Rebound Effects

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Kenneth Gillingham
Yale University

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Abstract

In environmental and energy economics, rebound effects may influence the energy savings from improvements in energy efficiency. When the energy efficiency of a product or service improves, it becomes less expensive to use, income is freed-up for use on other goods and services, markets re-equilibrate, and there may even be induced innovation. These effects typically reduce the direct energy savings from energy efficiency improvements, but lead to improved social welfare as long as there are not sufficiently large externality costs. There is strong empirical evidence that rebound effects exist, yet estimates of the different effects range widely depending on context and location.

Keywords

Energy efficiency; climate policy; take-back effect; backfire; emissions; welfare; greenhouse gases; derived demand

Introduction

Energy efficiency policies are among the most common environmental policies around the world. Holding consumer, producer, and market responses constant, an increase in energy efficiency for an energy-using durable good, such as a vehicle or refrigerator, will unambiguously save energy. Rebound effects are consumer, producer, and market responses to an increase in energy efficiency that typically reduce the energy savings that would have occurred had these responses been held constant. The use of the term "rebound" is intuitive: the responses lead to a rebounding of energy use back towards the energy use prior to the energy efficiency improvement. For this reason rebound effects are sometimes also called "take-back" effects, for some of the energy savings are "taken-back" by the responses.

Often rebound effects are referred to in the singular, as "the rebound effect," but it is widely understood that there are actually several effects at work. At one extreme, these rebound effects can lead to *additional* energy use above the amount used prior to the energy efficiency improvement. This is often called "backfire," referring to the energy efficiency improvement "backfiring" in terms of saving energy. At the other extreme, *negative* rebound effects, whereby the responses increase the energy savings, are may be possible as well. In economics, rebound effects most often are in reference to energy use, but of course rebound effects can also be described in terms of greenhouse gas emissions or other measures of environmental impact. Moreover, rebound effects are possible in other areas as well, such as materials or water. This article follows the convention and focuses on rebound effects in energy use.

Figure 1 illustrates the importance of rebound effects for the energy savings that can be expected from the 2017-2025 Corporate Average Fuel Economy Standards in the United States. This illustration assumes a 30 percent total rebound effect, which would "take-back" 0.30 quadrillion BTU of the energy savings that would have been expected from the policy.

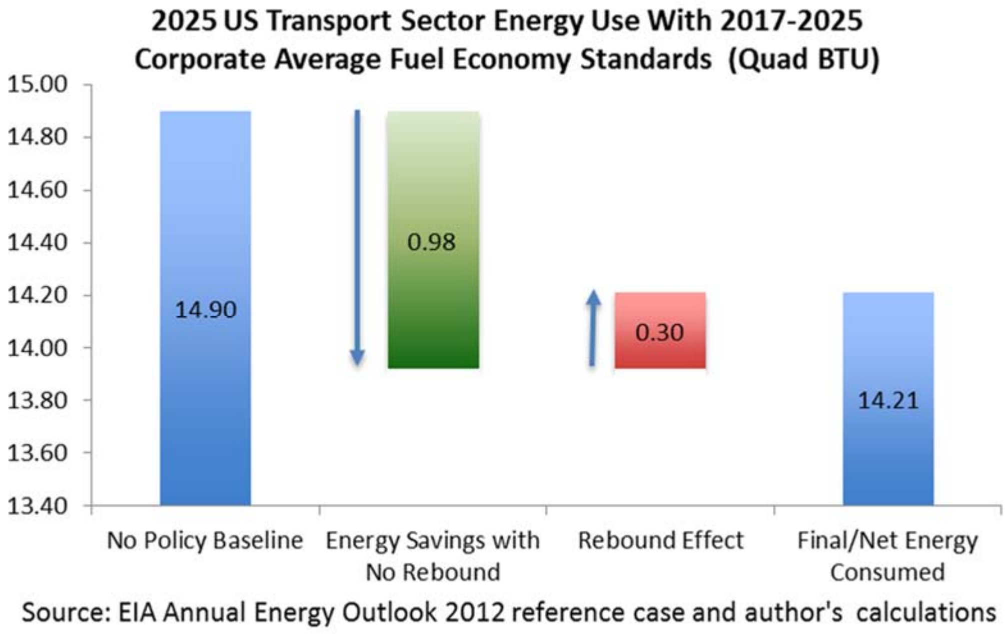

Figure 1. 2025 US transport sector energy use with the 2017-2025 CAFE standards illustrating how rebound effects may influence energy savings (Gillingham et al., 2013). The figure assumes a 30% rebound effect for illustrative purposes.

