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RESPONSE

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Energy efficiency: rebounding to a sound analytical perspective

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Abstract

Recent controversy suggests that energy efficiency policies used to reduce carbon emissions might actually increase overall energy consumption. The result would be an unintended increase in carbon emissions. This paper examines the underlying issues of this so-called "rebound effect" from both a historical perspective and through the results of a recent macroeconomic analysis completed for the United States. Depending on the assumptions of income and price elasticities, as well as the supply/demand interactions within a macroeconomic model, the rebound effect might reduce overall savings by about 2-3% compared to a pure engineering analysis. In other words, an economy-wide, cost-effective engineering savings of 30% might turn out to be only a 29% savings from a macroeconomic perspective. Despite the impact of a rebound effect, the net result of energy efficiency policies can be a highly positive one. Published by Elsevier Science Ltd.

Keywords: Elasticities; Macroeconomic perspectives; Energy policies

1. Introduction

A modest little article in a recent issue of New Scientist seems to have resurrected a vigorous debate on whether energy efficiency actually saves energy, or, in fact, whether it encourages greater energy use. The article by Pearce (1998) notes: "A leading green analyst is now claiming that policies to promote energy conservation could trigger such a sharp fall in energy prices that fuel use and emissions of greenhouse gases will actually rise. And several influential economists agree".

While some economists may agree about this so-called rebound effect, the more appropriate question may be, does the market itself believe that increased energy efficiency will accelerate overall energy consumption? In a recent exchange of e-mail on this topic with a colleague (also an economist), we wondered that if the energy industry actually believed this line of thinking, why would it not be arguing for a heavy promotion of energy-efficiency programs across the board? (DeCanio, 1998)

Still, there is a need to take the question seriously to better understand its impacts. In the process of unbundling the different issues that are embedded in the concept, there is a need to clarify both the opportunity and the limitations for energy efficiency as a climate change policy. This article examines the question from the macroeconomic perspective by exploring three different aspects. What is the real question that is to be asked? What is the historical perspective of efficiency trends within the US economy? And what can recent modeling exercises tell us about the magnitude of the rebound effect? The article then concludes with observations about what level of analysis may still be needed to assist policy makers with insights about cost-effective opportunities to reduce energy consumption and still maintain net economic benefits.

2. Background

Particularly following the 1973 OPEC Oil Embargo, a number of prominent books and articles were written that documented the opportunities and benefits of improved energy efficiency (Energy Policy Project, 1974; Hayes, 1976; Lovins, 1977). By 1980, however, Khazzoom (1980) advanced the argument that because...
energy efficiency investments reduced the cost of energy services, such investments would result in a "rebound effect" that would tend to offset at least part of the initial energy savings. Brookes (1990) further suggested that if reductions in energy use per unit of output are cost-effective, then such reductions would lead to increases rather than decreases in energy use within the larger economy. As other authors extended this thinking (Sauders, 1992; Inhaber and Sauders, 1994), the notion became known as the "Khazzoom-Brookes postulate".

Howarth (1997) examined the Khazzoom-Brookes hypothesis and concluded that: (1) since energy costs do not generally dominate the total cost of energy services, and (2) since expenditures for energy services do not constitute a large share of economic activity, then energy efficiency improvements will generate long-term reductions in energy use. DeCanio (1997) provided a series of calculations to show that if the economy is operating on the production possibilities frontier, technical progress in the production of ordinary goods and services will always result in increased production of those goods and services. It will also result in the improvement of environmental quality if ordinary goods and environmental quality are complements rather than substitutes with respect to consumer preferences.

DeCanio further noted, however, that if we relax the assumption that the economy is operating on the production frontier and acknowledge that there exists an efficiency gap, then a tradeoff between the environment and the production of ordinary goods and services is no longer inevitable. The existence of an energy efficiency gap has been documented by a number of groups, most recently the American Council for an Energy-Efficient Economy (Geller et al., 1998) and the World Wildlife Fund (1999), among others.

