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Kenneth Gillingham, David Rapson, and Gernot Wagner

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The Rebound Effect and Energy Efficiency Policy

Kenneth Gillingham[*], David Rapson[†], and Gernot Wagner[‡]

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Abstract

What do we know about the size of the "rebound effect," the well-known phenomenon that improving energy efficiency may save less energy than expected due to a *rebound* of energy use? Is there any validity to the claims that energy efficiency improvements can actually lead to an *increase* in energy use (known as "backfire")? This article clarifies what the rebound effect is, and provides a guide for economists and policymakers interested in its existence and magnitude. We discuss how some studies in the literature consider a rebound effect that results from a costless exogenous increase in energy efficiency, while others examine the effects of a specific energy efficiency policy—a distinction that leads to very different welfare and policy implications. We present the most reliable evidence available about the size of the energy efficiency rebound effect, and discuss situations where such estimation is extraordinarily difficult. With this in mind, we present a new way of thinking about the macroeconomic rebound effect. We conclude that overall, the existing research provides little support for the so-called backfire hypothesis. However, our understanding of the macroeconomic rebound effect remains limited, particularly as it relates to induced innovation and productivity growth.

JEL classification numbers: H23, Q38, Q41.
Keywords: energy efficiency, rebound effect, take-back effect, backfire, Jevons Paradox.

[*] Yale University and the National Bureau of Economic Research; e-mail: kenneth.gillingham@yale.edu.
[†] University of California, Davis; e-mail: dsrapson@ucdavis.edu.
[‡] Environmental Defense Fund, and School of International and Public Affairs, Columbia University; e-mail: gwagner@edf.org.

INTRODUCTION

Buy a more fuel-efficient car, drive more. This is perhaps the simplest illustration of what has come to be known as the “rebound effect”—the phenomenon that an increase in energy efficiency may lead to less energy savings than would be expected by simply multiplying the change in energy efficiency by the energy use prior to the change. The existence of the rebound effect has been clear for a long time. In fact, Jevons (1865) hypothesized that greater energy efficiency may even lead to a “backfire,” whereby industrial energy use *increases*. However, the size of the rebound effect is much less clear. There is great variation in estimates, which stems from differences in definitions of the rebound effect, as well as in the quality of the data and the empirical methodologies used to estimate it. This has clear policy implications because both researchers and policy makers need reliable information about the magnitude of the rebound effect to evaluate the energy savings and economic welfare implications of energy efficiency policies. While the rebound effect is just one component of this more important analysis, it has received significant attention, including in the popular media, which is often in search of ‘counter-intuitive’ results.

The goal of this article is to more clearly define the rebound effect in the context of energy efficiency improvements, including clarifying its various channels, and to critically assess the literature that estimates its magnitude. In particular, we distinguish between the rebound effect from a costless exogenous energy efficiency improvement—what we will refer to here as a zero-cost breakthrough—and the rebound effect from an actual (typically costly) energy efficiency policy—what we will refer to here as a policy-induced improvement. Recognition of this distinction can be helpful for interpreting estimates in the literature, which often conflate the two, leading to inappropriate conclusions and an exaggerated rebound effect.

The most common approach in the literature for estimating the rebound effect is to empirically estimate fuel price or operating cost elasticities of demand. However, such estimates should be treated with caution precisely because they conflate the zero-cost breakthrough and policy-induced improvement effects. When we consider the cumulative rebound effect, especially if we include rebound effects that may occur at the macroeconomic level, reliable empirical estimates are much harder to come by.

The article is structured as follows. First we define the different components of the rebound effect. Then we review the quantitative evidence in the literature on the different microeconomic and macroeconomic channels of the rebound effect and discuss challenges to identifying causal rebound effects for each channel. We conclude with a discussion of the implications of the rebound effect for energy efficiency policy.[1]

DEFINING THE REBOUND EFFECT

The classic way that researchers have approached the rebound effect in the literature has been to consider an improvement in energy efficiency and then compare the *achieved* reductions in energy use to those *forecasted* without any consumer and market responses to the energy efficiency improvement. Such consumer and market-wide responses are likely to occur because the energy efficiency improvement itself changes relative prices (and, thus, real income). The

[1] Throughout the article, we highlight common misconceptions about the rebound effect and how to address them. See the online supplementary materials for a table that summarizes the main misconceptions about the rebound effect.

rebound effect is then expressed as the percentage of the forecasted reduction in energy use that is 'lost' due to the sum of the consumer and market responses.

To illustrate, consider an air conditioner with annual electricity use of 100 kWh/year. Suppose a more efficient air conditioner shaved 10 kWh/year off this total before accounting for any consumer and market responses. If these responses increased electricity use by 1 kWh/year, then the rebound effect would be equal to 10 percent – i.e., 1 of the 10 kWh per year in expected energy savings would be "taken back" due to the consumer and market responses.[2]

Exogenous vs. "Bundled" Improvements in Energy Efficiency

Although this broad definition captures the essence of the rebound effect, it neglects the way in which energy efficiency is actually improved. The literature makes different assumptions about this key issue, which can cause misconceptions about exactly what the rebound effect is, how to estimate it, and how to interpret those estimates. It is helpful to begin with the distinction between (1) an *exogenous* increase in energy efficiency (holding other product attributes constant) and (2) a change in energy efficiency that is "bundled" with changes in other product attributes (e.g., a more energy-efficient air conditioner that is also smaller overall and, thus, can work in different windows), which may induce a change in the energy service provided and perhaps also in the cost of the product.[3]

To illustrate this distinction, first consider an exogenous increase in energy efficiency—a zero-cost breakthrough—in which an innovation allows a product (e.g., an appliance)

[2] Here we follow the literature by defining the rebound effect with respect to energy. One could analogously define the rebound effect with respect to emissions (Thomas et al. 2013), which in many cases is proportional to the energy rebound. Exceptions include biofuels policies that lead to indirect land use emissions, or policies that lead to fuel switching, for example from coal to natural gas, and, thus, from carbon to methane emissions.

[3] Energy is a demand that is derived from the consumers' demand for energy *services* (e.g., miles driven in a particular car, refrigeration). These energy services themselves may change along with the attributes of a product (e.g., a refrigerator with an ice maker provides a different energy service than a refrigerator without an ice maker).

manufacturer to increase energy efficiency costlessly, while holding all other attributes of the product the same. The resulting consumer and market responses are a *pure* rebound effect because they capture only those responses induced by the improvement in energy efficiency.

