Consumer End-Use Energy Efficiency and Rebound Effects

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Abstract

Energy efficiency policies are pursued as a way to provide affordable and sustainable energy services. Efficiency measures that reduce energy service costs will free up resources that can be spent in the form of increased consumption—either of that same good or service or of other goods and services that require energy (and that have associated emissions). This is called the rebound effect. There is still significant ambiguity about how the rebound effect should be defined, how we can measure it, and how we can characterize its uncertainty. Occasionally the debate regarding its importance reemerges, in part because the existing studies are not easily comparable. The scope, region, end-uses, time period of analysis, and drivers for efficiency improvements all differ widely from study to study. As a result, listing one single number for rebound effects would be misleading. Rebound effects are likely to depend on the specific attributes of the policies that trigger the efficiency improvement, but such factors are often ignored. Implications for welfare changes resulting from rebound have also been largely ignored in the literature until recently.

Contents

1. INTRODUCTION

End-use energy efficiency policies have been proposed and adopted by several countries as a way to reduce energy consumption and associated negative externalities, such as emissions of greenhouse gases (GHGs) and criteria air pollutants. Another reason to pursue energy efficiency strategies includes avoiding or reducing the construction of new supply-side energy infrastructure to meet demand and to decrease the reliance on foreign fuel sources. In many cases, end-use energy efficiency policies are pursued on the grounds that they are cost-effective, namely when compared to building additional energy supply infrastructure.

The study of end-use energy efficiency policies often results in as many new questions for future research as answers. As energy efficiency policies and strategies are pursued, how will consumers react? Will they use the savings they realize to increase their consumption of energy services or non-energy services? In recent years, researchers in the behavioral, decision, and social sciences have begun to address these questions, finding disparate answers.

If energy efficiency strategies are, on a lifetime basis, saving money to a consumer, the energy services become cheaper relative to other goods and services, so the consumer may purchase more energy services. She will also see an increase in her net income. She can then spend more money on energy services or on other goods and services (which may require energy to be produced). Energy modelers, energy economists, and policy makers have long debated the magnitude of these effects. In the past three decades, the debate over the magnitude of these rebound effects—i.e., the extent to which some of the anticipated energy gains (or emissions reductions) from energy efficiency measures will be eroded due to consumer behavior—has occasionally been revived (1).

This review focuses on rebound effects related to consumer adoption of energy-efficient technologies, strategies, and measures and in reaction to energy efficiency policies. A parallel and similar discussion could be pursued from the perspective of firms, but that is outside the scope of this review.

The literature on energy efficiency often refers to an energy efficiency gap, i.e., the difference between the current level of energy consumption and the level of energy consumption that would occur if consumers were to select cost-effective, life-cycle, energy-efficient, end-use alternatives. For economists, this energy efficiency gap refers explicitly to the agent's failure to pursue seemingly cost-effective investments in efficiency improvements and technologies. This gap is generally attributed to several simultaneous factors, including market failures and market barriers, misplaced incentives (for example, between tenants and landlords, also known as the principal-agent problem), lack of access to capital or financing options, uncertainty about the future price of electricity or other fuels, low priority of energy issues among consumers in the face of their other types of expenditures, consumers' limited cognitive capacity, insufficient or inaccurate information, the fact that energy efficiency often is inseparable from unwanted features in products, and energy prices that do not reflect their true cost (sometimes caused by distortional regulation or the non-inclusion of negative externalities that are associated with the provision of energy services) (2–7). The National Research Council report on *America's Energy Future* (8) states that well-designed policies such as building energy codes, Energy Star product labeling, and efficiency standards could generally help to overcome these barriers.

For households that pursue cost-effective energy efficiency investment, there may be key differences between the ex ante projected energy savings and the realized savings (ex post). One of the contributing factors for this energy efficiency measurement gap may be the so-called rebound effect. Policies may help overcome the rebound effect (if one exists) when such an effect is preventing policies from achieving their intended goal (such as reducing by a certain amount the environmental or health effects associated with emissions). However, the extent to which policies are needed, and how effective they are at avoiding rebound, is largely unknown.

Jevons (9) first introduced the idea of rebound in 1865, though without calling it a rebound effect. He stipulated that improvements in technology would reduce the price of providing such services, therefore increasing demand for those or other services. The Jevons' Paradox, as it is called, was elaborated by Jevons for the case of coal consumption in nineteenth-century England. In Chapter VII of *The Coal Question*, after describing several efficiency improvements, such as improvements in the Stirling engine and Siemens's regenerative furnace, Jevons writes, "But no one must suppose that coal thus saved is spared—it is only saved from one use to be employed in others" (9, p. VII.26). Alcott (10) provides a detailed review of *The Coal Question* and highlights its relationship with the more recent literature on technological change. In his concluding remarks, Alcott writes, "Certainly, theoretical work must see whether the environmental 'efficiency strategy' is reconcilable with standard growth theory" (10, p. 19).

Much of the debate regarding rebound effects and Jevons' Paradox on resource consumption remained on a hiatus until the late 1970s. The debate reemerged in the works of Brookes in 1979 (11) and Khazzoom in 1980 (12), in what has come to be known as the Khazzoom-Brookes postulate (or KBP). As first articulated by Saunders, the KBP stipulates that, "with fixed real energy price, energy efficiency gains will increase energy consumption above what it would be without these gains" (13, p. 135). Or alternatively, as explained by Sorrell (14, p. vii), "[I]f energy prices do not change, cost effective energy efficiency investments will inevitably increase economy-wide energy consumption above what it would be without those improvements."

However, the focus of the works of Khazzoom and Brookes are fundamentally different (as discussed in 15). Khazzoom focuses on direct and micro rebound impacts, whereas Brookes's work emphasizes macro effects. For example, instead of focusing, as Jevons did, on the role of technological change in productive sectors, Khazzoom (12) turned his attention to the specific case of the impact of energy efficiency standards for household appliances. Khazzoom discussed the difference between the technical potential of energy efficiency and what in fact could be expected to happen given an elasticity of energy demand with respect to appliance efficiency, which under certain assumptions is equivalent to the elasticity of energy demand with respect to energy prices. In his seminal paper (12), he concludes that "[c]onditions exist in which a program of accelerated improvement in efficiency can backfire,"[1] and that "there is no empirical evidence that would lead one to expect that [energy savings from efficiency standards] would apply similarly to all end uses" (p. 23). Furthermore, he expressed dismay that policy makers had not incorporated the consumer price elasticity when estimating the energy savings that would result from implementing energy efficiency standards.

Much of the discussion on rebound in the decades that followed Khazzoom's work focused on producer rebound effects rather than consumer rebound effects. Although those producer rebound effects are outside the scope of this review, there are many similarities between Khazzoom's later work and the work that was produced by Brookes (16) and others, which are briefly summarized here. Brookes, using a macroeconomic approach and focusing on the production side of rebound effects, showed that energy efficiency investments could lead to a net increase in energy demand. Brookes argued that energy price–induced substitution of energy for capital or labor, i.e., energy productivity, can increase overall energy consumption and GHG emissions. Subsequent work from Saunders (13, 17, 18) regarding production-side rebound effects expanded the work of Brookes by considering different types of production functions and found that rebound effects could theoretically range from being negative to being larger than 100%. A series of papers—and back and forth arguments—on the implications of assuming different production functions followed, with pieces such as Howarth's (19) showing that when incorporating the distinction between physical energy and energy services, and given an assumption that the production of energy services from physical energy occurs by means of the Leontief production function, Brookes's findings do not hold. Additionally, Saunders's (18) response showed that under Cobb-Douglas production functions, fuel consumption would increase as efficiency investments are pursued. In summary, in all these pieces the authors provide theoretical exercises to assess the extent of the economy-wide rebound, while arguing about the importance of specific functional forms to model the economy.

In the early 2000s, Binswanger (20) and others reignited the discussions on rebound effects for consumers, very much in the spirit of the earlier works from Khazzoom. Binswanger starts with a derivation for the rebound effect for a single service in a neoclassical framework and shows that the "overall effect of an increase in energy efficiency on energy consumption depends on the substitutability between different services and on the direction of the income effect" (p. 119). Since then, every so often the debate regarding the magnitude of rebound effects and its implications for energy efficiency policies reemerges. As mentioned by Brookes (16) in his 2000 paper revisiting his prior work of the 1990s, "the debate continues."

