regression discontinuity design. The assumption in this research design is that the pre-period can act as a sufficient control for the treatment period. Regression discontinuity designs can also be used when there are other thresholds that lead to a random assignment of the treatment to one side of the threshold, such as program eligibility cutoffs. A third common approach is matching, whereby treated entities are matched with similar control entities based on observables to attempt to replicate randomization as closely as possible. All of these approaches are often called “quasi-experimental” (Greenstone & Gayer 2009) and are increasingly being used in energy efficiency evaluations (Stewart & Todd 2015).

Economists and many evaluators consider these ex post revealed-preference approaches generally preferable to the common and less-expensive before-after and deemed savings approaches.<sup>6</sup> Using revealed preference estimates from RCTs or quasi-experimental approaches

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<sup>5</sup> See <http://aceee.org/portal/market-transformation> for more on how energy efficiency advocates think about market transformation activities.

<sup>6</sup> While this approach is common for evaluating particular efficiency measures, such as incentives for efficient light bulbs or other equipment upgrades, it is less common for policy evaluations that have a broader form of impact, such as new building codes or energy efficiency resource standards. Note that we are using “deemed savings” to describe any approach that does not use a comparison group to derive savings estimates (Palmer 2016).

may be more resource-intensive, but is useful for providing a benchmark against which to compare deemed savings estimates. As shown in the next section, it appears that engineering deemed-savings estimates tend to be overestimates of the energy savings from energy efficiency interventions.

This finding of overestimates of energy savings may be further fueling the trend toward increased use of RCTs and quasi-experimental approaches in evaluations. However, it is important to note that not all empirical approaches that use customer-level consumption data and compare changes in consumption after the program with a control group do a good job of approximating true randomization. For example, suppose a city decides to offer a rebate for energy-efficient light bulbs, and only households that are undertaking major renovations purchase these light bulbs with the rebate. These households may also be improving their efficiency through renovations. Thus, unless the renovations are observed, any attempt at a matching approach based on observed household characteristics would lead to an upwardly biased estimate of the energy savings attributable to the rebate. This issue is referred to as a “selection bias” because the households that opted into the program were selected from a population that was different from the control group. In the example given, the selected population would have experienced some energy savings anyway, even without the more efficient light bulbs. The beauty of the RCT is that it eliminates this selection bias through randomization. Finding ways to minimize selection bias in evaluations is an area of ongoing effort and aspiration for both academic economists and professional evaluators.

Incentives for professional evaluators and academic economists can influence the conduct and findings of an evaluation as well as the types of questions being addressed. Professional evaluators face incentives to be as rigorous as possible given their funding and to make their clients—often utilities—happy. Sometimes these incentives align to yield accurate evaluations, but other times they may not. Keeping clients satisfied may involve confirming expectations (e.g., making sure the savings are not too different from ex ante estimated savings used to justify the program initially) or simply showing at least some savings so that the clients save face in their discussions with regulators. Given the repeated game between utilities and professional evaluators, there is a clear incentive for evaluators to make sure that their results not preclude being hired for future evaluation work. This concern may affect some evaluators more than others depending on their ability to bring in business based on their reputation for doing on-time, high-quality work, which may override other concerns. Combined with the added challenges of RCTs, this incentive can translate into a resistance to RCTs and a preference for deemed savings

approaches. One practice that could help keep these incentives in check is for evaluators to work for a third-party entity (Kaufman & Palmer 2012).

In contrast, academic economists are often rewarded in the publication process for results that use the most rigorous methods possible, but that are counterintuitive on the surface and buck trends, reflecting a desire to change the way people perceive an issue. Thus academics can face the opposite incentive: to develop rigorous studies to show that what has been done in the past is incorrect.

#### **4. Recent Evidence from the Peer-reviewed Literature**

The recent empirical literature on energy efficiency economics has made two major contributions. The first includes studies that use empirical methods to evaluate the validity of economic theory explaining the energy efficiency gap. The second includes policy evaluation studies that assess energy efficiency programs by estimating their energy savings and cost-effectiveness. In both, we focus on only the most recent peer-reviewed evidence.

##### ***4.1. Empirical Evidence Regarding the Energy Efficiency Gap***

The first set of studies uses empirical methods to examine evidence on market or behavioral failures that could contribute to the energy efficiency gap.

Of those focused on market failures, several studies find evidence of asymmetric information causing principal-agent or split incentive problems that lead to higher energy consumption and lower investment in energy efficiency. Davis (2012) finds evidence of a split incentive problem in the tenant-landlord relationship, concluding that renters paying their own utility bills are significantly less likely to have energy-efficient appliances such as refrigerators, clothes washers, and dishwashers. Gillingham et al. (2012) also investigate split incentives between tenants and landlords and find that tenants paying for their own heating and cooling are 16 percent more likely to change the temperature setting at night. Additionally, owner-occupied homes in which the residents pay for heating and cooling are 20 percent more likely to have attic and ceiling insulation and 13 percent more likely to have exterior wall insulation. Following this work, Myers (2015) demonstrates that asymmetric information in the tenant-landlord relationship creates split incentives such that changes in the relative prices of oil and natural gas lead to fewer conversions from oil to natural gas heating in the landlord-pay regime than in the tenant-pay regime. Jessoe et al. (2017) investigate the tenant-landlord split incentive problem in the commercial sector and find that it leads to higher electricity usage for the top consuming

customers. Finally, Giraudet & Houde (2014) and Giraudet et al. (2016) show that asymmetric information between energy users and the suppliers of energy efficiency-enhancing products can lead to moral hazard in the provision of quality for energy efficiency investments. For home energy retrofits, a hard-to-observe measure, they find evidence that contractors take advantage of homeowner lack of expertise by providing lower-quality retrofit installations, which leads to lower realized energy savings. These information problems therefore have the potential to reduce the effectiveness of energy efficiency policy.