In contrast, consider a policy-induced improvement, whereby a policy *requires* manufacturers to improve the energy efficiency of a particular product. In this case, the energy efficiency improvement may be costly, potentially raising the price of the product. At the same time, the policy may induce or even necessitate changes in other attributes of the product, such as size, weight or capacity. In this case, both the price of the product and the energy service it provides may change along with the improvement in energy efficiency.[4]

Thus, for both estimation and policy purposes, it is crucial to distinguish between zero-cost breakthroughs and policy-induced improvements. If we are seeking to estimate a response attributed *directly* to an energy efficiency improvement, then the zero-cost breakthrough approach is likely to be a better measure of the rebound effect. Any empirical estimation that controls for all of the key attributes of a product is aiming to identify this pure effect. In fact, this is the most common approach used to estimate what most researchers call the rebound effect.

In contrast, if we are interested in the *overall* effect of a policy—the bundle of changes that occurs, including but not limited to energy efficiency—then focusing on a policy-induced improvement is the appropriate approach. In this case, the goal would be to estimate a compound effect that combines the energy savings from the efficiency improvement with the energy adjustments due to changes in the attributes and cost of the product. This estimate may even capture changes in sales of the product or other consequences. To calculate the policy-induced

[4] There may be a continuum between zero-cost breakthroughs and policy-induced improvements, whereby a rebound effect captures some, but not all, of the changes from a policy. However, such intermediate cases may be more difficult to interpret in terms of policy implications. Thus, we focus our discussion here on the two extremes: zero-cost breakthrough and policy-induced improvement.

improvement rebound effect, one could examine the difference in the forecasted energy savings (based on a simple engineering calculation) and the empirically estimated effect. This result may be appropriate for considering the energy implications of a specific policy, but is generally not equivalent to the more 'pure' concept of the rebound effect represented by the zero-cost breakthrough approach.

Which is the Preferred Approach for Policy Analysis?

Neither the zero-cost breakthrough nor the policy-induced improvement approach is unambiguously a better choice for policy analysis. The choice depends on context, and the specific question at hand. The zero-cost breakthrough approach, which isolates the effect of an exogenous energy efficiency improvement on the consumer and market responses, provides clear guidance on how changes in energy efficiency alone would change energy use. These results are likely to be more widely applicable than focusing on a specific policy-induced improvement, because the approach holds constant potentially confounding variables. Thus, the results can be used to establish the degree to which the rebound effect improves social welfare by providing cheaper energy services that consumers value. Moreover, if policy-induced energy efficiency improvements are associated with only negligible costs and changes in attributes, then estimates for zero-cost breakthrough may be similar to those for policy-induced improvements. However, in most cases, an energy efficiency policy also causes changes in costs and attributes. It is difficult to disentangle these responses empirically because it is essential to know *all* of the pertinent consumer and market responses to the improved efficiency, the changes in attributes, and the increased cost of the product itself. All of these responses (which comprise the policy's overall effect) play a role in what ultimately matters most to policy makers: the energy efficiency policy's effects on social welfare.

MICROECONOMIC CHANNELS FOR THE REBOUND EFFECT

Before moving to empirical estimates of zero-cost breakthroughs and policy-induced improvements, it is useful to review some basic microeconomic theory to highlight the channels by which the microeconomic rebound occurs. These channels stem from the classic substitution and income effects of consumer theory. We focus only on consumer theory here, but address rebound effects from producers in our discussion of the macroeconomic rebound.

Substitution and Income Effects

When energy efficiency improves, the price of energy services changes. Substitution and income effects arise, which influence consumers' consumption of the energy services and, ultimately, energy use. Measuring these effects is not straightforward. In the case of a zero-cost breakthrough, the decline in the cost of the energy services implies that consumers will make a series of four adjustments to their consumption bundle,[5] which may in turn affect their derived demand for energy. First, consumers will substitute *towards* the more energy-efficient product, which is now relatively less expensive. Second, consumers will substitute *away from* other now relatively more expensive goods.[6] Third, the lower effective price for the energy service increases the consumer's purchasing power, which means consumers will further increase consumption of the more energy-efficient product (assuming it is a normal good). Finally, their increased purchasing power means that consumers will also increase their consumption of other normal goods. Each of these adjustments will either increase or decrease the amount of energy used for the consumer's consumption bundle.

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[5] See Borenstein (2015) for a more technical discussion of these channels of behavioral adjustment. .

[6] More broadly, consumers will change their bundle of consumption towards complements to (and away from substitutes for) the energy efficient product.

The Direct Rebound Effect

These four effects do not perfectly match the terms most commonly used in the literature on the rebound effect. The 'direct rebound effect' is generally defined as the change in energy use resulting from the combined substitution and income effects *on the demand for the energy-efficient product* (Sorrell et al. 2008). This definition is convenient because economists typically estimate elasticities of demand (e.g., the marginal change in demand for air conditioning as the operating cost of the air conditioner changes), which can be easily converted into a direct rebound effect. Using these elasticity estimates implicitly adopts the zero-cost breakthrough approach to the rebound effect, since it tells us, e.g., how much additional air conditioning consumers will use if their operating cost changes on the margin, holding all other product attributes constant. For example, if the elasticity of demand with respect to the operating cost is -0.5, then 50 percent of the reduction in energy use from an improvement in energy efficiency on the margin will be "taken back" by the substitution and income effects, which increases the energy use.[7] It is important to note that this estimate of the direct rebound effect ignores any changes in the demand for *other* goods due to either the change in relative prices or purchasing power. Nonetheless, the direct rebound effect is useful for quantifying and understanding the first order consumer response to an increase in energy efficiency.