The first mention of rebound effects goes back to the English economist William Stanley Jevons in 1865. Jevons lived at a time when coal-fired steam engine technology was dramatically improving in England. Yet, despite improvements in engine efficiency, coal use was not declining, but rather was increasing. Jevons attributed this to the improved productivity of coal use, leading to more investment and growth in the sectors of the economy that used coal. Jevons famously stated “It is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth” (Jevons, 1865). The backfire that Jevons was positing has more recently been called the “Jevons Paradox,” for it seems paradoxical to have an energy efficiency improvement lead to more energy use.

More recently, policymakers and academics have been increasingly interested in rebound effects from energy efficiency policies. If there are large rebound effects leading to backfire, energy efficiency policies may not save energy at all. Moreover, larger rebound effects would be expected to widen the welfare difference between first-best policies to address market failures, such as price policies to correct for externalities, and energy efficiency policies, which are generally considered second-best policies (unless there are behavioral failures, as described in Gillingham and Palmer (2014) and many other papers). Such observations have led to a vibrant academic and policy debate over the magnitude of the effects.

Rebound effects are often broadly classified into their microeconomic and macroeconomic effects. We proceed by discussing each and then turn to quantification and policy implications.

Microeconomic Rebound Effects

The microeconomic rebound effect may occur for both consumers and firms when there is an energy efficiency improvement. Most of the economic literature focuses on consumers, so we begin here with the microeconomic rebound effect from the consumer perspective.

The microeconomic rebound effect for consumers captures the change in the consumption bundle of all goods and services when there is an energy efficiency improvement in one product. For consumers, it stems from the classic substitution and income effects of a price change, as in the Slutsky equation (Gillingham et al., 2015). Unfortunately, the literature is inconsistent in the terminology used, so it is instructive to begin with some simple microeconomic theory. The following exposition loosely follows Borenstein (2015).

Suppose we have an energy efficiency improvement in an energy-using good 0. For instance, this could be a vehicle, light, or air conditioner. Let the original energy intensity (i.e., the reciprocal of energy efficiency) of the good be e_0 and the new energy intensity be e_0'. With greater energy efficiency, the cost or price of using good 0 drops (i.e., the energy cost of the energy service drops). Denote the price of using good 0 as p_0 and the change in price with the efficiency improvement as Δp_0. Similarly let the demand for good 0 be q_0. At the same time that the price decreases, there may also be a cost (C) associated with the energy efficiency improvement.

The combination of such a price decline and change in income leads to a consumer response in four ways as they re-optimize their consumption bundle.

First, there is a substitution effect, whereby the consumer substitutes from other goods and services to good 0 along the Hicksian (compensated) demand curve of the use of good 0. The amount of increased consumption is just the marginal change in the Hicksian demand with a price change $(\frac{\partial q_0^H}{\partial p_0})$ times the change in the price of usage Δp_0. The increased consumption of course uses energy. The change in energy use from the substitution effect is the new energy intensity of the good times the increased consumption: $e_0' \frac{\partial q_0^H}{\partial p_0} \Delta p_0$.

Second, there is an income effect. Since the consumer is no longer spending as much on using good 0, the consumer may have income to re-spend $(q_0 \Delta p_0)$. For example, if a consumer is now spending less to drive a mile, they have increased purchasing power. However, the energy efficiency improvement may come with a cost, so the total change in income is $q_0 \Delta p_0 - C$. This change of income may be positive or negative depending on how costly the efficiency improvement is. Furthermore, it can be expected to influence the demand for using good 0. Let the demand for using good 0 be given by q_0 and income be given by I, so the marginal change in demand with a change in income is $\frac{\partial q_0}{\partial I}$. Thus, the change in demand for using good 0 with the energy efficiency improvement is given by $\frac{\partial q_0}{\partial I}(q_0 \Delta p_0 - C)$ and the change in energy use due to the income effect is then $e_0' \frac{\partial q_0}{\partial I}(q_0 \Delta p_0 - C)$.