Many studies focus on determining whether behavioral failures cause systematic bias in consumer decisions. Sallee (2014) finds empirical evidence of rational inattention, in which what appear to be cognitive biases are indeed consumers behaving rationally. He finds that this explanation is plausible in markets for durable goods such as vehicles and home appliances, where the variation in future energy costs is minor relative to the variation in up-front product prices.

A major thread of recent studies uses empirical methods to determine whether consumers appear to have high implicit discount rates (consistent with myopia) or undervalue future fuel savings when purchasing durable goods. Allcott & Wozny (2014) and Grigolon et al. (2017) find that consumers purchasing vehicles modestly undervalue future fuel costs. However, Busse et al. (2013) and Sallee et al. (2009) do not find evidence of undervaluation of future fuel costs in vehicle purchase decisions. Allcott (2016) concludes that consumers make systematic mistakes in the purchase of energy-consuming durable goods but that the magnitude of these mistakes is small in comparison with the impact of the regulatory standards in place to address them.

Another aspect of possible myopia behavioral failure, described at length in Ungemach et al. (forthcoming), stems from bounded rationality, under which consumers' decisions are affected by the framing of their choices. The authors find that fuel attribute descriptions affect car choices and that consumers with strong pro-environmental values are more likely to choose fuel-efficient cars when their fuel economy is described in terms of greenhouse gas emissions. Such a response to framing could lead to under- or overvaluation of future fuel savings.

Further studies focus on other types of behavioral failures that bias energy efficiency decision-making. Sexton (2015) focuses on the issue of energy price salience. He studies the effects of automatic bill payment (ABP) programs on energy consumption and finds that ABP enrollment increases energy usage for both firms and households. Such programs have the potential to reduce the price elasticity of electricity demand and challenge efforts to increase the price salience of energy with implications for optimal policy design. Heutel (2017) finds some

evidence that prospect theory can explain consumers' investments in energy efficiency by observing that consumers with higher loss aversion are less likely to invest in energy-efficient goods such as alternative fuel vehicles and efficient light bulbs. This result suggests that a high degree of loss aversion should be met with greater energy efficiency subsidies and that the standard Pigouvian externality tax should be modified to account for behavioral failures. Similarly, Tsvetanov & Segerson (2014) study energy efficiency decisions in the purchase of refrigerators and find evidence that when individuals do not act rationally, product standards can result in higher welfare than price-based policies. The greatest gains tend to accrue to lower-income households, which are more likely to select less efficient products.

#### ***4.2. Empirical Evaluations of Energy Efficiency Programs***

The second set of studies we review aims to evaluate specific energy efficiency interventions and estimate causal relationships. The ex post studies we focus on hold distinct advantages over the bounty of ex ante studies and have led, in many cases, to substantially different results. Many studies surveyed in this section employ well-designed RCTs, and others follow quasi-experimental methods, such as those outlined in Section 3. Additionally, many studies have attempted to capture the nuances of program results by examining factors such as heterogeneity of effects across consumers and changes in outcomes over time. This section reviews studies of three major types of energy efficiency programs: behavioral and information programs, program standards, and financial incentives. Energy savings and cost-effectiveness estimates are displayed in Table 1.