2. TAXONOMY

One broad definition of the rebound effect (R) for consumers is the gap between engineering assessments of potential energy (or emissions) savings (PES) and actual energy (or emissions) savings (AES) that are measured after the energy-efficient technology or measure is adopted (21, 22), or

$$R = 1 - \frac{\text{AES}}{\text{PES}}. \qquad 1.$$

[1] Khazzoom uses the term "backfire" to mean not only that energy and emissions are not saved, but that ultimately they will increase.

This definition raises questions about the scope and boundary of analysis. For example, as a consumer invests in more efficient lighting in her house, should the baseline energy (or emissions) consumption used to compute the PES include only lighting consumption or the overall household electricity consumption?[2] Or should the baseline instead include the entire household energy (or emissions) consumption associated with all energy carriers and sources, i.e., electricity, natural gas, gasoline, etc.? Should the PES include only energy used on site or also the energy (or emissions) embodied in the goods and services consumption? Over which time frame are the effects of the energy efficiency intervention being measured?

To address some of these issues, researchers have generally decomposed rebound into direct, indirect, and economy-wide rebound effects. An improvement in the efficiency of an end-use device will lead, *ceteris paribus*, to a decrease in the cost of providing that energy service. This, in turn, may result in consumers making greater use of that same end-use more often or more intensely. For example, one might buy a more efficient car and drive more miles, or buy more efficient light bulbs and leave them on for a longer period of time. This expanded or intensified use of the energy services is called the direct rebound effect (14, 20, 22).

If the energy efficiency measure being pursued saves money to the consumer over its lifetime, this means the consumer would actually experience a net increase in income. She might then use some of that income to increase her consumption of that same energy service, but the rest of it will be spent on other goods and services (or allocated to savings for future consumption). Some of these goods and services may have a large energy or carbon footprint, whereas others will not. For example, the net income gained from using a more efficient vehicle might be used for more air travel, more food, or increased electricity use, leading overall to less energy and emissions savings than one would anticipate. This is the indirect rebound effect (22–24).

Finally, as these energy efficiency investments are pursued and the effective price of energy services declines, changes will occur in the equilibrium between supply and demand of different goods and services across the economy. Patterns of innovation and growth may also change as a result. This overall effect is called the economy-wide rebound effect (16–20, 25–41) and is usually modeled in general equilibrium models of the economy. Some of these models also account for investment and disinvestment in different economic sectors and for labor market changes. Quite a few of the efforts to estimate economy-wide rebound effects have found that backfire can occur; that is, as a result of energy efficiency investments, the consumption of energy (or emissions) increases above where it was before the intervention (31). However, other general equilibrium models have found that investments in energy efficiency may actually lead to a contraction of the economy and result in a negative rebound effect (31).

Although the definitions above are helpful in terms of determining the boundaries of analysis, they still leave open the question of whether embodied energy (or emissions) of goods and services is included in the boundaries of analysis. **Figure 1** maps the different scopes of analysis and rebound effects that one could consider.

The left part of **Figure 1*a*** shows the different boundaries and the scope of end-use household-related energy efficiency rebound effects. Analysis may include just one energy service (with or without embodied energy or emissions), consumption or emissions of all end-uses at the household level (including or excluding embodied energy), or all sectors of the economy (as is the case when assessing economy-wide rebound effects). Note that throughout this review, embodied energy

[2]For example, as a consumer replaces incandescent lamps with more efficient alternatives, such as compact fluorescent lamps or light-emitting diodes, there will be changes in the heating service that need to be provided by the heating systems and decreases in the cooling service that need to be provided by the cooling systems, because incandescent bulbs release up to 95% of input energy as heat. This is known as the "heat replacement effect" in the engineering literature.

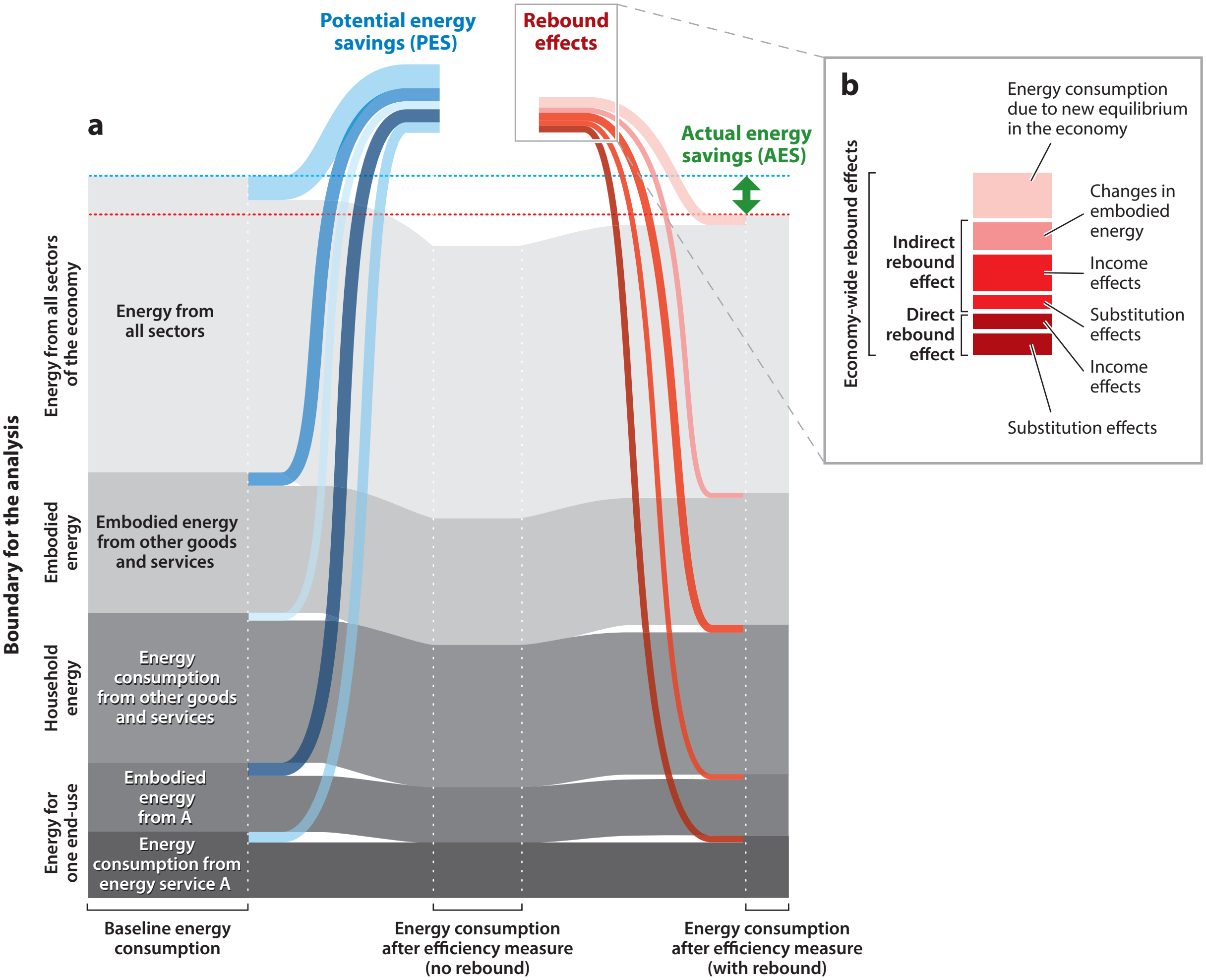

Figure 1

(*a*) Energy consumption for a baseline case (*left*), an efficiency measure with no rebound (*center*), and an efficiency measure after rebound is considered (*right*), for different scopes of analysis. (*b*) Different components of the rebound effect.

means the energy associated with the provision of the capital used to provide an energy service. Consider the example of energy service *A* corresponding to the household-lighting energy service. One can account for just the energy consumption (or emissions) from operating the lights, or expand the analysis to account for the environmental life-cycle energy (or emissions) associated with the provision of the lighting service (i.e., upstream energy or emissions from electricity) and energy or emissions associated with the manufacture, distribution, and disposal of light bulbs (denoted as "embodied energy from *A*").