3. Historical perspective

We can examine the more recent trends since the OPEC Oil Embargo to understand better the contribution of improved energy efficiency within the US economy. In 1973 the United States consumed about 78.4 exajoules (EJ) of primary energy. For every dollar of Gross Domestic Product (with GDP measured in constant 1992 dollars), the economy then required an estimated 20.0 megajoules (MJ) of primary energy. Today, the US economy — hovering around $7.6 trillion (again in 1992 dollars) — now requires about 13.2 MJ per dollar of GDP. This means that, as a nation, the United States consumes about 100 EJ of primary energy (EIA, 1998a, b).

Had there been no decline in the nation's energy intensity since 1973, a rising US economy would have pushed annual energy consumption closer to 150 EJ by 1998. Looking deeper into the influences behind these numbers, we might draw two important conclusions.

The first conclusion is that some combination of factors did, in fact, allow the nation's energy intensity to abate in an economically positive manner. The reasons included structural change (i.e., emphasizing a greater mix of services within the economy instead of the production of manufactured goods), changed consumer preferences, and investments in energy efficiency. Golove and Schipper (1997), for example, have suggested that about 75% of the decline in E/GDP is the result of lower energy intensities with the balance the result of structural changes in the economy.

The second conclusion is that, although the nation’s rate of energy intensity has been reduced by about 30% since 1973, the United States can do better. A "normal" rate of decline will lower the nation's energy intensity from 1.32 to 11.8 EJ by the year 2010. However, the nation’s GDP will likely increase at a faster rate than this — to perhaps $9.9 trillion. As a result, total energy use will increase to about 117 EJ by 2010 (EIA, 1998b). This increased consumption means there will be an increase in both carbon emissions and other pollutants.

At the same time, there are a variety of studies by groups as the Alliance to Save Energy and the Tellus Institute which suggest that existing or near-term technologies can improve the nation’s energy intensity to 10.2 MJ or less by 2010 (ASE, 1997). This implies that the nation’s energy use might be reduced to 101 exajoules in 2010 — despite the growth in GDP. If, at the same time, we begin switching to lower carbon fuels, overall carbon emissions could be closer to 1250 million tonnes (MtC) in 2010 compared to the 1790 MtC forecasted by the Energy Information Administration’s Annual Energy Outlook 1999 (EIA, 1998b).

The smaller level of carbon emissions would allow the US to meet its international commitment on climate change as outlined in the so-called Kyoto Protocol. The precise timing and the mix of policies that are needed to move us onto this more efficient path have yet to be spelled out, however.

But how does the Khazzoom-Brookes postulate fit into all of this? First, there is the very real possibility that energy efficiency investments will improve overall national income and reduce energy prices. That greater level of income, coupled with possibly lower energy prices, may cause overall energy use to rebound at a faster clip than the rate of efficiency improvements. History has suggested that this is an unlikely outcome, however. Recall that since 1973, when the nation’s income was about half of what it is today, energy intensity has improved by better than 30%, dropping from 20.0 to 13.2 MJ per dollar of GDP.

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4. An indicative example

Still, there is likely to be some measure of rebound as a result of improved GDP and potentially lower energy prices. Yet, the rebound will undoubtedly be small compared to the overall gains in efficiency and low-carbon fuels. To illustrate this point in a simplified and straightforward manner, let us set up a functional relationship between carbon emissions and a combination of GDP, energy prices and technology policy. The purpose will be to highlight the key changes in economic variables as they might affect changes in carbon emissions between the years 1998 and 2010:

\[
\text{MtC}_{2010} = \text{MtC}_{1998} \times \text{GDP}^{\text{elasticity}} \times \text{NRG price}^{\text{elasticity}} \times \text{Tech Policy},
\]

Starting with carbon emissions in 1998, the anticipated growth in GDP, coupled with a positive elasticity, indicates a growth in carbon emissions as measured in million tonnes (MtC) for the year 2010. If energy prices are to increase as well, this will tend to put a downward pressure on carbon emissions since the elasticity will be negative. Finally, an aggressive technology policy that accelerates investments in low-carbon technologies would be expected to further reduce carbon emissions. The prospective array of low-carbon technologies includes energy efficiency, fuel switching, and renewable energy resources.