**Table 1. Energy Savings and Cost-effectiveness of Energy Efficiency Interventions for Energy Use in Buildings**

Authors and year	Evaluation type	Where multiple results available, relevant subset	Percent change in energy usage	Cost-effectiveness (cents per kWh saved, 2015\$) <sup>1</sup>	Engineering estimates of percentage change in energy usage
<b>Behavioral Programs</b>					
Allcott (2011)	RCT		-2%	3.6	
Allcott and Rogers (2014)	RCT	One-shot intervention		4.4	
		Two-year intervention		1.1 to 1.8	
		Four-year intervention		1.2 to 1.8	
Ayres et al. (2012)	RCT	Sacramento	-2%	5.5	
		Puget Sound	-1.2%	2.0	
Costa and Kahn (2013)	RCT	Political liberals	-3.6%		
		Political conservatives	-1.1%		
Graff Zivin and Novan (2016) <sup>2</sup>	RCT	Households with AC units	-24%		
		Households without AC units	0%		
LaRiviere et al. (2014)	RCT		2%		
<b>Building Codes</b>					
Aroonruengsawat et al. (2012)	PD regression, fixed effects	Nationwide	-5.0%		
		California	-4% to -7.7%		-6%
Jacobsen and Kotchen (2013)	RD analysis	Electricity	-4.3%		-2%
		Natural gas	-6.7%		
Kotchen (2017)	RD analysis	Electricity	0%		
		Natural gas	-13.5%		
		Electricity and natural gas	-2.9%		-2%
Levinson (2016)	Multiple methodologies	Electricity	-10% to -15%		-80%
		Natural gas	-25%		
Novan et al. (2017) <sup>3</sup>	RD analysis		-13%	24.4 <sup>4</sup>	-20%
<b>Efficient Equipment or Energy Savings Subsidy</b>					
Alberini and Towe (2015)	Matching		-5.3%	3.9 <sup>4</sup>	
Alberini et al. (2016)	DID regression	Rebate of \$1,000 or more	0%		
		Rebate of \$450	-5.5%	47.9 <sup>4</sup>	
		Rebate of \$300	-6.2%	28.2 <sup>4</sup>	
		No rebate	-16%		
Burlig et al. (2017) <sup>5</sup>	Machine learning		-2.9 to -4.5%		-11.6 to -18% <sup>4</sup>
Costa and Gerard (2015)	DID regression	Short-term effects (9 months)	-23%		-20%
		Long-term effects (10 years)	-11%		
Davis et al. (2014)	DID regression	Refrigerators	-8%	27.2	
		Air conditioners	1.7%		
Ito (2015)	RD analysis	Inland	-4%	3.0	
		Coastal	0%	114.7	
<b>Information Provision</b>					
Alberini and Towe (2015)	Matching		-5.5%	4.5 <sup>4</sup>	
Asensio and Delmas (2015)	RCT	Information on social costs	-8.2%		
		Information on private costs	Insignificant		
Byrne et al. (2014)	Multiple methodologies	Immediate treatment effect	0%		
		Treatment effect after 7 months	-4.6%		
		Households who overestimate their usage	7%		
		Households who underestimate their usage	-5%		
<b>Information Provision and Energy Savings Subsidy</b>					
Allcott and Greenstone (2017)	RCT	Natural gas	-5.3%		-18.5%
		Electricity	-5.2%		-1.9%
<b>Weatherization</b>					
Fowlie et al. (forthcoming)	RCT		-19%		
	DID regression		-9.5%		
Graff Zivin and Novan (2016)	FE regression	Households with AC units	-7%		-14%
		Households without AC units	0%		

<sup>1</sup>When dollar years are not specified we use the dollar year from the final year of the program(s).

<sup>2</sup>Evidence of energy savings is conditional on participation in WAP program.

<sup>3</sup>Authors suggest that projected savings should be closer to actual savings because energy use in pre-retrofit houses was lower than projected.

<sup>4</sup>Calculated using estimates from study.

<sup>5</sup>Study focuses on energy efficiency in schools.



### **4.3. Behavioral and Information Programs**

A major area of growth in the academic literature has been studies focusing on energy efficiency programs that address behavioral failures and information problems. These programs generally administer interventions that “nudge” consumers to conserve energy. Examples of such nudges include giving consumers social comparisons of their energy usage and asking consumers for nonbinding commitments to reduce energy usage. Several recent studies provide estimates of program treatment effects by employing randomized controlled natural field experiments. For example, several run RCTs using the company Opower, which sends home energy reports to residential utility customers about their energy usage relative to that of neighbors, along with suggestions regarding ways to conserve energy. Many studies estimate both energy savings results and overall program cost-effectiveness, and some examine either persistence of the effects over time or the heterogeneity in results due to different household characteristics (see Table 1).

Allcott (2011) studies the effects of the Opower treatment to find energy savings of 2 percent and treatment effects that decay over time after home energy reports are received but increase again whenever the next report is received. A subsequent Opower study by Allcott & Rogers (2014) investigates the decay of treatment effects over a longer time period and observes a similar initial pattern of usage reductions followed by backsliding; however, this cycle lessens over time, and average treatment effects are greater for customers that received reports for at least two years than for those with shorter exposure to the program. These results suggest that consumers may primarily make behavior changes in early treatment periods and either adopt lasting habits in the longer term or invest in energy-efficient durable goods. Habituation of energy-efficient behavior and investment in durable goods can improve the cost-effectiveness of longer-lasting programs, and in fact, Allcott & Rogers (2014) find that sending a single Opower report has a cost-effectiveness of 4.3 cents per kWh saved, while sending reports to customers over two years has a cost-effectiveness of 1.1–1.8 cents per kWh saved.

Studies that examine the heterogeneity of results across customers can also provide lessons for designing more cost-effective interventions. For example, the effects of interventions may differ depending on what consumers learn about their baseline level of consumption. Allcott (2011) finds that consumers with higher baseline consumption conserve more electricity. Those with lower baseline consumption barely reduce their energy consumption; however, they do not display a “boomerang effect,” under which low baseline consumers would actually increase their electricity usage. Ayres et al. (2012) also find no evidence of the boomerang effect for low baseline consumption customers. Byrne et al. (2014), in contrast, study the effects of information

provision in Australia using an RCT and find evidence of the boomerang effect for consumers that underestimated their baseline energy consumption. They observe that underestimating households decrease consumption and vice versa.