Third, there may be a substitution effect for every other good and service. For goods that are substitutes for good 0, there would be a decrease in consumption with a price decrease of good 0. For complements, the opposite. Let the Hicksian (compensated) demand for good i be given by

q_i^H, and the marginal change in Hicksian demand for good i with a change in p_0 be given by $\frac{\partial q_i^H}{\partial p_0}$. Then, for any good i, the change in energy use from the energy efficiency improvement in good 0 is $e_i \frac{\partial q_i^H}{\partial p_0} \Delta p_0$, where e_i is the energy intensity of good i (i.e., the amount of energy used in providing the energy service). Thus the aggregate change in consumption for all other goods *besides good 0* is $\sum_{i \neq 0} e_i \frac{\partial q_i^H}{\partial p_0} \Delta p_0$. Since some goods are substitutes and others are complements, and goods differ in energy intensity, the sign of this term is ambiguous (Chan and Gillingham, 2014, Borenstein, 2015, Berkhout et al., 2000). In general, one might expect it to be negative, for there is a general substitution in consumption towards good 0 when its efficiency increases.

Fourth, there may be an income effect for every other good and service. If there is additional income freed-up from the energy efficiency improvement, it can be re-spent on other goods and services as the consumer re-optimizes consumption. As mentioned above, the change in income associated with the energy efficiency improvement is $q_0 \Delta p_0 - C$. Thus the change in consumption for any good i when good 0 has an energy efficiency improvement is simply the marginal change in demand of good i with a change in income ($\frac{\partial q_i}{\partial I}$) times the change in income: $\frac{\partial q_i}{\partial I}(q_0 \Delta p_0 - C)$. The change in energy use for good i is then $e_i \frac{\partial q_i}{\partial I}(q_0 \Delta p_0 - C)$, and the aggregate change in energy use for all goods *besides good 0* is $\sum_{i \neq 0} e_i \frac{\partial q_i}{\partial I}(q_0 \Delta p_0 - C)$. The sign of this income rebound effect is ambiguous as well. It depends on the change in income, as well as the relative energy intensity of normal goods versus inferior goods. If nearly all goods are normal goods and the change in income is positive, one would expect a positive sign for this effect.

The sum of these four responses forms the basis of the microeconomic rebound effect, which quantifies the change in energy use with a change in energy efficiency:

$$R = e_0' \frac{\partial q_0^H}{\partial p_0} \Delta p_0 + e_0' \frac{\partial q_0}{\partial I}(q_0 \Delta p_0 - C) + \sum_{i \neq 0} e_i \frac{\partial q_i^H}{\partial p_0} \Delta p_0 + \sum_{i \neq 0} e_i \frac{\partial q_i}{\partial I}(q_0 \Delta p_0 - C).$$

The first two terms (substitution and income effects for good 0) are nearly always defined as the **direct rebound effect**, for they capture the direct consumer response in good 0 to the energy efficiency improvement (Sorrell and Dimitropoulos, 2008). Assuming a positive change in income and usage of good 0 being a normal good, one would expect a positive sign for the direct rebound effect.

However, the other terms are defined in various ways in the literature, potentially leading to confusion (Turner, 2013). In particular, the **indirect rebound effect** is a term widely used in the literature, yet its usage is inconsistent (Azevedo, 2014, Gillingham et al., 2015). Its name indicates the more indirect nature by which energy savings are reduced. Many studies refer to the indirect rebound effect as the sum of terms three and four (Chan and Gillingham, 2014). Other studies recognize that the indirect rebound effect includes both terms, but focus on only estimating the income effect on other goods and services (the fourth term) as a measure of the rebound effect (Chitnis et al., 2014). Others simply define the indirect rebound as the fourth term

(Borenstein, 2015). Still others either explicitly or implicitly use a much broader definition for the indirect rebound, which includes both the third and fourth terms as well as additional rebound effects.