Drawing from the Annual Energy Outlook 1999 (often referred to as the AEO99), we can adapt an indicative analysis to compare the reference case growth in carbon emissions between the years 1998 to 2010. Hence, we can parameterize the above expression with reasonable values drawn from AEO99 as:

\[
\text{MtC}_{2010} = 1484_{1998} \times 1.31^{0.82} \times 1.12^{-0.30} \times 1.00 = 1790.
\]

According to the most recent EIA data, US carbon emissions are estimated to be about 1484 MtC for 1998. Compared to the 1998 level, real GDP is projected to increase 31% by the year 2010. For purposes of this illustration, and based upon AEO99 estimates, we adopt an income elasticity of 0.82. Energy prices are similarly expected to increase, according to AEO99, but by the much smaller 12.0%. Consistent with economic theory, the price elasticity is negative. Again staying within the framework of data from AEO99, it is shown here as -0.30. Finally, if we assume an unchanged technology path for the AEO99 reference case scenario (giving us a coefficient of 1.00), then total carbon emissions would be projected to rise by 20.6% above the 1998 level to an estimated 1790 MtC in the year 2010.

But let us now assume a set of policies designed to strengthen the technology response such as those envisioned in the Energy Innovations study. This was published by a consortium of research groups in the United States (ASE et al., 1997). Let us further assume that the technology "innovation path" is designed to reduce emissions to seven percent below 1990 levels, or to about 1252 MtC. This implies that technology policy would need to drop carbon emissions by about 30% compared to the reference case forecast. In this circumstance we might find the following relationship:

\[
\text{MtC}_{2010} = 1484_{1998} \times 1.31^{0.82} \times 1.12^{-0.30} \times 0.70 = 1282.
\]

But, in fact, this level of technology response is unlikely to leave either GDP or energy prices at the same level as in the reference case. As is shown later, GDP might be expected to increase slightly while energy prices would be expected to fall. The latter would decrease somewhat as a result of both technology improvements in the supply of energy and a somewhat lower demand for that energy. For purposes of this illustration, we will assume that GDP would grow about 1% more than in the reference case, while energy prices decline by about six percent over the reference case as a result of that reduced demand. Here we might see the following expression:

\[
\text{MtC}_{2010} = 1484_{1998} \times 1.31^{0.82} \times 1.12^{-0.30} \times 0.70 = 1252.
\]

Based strictly on an engineering analysis, we might estimate a decline in carbon emissions from 1790 to 1252 MtC, or a decrease of about 30%. Including the feedbacks of higher a income (in the form of a larger GDP) and the lower energy prices as shown above, however, we find carbon emissions reduced by only 28.0%. Hence, the so-called rebound effect appears to increase carbon emissions by about 2.4% as shown in this indicative example (or 1282/1252 - 1).

We can extend this analysis in yet another direction. With the income and price elasticities shown above, we might ask: "To what level would GDP need to rise in order for the rebound effect to totally offset the carbon emission reductions as otherwise suggested above?" It turns out that by holding all else equal and solving for the desired value in the second equation above, GDP would need to increase to an index of about 2.03 instead

It should be noted that the elasticity estimates used in this exercise are well within the range of both theory and the literature.
of 1.31 in order for this to happen. That is: a 30% improvement in the efficiency of the nation's energy technologies (which accounts for roughly seven percent of overall GDP) would have resulted in a 55% increase in GDP from what would have happened otherwise! There is no endogenous growth theory that will give us that kind of rebound effect!

Similarly, and all other things being equal, primary energy prices would need to be at 34% of what they are today in order for the rebound effect to offset the carbon reductions made possible by the high efficiency scenario. In this case, the 30% efficiency progress would have to trigger a 66% reduction in the price of primary energy resources. This scenario would clearly not be compatible with the relatively high level of energy demand — perhaps only 15% less than the business-as-usual scenario.