Other work provides suggestive evidence of the mechanisms through which consumers are incentivized to exhibit more energy-efficient behavior. This evidence comes primarily from experiments that exploit variation in consumer characteristics and those that vary the framing of interventions (i.e., framing information around private cost savings versus social cost savings). A study of Opower by Costa & Kahn (2013) finds that liberal and environmentalist households have a more energy-efficient baseline than conservative households, and they are also more responsive to the home energy reports (although both liberal and conservative households reduce energy usage), suggesting that private costs may not be the most salient factor in consumer decision-making. LaRiviere et al. (2014) conduct an RCT intervention similar to that of Opower, in which home energy reports are sent to households, and also find that energy savings results differ based on political affiliation; however, they find that when nudges are framed to emphasize the public good of energy savings, Republican and mixed-affiliation households are most responsive. In a related but non-Opower study, Asensio & Delmas (2015) find that environmental- and health-based messages are better drivers of behavioral change than monetary savings information and are particularly effective for families with children. Ayres et al. (2012) evaluate Opower programs and observe that treatment effects were highest on Sundays, a result suggesting that the impacts may have been driven by behavioral changes rather than changes in the household stock of durable goods.

Heterogeneity in treatment effects can also stem from differences in households' durable energy-consuming goods. Graff Zivin & Novan (2016) study an RCT that administered behavioral interventions—including information provision and requests for nonbinding energy conservation commitments—to recipients of free home retrofits through the federal Weatherization Assistance Program (WAP) and find that these behavioral interventions led to an additional 23 percent decrease in electricity usage but only in households with air-conditioning units. This result suggests that changes in air-conditioning usage are a substantial source of energy use reductions under such behavioral programs.

Another set of studies examines whether information and behavioral interventions to encourage home energy audits can lead to audit uptake and energy efficiency investments. Gillingham & Tsvetanov (2017) use an RCT to investigate the effects of information provision on home energy audit uptake and find that a message to consumers combining the effects of social norms and salience improves audit uptake by 20 percent. The effects are strongest in rural

communities with strong social networks. LaRiviere et al. (2014) find that in an information provision program, the framing of information affected results, as privately framed signals (emphasizing electricity expenditures and kWh usage) tended to affect mainly audit uptake, and public good framed signals (emphasizing CO<sub>2</sub> emissions from electricity usage) tended to affect mainly electricity consumption. This finding supports the theoretical argument that different types of framing can have varying levels of effectiveness (Darby 2006).

Furthermore, Allcott and Greenstone (2017) observe that privately framed signals that are effective at inducing audit uptake are not effective at inducing those customers to make energy efficiency installations. They find that information and behavioral interventions had impacts that were statistically and economically insignificant, and only audit subsidies increased audit uptake. Consistent with LaRiviere et al. (2014), they also find that consumers who were marginal to audit subsidies were less likely to ultimately make energy efficiency investments than those that were inframarginal. Alberini & Towe (2015), however, study the effects of a free home energy audit program in Maryland and find that it led to reduced electricity usage of 5.5 percent.

#### **4.4. Product Standards**

Product standards are a popular policy around the world designed to require goods to achieve a minimum threshold of energy efficiency. Under the assumption that individuals make rational, utility-maximizing choices, standards are less economically efficient than price-based policies that directly address the externality, but standards can have economic advantages when behavioral failures prevent consumers from responding rationally to price signals. The effectiveness of standards, however, may be reduced by factors such as the rebound effect.

Building codes are the primary policy to influence the energy efficiency of newly constructed or renovated buildings. Aroonruengsawat et al. (2012) study the effects of US state-level building codes and find that on average, building codes reduce energy consumption by 2–5 percent. While this provides a high-level aggregate estimate, much of the literature focuses on specific building codes. Jacobsen & Kotchen (2013) exploit a tightening of Florida's state energy code and, using a regression discontinuity approach, find that the more stringent code caused a 4 percent decrease in annual electricity consumption and a 6 percent decrease in annual natural gas consumption. They also find larger effects on days when the demand for heating and cooling was highest, suggesting that reduced energy consumption was consistent with reduced consumption of air-conditioning and heating.

Levinson (2016) raises concerns that these findings do not account for the possibility that newer and older homes vary in ways that are correlated with energy consumption but not caused by the energy code changes. Accounting for this possibility, he finds that houses constructed under the California residential building energy code consumed 10–15 percent less electricity than those built before the codes were instituted; however, they did not increase their electricity usage less on high-temperature days, and the overall electricity consumption decrease was no different from that in other states with less stringent building codes. For natural gas, usage declined by 25 percent, and the newer houses did increase gas usage less on low-temperature days, but the difference was no greater for houses in California than in the other states. These findings imply that building codes are less effective than Jacobsen & Kotchen's results suggest.