The Indirect Rebound Effect

The effect of an energy efficiency increase on the demand for all *other* goods, and the subsequent change in energy use, is called the 'indirect rebound effect.' However, the literature is not consistent in how this term is used. Some studies include any changes in energy use resulting from changes in the demand for other goods, including substitution effects, income

[7] Note that this approach ignores the substitution and income effects on other goods.

effects, and any embodied energy used to create the energy efficiency improvement (Azevedo 2014). Other studies use the term "indirect rebound effect" even more broadly, by including substitution effects, income effects, embodied energy, and even macroeconomic rebound effects (Sorrell et al. 2008). However, the most common approach in the literature is to refer to the indirect rebound effect as including *only* the income effects on the consumption of all other goods. For example, buyers of a more fuel-efficient vehicle may decide to spend the savings on a flight for a vacation—another energy-intensive activity—or on something much less energy intensive, such as books and movies. The sign and magnitude of this indirect rebound effect depends on the difference in energy intensity (per dollar) between the energy-efficient product (prior to the efficiency improvement) and other goods consumed on the margin. It is important to recognize that this more common definition of the indirect rebound effect ignores the substitution effects on other goods that arise from the decrease in the cost of using the more energy-efficient product.[8] Along the same lines, the literature commonly ignores any cost of the efficiency improvement, even though such a cost would produce income effects—reducing (increasing) the indirect rebound effect if, before the improvement, the energy-efficient product is more (less) energy intensive than the marginal consumption bundle (Borenstein 2015).

The Microeconomic Rebound and Welfare

The income and substitution effects described here are no different from any other adjustments that consumers make when confronted with a change in relative prices. By revealed preference, consumers are enjoying private surplus gains. Thus, it follows that a net welfare *decrease* from a rebound effect is only possible if the external costs associated with these adjustments to the consumer's consumption bundle outweigh the private gains. For example, the

[8] These substitution effects are typically implicitly assumed away as being insignificant.

external pollution costs from particularly dirty electricity use could outweigh the consumer surplus benefits from consumers increasing usage of a more efficient air conditioner and re-optimizing their consumption bundle.[9]

ESTIMATING MICROECONOMIC REBOUND EFFECTS

We now turn to estimation. Because the microeconomic rebound effect consists of substitution and income effects across *all* goods, an attempt to fully measure the rebound effect would require estimating the substitution and income effects for all goods in the economy—clearly an infeasible task. Instead, most studies ignore the demand for other goods and focus on estimating the price elasticity of demand for the more energy-efficient product—the zero-cost breakthrough approach. A few studies estimate the effect of a policy—the policy induced improvements approach—although again they generally ignore effects on other goods in the economy. There are also a few estimates of the income effects from changing the energy consumption of all other goods, but these are generally based on the average rather than the marginal consumption bundle. We are not aware of any studies that estimate these own- and other-good effects jointly using comparable data sources. This may bias rebound effect estimates because a greater increase in demand for the energy efficient product (i.e., direct rebound) generally implies a smaller increase in demand for other goods (i.e., substitution and income effects on other goods) (Chan et al. 2014).

Caveats

Before discussing specific estimates, additional caveats are in order. First, to provide reliable guidance for analyses, it is critical that studies estimate a *causal* effect. This is

[9] See Chan and Gillingham (2014) for a detailed examination of these welfare effects.

particularly important when using demand elasticities to quantify the rebound effect.[10] For example, studies that rely on cross-sectional variation in fuel prices or operating costs may have difficulty controlling for unobserved heterogeneity. Such studies, even if otherwise well-executed, tend to find much more elastic demand than studies that include other sources of variation (e.g., see West (2004)).

Second, the conversion of a demand elasticity into an estimate of the direct rebound effect requires an assumption about symmetry of consumer response to changes in fuel prices and energy efficiency. Under standard neoclassical assumptions, the utilization of an energy-consuming good is based on the operating cost (i.e., the fuel price divided by the energy efficiency). Therefore, a change in both the fuel price and in the energy efficiency of the good will change the operating cost in identical (but opposite) ways. Thus, it is common in the literature to describe the fuel price elasticity of demand as being the direct rebound effect, as we will see below. However, in settings where multiple energy services use the same fuel, the fuel price elasticity and the direct rebound effect are not one and the same (Chan et al. 2014). Furthermore, recent evidence concerning passenger transportation suggests that consumers may respond less to changes in energy efficiency than to changes in fuel price (Gillingham 2011). This may occur because fuel prices are more salient: consumers see them every time they pay their energy bill. In this case, using the fuel price elasticity of demand would overestimate the direct rebound effect. However, other studies show either no asymmetry in response (Frondel et al. 2013) or a greater response to changes in energy efficiency than to changes in fuel price (Linn 2013). One potential explanation for a greater response to changes in energy efficiency is the perceived longevity of such changes. Li et al. (2014) find that gasoline taxes appear to be more

[10] Many studies estimating demand elasticities do not meet current standards for identification and fail to address standard endogeneity issues such as simultaneity.

salient than fuel prices, perhaps again due to perceived longevity. Thus, further research is needed into the symmetry of fuel price elasticities and energy efficiency elasticities.

Third, the consumer response to any change in usage costs may vary depending on the timeframe of the response. For example, when fuel prices change, in the short run consumers can choose how many trips to take, what route to take, which vehicle to take (if they have multiple vehicles), and whether to take public transportation (if available). In the medium run, they can purchase or scrap vehicles, and in the long run they can choose where to live and work. It is likely that long-run energy demand is more elastic than short-run demand; yet long-run elasticities are harder to estimate credibly, and thus harder to come by.

Finally, each estimate of price elasticities is for a particular time and place, and energy demand could vary with the specific setting. For example, Gillingham (2014) shows that the elasticity of demand for driving with respect to the price of gasoline exhibits noticeable heterogeneity across different counties in California. One could imagine that there would be even greater differences when examining a developing country or a country with an extensive public transportation system. The bottom line here is that even if an elasticity estimate is internally valid, we need to examine its external validity before applying it elsewhere.

With these caveats in mind, we next review the relevant elasticity estimates in the literature that may be useful in providing policy guidance to economists and policymakers.

Elasticities for Developed Countries

We first discuss the literature for developed countries. Given the vast number of estimates, we present selected reliable estimates, with a focus on studies of overall demand or household-level demand (Table 1).[11]

Table 1. Selected elasticity estimates for developed countries.