One of these additional rebound effects is the **embodied energy rebound effect**, which captures the energy used to create the energy efficiency improvement. The sign of this effect is context dependent. A more energy efficient product may take more or less energy to produce. If the process of building a more efficient product is more energy intensive, then the embodied energy rebound would be expected to be positive. Of course, there may be energy embodied in other goods and services as well, so a broader definition of the embodied energy rebound would include the change in energy use from embodied energy from other goods and services as well.

It is common to include the embodied energy rebound as part of the indirect rebound effect. For example, Azevedo (2014) and Thomas and Azevedo (2013b) define the indirect rebound effect as the sum of terms three and four above, and use an energy intensity e_i that includes the embodied energy in both good 0 and all other goods and services. Sorrell (2007) defines the total economywide rebound effect as the sum of the direct and indirect rebound effects. Under this definition, the indirect rebound effect is a residual that includes the third term, fourth term, all embodied energy effects, and macroeconomic rebound effects.

Another proposed definition is to call the first three terms in the equation above the “net direct rebound effect” for they account for the direct rebound as well as the change in energy use from all other goods and services, including the ones being substituted away from (Borenstein, 2015). If this third term is negative, we would expect a smaller net direct rebound than direct rebound effect.

For the net energy savings from an energy efficiency improvement (abstracting from any macroeconomic rebounds), we can compare the microeconomic rebound effect (R) to the upfront energy savings from the efficiency improvement. Thus, the net energy savings after the microeconomic rebound would be given by the energy savings, $q_0(e_0 - e_0')$, minus R and minus any embodied energy effect (E):

$$Net\ Savings = q_0(e_0 - e_0') - R - E.$$

As mentioned above, the microeconomic rebound effect may also occur for firms. Consider a firm that is using capital and labor to produce a good or service. When there is an energy efficiency improvement, there is a factor-substitution effect: capital becomes relatively more productive, so more (energy-using) capital and less (non-energy-using) labor is included in the optimal production factor mix. Moreover, the marginal cost of production may decline, increasing the optimal amount of production. Both the switch to more energy-using inputs and increase in production may lead to a rebound effect on the production side (Berkhout et al., 2000). While these production-side rebound effects clearly have microeconomic foundations, nearly all research on them has been at the macroeconomic level, which often aims to take into account the full set of changes in production and prices across the economy.

Macroeconomic Rebound Effects

The macroeconomic, or sometimes "economy-wide," rebound effects involve several channels by which market responses could influence the energy savings from an energy efficiency improvement. There is a **macroeconomic price effect** or energy market effect, which describes how a shift inwards in demand for energy in the market due to the energy efficiency improvement will be accompanied by a subsequent re-equilibration as prices and quantities are set so that supply equals demand. This market response will mean that the reduction in demand will be less than the amount that demand is shifted inward. It is governed by the slopes of the supply and demand curves. The macroeconomic price effect is small if demand is highly elastic and supply is inelastic, for then the market will re-equilibrate at nearly the same quantity as what you would have without the re-equilibration process. Similarly, the macroeconomic price effect is large if demand is inelastic and supply is elastic (Borenstein, 2015, Gillingham et al., 2013).

This macroeconomic price effect can occur in any market, but is particularly easy to understand when there is an energy efficiency improvement shifting demand inward in a single region (e.g., from a fuel economy standard in the U.S.) and there is a broader market for fuel (e.g., the global oil market). In the case of oil, the reduced demand for oil in the U.S. leads to a lower global oil price, and thus induced oil demand elsewhere.

Another category of macroeconomic rebound effects can be called the **macroeconomic growth effect**, for it describes how the amount of economic growth and patterns of economic growth can be influenced by the energy efficiency improvement (Gillingham et al., 2013). Jevons was on to a version of this type of rebound effect: a sectoral reallocation rebound effect. Just like the substitution effect in consumption, there is analogous effect in investment and production in the economy. When the relative rate of return of a sector increases, we would expect to see more investment and economic growth in this sector. Of course, this sectoral general equilibrium effect depends on two factors: (1) the degree to which the energy efficiency improvement increases the rate of return of the sector and (2) the energy intensity of production in the sector relative to other sectors. The sectoral reallocation rebound could be positive or negative, depending on the cost of the energy efficiency improvement (e.g., is it a mandatory and costly energy efficiency increase?) and the energy intensity of the energy-using sector relative to other sectors (e.g., is the shift in production from more energy-intensive or less energy-intensive sectors?). The sectoral reallocation effect can also be extended to a reallocation of innovative activity and human capital, such that higher returns in a sector can lead to more innovative activity and human capital moving into that sector (Lemoine, 2014).