If we try to combine the two factors, we might find that the rebound would need to trigger a 22% increase in GDP from business-as-usual (from 1.31 to 1.60) and the primary energy price would need to be 42% lower (at an index value of 0.58). These scenarios are clearly unrealistic. Assuming that the elasticities referenced above are well within the literature, with this simple method, we can, therefore, demonstrate that the full rebound effect stands little probability of occurring.

An integrated technology scenario analysis

Building now on a recent analysis released by the US Environmental Protection Agency (EPA) and the Lawrence Berkeley Laboratory (LBNL), we can use actual modeling results to underscore the points made in the indicative exercise shown above.

The perception among many policy makers and industry leaders is that the twin objectives of reducing greenhouse gas emissions and promoting a more competitive economy are inherently contradictory. However, the EPA/LBNL analysis indicates that a technology-led investment strategy can secure substantial domestic reductions at a net positive impact on the US economy (Koomey et al., 1998). The reason is that at any given level of economic activity — and even at current energy prices — the US economy falls short of a cost-effective level of overall carbon efficiency (measured as the number of kilograms of carbon emitted per constant dollar of GDP).

Most modeling of the costs of reducing carbon emissions understates the opportunity for widely available but underutilized and cost-effective technologies to reduce greenhouse gas emissions. The new EPA/LBNL report describes possible technology-based scenarios for the US energy system that would result in both carbon savings and net economic benefits.

The study used a modified version of the Energy Information Administration's National Energy Modeling System (LBNL-NEMS) to assess the potential energy, carbon, and bill savings from a portfolio of carbon saving options. This analysis is based on technology resource potentials estimated in previous bottom-up studies, including an analysis sponsored by the US Department of Energy (Interlaboratory Working Group, 1997) and the previously cited Energy Innovations analysis. The information from these studies was integrated into the LBNL-NEMS framework to assess interactions and synergies among the many technology options.

According to the EPA/LBNL study, the US economy emitted about 190 g of carbon for each dollar of value-added that is produced in 1998 (measured as GDP in constant 1996 dollars). With a “normal rate of improvement” in the reference case, it appears that by the year 2010, the nation would reduce this emissions rate to about 173 g per dollar. Despite this improvement in the emissions rate, however, the anticipated growth in the economy will increase total carbon emissions to 1803 MtC in 2010 as previously stated. Again, this is about 18% above 1998 levels projected in the study.

The EPA/LBNL analysis further suggested that implementing a set of policies to encourage the development and deployment of energy-efficient and low-carbon technologies could close this gap — to the benefit of both the climate and the economy. Based upon what might be termed a moderately aggressive engineering analysis, an energy efficiency/low-carbon technology path could reduce carbon emissions by about 280 MtC by 2010. Once these parameters were mapped into the LBNL-NEMS model, the macroeconomic interactions reduced this potential to about 274 MtC. In other words, the dynamic integration of supply, demand, income, and prices within the model generated a rebound effect that first sought to reduce emissions to 1523 MtC (or 1803-280 MtC), but then settled on an amount that was 6 MtC larger, or 1529 MtC. Consistent with the simplified example reviewed above, the rebound effect within the LBNL-NEMS study amounted to about a 2.2% reduction from the non-integrated analysis.

The integrated technology scenario analyzed in the EPA/LBNL study would result in significant annual net savings to the US economy — even after accounting for all relevant investment costs, program implementation costs, and the so-called rebound effect. This strategy implies that roughly at least 50% of the carbon reductions needed for the US to meet the Kyoto protocol — assuming a 7% below 1990 level — could be achieved with domestic technology investments. Not pursuing this technology-led investment strategy would have an opportunity cost of more than $50 billion per year for the US economy in 2010 (Koomey et al., 1998). Other studies (e.g., Energy Innovations) indicated an even larger economic benefit for the United States.
6. Conclusions

The evidence strongly suggests that cost-effective energy efficiency investments can reduce overall energy consumption within an economy (Laitner et al., 1998). Still, a change in “consumer preferences” could diminish these prospective gains. If, as a result of efficiency improvements, both consumers and businesses choose a greater utility that is energy-consuming (e.g., turning down the thermostat to increase the level of cooling in homes and offices), then that change in consumer preference may erode even more of the efficiency benefit. Nonetheless, increased awareness about the link between energy consumption and environmental impacts, coupled with continued improvements in the design of energy-consuming technologies, should minimize significant changes in consumer preferences that would otherwise lead to increased energy consumption. The Khazzoom–Brookes postulate notwithstanding.