Study	*Type of price elasticity*	*Estimated Value*
Allcott (2011)	Illinois short-run elasticity of electricity demand, 2003 & 2004	-0.1
Barla et al. (2009)	Canada short-run elasticity of VMT demand, 1990-2004	-0.08
Frondel et al. (2013)	Germany short-run elasticity of VMT demand, 1997-2009	-0.458[ǂ]
Gillingham (2014)	California medium-run new vehicle elasticity of VMT demand, 2001-2009	-0.23
Hughes et al. (2008)	U.S. short-run elasticity of gasoline demand, 1975-1980	-0.21 to -0.34
Hughes et al. (2008)	U.S. short-run elasticity of gasoline demand, 2001-2006	-0.034 to -0.077
Ito (2014)	California medium-run elasticity of electricity demand, 1999-2007	-0.088
Jessoe and Rapson (2014)	Connecticut short-run elasticity of electricity demand, 2011	-0.12

[11] For more comprehensive reviews of estimates of elasticities in different sectors, see Greening et al. (2000); Sorrell (2007); Jenkins et al. (2011); and Gillingham (2011). Not surprisingly, these reviews show large ranges of estimates in most sectors.

Small and van Dender (2007)	U.S. short-run elasticity of VMT demand, 1966-2001	-0.045[γ]

Notes: All electricity demand elasticity estimates are for residential customers. VMT refers to vehicle-miles-traveled.

[γ] We use the estimate from the 1997-2001 period; earlier elasticities were higher in absolute value.

[ǂ] We report the fixed effects estimate, which we believe to be the most reliable.

The studies we include in Table 1 were selected because they are more recent and use rigorous empirical methods such as panel data methods, experimental or quasi-experimental designs. These studies attempt to address potential endogeneity concerns and present some evidence of internal validity. They tend not to rely exclusively on cross-sectional variation. All provide either short-run or medium-run estimates. As emphasized by Hamilton (2009) and Gillingham (2011), including a lagged dependent variable to distinguish between short-run and long-run responses requires strong assumptions. Yet, nearly all estimates of long-run responses are based on either an ordinary least squares (OLS) regression with a lagged dependent variable or on cross-sectional variation (with the assumption that it is capturing a long-run equilibrium). Thus, we believe that the short-run and medium-run estimates are more reliable.

The primary theme that emerges from our review of this literature is that the short-run and medium-run elasticities of demand for gasoline/driving and electricity are generally in the range of -0.05 to -0.40, suggesting a direct rebound effect on the order of 5 to 40 percent, with most of the studies falling in the range of 5 to 25 percent. All of these studies focus on gasoline or electricity use, and it may not be appropriate to apply the estimates to other energy services, including those that use natural gas, heating oil, or other fuels. Unfortunately, there is scant evidence on the price elasticity of demand for other energy services; all of the published papers we could find are more than a decade old and use limited data. In a review of the older literature, Sorrell (2007) finds wide ranges for most residential energy services. Thus, we believe that new research is needed on these other energy services. Moreover, new studies are needed to help us identify the size of the error from using own-price elasticities for the direct rebound.

Most of the studies cited in Table 1 are for the U.S. Because each country has unique circumstances, it may be inappropriate to apply the estimates in Table 1 to other regions and countries, both developed and developing.[12]

Elasticities for Developing Countries

For developing countries, one might hypothesize a greater elasticity of demand to price changes, and thus direct rebound effect, because of the greater unmet demand for energy services. However, there are a variety of country-specific factors that may affect responsiveness in any given market, such as the wealth of those who own vehicles or appliances. In our review of the literature, we found a surprising number of studies estimating elasticities of usage for durable goods in low and middle income countries. However, the authors of these studies often face severe data limitations and measurement error in the data. Moreover, these studies rarely meet current standards for identification in applied economics, and the caveats above certainly apply here.

Table 2 shows a representative sample of studies published in peer-reviewed journals. We have not screened these studies for reliability (as we did for the developed countries) because nearly all of them face data limitations. We should, thus, be very cautious in viewing them as

[12] For example, Frondel et al. (2013), which uses data for Germany—a country with better public transportation and higher gasoline prices than the U.S.—finds a more elastic response in driving to changes in gasoline prices than the other studies in Table 1.

causal estimates of price elasticities. These estimates of demand elasticities in developing countries range widely, with the most common range on the order of -0.10 to -0.40 in the short-run. Despite the limitations of some of these studies, it is interesting to note that the estimated elasticities for developing countries are in the same range as the estimates for developed countries.

Table 2. Representative sample of recent price elasticity estimates for low and middle income countries.

Study	*Type of elasticity*	*Estimated Value*
Al-Faris (2002)	Gulf Cooperation Council short-run elasticity of total electricity demand, 1970-1997	-0.09
Alves et al. (2003)	Brazil short-run elasticity of gasoline demand, 1974-1999	-0.09
Atakhanova et al. (2007)	Kazakhstan short-run elasticity of electricity demand, 1994-2003	-0.128[‡]
Athukorala et al. (2010)	Sri Lanka short-run elasticity of total elasticity demand, 1960-2007	-0.16
Ben Sita et al. (2012)	Lebanon short-run elasticity of gasoline demand, 2000-2010	-0.623
Crotte et al. (2010)	Mexico short-run elasticity of gasoline demand, 1980-2006	0 to -0.15
Halicioglu (2007)	Turkey short-run elasticity of electricity demand, 1968-2005	-0.33 to -0.46
Iwayemi et al. (2010)	Nigeria short-run elasticity of gasoline demand, 1976-2006	-0.25
Jamil et al. (2011)	Pakistan short-run elasticity of total electricity demand, 2000s	-0.07
Lin et al. (2013)	China medium-run elasticity of gasoline demand, 1997-2008	-0.196 to -0.497
Nahata et al. (2007)	Russia short-run elasticity of electricity demand, 1995-2000	-0.165 to -0.28
Ramanathan (1999)	India short-run elasticity of gasoline demand, 1972-1993	-0.21
Sene (2012)	Senegal short-run elasticity of gasoline demand, 1970-2008	-0.12

Zein-Elabdin (1997)	Sudan short-run elasticity of charcoal demand, 1960-1990	-0.55
Ziramba (2008)	South Africa short-run elasticity of electricity demand, 1978-2005	-0.02
Notes: Gulf Cooperation Council countries are Saudi Arabia, Kuwait, Bahrain, Qatar, UAE, Oman). All electricity demand elasticity estimates are for residential customers unless otherwise noted. ǂ We report the IV fixed effects estimate.		