The macroeconomic growth effect may also involve innovation in another way. The process of researching to find new ways to improve energy efficiency may engender spillovers to other processes and sectors. For example, finding ultra-lightweight materials for aircraft may spillover to other manufacturing areas, such as that of electronics or bicycles, spurring economic growth in other sectors. Thus, energy efficiency improvements may change the path of innovation in multiple areas, leading to broader economic growth.

Another possible pathway for a macroeconomic growth effect is through a macroeconomic multiplier. Macroeconomists have posited that income gains (usually from a government program) may have a multiplier effect in times of high unemployment when there is unused capacity in the economy (Ramey, 2011). This multiplier effect would occur if a dollar of additional income is spent in a way that uses some of the under-utilized labor and capital in the economy. Thus, additional income would generate further income and economic growth more broadly. Of course, this effect may be dampened by any future expected taxes or debt incurred to provide the income. However, in the context of freed-up income from an energy efficiency improvement, the multiplier would not be associated with any additional taxes or government debt, so the effect might be expected to be different (Borenstein, 2015).

Other channels may also influence the macroeconomic rebound. For example, Lecca et al. (2014) and Turner (2009) posit an interaction between the macroeconomic price effect and sectoral reallocation, which they call "disinvestment effects." In the short run, the shift away from energy can lead to excess capacity in energy supply, leading to lower energy prices and thus a greater rebound. In the longer run, the returns to capital will drop, so this excess capacity will be divested, which will put upward pressure on energy prices, serving to constrain the macroeconomic rebound. Thus, in contrast to previous theoretical predictions (e.g., Wei (2007) and Saunders (2008)), the macroeconomic rebound may be larger in the short run.

Evidence on Rebound Effects: Historical Background

There is an extensive literature aiming to estimate rebound effects in one form or another. Work on the subject ranges from theoretical models with calibrated simulations to empirical estimations and computable general equilibrium models. Yet the magnitude of the total rebound effect varies by context and remains controversial. While the literature provides strong guidance for some microeconomic rebound effects in many contexts, such as the direct rebound effect, it is clear that the relevant magnitude varies by location and setting. The current literature provides less guidance on macroeconomic rebound effects, with different studies capturing different effects, and magnitudes ranging from limited rebound to significant backfire.

The rebound effect first entered into the modern academic literature in 1979 with Brookes (1979) and Khazzoom (1980), who resurrected the Jevons Paradox in the context of modern energy efficiency policies. In fact, the Jevons Paradox has been referred to as the "Khazzoom-Brookes Postulate" by later studies (Saunders, 1992). Khazzoom (1980) was particularly focused on microeconomic rebounds and Brookes (1979) on macroeconomic rebounds, but both posited that improvements in energy efficiency may lead to backfire.

This view was shortly thereafter critiqued in papers such as Lovins (1988), Henly et al. (1988), and Grubb (1990), which point out that energy demand is relatively inelastic and energy typically is a small percentage of the cost of energy services, so rebound effects for most energy services might be expected to be small. This led to a series of papers exploring what functional forms on economy-wide production could lead to backfire when there is an energy efficiency improvement. Saunders (1992) assumes a Cobb-Douglas production function, which allows substitutability between inputs, and finds that backfire is not only possible, but may even be likely. In contrast, Howarth (1997) assumes an alternative (Leontief) production function where energy, labor, and capital are complements, rather than substitutes, and finds that backfire is not likely. A take-away from this theoretical literature is that if it is easier to substitute across inputs into production, then backfire becomes more likely.