The left area in **Figure 1*a*** shows conceptually the baseline energy consumption (or emissions) before an energy efficiency intervention, for different boundaries of analysis. This is the baseline from which the PES and AES are computed, where PES and AES are the energy consumption (or emissions) before and after the energy efficiency measure or technology is in place. Of course, whether some or all of the portions of these contributions to energy or emissions are to be included in the analysis depends on the specific energy efficiency improvement. For example, for cases in which consumers are considering the purchase of incandescent bulbs or light-emitting diodes, it may make sense to include the embodied energy associated with the manufacturing and disposal of these bulbs. However, if the decision faced by the consumers is whether to keep an existing furnace or buy a new, more efficient one, then the energy or emissions from manufacturing the old furnace should not be included, as they already occurred and will not change as a function of the consumer decision to invest or not to invest in new technology.

In the central part of **Figure 1*a***, we show the energy consumption (or emissions) for different system boundaries after the efficiency measure is in place. As more efficient lights are used, for example, the amount of energy consumption (or emissions) would decrease, and the embodied energy (or emissions) from providing the lighting service may increase or decrease. There may also be changes in other goods and services and their associated energy use. For example, incandescent light bulbs release 95% of their energy as heat. When a consumer transitions from incandescent light bulbs to light-emitting diodes, the demand for cooling in the summer also decreases, but the demand for heating in the winter increases. For other energy efficiency measures, there may be no changes at all in the energy consumption (or emissions) for other goods and services, nor in the energy (or emissions) from other sectors of the economy, which would bring to zero the top three blue flows for the PES shown in the diagram.

The right portion of **Figure 1*a*** shows that the actual energy consumption after the efficiency interventions would be slightly higher than the middle section of the diagram (the "no rebound case") because of rebound effects. Note that the sizes of the PES, rebound effects, and AES are purely illustrative. Finally, **Figure 1*b*** highlights the different contributors to those rebound effects. For an exhaustive list of potential rebound effects, see Van den Bergh (38).

Even the simplest definition of rebound effects, such as the one shown in Equation 1 or illustrated in **Figure 1**, requires assumptions about the time period for analysis. In the case of end-use rebound effects for consumers, rebound effects can be assessed in either the short run, including changes in energy service demand, or the long run, incorporating capital costs and long-term trends in increasing market saturation of appliances. Some authors argue that over long periods, such as decades or centuries, some energy services can be associated with large rebound effects and backfire (39–41).

Recent studies have attempted to formalize the direct and indirect rebound effects for consumers using a neoclassical economics approach. For example, Sorrell & Dimitropolous (22), Berkhout et al. (21), and, more recently, Borenstein (42) provide explicit derivations of the direct and indirect rebound effects. For Sorrell & Dimitropolous (22) and Berkhout et al. (21), indirect rebound is explained in terms of the cross-price elasticity of the demand for other goods with respect to energy services and the energy intensity of spending on other goods. Both authors use a neoclassical microeconomic framework, which assumes that the consumer maximizes her utility and that it is not the energy consumption, per se, that provides utility, "but rather the services of the equipment that operates on energy" (21, p. 427). The price of energy, the efficiency of the equipment, and the cost of the equipment itself will all be determinants of how much of the different commodities the consumer will purchase. Berkhout et al. (21, p. 427) assume that an "improvement of the efficiency of an equipment would imply a relative price decrease of the energy services of the equipment" and that "a rational consumer chooses a new optimal consumption bundle, corresponding to the new relative prices." Borenstein (42) provides clear derivations of the indirect and direct rebound using a standard neoclassical microeconomics consumer behavior model, resulting in an expression similar to that of Thomas & Azevedo (23).

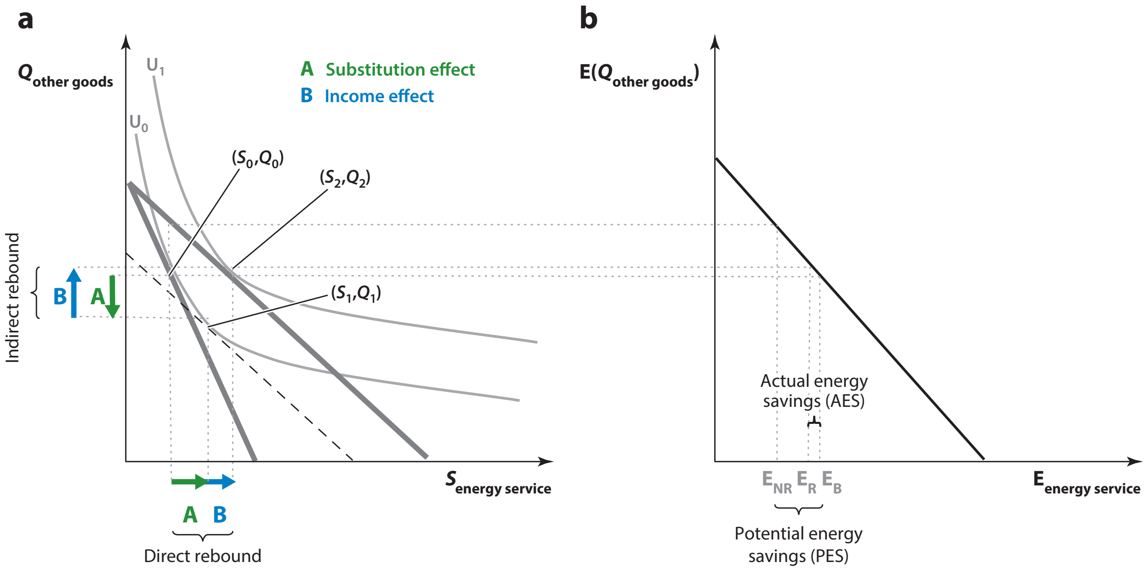

Figure 2

(*a*) Rebound in energy services, highlighting the decomposition between direct and indirect rebound effects and between substitution and income effects. (*b*) Same as panel *a*, but here the horizontal axis represents energy (e.g., kWh) instead of energy services (e.g., lumen). Figure adapted from Reference 23, with permission.

Figure 2, which expands on Berkhout et al. (21), Thomas & Azevedo (23), and Thomas (43),[3] shows the different components and mechanisms for household direct and indirect rebound effects in terms of energy services and actual energy quantities, before and after an investment in energy-efficient equipment. The horizontal axis in **Figure 2*a*** represents energy services, i.e., lumen or vehicle miles traveled. The vertical axis shows the consumption of all other goods or services, Q. Before an improvement in the energy efficiency of the energy service S, the optimal bundle for the consumer is (S_0, Q_0), with a utility U_0. With the energy efficiency improvement, the effective price of delivering energy service S decreases. The budget constraint is a function of appliance efficiency, and as the equipment becomes more efficient, the budget constraint moves outward. Prices for other goods and services do not change, so the intersection with the vertical axis remains unchanged before and after the efficiency improvement. The optimal consumption bundle becomes (S_2, Q_2), and the utility levels increase from U_0 to U_1.

The change in demand for energy services and other goods and services can be decomposed into the substitution (shown as A in both the vertical and horizontal axis in **Figure 2*a***) and income effects (labeled as B in both the vertical and horizontal axis in **Figure 2*a***). The substitution effect leads to a change in demand for energy services and other goods, holding utility constant [represented by (S_1, Q_1) in **Figure 2*a***], and the income effect leads to an increase in demand for all (noninferior) goods and services to achieve a higher utility level. The net change in the demand for energy services is the direct rebound effect, whereas the net change in the demand for other goods is related to the indirect rebound effect. Thus, both the direct and indirect rebound effects result from the substitution and income effects arising from the change in the price of energy

[3]The explanation in the subsequent paragraphs about **Figure 2** is adapted from Reference 23, with permission.

services after an efficiency investment. The larger the direct rebound effect is, the smaller the respending of energy cost savings from the efficiency investment. In fact, if the direct rebound is 100%, the cross-price elasticity would be zero, and if the direct rebound effect is 0%, all energy cost savings from an efficiency investment are respent on other goods and services, corresponding to a maximum possible cross-price elasticity (23).