Novan et al. (2017) enter this debate by looking at the effects of California's energy code and find that new codes led to sizable electricity savings. Specifically, houses in Sacramento County built after the code was implemented increased their cooling energy usage less on high-temperature days, corresponding to a 3 percent reduction in total energy usage. Finally, in a follow-up work, Kotchen (2017) addresses the issues raised in Levinson (2016) and concludes that over a longer time period, electricity consumption in the Florida post-energy code houses converged to the consumption levels of the pre-code houses. However, natural gas consumption did not converge, implying that building codes saved energy in the long run. This debate leads to a more nuanced view of building code effectiveness, in which the outcomes for electricity consumption are mixed, but there is some consensus that effects on natural gas consumption are more substantial. Savings estimates for building codes in general tend to be close to deemed savings estimates, although this is mainly driven by natural gas savings.

Product standards are also applied to vehicles, most notably in the case of the federal Corporate Average Fuel Economy (CAFE) standards. Knittel (2012) studies the trade-offs between fuel economy and other vehicle attributes and finds that the greatest progress in energy efficiency vehicle technology occurred when CAFE standards were most stringent and fuel costs were high, consistent with previous work showing that the rate of energy efficiency innovation depends on both energy prices and regulatory standards (Newell et al. 1999). Jacobsen (2013) conducts an analysis that incorporates consideration of the effects of CAFE in used vehicle markets and estimates that a 1 mile-per-gallon incremental addition to the stringency of CAFE standards reduces long-term gasoline use by 3 percent. Gillingham (2012) estimates that the rebound effect lowers total fuel savings from CAFE standards by around 15 percent. Jacobsen & van Benthem (2015) find evidence of used car leakage, in which used vehicle owners postpone their decision to scrap vehicles, particularly poor fuel economy vehicles, estimating that this

reduces energy savings by 13–16 percent. Archsmith et al. (2017) show that attribute substitution in household vehicle portfolios can further erode the savings of CAFE standards by leading households to purchase lower fuel-economy vehicles for their second vehicle. Klier & Linn (2011) study the trade-offs among vehicle fuel economy, power, and weight and find that the ability to choose among these characteristics lowers the overall cost of achieving fuel economy standard goals. Additionally, Ito & Sallee (2014) find that the common practice of employing attribute-based fuel economy standards, such as vehicle weight or size, as in the recent CAFE standards, distorts incentives to focus on the specified attribute rather than the true target of the standard.

Another set of product standards applies to appliances such as clothes washers and refrigerators. Houde & Spurlock (2015) analyze the impacts of past revisions of US energy efficiency appliance standards and find that they resulted in increased quality of products with only modest changes—and in some instances, even decreases—in price.

#### **4.5. Financial Incentives**

Another category of energy efficiency programs involves subsidizing energy efficiency investments. Subsidies often focus on replacing specific appliances or investing in building retrofits. Accurately measuring the effectiveness of these programs requires addressing potential free riding, adverse selection, and the rebound effect. Several studies empirically estimate the energy savings and cost-effectiveness of subsidy programs, accounting for these potential issues (again, see Table 1).

Alberini & Towe (2015) use a matching design to assess the impacts of subsidized heat pump replacement in Maryland, finding that the replacements led to lower electricity usage. Alberini et al. (2016) expand on this research, evaluating electricity usage of households that had both incentivized and nonincentivized recent heat pump replacements. They find that those who did not receive incentives reduced their electricity usage by 16 percent, while incentive recipients did not reduce their electricity usage. Furthermore, the larger the rebate a household received, the less the household reduced energy usage. The authors posit that these results may be due to a large rebound effect. Davis et al. (2014) also use a matching methodology to evaluate a program in Mexico that subsidized replacement of refrigerators and air-conditioning units and find that while refrigerator replacements reduced electricity consumption by 8 percent on average annually, air conditioner replacements actually increased electricity consumption, again consistent with a rebound effect. Rivers & Shiell (2016) examine Canadian subsidies for natural gas furnace retrofits and find

strong evidence of free riding, estimating that in the long run, over 80 percent of subsidy recipients would have eventually purchased identical furnaces without a subsidy.

Other studies examine the effects of building retrofits. Fowlie et al. (forthcoming) use both experimental and quasi-experimental designs to evaluate how receiving free WAP investments, such as insulation, affected energy usage in Michigan. They find that these investments reduced energy consumption on average by 10–19 percent, with most of those reductions coming from natural gas. The authors also analyze the indoor temperatures of homes and find no evidence of a rebound effect. Graff Zivin & Novan (2016) find that WAP investments decreased consumption by an average of 7 percent in households with air-conditioning units but had no effect on households without air-conditioning units. Burlig et al. (2017) investigate results from a school retrofitting program. Using a machine learning methodology to generate counterfactual outcomes, they find that the retrofits can lead to energy savings of 2.9 to 4.5 percent. On average, these realized savings represent only about 25 percent of the expected savings, but for some categories of retrofits, such as lighting and heating, ventilation, and air-conditioning, the realized savings are similar to the expected savings.