Estimated Policy-induced Improvements

Estimating the rebound effect for policy-induced improvements requires more than just the fuel price elasticity of demand, since other product attributes may also have changed. Recent studies have used variation from natural experiments to estimate rebound effects in this context.

For example, in a field experiment in which households are given more efficient clothes washers, Davis (2008) finds a price elasticity of clothes washing of -0.06. This estimate is similar to a zero-cost breakthrough, but with a key difference: the new clothes washers given to the households were larger and gentler on clothes than the old washers. This means that households may have adjusted their clothes washing behavior in response not only to the change in the price of the energy service, but also to improved non-price product attributes. In fact, the increase in clothes washer use resulted from households running more clothes in each wash. This estimate is capturing the direct rebound effect of a policy-induced improvement. That is, it captures the effects from *both* the change in energy efficiency and the change in the quality of the energy service (i.e., clothes washing).

In a similar study, Davis et al. (2015), examine a program in Mexico that provides direct cash payments and subsidized financing to consumers replacing old air conditioners and refrigerators with new energy efficient appliances, much like the cash-for-clunkers program for vehicles in the United States. They find that electricity use dropped by only seven percent after replacing the old refrigerator with a new, efficient one, and that electricity use actually *increased* after replacing an air conditioner. These results suggest a potentially very large change in the energy service (e.g., the new refrigerators may have been much larger or the air conditioners quieter), as well as an income effect from the transfer, which together lead to a large apparent rebound effect from this policy.

Finally, Gillingham (2013) examines the direct rebound effect of a policy-induced change in vehicle prices that leads to consumers purchasing different vehicles (each with bundles of attributes) and then driving them more. The result is an elasticity of driving with respect to operating costs of -0.15 for new vehicles in California. We believe that further research on the rebound effect of policy-induced improvements is very important for policy.

Estimates of Rebound Effects on Other Goods

As mentioned earlier, changing the energy efficiency of a good may affect overall energy demand through changes in the demand for other goods in the consumption bundle, which occur through the substitution and income effects on these goods. Most studies seek to estimate only the income effects for other goods (calling this the indirect rebound) by answering the question: If consumers are given an extra dollar, how will they spend it?[13] One approach has been to assume that consumers make purchases associated with the average energy intensity of all consumer goods, which is often referred to as 'proportional re-spending.' Studies that follow this

[13] Specifically, we would want to know how consumers would spend the dollar on all goods *except* the more energy-efficient one.

approach generally examine the energy intensity of the economy using either input-output tables or other aggregate statistics of economic activity and energy use. A second approach is to use cross-sectional data to compare consumption patterns across income brackets (Thiesen et al. 2008). A third approach is to use income elasticities that are based on how consumers' demand for goods changes over time as income rises (Druckman et al. 2011). The findings in this literature vary, but most recent studies tend to estimate a consumption elasticity with respect to income on the order of 5 to 15 percent (Druckman et al. 2011, Thomas et al. 2013). Thomas et al. (2013) also make assumptions in order to bound the estimated substitution effects for other goods. One would expect that these effects would vary depending on the cross-elasticities between the good in question and other energy using goods, the additional cost of the more efficient good, and any additional energy use from the production of the more efficient good. It is important to note that all existing estimates assume a zero-cost breakthrough scenario. Any additional costs would reduce the income effects on other goods, thus reducing the indirect rebound. In addition, most existing estimates are for developed countries, although there has been some work on the income elasticity of energy use in developing countries (see e.g., Wolfram et al. 2012).

MACROECONOMIC CHANNELS FOR THE REBOUND EFFECT

The macroeconomic rebound effect is complex. This is because markets re-equilibrate when the demand for an energy resource changes, and an increase in energy efficiency may affect overall energy demand through several channels of adjustment. In this section we seek to clarify this issue in four ways: 1) we define the "macroeconomic rebound" and review the theoretical pathways that are thought to generate it; 2) we describe the challenges inherent in trying to quantify the magnitude of the macroeconomic rebound, including discussing common pitfalls; 3) we review what the theoretical and empirical literature tells us about the potential magnitude of the macroeconomic rebound; and 4) we discuss what this means for environmental economics research and policymaking.

Defining Macroeconomic Rebound Effects

The literature defines the macroeconomic rebound effect as an increase in energy use after an energy efficiency improvement through market adjustments and innovation channels. Such an effect is easiest to consider in the context of a zero-cost breakthrough, which underpins much of the discussion that follows.[14] We divide our discussion into a macroeconomic *price* effect and a macroeconomic *growth* effect.

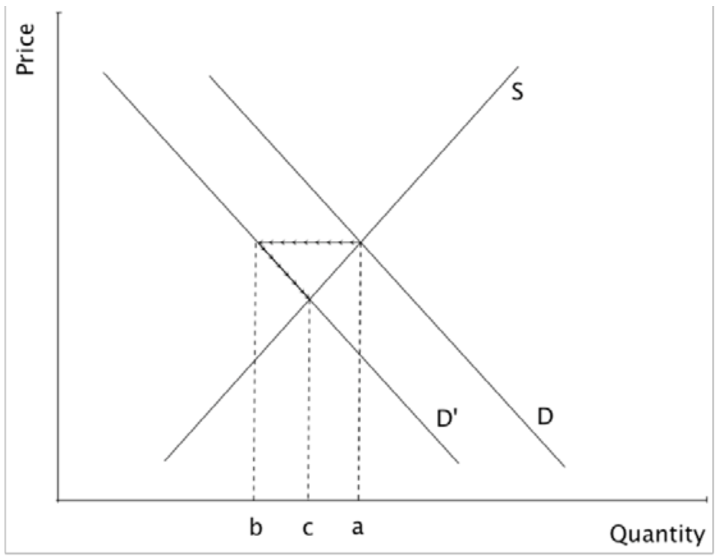
Macroeconomic Price Effect

The 'macroeconomic price effect' is an economy-wide analog to the microeconomic direct rebound effect that works through prices (Gillingham et al. 2013). When an energy efficiency improvement shifts the market demand curve for energy down (i.e., to the left), consumers and producers will adjust until a new equilibrium is reached. To illustrate, consider the global oil market. An efficiency improvement in, say, the United States, will lower the global oil price, which increases the global quantity of oil demanded. As shown in Figure 1, the initial increase in energy efficiency shifts the global demand curve down, from D to D'. Because *a* minus *b* is the shift in demand and *a* minus *c* is the change in equilibrium quantity, the

[14] Although in theory it is possible to consider macroeconomic rebound effects in the context of a policy-induced improvement, we have never seen this done in practice.

macroeconomic price effect is 1–(*a*-*c*)/(*a*-*b*). The magnitude of this rebound effect is thus a function of the slopes of the demand and supply curves, whereby increasingly inelastic supply and increasingly elastic demand induce a higher rebound.