Figure 2*a* illustrates the optimal bundle of goods in terms of energy services. Assuming energy prices are exogenous, **Figure 2*b*** shows the implications in terms of energy (or energy carrier) consumption for the good or service for which the energy efficiency performance was implemented (for example, gasoline, natural gas, or electricity). The budget constraint for energy remains unchanged before and after the energy efficiency improvements (because energy prices are exogenous). In that case, before any energy efficiency investment is made, energy consumption is at level E_B (for baseline). Once the energy efficiency improvement is made, one would assume that the energy consumption would drop to E_{NR} (no rebound); this is the level at which the energy services consumption remains the same before and after the efficiency measure is implemented. The difference between E_B and E_{NR} is what is generally called PES, as defined above. However, due to the rebound effect, the level of energy services consumed increases to E_R. The difference between the baseline energy consumption, E_B, and the energy consumption once rebound is taken into account, E_R, is AES. The rebound effect is then computed as shown in Equation 1. The magnitude of the effects in the figure is purely illustrative. Another component of rebound will be the changes in energy and emissions associated with the other goods (i.e., the energy or emissions associated with Q in **Figure 2**).

Recent work expands on this neoclassical approach to include supply-chain emissions associated with the production of goods and services, relying on environmental life-cycle models (23–26, 44) by coupling the fields of microeconomics and industrial ecology. Combining Slutsky relationships and the Engel aggregation property and using an environmental life-cycle input-output model, Thomas & Azevedo (23, 24) derive the direct and indirect rebound effects for a case with many goods in terms of cross-price elasticities. The authors include embodied energy or emissions by relying on an environmental input-output framework.[4] Borenstein (42) used a simpler approach using multipliers to account for upstream emissions to provide a first-order example of the potential direct and indirect rebound effects for end-use consumers. Borenstein starts with a model of consumer lifetime income, which can be spent on several goods and services, accounts for the life-cycle (embodied) energy consumption of the different goods and services consumed, and derives direct and indirect rebound effects, finding indirect rebound effects in terms of GHG emissions and energy.

3. ESTIMATES OF DIRECT AND INDIRECT REBOUND EFFECTS

Researchers with different areas of expertise, including economists, other social scientists, engineers, and policy analysts, have addressed rebound effects using a suite of methods such as econometric analysis, stated preferences, interviews, focus groups, engineering estimates, quasi-experimental studies, input-output analysis, randomized control experiments (the latter just emerging, enabled by lower costs associated with data collection from utilities on electricity and natural gas consumption), and the new field of big-data analytics. The UK Energy Research Centre (UKERC) main report and associated Technical Reports 1–5[5] (14, 45, 36) describe and discuss each method and the findings at length.

[4]The Environmental Input-Output Life Cycle Analysis (EIO-LCA) tool was developed at Carnegie Mellon University.

[5]These technical reports can be found at **http://www.ukerc.ac.uk/support/ReboundEffect**.

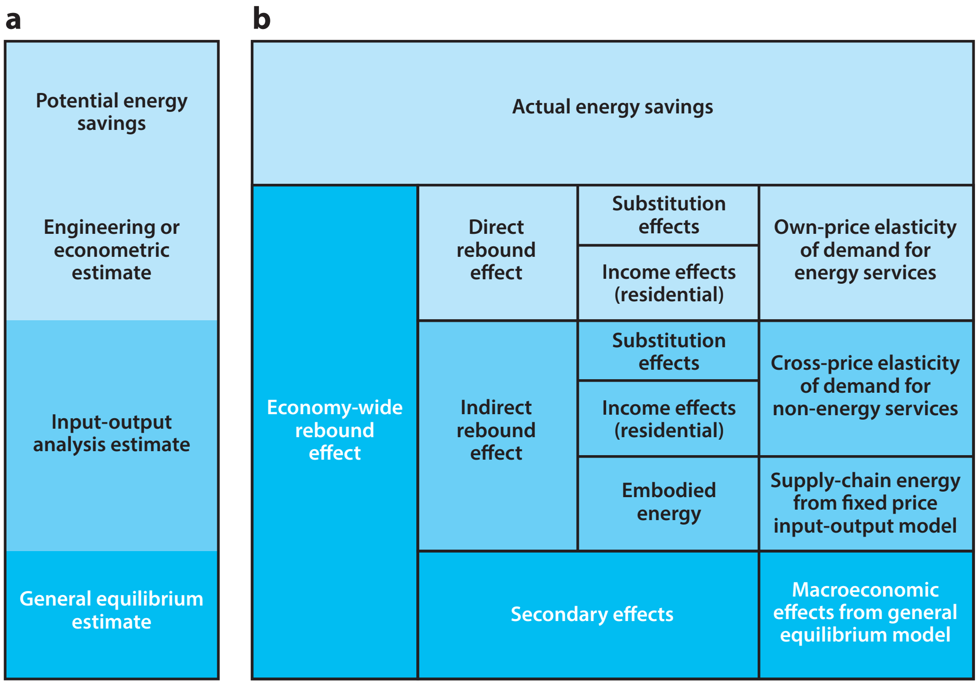

Figure 3

Rebound taxonomy for residential energy efficiency. (*a*) The models used to estimate different types of rebound effects. (*b*) The metrics used to estimate rebound effects. Modified with permission from Thomas (43), an expansion of a figure shown in Sorrell (14).

Few estimates of direct and indirect rebound effects for residential activities exist, and those that do differ with respect to the end-use energy services and uses considered, involve different scopes of analysis, and vary in time periods. The region of analysis also varies, as does the data quality.

A wide range of rebound effects is thus reported in the literature, even for those studies that focus only on direct rebound effects for a single end-use within a sector (27, 29). Studies focusing simultaneously on both direct and indirect rebound effects are even fewer and display larger variation. Authors disagree about the magnitude of both these indirect effects and the associated uncertainty. For example, Schipper & Grubb (30, p. 368) argue that "almost all other ways of consumer spending typically lead to only 5–15% of the expenditure going indirectly to pay energy use. . . . In other words, the energy intensity of respending is diluted by an order of magnitude or more." In contrast, Berkhout et al. (21) argue that direct and indirect rebound effects can be either positive or negative, depending on the characteristics of the good or service.

Figure 3, adapted from Thomas (43), shows the types of models generally used (in **3*a***) to estimate different types of rebound effects (specified in the first, second, and third columns), and the metrics generally estimated as proxies for those rebound effects (in **3*b***).

3.1. Direct Rebound Effects

Khazzoom's original formulation was in terms of efficiency elasticities of the demand for energy services from one appliance. However, this type of elasticity is rarely measured, and not all researchers agree that energy service elasticities are a proper measure of the rebound effect or that price-induced efficiency should be used in rebound analysis (16). **Table 1** (adapted from Reference 23) presents a review of articles using explicit energy services to assess direct rebound effects. Most of these studies conclude that consumers have inelastic behavior toward energy end-uses, even more inelastic than consumer behavior toward changes in energy prices (46). One could conclude from this that the difference between potential engineering-derived gains and actual gains should be negligible.

Binswanger (20) and Hertwich (15) remind us that the empirical estimates that rely on price elasticities as proxies for rebound rely on strong assumptions, including that (*a*) there is only a single energy service, (*b*) the energy cost is the only marginal cost of providing that energy service, and (*c*) the energy efficiency investments are reversible. Schipper & Grubb (30) reached that same conclusion using a top-down approach: They analyzed historical data on energy use and prices in different sectors of the economy and showed that "key measures of activity (car use, manufacturing output and structure, housing floor space, etc.) have changed little in response to changes in energy prices or efficiency, instead continuing their long-term evolution relative to GDP or other driving factors" (p. 367).

Without detailed energy service demand data for electricity, and given the limited variation in efficiency in transportation and natural gas demand, energy price elasticities have been used as a proxy for the energy service price elasticity in measuring the rebound effect. Hanly et al. (55) have shown in the case of transport that price elasticities of petrol demand are an upper bound for price elasticities of vehicle miles traveled because of the endogeneity between energy prices and efficiency choice. Studies using energy price elasticities as a proxy for energy service price elasticities are likely to overestimate the rebound effect. The data requirement for properly estimating the rebound effect by end-use is great, requiring disaggregated energy service consumption data over an appropriate timescale.