As an alternative to subsidizing specific efficient investments, other programs directly subsidize (or penalize) consumers for their energy consumption. Ito (2015) studies a financial incentive program in which consumers are offered rebates if they reduce their electricity usage by a specified percentage. The author finds that consumers in inland areas (generally with higher temperatures and lower incomes) reduced electricity consumption, while those in coastal areas (lower temperatures and higher incomes) did not reduce consumption. Effects were higher for households with air conditioners, suggesting some portion of the effects was due a cooling behavioral response. Another study by Costa & Gerard (2015) examines a temporary program in Brazil aimed to mitigate an energy supply crisis. Residential consumers were given electricity quotas and various financial incentives to meet those quotas. The authors examine whether energy savings continued in the long term after the termination of the program and find that energy savings persisted up to 10 years after program termination. Surveys of households in the study indicate that the main mechanism in continued savings was habit-formation rather than investments in efficiency.

## **5. The Cost-effectiveness of Energy Efficiency in Aggregate**

The empirical literature reviewed above focuses on specific interventions. With the exception of building codes, most of these interventions are the types of information, behavioral, or incentive programs that utilities routinely pursue. However, there is a glaring lack of empirical

evidence on many popular types of programs such as lighting upgrades, which account for the majority of energy savings from utilities' residential efficiency programs (Hoffman et al. 2015). Additionally, policymakers are often interested in a measure of how all ratepayer-funded utility programs perform in the aggregate. This is a challenging task, as there is no ideal database for assessing aggregate savings outcomes.<sup>7</sup>

One data source that has been used in the past is the annual energy savings and energy efficiency expenditure data collected by the Energy Information Administration (EIA) survey form 861 from utilities and energy efficiency program agencies funded by utility ratepayers.<sup>8</sup> Important caveats apply to these data. First, the savings estimates are reported by utilities and make use of a variety of methodologies, including deemed savings estimates. Most of the underlying program-specific estimates are not based on RCTs or on quasi-experimental studies, and in recent years, they are based on predictions of lifetime savings going forward. Second, the cost estimates are program administrator costs and do not capture the full costs to consumers associated with many efficiency interventions.

However, keeping these caveats in mind, one approach to developing an aggregate estimate of the average cost per kWh saved of utility energy efficiency programs (a measure of cost-effectiveness that can be compared to the social cost of generation) using the EIA data is the perpetual inventory methodology used by Gillingham et al. (2006).<sup>9</sup> A second approach uses EIA data on electricity sales and energy efficiency expenditures to econometrically estimate the effects of efficiency programs on electricity demand. These papers (Loughran & Kulick 2004; Auffhammer et al. 2008; Arimura et al. 2012) use a panel data approach to conduct an ex post analysis of how changes in energy efficiency program spending affected electricity sales at the utility level, which by virtue of the approach provides an estimate of net impacts.

We use the first approach here, utilizing EIA data from 1997 to 2016. Details of the calculation are presented in Appendix A. Our resulting estimates of energy savings and the cost per kWh saved (in 2015\$) are presented in Figure 1. Related findings from the literature (all point estimates) are also included at the point in time that approximates the end of the time series component of the panel data used in each analysis. Aggregate annual energy savings are

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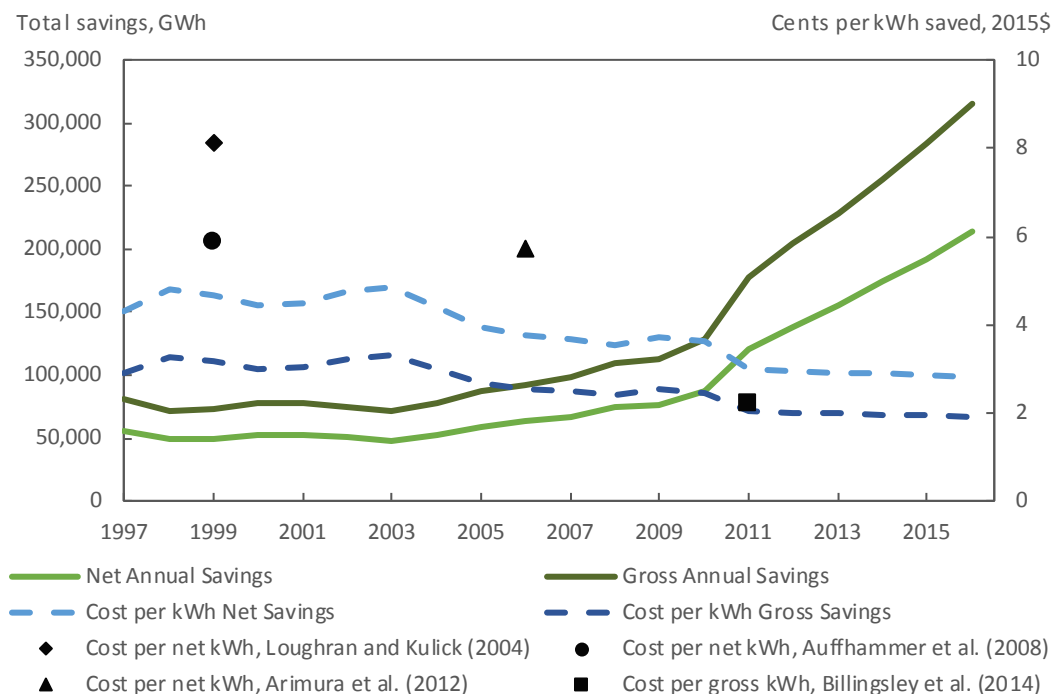
<sup>7</sup> State regulatory proceedings do involve data collection, but states use many different tests to assess cost-effectiveness of efficiency programs (National Action Plan for Energy Efficiency 2008; Brennan 2010).