Figure 1. *Macroeconomic Price Effect*



Note: This graph depicts the macroeconomic price effect associated with an energy efficiency policy that shifts demand inwards from *D* to *D'*. The shift in demand reduces the quantity of energy demanded from *a* to *b*; however the equilibrium outcome yields a smaller energy reduction due to the price effect, which moves quantity from *b* to *c*.

Macroeconomic Growth Effect

The 'macroeconomic growth effect,' which is often cited but poorly defined, is the rationale behind many of the "backfire" claims in the literature—i.e., that energy efficiency improvements will actually *increase* energy use.[15] In fact, the classic example given by Jevons

[15] For example, Jenkins et al. (2011) state: "The more efficient production and use of energy at a macroeconomic scale drives economic productivity overall and encourages the substitution of energy for other factors of production (e.g., labor), resulting in more rapid economic growth and energy consumption ('macroeconomic rebound' effects)."

(1865) postulates a type of macroeconomic growth effect. The basic premise is that an increase in the efficiency of energy-consuming durables may spur economic growth—and that economic growth requires additional energy consumption. There are three main channels through which a change in energy efficiency could lead to the macroeconomic growth effect.

First, sectoral reallocation may occur due to a change in the relative returns of economic sectors.[16] For example, a change in the productivity of energy inputs in an energy-intensive sector may improve the relative return on investment in that sector, leading that sector to grow relative to others. This can be (roughly) thought of as the supply-side analogy to the substitution effects discussed in the context of the microeconomic rebound.

A second potential channel is induced innovation—i.e., a shock to total factor productivity. One possibility is that an energy efficiency policy (a policy-induced improvement) leads manufacturers to update their processes, thus inducing innovation. Alternatively, a zero-cost breakthrough in one sector may spill over to others. For example, the development of lighter-weight aircraft to improve aircraft efficiency may spill over to other sectors and lead to lighter-weight vehicles. Of course, to be considered a rebound, the innovation in other sectors must be directly attributable to the spillovers from the energy efficiency improvement. Should such spillovers exist, they could increase or decrease energy use in the other sectors.

The third potential channel for the macroeconomic growth effect concerns the deployment of inframarginal resources (i.e., money in the economy that would previously have been spent on energy) that are freed by a zero-cost breakthrough. These may be subject to a fiscal multiplier (e.g. see Ramey 2011). That is, dollars that were previously spent on energy can now be spent in ways that engage "new" economic activity that utilizes previously idle

[16] Sectoral reallocation in response to changing costs is equivalent to a reallocation of inputs into aggregate production in response to changing costs.

resources. Surplus created from this new activity may cause the overall economic impact to exceed the initial amount by some multiplier (Borenstein 2015). Of course, for such a multiplier effect to occur, idle resources must be available so that the incremental resources do not simply crowd out private investment. Although this may be the case during recessions, it is less likely to be the case during economic upswings. More generally, there is strong disagreement among macroeconomists about the size of the fiscal multiplier (Ramey 2011). However, the multiplier in the rebound setting is slightly different because there is long-term debt associated with fiscal stimulus, but not with a zero-cost breakthrough. We are not aware of any study focusing directly on estimating such multipliers in the context of energy efficiency. We turn next to the challenges of estimating macroeconomic rebound effects.

Challenges of Estimating the Macroeconomic Price Effect

The magnitude of the macroeconomic price effect depends on the relative supply and demand elasticities.[17] If the demand elasticity is low and the supply elasticity is high, then the effect will be small. The estimates discussed earlier concerning the price elasticity of gasoline use suggest a relatively inelastic oil demand function, at least in the medium-run. The supply of oil is considered to be relatively inelastic in the short-run due to capacity constraints. However, oil supply would be expected to be more elastic in the long-run because it depends on how development of new extraction technologies responds to price. Unfortunately, there is very little empirical evidence on such supply elasticities. Borenstein (2015) uses oil supply elasticities of

[17] This should be clear from Figure 1.

0.2, 0.6, and 1.0 for a sensitivity analysis of the macroeconomic price effect, but asserts that the long-run oil supply elasticity may be rather high.[18]

The estimates in Borenstein (2015) indicate that with an oil demand elasticity of -0.4 and an oil supply elasticity of 1.0, the macroeconomic price effect is approximately 30 percent. Using linear demand and supply functions, we arrive at a similar result. However, the possible range for the macroeconomic price effect is quite large: with a supply elasticity of only 0.2 and demand elasticity of -0.6, we can expect to see a macroeconomic price effect as large as 76 percent. We believe that it is far more likely that long-run oil supply is highly elastic, so we would not expect an effect *this* large, even if it is possible. Given the likely high long-run oil supply elasticity and low or moderate demand elasticity, we suspect that the macroeconomic price rebound in oil markets is on the order of 20-30%. However, we have not yet seen evidence for other energy markets (e.g., electricity, natural gas). Moreover, for all markets, it is important to recognize that the macroeconomic price effect will always be less than one (demand curves slope downward and supply curves slope upward, by construction). This means that it is theoretically impossible for backfire to occur due solely to the macroeconomic price effect.

Challenges in Estimating the Macroeconomic Growth Effect

Despite being central to backfire claims, the macroeconomic growth effect is the rebound effect topic with the least amount of concrete evidence. Attempts to quantify the macroeconomic growth effect are plagued by the same challenges that are encountered in most macroeconomics research. That is, the global economy is a single, interconnected, complex dynamic system,

[18] Given the remarkable innovations in oil extraction over the past several decades due to high oil prices, we agree with Borenstein's assertion.

making definitive arguments about cause and effect nearly impossible. This means, for example, that we cannot say with *empirical* certainty how U.S. fuel economy standards affect long-run energy use in the U.S., let alone in China.