3.2. Using Price Elasticities as a Proxy for Direct Rebound

Many studies estimating direct rebound effects rely on econometric methods, often using price elasticity for energy end-uses as a proxy for direct rebound. Top-down studies generally use aggregated or country- or regional-level data on electricity consumption, prices, weather, and other control variables. Bottom-up studies generally use either a cross-sectional or a panel data set for households over time, with data that usually exhibit more detailed information about the households and the dwellings. **Table 2**, adapted from Reference 56, and relying on previous reviews from Taylor (60), Hanly et al. (55), Azevedo et al. (56), Espey & Espey (63), and others (64, 65), reports the ranges of residential electricity price elasticities that have been found in previous studies. The first set of studies estimating price elasticity (57–62) found that, in the short run, residential demand for electricity was inelastic to variations in the price of electricity and to income variations and that, in the long run, residential demand for electricity was elastic to variations in the price of electricity, with no agreement as to the value of the long-run income elasticity of electricity consumption. Some studies offered insights to specific regions or factors that influence residential demand of electricity, namely (*a*) the difference in the income elasticity of demand between more and less urbanized areas, with more urbanized areas having a higher income elasticity of demand (59), and (*b*) the fact that the price elasticity of electricity consumption is higher for higher-income households.

Taylor (60) reviewed several studies produced up to 1975 and offered several criticisms to this first generation of studies concerning (*a*) the existence of multistep decreasing block pricing and its implications as to what measure of electricity price should be included in the demand equation

Table 1 Selected review of US direct rebound studies using energy services model (adapted from Reference 23)

Authors/year (reference number)	Method	Sample size	Sample years	Region	Direct rebound	Notes
A. Space heating/electric end-uses						
Hirst et al. 1985 (47)	Pre- versus post-measurements	79	1981–1983	Pacific Northwest, US	10–15%	Control group, low income groups have higher take-back
Dubin et al. 1986 (48)	Energy service price elasticity	214–396 (cool), 252 (heat)	1982–1983	Florida	8–12%	Electric space heating and cooling
Dinan & Trumble 1989 (49)	Pre- versus post-thermostat settings	254	1984–1986	Oregon	3%	Only 5% of gap between engineering estimates and actual savings is due to behavior change (thermostat changes)
Schwartz & Taylor 1995 (50)	Energy service price elasticity	~270	1984–1985	9 census divisions	1–3%	Electric space heating
Davis 2008 (51)	Energy price elasticity, controlling for self-selection in field trial		1997	Bern, Kansas	6%	Compared electricity and water use from residential clothes washers in field trial; controlled for unobserved factors
B. Transport						
Haughton & Sarkar 1996 (52)	VMT elasticity of fuel intensity (inverse of fuel economy)		1970–1991		16% (SR) and 22% (LR)	CAFE standard variable is correlated with historical high price variable
Small & van Dender 2007 (46)	VMT elasticity of fuel economy	1734	1966–2001	US states panel	5% (SR) and 22% (LR)	Declining with income and over time
Gillingham 2012 (53)	VMT elasticity for the cost per mile driven	>1 million	2000–2006	California households/ vehicles	6%	Structural model for vehicle choice and utilization
	VMT elasticity of gas prices				15%	
Greene 2012 (54)	VMT elasticity of fuel cost per mile	51	1970s–2007	US states aggregate time series	3% (SR) and 13% (LR)	Time-series regression and fuel economy variation are small

Abbreviations: CAFE, corporate average fuel economy; LR, long run; SR, short run; VMT, vehicle-miles traveled.

Table 2 Estimates of US price elasticity for residential electricity consumption (adapted with permission from Reference 56)

Author/year (reference number)	Region	Time period	Price elasticity
Houthakker 1951 (57)	United Kingdom	1937–1938	−0.89
Fisher & Kaysen 1962 (59)	US states	1946–1957	−0.16 to −0.24
Houthakker & Taylor 1970 (58)	US states (46 states)	1960–1971	−0.13 (SR); −1.89 (LR)
Mount et al. 1973 (62)	US states (47 states)	1947–1970	−0.14 (SR); −1.20 (LR)
Taylor 1975 (60)	Review of several studies	Review of several studies	−0.90 to −0.13 (SR); −2.00 to 0 (LR)
McFadden et al. 1977 (67)	US nationally representative survey	1975	−0.71 (state level); −0.31 (household data)
Barnes et al. 1981 (69)	Household data	1972–1973	−0.55 (SR)
Bohi & Zimmerman 1984 (64)	Review of several studies	Review of several studies	−0.2 (SR); −0.7 (LR)
Maddala et al. 1997 (70)	US states (49 states)	1970–1990	−0.28 to −0.06 (SR); −0.87 to 0.24 (LR)
Garcia-Cerrutti 2000 (75)	California	1983–1997	−0.79 to 0.01
Paul et al. 2009 (74)	US states	1990–2004	−0.15 to −0.11 (SR); −0.01 (LR)
Lee & Lee 2010 (72)	25 OECD countries	1978–2004	−0.01 (LR)
Nakajima & Hamori 2010 (73)	US states	1993–2008	−0.34 to −0.12
Azevedo et al. 2011 (56)	US states and NERC regions	1990–2004	−0.32 to −0.17
Ito 2014 (66)	Two utilities in California	1999–2006	−0.18 to −0.20 during the California electricity crisis; −0.13 to −0.26 under 5-tier increasing-block price schedules (2001–2006).

Abbreviations: LR, long run; NERC, North American Electric Reliability Corporation; SR, short run.

for electricity, (*b*) the simultaneity between price of electricity and electricity consumption, and (*c*) the estimation of long-run and short-run elasticities. The existence of multistep decreasing block pricing biases the estimation of the price elasticity of demand if measures of marginal prices are not included in the estimation equation. That is, in the absence of measures of marginal price and average price in the demand equation, there is an omitted variable problem that, depending on its correlation with average price and income, will bias the estimate of the price elasticity of electricity demand. However, studies do not feature rate schedules as faced by the consumer, but rather average prices obtained "from some form of ex post calculation" and therefore suffer from a simultaneity bias (60, p. 103). However, a recent paper by Ito (66) finds that consumers seem to be more responsive to bills than to marginal price. Finally, given that not all the studies include a lagged variable, the distinction between short-run and long-run elasticity hinges on frail arguments. Some of these criticisms were addressed by McFadden et al. (67), Taylor (68), and Barnes et al. (69). Barnes et al. (69) took into account the rate schedule faced by the consumer and the simultaneity between the determination of price and quantity consumed and found a larger value for the price elasticity of demand than the previous studies.

A subsequent set of studies has proceeded to determine the best econometric estimator to assess the approximate price elasticity of demand. This set of studies included estimations of price elasticity for either gasoline or electricity use, among others. Although **Table 2** shows only the results for residential electricity, the discussion on best estimators also applies to transportation studies. For example, Baltagi & Griffin (71) analyzed the price elasticity of gasoline consumption in OECD countries using different estimators. Their study reveals that traditional techniques such as generalized least squares, the within estimator, and ordinary least squares perform better in terms of minimizing forecast errors than do other estimators.

A third and more recent generation of studies includes Lee & Lee (72), who estimated the income and price elasticity of the total demand for energy and total demand for electricity in 25 OECD countries, using panel cointegration techniques, unit root techniques, and panel causality techniques. Nakajima & Hamori (73) used a panel cointegration technique to understand the effect of deregulation on the price elasticity of electricity demand.

3.3. Ranges of Direct Rebound Effects

Overall, across different methods, regions, and end-uses, estimates of direct rebound effects for the residential sector are found to range from 0% to 60%. For personal transportation, studies on rebound effects report ranges from 3% to 87%. Rebound effects in the commercial and industrial sectors, and indirect and economy-wide effects for all sectors, have received less attention, and there is great uncertainty about the magnitude of these effects. There is little evidence of direct or indirect rebound effects exceeding 100% (so-called backfire) for household energy efficiency investments in developed countries. Although economy-wide rebound effects are outside the scope of this review, it is worthwhile to note that some economy-wide estimates have indeed found rebound effects higher than 100% (see, for example, 76–79), whereas others have found negative economy-wide rebound effects.