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Energy efficiency and consumption — the rebound effect — a survey

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Abstract

Technology policies are one of the options available for the reduction of carbon emissions and the usage of energy. However, gains in the efficiency of energy consumption will result in an effective reduction in the per unit price of energy services. As a result, consumption of energy services should increase (i.e., "rebound" or "take-back"), partially offsetting the impact of the efficiency gain in fuel use. Definitions of the "rebound" effect vary in the literature and among researchers. Depending on the boundaries used for the effect, the size or magnitude of this behavioral response may vary. This review of some of the relevant literature from the US offers definitions and identifies sources including direct, secondary, and economy-wide sources. We then offer a summary of the available empirical evidence for the effect for various sources. For the energy end uses for which studies are available, we conclude that the range of estimates for the size of the rebound effect is very low to moderate. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Energy; Conservation; Rebound; Energy demand

1. Introduction.

Potential carbon reductions resulting from technological improvements in the consumption of energy may be reduced by the "rebound" effect (Wigley, 1997). The "take-back" or "rebound" effect refers to an increase in the supply of energy services1 with a corresponding decrease in the effective price, the size of which depends upon the underlying cost structure. This in turn may result in an increase in demand in response to these price decreases. Therefore, increased demand for the service, without an offsetting increase in fuel price,2 can erode technological efficiency3 gains. Although this premise is undeniably rooted in neoclassical economic theory, the real controversy lies in the identification of sources and size of the rebound. Depending on the definition used for the rebound, the size of this effect can be either insignificant or can result in an increase in fuel consumption (Grubb et al., 1995; Grubb, 1996; Brookes, 1990, 1992, 1993). The upper-bound estimates of the rebound suggest that improvements of energy efficiency would increase, not decrease energy use. Consequently, resolution of the source and size questions is particularly important for the design and timing of an effective set of carbon reduction policies. High rebound estimates imply that technology policies require reinforcement with higher energy prices, otherwise technologically achievable carbon and energy savings would not be realized.

Recent discussions of the rebound effect have expanded from the original definition in the microeconomic...
The term was first applied narrowly to the direct increase in demand for an energy service whose supply had increased as a result of improvements in technical efficiency in the use of energy (Khazzoom, 1980, 1982, 1987, 1989; Khazzoom and Miller, 1982). Since then, the rebound has been more broadly construed to include wider economic effects (Brookes, 1978). Increases in gross output in response to an increase in the productivity of fuel and increases in fuel consumption as a result of an effective decrease in price have been used as indicators of the rebound at an economy-wide level (e.g., Brookes, 1990). However, we return to a narrower use of the term rebound or takeback and employ other terms for the economy-wide phenomenon. Our intent is to retain consistency with the published literature of rebound estimates, while giving due consideration to the full range of behavioral responses to technical efficiency improvements.

This discussion is designed to offer a more precise definition of the rebound effect, identify some potential sources, and provide an approximate estimate for the rebound from these sources. Section 2 provides a series of definitions and supporting theory for the various sources of the rebound. As part of this discussion we extend our typology beyond its origins in the microeconomics literature to include secondary and economy-wide sources. Sections 3 and 4 provide a summary of important points drawn from our review of 75 empirical studies for this typology, where we have concentrated our efforts on evidence from the US. Other research efforts are underway on the valuable insights offered by the international experience. Although we can speculate on secondary and economy-wide effects, especially the effects on fuel markets, we have no definitive empirical evidence as to potential magnitude from these sources. The final section presents conclusions and some recommendations for future research in the area.