<sup>8</sup> These energy efficiency agencies include Efficiency Vermont, Efficiency Maine, and DC Sustainable Energy Utility.

<sup>9</sup> Billingsley et al. (2014) use a similar approach with estimates of gross energy savings from state program evaluations to develop an estimate based on gross energy savings.

measured against the left-hand axis and presented in both gross and net terms, and cost per kWh (the dotted lines) is measured against the right-hand axis. Our estimate for 2016 is 2.8 cents per kWh net savings, or 1.9 cents per kWh gross savings. Utility-reported savings have increased over time, particularly since the burst of spending associated with the American Recovery and Reinvestment Act in 2009, which directed roughly \$17 billion dollars to support energy efficiency programs (ACEEE 2009).

**Figure 1. Annual Energy Efficiency Savings and Cost-effectiveness**



Notes: Cost-effectiveness point estimates for Loughran and Kulick (2004) and Auffhammer et al. (2008) are the lower bound of estimates. The upper bound estimates are 29.5 and 16.7 cents per kWh, respectively. The point estimates for Arimura et al. (2012) and Billingsley et al. (2014) are the average estimates.

The aggregate energy efficiency studies reported here provide further evidence on the distinction between ex post evaluation estimates and deemed savings estimates. Loughran & Kulick (2004) find that realized savings were significantly lower than deemed savings, leading to an estimate of 14–22 cents per kWh saved, which can be compared with projections of 2–3 cents per kWh saved. However, Auffhammer et al. (2008) revisit the Loughran & Kulick (2004) paper and find instead that the evidence does not allow them to reject the deemed savings estimates. Arimura et al. (2012) also calculate savings estimates within a range of deemed savings and find their cost-effectiveness estimates of 5 cents per kWh saved within the range of cost-effectiveness estimates based on reported expenditures and deemed savings. Following from these findings,



the information in the graph shows that ex post evaluations tend to produce higher estimates of cost per kWh saved; however, they are not statistically significantly different from the estimates derived directly from savings data reported to EIA or collected by states.

Some economists make the argument that measuring cost-effectiveness in terms of the cost per kWh saved is not the ideal way to assess energy efficiency programs. Instead, measures of program effectiveness should estimate total welfare impacts that account for other potential costs of policy implementation to consumers. Allcott and Kessler (forthcoming), for example, evaluate Opower programs using a methodology based on consumer willingness-to-pay for future participation in a Home Energy Report program that offers a more comprehensive measure of welfare impacts. The field is still far from having aggregate estimates of the welfare impacts of energy efficiency interventions, but we view this as a promising development.

## 6. Conclusions

The literature on the motivation for and evaluation of energy efficiency interventions is extensive and rapidly growing. Our review finds that recent academic studies of the topic have produced mixed results. It is clear that many energy efficiency policies lead to energy savings, and some appear to have costs per kWh below private marginal electricity supply costs. The evidence suggests that behavioral and information programs, often characterized as “nudge” programs, tend to be the most cost-effective; however, the magnitude of their savings potential is relatively small. More traditional policies, including product standards and financial incentives, may have higher energy savings potential but appear to be more likely subject to misvaluation, and several recent academic papers using “gold standard” evaluation approaches estimate relatively high costs per kWh saved.

Our analysis of program cost-effectiveness in aggregate uses the latest EIA data to update prior estimates and finds that in 2016, the surveyed energy efficiency programs cost 2.8 cents per kWh net savings, or 1.9 cents per kWh gross savings. In comparison, we estimate the social marginal cost of electricity generation to average 5.6 cents per kWh in 2015, suggesting that the surveyed energy efficiency programs are relatively cost-effective, with the caveat that the data used are self-reported utility data. Recent academic studies find a range of cost per kWh estimates that tend to be higher than our aggregate estimates and in many cases exceed the social cost of electricity supply.

We also raise challenging questions for evaluation, the solutions to which generally involve trade-offs. While in an ideal world all programs would be evaluated using RCTs, their

cost and time requirements render this infeasible, and other approaches need to be used in many cases; otherwise, program evaluation may not happen at all. Increasing the use of RCTs will certainly help in improving estimates of program results, although we acknowledge that they are not the sensible approach in every case. Expanded use of quasi-experimental methods that exploit program features such as eligibility criteria or staggered phase-in of programs over time could help improve the accuracy of program evaluations.

Even when programs are accurately evaluated, another question arises regarding the evaluation's external validity, which is the legitimacy of applying its results to infer the results from other programs in other contexts. If high-quality evaluations like RCTs are externally valid, then one could imagine something akin to benefits transfer to estimate the results of similar programs. Allcott (2015) provide some evidence suggesting that we should exercise this approach with care; they find evidence that RCT programs tend to be selected on program-level characteristics that make them favorable for conducting rigorous evaluations and might render extrapolation to other programs less accurate. Finally, the incentives faced by professional evaluators and academic economists may sometimes influence results, and we believe that efforts to address these issues would help further improve the accuracy of evaluations. One possible solution on the evaluator side could involve allocating evaluation money into a third party-administered fund.