Fortunately, basic economic theory provides some clear guidance on the macroeconomic growth rebound most commonly discussed: sectoral reallocation. The key theoretical insight is that the extent to which a zero-cost breakthrough leads to increases or decreases in overall energy use depends on the elasticities of substitution in consumption and production. To illustrate, consider a household that consumes two goods—an aggregate consumption good (e.g., food or clothing) and an energy service (e.g., driving). This means that households can use their income to purchase either the consumption good or a car and the energy to power it. The question of interest here is: what happens to *aggregate* energy use in the economy if cars are made more energy efficient?

In the consumer sector, the answer depends on the elasticity of substitution between goods and energy services in the household utility function. To illustrate, let's consider the extremes. If goods and energy services are perfect substitutes, then the household will spend its entire budget on whichever good has the highest utility per dollar spent. If energy services become less expensive than goods (in utility per dollar), then the household may shift its entire budget toward energy services. On the other hand, if goods and energy services are perfect complements, then they will be optimally consumed in fixed proportion. In this case, making one of the goods marginally cheaper (e.g., through energy efficiency standards) will make little difference in consumption and overall energy use because energy is a derived demand (i.e., from energy services). This means that although zero-cost breakthroughs may cause the level of *energy services* to increase, less *energy* will be used than before the zero-cost breakthrough.

Based on these two extremes, it is clear that there must be a high degree of substitution towards energy services in consumption for the level of actual energy use to increase above pre-energy efficiency improvement levels.

So far, the logic we have presented is the same as the logic behind the microeconomic substitution effects. This means that the consumer substitution effects will be contained in estimates of the sectoral reallocation effect. But sectoral reallocation is even broader; it depends not only on patterns of consumption, but also patterns of production. For production, precisely the same logic applies as for consumption. Where production occurs by combining energy inputs with non-energy inputs (e.g., capital and labor), the degree of substitutability/complementarity in production determines the overall effect of a zero-cost breakthrough on energy use. If the inputs are highly substitutable, an increase in energy efficiency in production will cause a large swing towards increasing energy inputs. If they are complements, they must be used in fixed proportion, and energy demand will remain unchanged.

A useful implication of these theoretical insights is that the sectoral reallocation rebound is largely driven by the magnitude of substitution elasticities. Intuitively, we would view energy and non-energy inputs as being more complementary than substitutable in both consumption and production because energy cannot be directly consumed; rather, we use it to help us meet our broader consumption needs. This intuition is shared by Goulder et al. (1999), whose simulation model of alternative abatement policies assumes complementarity of energy and other inputs to production.[19] This leads us to believe that macroeconomic growth rebound effects are likely to

[19] Goulder et al. (1999) assume an elasticity of substitution of 0.8. It may be even lower in the context here, since the energy efficiency intervention itself will already dictate substitution towards more energy efficient production technology.

be small. However, there is clearly a need for more research to quantify the relevant substitution elasticities.

Empirical Evidence on the Macroeconomic Growth Effect

The theoretical insights just discussed are particularly useful when interpreting the empirical literature on the macroeconomic growth effect, which focuses primarily (but not exclusively) on sectoral reallocation. Other channels may be implicitly included in the macroeconomic growth effect, but to the best of our knowledge have not been identified separately. There are three strands in the literature that quantify the macroeconomic growth rebound. The first strand uses a structural model of the production function of the economy to make theoretical predictions about the rebound effect. The second attempts to econometrically estimate the total rebound effect (macroeconomic and microeconomic) using historical time series data. The third involves simulation models of the economy based on input-output tables of economic activity and calibrated relationships between key variables governing economic growth.

Structural Models

Beginning with Saunders (1992), there has been a stream of studies in the energy economics literature that relies on a neoclassical growth model to provide theoretical insight into the sectoral reallocation rebound. For example, using a single sector neoclassical growth model that includes capital, labor and energy inputs, Saunders (1992) examines how energy efficiency improvements affect overall energy consumption. In this simple setting, the consumer considers energy-intensive goods as perfect substitutes for non-energy-intensive goods. Thus, by construction, Saunders finds that 'backfire' can occur.

Our concern with this and many other models in this literature is that they rely heavily on structural assumptions. For example, switching to a production function that assumes perfect complementarity of inputs (i.e., a Leontief production function) would immediately imply *zero rebound*. Of course, the structural assumption here is just as restrictive as in the single sector neoclassical growth model. While such theoretical exercises are interesting, their limitation is that nearly any outcome is possible depending on the choice of structural assumptions and functional forms.

Econometric Estimates

Although this observation should not be surprising to macroeconomists, these limitations of structural models have made the use of empirical analyses all the more important for providing reliable guidance on the magnitude of the macroeconomic growth rebound. However, this is where demonstrating *causality* is critical—but also extremely difficult. For the last century, we have seen large increases in both energy use and the energy efficiency of many durable goods. But in order to claim a causal relationship between energy efficiency and energy use, it must be shown that energy consumption has not increased due to some other factor. Ideally, the experiment needed to identify a zero-cost breakthrough would consist of two worlds—one with the zero-cost breakthrough and one without. Unfortunately, as for many issues in macroeconomics, such an experiment is impossible. In fact, it is extremely difficult, if not impossible, to separate the effect of energy efficiency improvements from exogenous economic growth and the simultaneous dramatic improvements in energy services. Not surprisingly, the few econometric investigations that have relied on historical data to provide evidence of a combined macroeconomic and microeconomic rebound effect leading to backfire (e.g., Tsao et al. (2010) and Saunders (2013)) have not been published in economics journals, where the standard for empirically identifying a causal effect tends to be higher.

Simulation Models

In the absence of credible empirical strategies, macroeconomists often build models of the economy that *simulate* the effects of policies. This brings us to the third class of approaches used to estimate the macroeconomic rebound effect: calibrated simulation models. These models tend to be general equilibrium models based on input-output tables of economic activity or estimated macro-econometric models with hundreds of equations. Of course, the results of such models are driven by the structure of the model and the parameterization of the relationships. For this reason, many macroeconomic modelers focus on modeling to build intuition, rather than numerical estimates.