The first empirical estimates used to describe rebound effects were simply estimates of price elasticities of demand for energy services, which are taken as a proxy for the direct rebound effect defined above. Greening et al. (2000) perform a review of the literature estimating price elasticities of demand for a variety of energy services for both consumers and firms. They find price elasticities of demand in the wide range of 0 to -0.5, with most studies falling in the range of -0.1 to -0.3 (estimates included are both long-run and short-run). This would be interpreted as a direct rebound effect of 0 to 30 percent. Greening et al. (2000) also coined the terms “direct effect,” “indirect effect,” “economy-wide effect,” “transformational effect.” The transformational effect had a vague definition relating to changing preferences and has not been continued in the subsequent literature. Schipper and Grubb (2000) make perhaps the first rough estimate of the indirect rebound effect, finding that re-spending leads to a 5 to 15 percent rebound. None of the studies estimate the substitution effect on other goods and services described above.

Since 2000, the literature on rebound effects has grown dramatically and reached beyond economics into engineering fields, such as industrial ecology. There are three key strands of current literature. Most studies on rebound effects estimate a price elasticity of demand for an energy service, call this the direct rebound effect, and stop there. But there are a few studies estimating the indirect rebound effect. In addition, there has been recent work using computable general equilibrium models and econometric simulation models aiming to estimate different macroeconomic rebound effects. The next sections discuss each of these three strands of literature in turn.

Evidence on Rebound Effects: Price Elasticities of Demand

The literature estimating price elasticities of demand for energy services is quite large with perhaps hundreds of papers. Of course, with a literature so vast, current estimates still range widely, depending on the energy service, time frame (short-run or long-run), years covered, location, and estimation methodology. Some of the most recent reviews of the literature that focus on the rebound effect include Sorrell (2007), Azevedo (2014), and Gillingham et al. (2015). Each of these papers includes a table reviewing the estimates in the literature. Broadly, estimates for the direct rebound effect still tend to be in the range of 0 to 50 percent, just as in the earlier Greening et al. (2000) review. Gillingham et al. (2015) narrows this set further by looking at only more recent studies for a variety of energy services that the authors believe deal with empirical identification issues in a convincing way; these short-run estimates are in a range of 5 to 40 percent, with most studies falling in a range of 5 to 25 percent.

Notably, most well-identified estimates of the price elasticity of demand are from developed countries, with the most common relating to transport in the United States. Sorrell (2007) and others have suggested that the direct rebound effect in developing countries may be larger since the demand for energy services may be far from saturated. Indeed, studies from developing countries show an even greater range of estimates, including some very large direct rebound effect estimates (Sorrell, 2007). Gillingham et al. (2015) argue that these should be interpreted cautiously and that most of the developing country estimates tend to fall in the same 0 to 50 percent range as estimates from developed countries.

The studies on price elasticities of demand for energy services that contribute to the ranges of estimates above tend to use detailed disaggregated data from short time periods. This is useful for understanding the price responsiveness during that time period, but says little about the responsiveness during other time periods. A few studies take a longer-term economic history perspective. For example, Fouquet and Pearson (2012) uses historical time series data on lighting in the United Kingdom from 1750 to the present and estimates a time-varying price elasticity of lighting demand. The results indicate a price elasticity in the eighteenth and nineteenth centuries that was indicative of backfire. After 1900, the elasticity was closer to zero, but still indicated a substantial responsiveness to price (e.g., in the range of -0.5 to nearly -1).

Fouquet (2012) performs a similar analysis for transport in the United Kingdom and also finds a declining responsiveness to energy service price, with the long-run price elasticity of passenger transport demand changing from -1.5 in 1860 to -0.6 in 2010. While these estimates are indicative of more responsiveness than other recent estimates of the price elasticity of transport demand from the United States (e.g., Small and van Dender (2007) and Gillingham (2014)), it is possible that they are consistent; not only is the setting is different (e.g., gasoline and diesel prices are higher in the United Kingdom) and but the time frame of the estimate is different (e.g., long-term versus short-term or medium-term).