The issue of external validity raises a final question for policymakers: What is the threshold of evidence sufficient to justify repeating or expanding a program? Should results from less-than-ideal studies be used? This is a particularly tricky question in light of calls to decrease the default p-value threshold for statistical significance of a new finding from 0.05 to 0.005 because of a desire to ensure reproducibility (Benjamin et al. 2017). Such a change would require even larger and more expensive RCTs to provide sufficient statistical power, which might mean that even fewer RCTs are run due to their expense. This trade-off between ensuring the credibility of findings and having any findings at all leaves policymakers in a difficult position. It would seem unreasonable to spend most of a program's budget on evaluating the program. Perhaps a compromise could be that every type of program have at least one large-scale RCT examined at the highest level of rigor, while subsequent program evaluations can use other, less expensive approaches. A major challenge with this proposed compromise is that heterogeneity in program results across time and space may mean that it is inappropriate to use the results of the single RCT to inform decisions made about the same type of program in other contexts.

While we recognize the difficulties in addressing these challenges going forward, we are impressed by the many new developments in this field of inquiry over the past decade and are optimistic that continuing advances in the study of energy efficiency policy coupled with collection of more detailed data on energy use will lead to new insights and improved policymaking in the future.

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## **Appendix A: Calculation of Aggregate Cost-effectiveness of Rate-Payer Funded Energy Efficiency based on EIA Survey Data**

EIA collects data annually from utilities and energy efficiency program agencies (funded by rate payer dollars) on efficiency expenditures, and up until 2012, on both incremental energy savings in a particular year and annual net energy savings (meaning savings attributable to the program) resulting from efficiency expenditures during that year and all relevant prior years. After 2012, based on consultations with those who design, operate, and evaluate energy efficiency programs, EIA changed its survey questions to focus on annual efficiency spending by program administrators and estimated lifetime energy savings associated with those programs going into the future. It also changed the survey to focus specifically on gross savings and thus does not exclude savings by program participants who would have altered their energy use without the program being in place (often referred to as free riders).

We use the recent EIA survey data to extend the time series of rate payer funded energy savings and cost-effectiveness originally developed by Gillingham et al. (2006). Translating the data reported by utilities and energy efficiency agencies to the Energy Information Administration (EIA) into a consistent time series of savings and rate payer (also known as program administrator) costs associated with those savings involved reconciling inconsistencies in the data over time and then translating information about one-time investment costs in efficiency programs into annual costs associated with energy savings in each year.

To accommodate the change in the definition of the energy savings information requested by EIA after 2012, we developed a methodology to extend the time series of net annual energy savings through 2016. To do this, we used information on average program lifetimes for utility efficiency investments (between 10 and 11 years) collected by EIA to translate lifetime savings reported to EIA into annual incremental savings to be added to energy savings carried forward from prior years. To create consistent time series of both net and gross energy savings, we used a net-to-gross ratio of 68 percent estimated by Navigant through a study of 42 US and Canadian jurisdictions (Brannan et al. 2013; Violette & Rathburn 2014) to translate gross annual savings post 2013 into net annual savings and, analogously, to translate net savings prior to 2013 into gross savings. Note that this approach to converting gross savings to net savings is based on an aggregate estimate that is constant in all years. Thus, another caveat in using this approach is that this ratio could be changing over time. For example, if recent programs have a larger component of nudge programs run as RCTs, then the savings estimates for those programs are all net savings, so the ratio of net to gross may be changing over time as the mix of program types evolves.

The cost of savings achieved in any particular year are not equivalent to expenditures in that year because energy efficiency program expenditures are investments that yield savings over a period of time. To translate the stream of investments into a time series of annual costs we follow Gillingham et al. (2006) and use a perpetual inventory method to translate annual investments into a measure of total efficiency capital stock and then multiply the annual value of that capital stock by a rental price of capital of 18 percent equal to the sum of the 11 percent annual depreciation rate for general private industrial equipment used in the national income accounts (Fraumeni 1997) and the real discount rate estimated at 7 percent. Cost-effectiveness is then estimated as the ratio of this product to the annual energy savings measures described above.

**Appendix B: Dollars Per Ton of CO<sub>2</sub> Avoided**

Authors and year	Evaluation type	Where multiple results available, relevant subset	Dollars per ton of avoided CO <sub>2</sub> , 2015\$ <sup>1</sup>
<b>Efficient Equipment or Energy Savings Subsidy</b>			
Alberini and Towe (2015)	Matching		64
Alberini et al. (2016)	DID regression	Rebate of \$450	62 to 72
Davis et al. (2014)	DID regression	Refrigerators	489
Ito (2015)	RD analysis	Inland Coastal	56 2,536
<b>Information Provision</b>			
Alberini and Towe (2015)	Matching		52 to 74
<b>Weatherization</b>			
Fowlie et al. (forthcoming)	RCT		329

<sup>1</sup>When dollar years are not specified we use the dollar year from the final year of the program(s).