Most recent studies on the direct rebound effect focus on the residential sector. Here, rebound effects can occur in various areas and energy services such as residential lighting, space heating, space cooling, water heating, dish and clothes washing machines, and refrigerators. Therefore, it is difficult—and likely wrong—to estimate overall general direct rebound effects from energy efficiency strategies in the residential sector. **Table 3** summarizes the extensive reviews and meta-analyses from Jenkins et al. (29), Sorrell (14), Greening et al. (27), and Sorrell & Dimitropoulos (22) to illustrate the range of rebound estimates for different consumer energy services in developed nations.

Considering 16 studies on direct rebound effects for personal automotive transport, Sorrell & Dimitropoulos (22) find short-run rebound effects ranging from 5% to 87% and long-run rebound

Table 3 Ranges of estimates for direct rebound effects for different end-uses[a]

Energy service	Range of estimates (%)	Number of studies
Residential lighting	5–12	4
Space heating	2–60	9
Space cooling	0–50	9
Water heating	10–40	5
Personal transportation	5–87 (short term) 5–66 (long-term)	16
Other consumer energy services	0–9	3

[a]Sources: "Water heating" from Jenkins et al. (29); "space heating" and "other consumer energy services" from Sorrell (14); "residential lighting" and "space cooling" from Greening et al. (27); "personal transportation" from Sorrell & Dimitropoulos (22).

effects between 5% and 66%. However, the reported studies are of only limited comparability because they use different kinds of data and methods. Some studies have used aggregate time-series or cross-sectional data, others disaggregate data or aggregate panel data to estimate rebound effects, and still others use surveys. Moreover, out of the 16 studies, 12 are based on data from the United States; one from the OECD-25; one from the OECD-17; one from the United Kingdom, France, and Italy; and one from Germany. Sorrell & Dimitropoulos conclude that "personal automotive transportation provides one of the few areas where the evidence base for the direct rebound effect is strong and where the size of the effect can be estimated with some confidence" (45, p. vii).

Small & van Dender (46) found that the rebound effect in personal vehicle travel in the United States has been declining over time as incomes rise, from 5% (in the short run) and 22% (in the long run) for US states panel data between 1966 and 2001 to less than 3% (in the short run) and 12% (in the long run) for the 1997–2001 data. Greene (54) found similar results for the 1966–2007 US national travel time-series data. Fouquet (41) found that in 2010, long-run income and price elasticity of aggregate land transport demand were 0.8 and 0.6, respectively.

3.4. Indirect Rebound Effects

The definition of indirect rebound effects has varied considerably across recent papers. The estimates from indirect rebound effects in the economic literature generally focus on the energy or emissions effects associated with the marginal changes in energy services consumption as the price of energy services declines (which is assumed to be equivalent to an increase in energy efficiency) and is jointly estimated with the direct rebound effect. In recent papers in the industrial ecology literature, the notion of the indirect rebound effect has been expanded from its original definition to include the supply-chain or embodied energy or emissions from average spending patterns, independent of price changes and the direct rebound effect (23, 24, 28, 29, 44). **Table 4** provides an expanded version of a table from Thomas & Azevedo (23) and Chitnis et al. (80) and lists the studies that estimated both direct and indirect rebound effects.

4. RESEARCH GAPS

4.1. Understanding and Modeling Consumer Behavior

Consumers make decisions every day. Should I take the bus or the car today? Should I turn off the light or leave it on when I leave the room? Should I buy a hybrid electric vehicle or a conventional vehicle? Overall, few of the decisions consumers make over their lifetimes involve any direct consideration of energy. However, many of these decisions influence energy consumption and associated emissions. There is much evidence that such decisions (and consumer behavior more broadly) often depart from a neoclassical, utility-maximizing approach. Consumers' choices and behaviors are influenced by many factors, such as their perceptions of prices, prestige and status effects, attitudes and values, lack of knowledge about the application of energy-efficient devices, lifestyles, what others are doing, moral licensing and personal norms, and habits (1).

Most papers in the literature on rebound still rely on standard utility models and on fitting empirical data to estimate consumer price, income, and substitution elasticity. Models relying on the premise of rational choices (i.e., that the economic agent has and obeys a clear set of preferences that are transitive and insatiable, where more consumption leads to higher utility) are the norm (21). An additional, more disputed assumption in neoclassical microeconomic models is that the economic agent optimizes her behavior and choices by maximizing her utility (19). As noted by Berkhout et al. (21, p. 426), the "rationality assumption is a necessary condition for the existence of

Table 4 Literature review of direct and indirect rebound studies (adapted with permission from Reference 23)

Author/year (reference number)	Sample period	Number of sectors	Country	Action	Respending scenario	Direct rebound parameter	Embodied energy	Direct rebound	Indirect rebound, energy/GHG
Lenzen & Dey 2002 (81)	1995	150	Australia	Efficiency, behavior change	Proportional spending	No direct effect	Scope 1–3	NA	45–50% for GHGs, 112–123% energy
Alfredsson 2004 (82)	1996	300	Sweden	Behavior change (food, travel, utilities)	Income elasticity	Energy service/price elasticity	Scope 1–3	10–30%	14–300%
Brannlund et al. 2007 (83)	1980–1997	13	Sweden	Efficiency in heating, transport, both	Linear AIDS	Energy price elasticity	Scope 1–2	15%	106%
Mizobuchi 2008 (84)	1990–1998	13	Japan	Efficiency in heating, transport, both	Linear AIDS	Energy price elasticity	Scope 1–2	111% electricity, 5% transport	84% (electricity), 22% (gasoline)
Thiesen et al. 2008 (85)	2001–2003	34	Denmark	Behavior change and price change (food, i.e., cheese)	Slopes in spending, by income	No direct effect	Scope 1–3	NA	NA
Nässén & Holmberg 2009 (44)	2003	42	Sweden	Efficiency in space heating, appliances, and transport	Income elasticity	Energy service price elasticity	Scope 1–3	9 to 22%	−1% to 26%
Kratena & Wueger 2010 (86)	1972–2005	6	US	Efficiency	Quadratic AIDS	Energy service price elasticity	Scope 1–2	14% (gas) to 19% (electricity)	−57% (electricity), 71% (gasoline)
Girod & de Haan 2010 (87)	2002–2005	450	Switzerland	Behavior change (food)	Income elasticity	No direct effect	Scope 1–3	NA	53%
Freire-Gonzalez 2011 (88)	2000–2008, 2005 IO tables	31	Catalonia, Spain	Efficiency	Income elasticity and proportional spending	Energy price elasticity	Scope 1–3	36% (SR), 49% (LR)	20% (SR), 16% (LR)
Murray 2011 (89)	2003–2004	36	Australia	Efficiency	Income elasticity	No direct effect	Scope 1–3	NA	5–40%
Druckman et al. 2011 (33)	1992–2004, 2008 elasticities	16	UK	Behavior change/conservation	Income elasticity	No direct effect	Scope 1–3	NA	7–51%
Chitnis et al. 2012 (80)	2004	16	UK	Efficiency, investments, and behavior change	Income elasticity	No direct effect	Scope 1–3	NA	3–11% with capital costs, 15–20% without capital costs
Wang et al. 2012 (90)	1994–2009	7	China	Personal transport efficiency	Linear AIDS	Energy price elasticity	none	2–246%	NA
Thomas & Azevedo 2013 (23, 24)	2004	428	US	Efficiency improvement in electricity, natural gas, or gasoline for household end-uses	Different models: linear AIDS, proportional respending	Energy service elasticity	Scope 1–3	10%	Primary energy and GHG: 5% to 17% across electricity, natural gas, and gasoline efficiency measures; NO_x and SO_2: 0% to 40%

Abbreviations: AIDS, almost ideal demand system; GHG, greenhouse gas; IO, input-output; NA, not available.

rebound." Another, potentially problematic, pair of issues with neoclassical models used to assess the magnitude of rebound effects is the assumption of certainty and complete information (21).

More specific to the rebound discussion, the efforts that empirically estimate rebound within the neoclassical economics framework are laudable, but much is yet to be done on this empirical front. However, to understand whether it is indeed rebound effects or other behavioral drivers that explain the difference between PES and AES, knowledge exchanges between different social science fields may be required.