Other long-term estimates include Tsao et al. (2010), who find backfire in lighting over several centuries and Saunders (2013), who estimates backfire or large rebound in many sectors over the past four decades. These backfire results are perhaps understood in light of the substantial assumptions involved in the analyses. For example, the estimates in Tsao et al. (2010) are based on the same Cobb-Douglas functional form from earlier work by Saunders (1992), along with many other assumptions. Saunders (2013) relies on a translog cost function, but makes other assumptions that have been critiqued (Gillingham et al., 2015). Another interpretation is that these studies are estimating something different than the rest of the literature, such as a longer-run effect that implicitly includes other rebound effects, such as macroeconomic rebound effects.

Evidence on Rebound Effects: Estimates from Policies

Rather than estimate price elasticities of demand for energy services, which hold all other attributes of the product constant and assume a costless increase in energy efficiency, a few studies relax these assumptions and analyze the rebound effect from a particular policy or treatment. Gillingham et al. (2015) name this type of rebound a “Policy-induced improvement” (PII). A perfect example is Davis et al. (2015). This study analyzes an experiment in Mexico that provides direct cash payments and subsidized financing to consumers replacing old refrigerators and air conditioners. The switch from an old to new appliance is potentially associated with a very large change in attributes, with the new appliances providing a much better energy service. Moreover, there is an income effect from the transfer. The results indicate an extremely large rebound from this policy; for instance, electricity use increases after replacement of the air conditioner and only drops by seven percent after replacement of the refrigerator.

Other examples of studies that estimate this type of rebound are Davis (2008) and Gillingham (2013). Davis (2008) examines a field experiment where households received free energy efficient clothes washers. Subsequently, they increased washing by 5.6 percent. These clothes washers were not only more energy efficient, but also were larger and gentler on more clothes, so this rebound effect estimated is the combined effect of the efficiency and the improved energy service. Gillingham (2013) estimates the effect of a policy that incentivizes consumers to purchase more efficient new vehicles in California. The results account for the differing attributes of the vehicles being purchased and imply an elasticity of driving with respect to operating costs of -0.15.

Evidence on Rebound Effects: Other Goods and Services

Given the inconsistent definition of the indirect rebound effect, it can be difficult to compare across studies. Many studies focus on only the income effects on other goods and services, which is more straightforward. Other studies aim to include at least a bound on the substitution effects on other goods and services.

To estimate the income effects on other goods and services, there are a few common approaches. Many of the studies cross over into the industrial ecology literature and rely on input-output analysis. It is also common for the studies in this literature to estimate rebound effects in terms of carbon dioxide or greenhouse gas emissions in addition to or instead of energy.

One approach is to assume proportional re-spending, so that any income available to be re-spent would be spent according to average spending patterns throughout the economy (e.g., see Lenzen and Dey (2002) and Thomas and Azevedo (2013a)). Thus the average energy intensity of economic activity is used to determine the reduction in energy savings due to the income effects on other goods and services. A concern with this methodology is that the spending of an additional marginal dollar may be very different than the average spending overall.

A second approach, aims to understand the energy implications of a marginal dollar of spending by comparing the spending patterns of consumers in different income brackets (Thiesen et al., 2008). The underlying assumption of this approach is that as any consumer becomes wealthier, they will begin to emulate consumers in higher income brackets. This is effectively using cross-sectional variation in income to estimate income elasticities. On the margin, this may be plausible, especially if the income brackets are fine enough and we are comparing consumers in the same location. The methodology is more questionable with coarse brackets or comparing consumers across a broad region. A third approach is to use income elasticities across a broad range of sectors estimated by other studies. Druckman et al. (2011), Chitnis et al. (2014), and Chitnis et al. (2013) use this approach in the United Kingdom.

Some studies use a combination of methods and also attempt to estimate both the substitution and income effects on other goods and services. Thomas and Azevedo (2013a) make several alternative assumptions using both income elasticities and the assumption of proportional re-spending. In addition, Thomas and Azevedo (2013a) aim to bound the substitution effects on other goods and services by using existing cross-price elasticity estimates.

Brannlund et al. (2007) and Mizobuchi (2008) take a different approach than all of the above studies and estimate a system of household demand equations to provide results on both the cross-price and income elasticities. This provides estimates of both the substitution and income effects on other goods and services.