The simulation models that are used to numerically estimate the macroeconomic rebound effect compare total energy consumption in a scenario that slightly perturbs the energy efficiency parameter to total energy consumption in the business-as-usual case. If the change in predicted energy use is less than the expected effect of energy efficiency, then the difference is attributed to the rebound effect; if total energy increases, it is consistent with backfire. Some of the most interesting studies in this literature build computable general equilibrium or econometric simulation models of the U.K. economy (e.g., Barker et al. 2009, Barker et al. 2007, Turner 2009). These find results ranging from negative rebounds to massive backfire. This large range of results is very useful for considering the implications of different combinations of structural assumptions and parameter values for the macroeconomic rebound effect. But the reliance of these studies on correlations to parameterize key relationships in the models leaves us unconvinced that they truly pin down the magnitude of the rebound effect. Thus, another valuable area for future research would be analyses that combine clever new empirical approaches with careful numerical simulations.

Implications for Environmental Economics Research and Policy

What does this discussion of the challenges of quantifying the macroeconomic rebound effect tell us about its likely magnitude? Note first that estimates of the sectoral reallocation macroeconomic rebound are *not* necessarily additive with respect to the *microeconomic* rebound effects, which are typically already aggregated into the macroeconomic measure. In addition, the macroeconomic price and sectoral reallocation effects may be partly offsetting because sufficiently lower equilibrium energy prices can lead to a reallocation away from energy (Turner 2009). Moreover, to the extent that numerical simulations are based on historical *correlations*, rather than causal effects, we need to be cautious about interpreting point estimates too literally.

That said, it is possible that there is a substantial macroeconomic growth effect in certain circumstances. Moreover, it appears likely that there is at least some increase in energy consumption from the macroeconomic growth effect, given that it has a theoretically sound basis. Thus, when considering a zero-cost breakthrough, we would recommend that the best current approach for a policy economist would be to calculate the macroeconomic price effect based on the best estimates of elasticities, and then perform a sensitivity analysis using different values of the macroeconomic growth rebound effect. Two recent estimates of the macroeconomic growth rebound that could be considered for such a sensitivity analysis are 11 percent (Barker et al. 2007) and 21 percent (Barker et al. 2009).[20] We do not believe that the literature currently provides convincing evidence of a backfire due to the macroeconomic rebound effect.

What does a macroeconomic rebound mean for the welfare effects of policy? The macroeconomic price effect of an energy efficiency improvement arises from reaching equilibria in markets, which improves welfare. Sectoral reallocation leads to more efficient production in an economy, improving welfare. If the energy efficiency improvement induces innovation, this would also improve welfare. However, because these welfare gains may be countered by losses from greater external costs of production or consumption, the net welfare effects are ambiguous.

CONCLUSIONS AND IMPLICATIONS FOR POLICY

The debate about the magnitude of the rebound effect continues, and has important implications for energy efficiency policy. This article has attempted to inform this debate through three main contributions. First, we have introduced the important conceptual distinction between a rebound effect associated with a costless energy efficiency improvement that holds other attributes constant (zero-cost breakthrough) and an energy efficiency policy that may be bundled with other product changes that affect energy use (policy-induced improvement). Second, we have distilled the empirical literature on the microeconomic rebound into a manageable number of estimates that we believe are the most reliable. Third, we have attempted to clarify the nature of the macroeconomic rebound and have presented an approach for conceptualizing (or estimating) the size of the effect.

[20] This 21 percent is based on the 2020 estimate, while the estimate for 2030 is 41 percent. However, both estimates include the income effect within the macroeconomic rebound.

We find that the existing literature does not support claims that energy efficiency gains will be *reversed* by the rebound effect. Thus we would argue that the continued focus on backfire in policy debates is largely unwarranted, and is perhaps distracting attention from the most important issues, such as the welfare implications of energy efficiency policies. In most cases, the total microeconomic rebound has been found to be on the order of 20 to 40 percent when all substitution and income effects are included (and perhaps even when the embodied energy in the energy efficiency improvement is included). Far less is known (or knowable) about the macroeconomic rebound. However, we have presented a framework that suggests three conclusions about the macroeconomic rebound. First, although in some markets the macroeconomic price effect may be substantial, it must always be less than 100 percent. Second, the rebound based on sectoral reallocation is likely smaller than the price effect because energy is more likely to be a complement to, rather than substitute for, other inputs in production. Finally, little is known about the effects of induced innovation and productivity on the rebound effect, beyond observing that such developments would almost certainly be welfare-increasing. In particular, there is a lack of consensus in the literature that examines how regulation affects total factor productivity. Nevertheless, if induced innovation and productivity lead to a rebound, then quantifying the effect would face the difficult challenge of determining a counterfactual path of innovation and productivity. There is currently scant evidence on this induced innovation channel and thus further research is needed on this topic.

The cumulative effect of these channels of rebound in a zero-cost breakthrough setting may be large in some situations and smaller in others. If pressed to offer our subjective assessment, in most cases we do not expect the total rebound effect to exceed 60 percent, but we recognize that it is possible to have a larger total effect.[21] One might expect a policy-induced improvement to have a larger rebound due to associated changes in product attributes that consumers value, but a smaller rebound to the extent that the cost of the policy mitigates both the income and macroeconomic growth effects. In fact, sufficiently costly energy efficiency policies may well engender negative rebound effects. In sum, while the energy savings from energy efficiency policies will be reduced by the presence of a rebound effect, a zero-cost breakthrough rebound is likely to both conserve energy and increase welfare. The same may be true for a policy-induced improvement rebound, but each policy will require its own analysis.

A primary conclusion of our review is that unless the rebound effect has severe external costs, it will be a benefit, rather than a cost, of an energy efficiency policy. Unfortunately, the focus on minimizing energy use, rather than the broader objective of maximizing economic efficiency, has caused some policy makers to make the mistake of designing policies to 'mitigate' the rebound effect. Such efforts, as discussed in the literature (e.g., van den Bergh (2011)) and the policy community (e.g., Gloger (2011)), are likely counterproductive from a welfare perspective. Rather than considering the rebound effect as a deterrent to passing energy efficiency policies, policymakers should include the welfare gains and losses as part of their analysis of the benefits of a policy.

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[21] This 60 percent estimate is based on a 30 percent long-run microeconomic rebound, 25 percent macroeconomic price effect, and 5 percent macroeconomic growth effect (accounting for the fact that estimates of the macroeconomic growth effect both range widely and may be implicitly including some of the other rebounds).

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