We do not yet adequately understand the factors that shape the demand of individuals, firms, and others for energy services. Theoretical and empirical research is needed that better articulates those factors, especially integrating behavioral and cultural considerations. Without this understanding, programs to promote greater energy efficiency may fail to anticipate their consequences.

4.2. How Do Drivers of Energy Efficiency Affect Rebound Estimates?

A general view in the rebound literature is that the causality starts with technological progress making equipment more energy efficient (20, 21). However, the decline in energy intensity is driven by technological progress, by policy interventions,[6] and by changes in consumer patterns of consumption.

The extent to which different drivers of energy efficiency may lead to different important outcomes related to energy consumption, emissions, and rebound effects is largely unexplored in the literature. This is a clear research priority as policy makers design and implement different forms of energy efficiency policies with different implications for energy savings. For example, when minimum energy standards are implemented, the consumer cannot choose between a baseline (a more inefficient) technology and the efficient substitute; the inefficient version simply stops being available. This is the case with the minimum efficiency standards for lighting currently in place in several countries. However, although this is true for capital goods with short lifetimes, strict standards for new long-lasting equipment could have the effect of extending the life of existing equipment (91).

The consequences of energy efficiency policy designs (e.g., standards, subsidies and rebates, or other market-based mechanisms) on consumer behavior and choice need to be further studied using approaches from both economics and other social sciences. Some of these policy mechanisms, such as energy efficiency subsidies and rebates, will create welfare transfers. The response of consumers to these policy drivers and corresponding rebound effects have to be distinguished in the literature from studies focusing on consumer adoption of more efficient technologies absent policy drivers (see, for example, Reference 92). Energy efficiency and demand-side management programs often provide consumers with rebates or other incentives, and thus consumers are not paying the full price for the energy service. Ongoing work by Gillingham et al. (93) is exploring some of these issues.

4.3. Non-Marginal Cost Pricing

Electricity and natural gas prices seen by consumers include a component of fixed charges associated with system delivery. Therefore, in many instances, consumers do not see prices that reflect marginal costs but rather prices that are set on a long-run break-even basis. Although this has been previously acknowledged in econometric studies assessing price and income elasticity, Borenstein

[6]Such policy interventions include, e.g., minimum efficiency standards, best-available technology policies, and energy efficiency and demand-side management programs by utilities and energy service companies.

(42) is the first to point out that the income rebound effect will therefore likely be smaller than what one would predict assuming that changes in energy consumption will be directly proportional to changes in energy retail prices.

4.4. Welfare Implications and Opportunity Costs

Too much past research on energy efficiency has treated rebound as a negative externality of energy efficiency investments without considering that the resulting increased use of energy may drive improvements in individual and social welfare (13). More research is needed that adopts a multiobjective or trade-offs perspective, quantifying the effects of energy efficiency measures in terms of energy, emissions, costs, and changes in overall welfare. Furthermore, for some end-uses and services, rebound might decrease as the level of energy services increases, due to saturation effects. For example, at least in the short term, there is a limited amount of potential direct rebound for heating and cooling in developed countries as comfort levels reach optimal levels, but the situation could be quite different in developing countries where demand for energy services is expected to grow as incomes grow. Also, Sorrell & Dimitropoulos (45) highlight constraints associated with real or opportunity costs that accompany increases in demand for energy services with the following two simple examples:

> Even if energy efficiency improvements are not associated with changes in capital or other costs, certain types of direct rebound effect may be constrained by the real or opportunity costs associated with increasing demand. Two examples are the opportunity cost of space (e.g., increasing refrigerator size may not be the best use of available space) and the opportunity cost of time (e.g., driving longer distances may not be the best use of available time). (45, p. 13)

4.5. Capital Costs of Energy Efficiency Measures and Time Value of Money

Most studies of the rebound effect focus on changes in the marginal price of energy services and disregard the income constraints imposed by the possibly higher investment costs of an energy-efficient technology. Very often, work on rebound effects does not consider the changes in upfront capital costs for the efficient device or energy efficiency measure because the premise is that the energy efficiency device or measure will be cheaper on an annualized basis. However, researchers who investigate how capital costs affect the rebound effect find, not surprisingly, that the higher capital cost of efficient technologies may lower the extent of the direct and indirect rebound effects (44, 84, 94, 95). Henly et al. (94) suggest that when including the capital costs of energy-efficient appliances, the rebound effect would be smaller because the discounted lifetime savings will be less.

An open area of research includes methods that capture consumers' sensitivity to the magnitude of initial capital costs (even if the efficiency strategy reduces the annualized or present value costs of switching from a baseline to an efficient technology) in energy demand and energy service demand models. By ignoring incremental capital costs for efficiency investments, estimates of rebound will likely provide upper-bound results (80, 84, 94).

If a consumer is choosing between energy efficiency equipment/technology options, the time value of money must be considered. However, surprisingly, most of the rebound effects literature ignores discount or interest rates or simply assumes that nominal and real interest rates are zero.

4.6. Assessing Rebound Effect in Terms of Energy or Emissions

Much of the energy efficiency rebound literature focuses on the implications for rebound effects in terms of an energy penalty. This is important when the goal of energy efficiency programs is to lower energy consumption as a way that, for example, reduces the need for additional supply-side infrastructure (i.e., slowing down or decreasing the amount and number of power plants needed to meet demand). However, often energy efficiency policies are pursued to achieve a diversity of goals that include decreasing the environmental and health effects associated with the provision of fossil fuel–based energy services. In cases in which the policy goal is to reduce emissions, it becomes important to understand the consequences of rebound in emissions terms. Such analysis can include site emissions, upstream emissions (in the case of electricity), or the emissions from the full supply chain that are associated with the provision of energy services and of other goods and services used by the consumer. Though work in this area is growing, few studies focus on rebound in terms of emissions, and even fewer highlight rebound in terms of multiple metrics that include the consequences of energy efficiency interventions in terms of energy, GHG emissions, and criteria air pollutant emissions. Thomas & Azevedo (23, 24) and others (15) provided recent studies in this area. Borenstein (42) also provided some examples of simple estimates of rebound in terms of both energy and GHGs for simple cases in which the fuel efficiency of a light-duty vehicle is doubled and in which lighting system efficiency is improved.

4.7. Developing Nations

So far, the drivers and consequences from increasing energy demand in developing nations have been largely understudied. As income levels increase in these countries, so will energy use. However, attributing this increase in energy use to a rebound effect is highly misleading and adds confusion to the rebound debate. A strict definition of the rebound effect, as described by Khazzoom (12) and Henly et al. (94), assumes that income, energy prices, and technology performance attributes are all held constant and that the increase in energy consumption arises solely from the adoption of technologies with improved energy efficiency. The focus on improved energy efficiency implies that a product with similar performance attributes but lower efficiency was already available in the marketplace and was in use. Even with no improvement in energy efficiency, energy use will increase as incomes rise and new products become available on the market.

A few studies have explicitly attempted to estimate direct rebound effects in developing countries and economies in transition. In all cases, the studies focused on a specific policy intervention promoting efficient end-use equipment. For example, a noteworthy study is one by Davis et al. (96) that assessed the effect of an incentive program for efficient refrigerators and air conditioners in Mexico, "Cash for Coolers." The authors suggest that although refrigerator replacements were found to result in an average 7% decrease in monthly electricity consumption, this policy also led to an increase in air conditioner use, leading to a net increase in electricity consumption. In India, Roy (97) found mixed evidence of the rebound effect: When the Ministry of New and Renewable Energy gave rural households free solar photovoltaic lanterns as a means to reduce kerosene lamp consumption, lighting demand increased from 2 h per day to 4–6 h per day, and kerosene lamps were still used at times when the SPV lanterns were not operational—a 50–80% rebound effect in kerosene consumption as a result of this program. However, Roy (97) notes that the presence of kerosene supply constraints, unmet demand for lighting, free provision of the efficient lantern, and large subsidies for kerosene are other possible reasons for the large rebound effect in the lighting case study.