The results of these studies diverge. Lenzen and Dey (2002) find very large estimates of the indirect rebound that lead to backfire when combined with the direct rebound for Australia. Thomas and Azevedo (2013a) and Druckman et al. (2011) are more recent and comprehensive studies that suggest estimates on the order of 5 to 15 percent for the United States and the United Kingdom respectively. The results in Brannlund et al. (2007) suggest backfire in Sweden, while the results in Mizobuchi (2008) account for capital costs and suggest much smaller rebound effect. Of course, these last two studies cannot be directly compared to the others, given their very different methodology.

Evidence on Rebound Effects: Macroeconomic

There are only a few studies aiming to estimate macroeconomic rebound effects, but it is an area of rapid growth. We begin with the macroeconomic price effect. While there is no question that the macroeconomic price effect exists, its magnitude depends on the slope of supply and demand curves in the energy market of interest. Borenstein (2015) performs a useful sensitivity analysis for the global market to emphasize how the effect may be quite significant depending on assumptions. Even with a relatively inelastic oil demand elasticity of -0.4 and an elastic oil supply elasticity of 1.0, the macroeconomic price effect is on the order of 30 percent.

Recent studies estimating macroeconomic growth effects tend to use computable general equilibrium models and econometric simulation models. These models include a variety of different channels, depending on the model. They generally include both microeconomic and macroeconomic rebound effects and model energy efficiency improvements as energy-augmenting technical change that has no impact on other factor inputs (Sorrell and Dimitropoulos, 2007). The range in results is wide: from negative rebound to backfire (Turner, 2009, Turner, 2013, Broberg et al., 2014).

Some notable recent estimates using econometric simulation models show macroeconomic rebound effects of 11 percent (Barker et al., 2007) and 21 percent (Barker et al., 2009). The estimates from these two papers include substitution effects on all other goods and services, but do not include the direct rebound effect (the direct rebound is treated separately). Other general equilibrium studies, such as Lecca et al. (2014), include all of the effects together, such that disentangling the different effects is not possible. More broadly, the current modeling efforts include a variety of channels, but do not tend to include macroeconomic rebounds from the macroeconomic multiplier or induced innovation, leaving these as open research topics.

Conclusions and Policy Implications

There is no debate that rebound effects can occur and are important to consider in analysis of energy efficiency policies. Rebound effects can reduce the energy and emissions savings from an energy efficiency improvement, which would reduce the energy savings of the policy. Moreover, rebound effects may have external costs associated with them, such as air pollution and carbon dioxide emissions, reducing the net benefits of the policy. Thus, rebound effects can increase the welfare difference between first-best policies, such as direct pricing of external costs, and second-best energy efficiency policies (Gillingham et al., 2015).

With such policy importance, a debate continues in the academic literature and policy communities about the magnitude of such an effect and whether anything should be done about it (Gillingham et al., 2013). A review of the literature reveals wide disparity in plausible magnitudes, depending on the context, location, and time frame of the rebound effects, as well was which of the rebound effects are quantified in the study. From a theory perspective, neither negative rebound nor backfire can be ruled out.

Fortunately, there is empirical evidence that can provide some guidance. Price elasticities of energy service demand suggest that for many energy services and contexts, the direct rebound effect is in the range of 5 to 60 percent and may be at the lower end for some important contexts where the empirical evidence is the strongest. Passenger transport in the United States is a notable example. Estimates of the indirect rebounds from the income and substitution effects on other goods and services vary as widely as the definition of the indirect rebound effect. Recent studies suggest estimates in the range of 5 to 15 percent in developed countries. Unfortunately, the evidence on both the direct and indirect rebound effects in developing countries is much weaker than in developed countries. Some recent studies are beginning to examine the rebound effects from a policy in both developed and developing countries, with varying findings depending on the context. Macroeconomic rebound effects are the least well-understood, and current estimates contain a variety of different channels, leading to a variety of different results ranging from backfire to negative rebound.

Stepping back, it is important to recognize that unless there are large external costs associated with rebound effects, they are generally social welfare improving, for they come about from the choice to use more of a valued energy service or from induced innovation (Chan and Gillingham, 2014, Gillingham et al., 2015). However, while they may be beneficial for social welfare, their existence may still reduce the energy savings from energy efficiency policy, tilting us further towards first-best policies to address externalities.

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