Wang et al. (90) studied the direct rebound effect for passenger transport in urban China through an Almost Ideal Demand System econometric framework, similar to Brännlund et al. (83) and Mizobuchi (84). Wang et al. estimated a national average rebound effect for transport of 96%, with significant regional variation ranging from 2% direct rebound in Shanghai to 246% in Jilin province. However, the translation from price and income elasticities to direct rebound effect

Table 5 Estimates of price and income elasticity for energy in developing countries and economies in transition from previous studies (adapted from 72)

Author/ year (reference number)	Country	Period	Price elasticity	Income elasticity
Dhungel 2003 (98)	Nepal	1980–1999	−3.45 to 1.65	3.04
Galindo 2005 (99)	Mexico	1965–2001	−0.43 to 0.07	0.45 to 0.64
Holtedahl & Joutz 2004 (100)	Taiwan	1957–1995	−0.15	1.57
Kulshreshtha & Parikh 2000 (101)	India	1970–1995	−0.66 to 0.12	0.67 to 1.57

estimate is not clear. In addition, few studies estimate price and income elasticities for specific energy services. In **Table 5**, we show a few examples of price and income elasticity of studies focusing on economies in transition or developing countries (for countries that were under that category at the time the referenced study was performed).

From the point of view of global strategy to limit the emissions of CO_2 and other GHGs, there is a clear and urgent need for more and better studies of rebound in developing economies. The magnitude of rebound likely to be observed in these studies will probably be much larger in some cases than the analogous values observed in the industrialized world, given both income and supply constraints in the provision of energy services. The policy implication of such results should not be to limit the introduction of energy-efficient technologies across the developing world. Rather, such results should be seen as reinforcing the need to search for strategies in both the industrialized and the developing world that support the provision and growth of social well-being, without doing major harm to the environment.

Also, assessing rebound effects in developing countries requires the assumption that an energy service or technology was cost-effective, which implies that it was available and affordable. Thus, it becomes important to disentangle energy demand growth due to income growth and first-time access to energy services from a rebound effect due to the adoption of efficient technologies.

4.8. Areas for Future Research

Several other issues potentially contribute to biased estimates of rebound effects and deserve greater research attention. Six of these are briefly mentioned below.

4.8.1. Energy service prices. The representation of the direct rebound effect as energy service price elasticity assumes that underlying energy prices are exogenous, which may not generally be the case (see, for example, Reference 55). Econometric studies focusing on price and income elasticity have started to address these issues over the course of the past decade, accounting for price endogeneity. However, in the rebound literature, this point is often ignored.

4.8.2. The role of income levels. Reiss & White (65) have found that consumer residential energy demand behavior varies by income. Henly et al. (94) and Hanly et al. (55) found that the price elasticity of residential electricity demand, an upper-bound estimate of the rebound effect, varies with income from as high as 49% for households with incomes below US$18000 to 37% for middle-income and 29% for high-income households. More studies on how rebound effects may vary as a function of income levels are warranted.

4.8.3. Substitutability for energy services. In most rebound effect studies, it is assumed that all other attributes of the end-use service under study are kept at the same level. Indeed, it is assumed that attributes such as safety, comfort, and quality are all held constant through the analysis. However, with the real-world choices faced by consumers, this is unlikely to be the case.

4.8.4. Accounting for negative externalities. The provision of energy services that rely on fossil fuels is often associated with negative health and environmental externalities. For example, the combustion of coal to produce electricity is associated with emissions of criteria air pollutants, such as $PM_{2.5}$. Borenstein (42) highlights that this issue may, in turn, lead to implications for rebound effects: "[B]ad air quality due to particulate emissions could force people to stay inside and engage in relatively low-energy-intensive activities, or it could lead to more people driving out of the area to get away from smog" (p. 9).

4.8.5. The energy efficiency gap and rebound effect paradox. As mentioned in the introduction, several factors have been cited as potential explanations of the energy efficiency gap. However, if those market barriers and market failures for energy efficiency persist and explain why consumers do not adopt cost-effective, energy-efficient technologies or strategies, it is likely also the case that they would lead to very small or no rebound effects. Borenstein (42) provides a series of anecdotal examples that make this point clear:

> [I]f a car buyer were myopic about the trade-off between purchase price and fuel costs, because they do not pay much attention to the cost of gasoline, it seems likely they would also be less responsive to a change in fuel economy that effectively lowers their fuel cost per mile. Or, if a landlord puts an energy inefficient refrigerator in an apartment because the tenant pays the energy costs, it seems unlikely that a regulation forcing the landlord to buy a more energy-efficient refrigerator will lead him also to buy a larger one. . . . In lighting, if people fail to purchase CFLs because they do not recognize the impact of lighting costs on their electricity bill, then they are less likely to respond to lower marginal lighting costs by leaving the lights on more. (pp. 10–11)

4.8.6. Economy-wide rebound. In the extreme, as technology efficiency improves, there will be a reduction in the price of the energy services, which in turn will lead to a new overall equilibrium of supply and demand for all goods and services in the economy. To understand these effects, one needs careful models of the entire economy, i.e., general equilibrium models. Calibrating these models to replicate current conditions and running them under alternate conditions is a daunting task, one that relies on assumptions about price, income, substitutions elasticity, a cost-minimizing behavior from producers, a utility-maximizing behavior from consumers, and many other inputs that are often uncertain. Some of these models have shown that backfire (31) can occur, while others have led to a negative rebound as the investments in energy efficiency may actually lead to a contraction of the economy (31). Also, in rebound effect studies that cover long periods of analysis, such as decades or centuries, authors argue that some energy services can be associated with large rebound effects and backfire (39–41).

5. CONCLUSIONS

Given the growing emphasis by policy makers around the world on including energy efficiency as one of the strategies to reduce GHGs and the other externalities of the energy system, and moving toward more sustainable energy systems, it is becoming ever more important to understand consumer behavior with respect to energy. The nature and extent of the rebound effect are several aspects of consumer behavior upon which more light needs to be shed.

For example, a rebound effect of 20% will mean that an energy efficiency measure that was expected to avoid 1 tonne (t) of CO_2 will avoid only 0.8 t of CO_2. If the cost-effectiveness of an intervention was predicted to be \$100/t of CO_2 avoided, it instead will cost at least \$125/t of CO_2 avoided. Not only will the measure save less energy or emissions than anticipated, but also that measure will be less cost-effective than initially predicted. However, considering that policies promoting energy efficiency will have multiple goals, it is noteworthy that this penalty in cost-effectiveness should be balanced by the greater welfare enjoyed by the consumer.

In cases in which the evidence suggests large rebound effects, energy efficiency policies could be improved by explicitly taking into account rebound effects, both in efficiency program design and in the energy scenarios and models that support policy decision making. If policy makers are concerned about the environmental and health externalities associated with rebound effects, appropriately designed taxes or cap and trade policies can assure that these negative externalities are accounted for when they arise from rebound effects, as well as from energy demand in general.

Difficulties arise in assessing rebound effects and including them in policy analysis as a result of inconsistencies in the definitions and in the boundaries used in analysis, as well as a large uncertainty in the magnitude of these effects. Another difficulty is the availability of data and models that support the granularity of regional and local policy decisions. Even when rebound effects are considered and boundaries are appropriately drawn, most energy efficiency strategies are still likely to be cost-effective, save energy, and avoid emissions. Thus, although there is a need to understand the real costs and benefits and the energy and emissions effects from energy efficiency measures, those who claim that energy efficiency policies should be terminated are simply wrong. However, the careful design of energy efficiency policies will be critical to achieve the intended energy savings. The evidence to date from econometric studies that use price elasticity, income elasticity, and elasticity of substitution suggests that direct and indirect rebound effects in developed economies are moderate. Such moderate rebound effects in turn imply that carefully designed energy efficiency policies can produce energy savings, although not as much as simple engineering analyses indicate.

As technology prices decrease and people achieve more net income in low-income communities, we can expect demand for energy services to increase. These conditions already hold or will hold soon in a number of developing countries and economies in transition. These income-related effects are distinct from rebound and should not be confounded with it because the standard definition of consumer rebound effect pertains to a reaction by consumers after an improvement in efficiency of a technology, while holding everything else constant.

Finally, economists often propose reducing the externality of energy use by increasing energy prices (by introducing energy taxes, carbon prices, etc.). If all negative externalities could be incorporated in the energy price, the only rebound effects would be those that improve social as well as private welfare.

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