2. Typology of the rebound

For this discussion, we use a four-part typology to encompass both the microeconomic and macroeconomic views of the rebound. The use of this typology helps to frame the discussion, and place boundaries on definitions during the examination of empirical evidence for the size of the rebound. These four categories of market responses to changes in fuel efficiency are: (1) direct rebound effects, (2) secondary fuel use effects, (3) market-clearing price and quantity adjustments (especially in fuel markets) or economy-wide effects, and (4) transformational effects. This typology is applied to energy services rather than the demand for fuel. Clearly, there is a certain amount of subjectivity in defining energy services, and this can be important from an economic perspective. The economic valuation of an energy service involves characteristics other than just the efficiency of fuel use. For example, in the case of personal automotive transportation, in addition to mobility, consumers also value comfort and performance characteristics of vehicles. As a result, consumers or firms can make trade-offs between attributes of an energy service as well as attributes of the inputs, i.e. fuel-consuming durable capital and fuel.

This capacity for a trade-off between attributes requires a distinction between potential technological efficiency improvements and realized or actual efficiency improvements. For example, manufacturers may elect to take portions of a technological advance in fuel consumption in the form of reduced pollution control costs, rather than reductions in fuel consumption. Therefore, potential fuel efficiency improvements, holding a firm's production costs constant, may in fact be realized as a somewhat smaller fuel efficiency gain. Most empirical estimates of the rebound currently in the literature are based on realized rather than potential efficiency improvements; i.e., these estimates capture trade-offs ex post. As the distinction between realized and potential efficiency improvements has entered the literature, measurements of the rebound have declined in size. Much of this decline can be attributed to the explicit consideration of the initial cost of energy-using capital (Besen and Johnson, 1982; Henly et al., 1987; Henly et al., 1988).

Following Khazzoom (1980), we limit the meaning of the direct rebound effect to the micro-level. At this level, a technological improvement in fuel consumption, ceteris paribus reduces the price of energy services by decreasing the amount of fuel required to produce them and should theoretically increase the supply. The price decrease should stimulate demand or a shift along the demand curve. This would be a direct effect or a pure price effect. For consumers, the direct effect of a price reduction may be decomposed into a substitution effect and an income effect. If the price of the energy service drops, consumers should substitute indefinitely for a given energy service. However, this ignores the potential for satiation for a given service, which limits potential levels of substitution, and the tradeffs with other expenditures that consumers make within a budget constraint. Currently, since all empirical estimates are uncompensated estimates, direct effects cannot be decomposed into substitution and income effects. Further, since the majority of these estimates are short-run, we cannot examine the long-run effects of changes in capital costs.4

Technologically induced reductions in the cost of energy services have similar effects on the demand for fuel...
by firms. Assuming short-run cost minimizing behaviors, if energy services decrease in effective price, a firm will substitute energy services for other factor inputs. In addition, a firm’s output will increase by the sum of the changes in the ratios of the price of energy services to every other input. Provided there are only diminishing returns to increased use of energy services, input substitution in favor of energy services (i.e., a substitution effect) will occur and more fuel will be consumed. However, these behaviors will be limited by the substitutability of fuel and capital in short-run production behaviors. Since these may be determined at the time of design (i.e., resulting in a Leon惕el production function), the size of the rebound from this source could be zero. In the long run, however, where greater factor substitution and output maximizing behaviors are assumed, a decrease in the price of energy services will result in an increase in the size of the industry and an increase in the demand for fuel (i.e., leading to economy-wide behaviors).

The increased real income of consumers and the reduced cost of firms’ output will have impacts beyond the immediate demand for energy services or the size of the industry in question. These secondary effects result from increases in demand for other goods and services, including consumption of other energy services. This increase in demand can result in increases in fuel consumption, but also lead to economic growth. The size of these secondary effects for a consumer is dependent on the share of the consumer’s total income or total expenditures spent on energy services. Since energy is a relatively minor share of an individual consumer’s total expenditures, the secondary effects are probably insignificant. For firms in a given sector, secondary effects result from (1) the increased demand for nonfuel inputs to their production process as a result of increased demand for output, and (2) the effect of the lower cost of one sector’s output on production costs of other sectors. Once again the rebound from this source is expected to be relatively minor.

All of the discussion of rebound effects thus far is based on the application of economic theory to a static situation. However, the Brookes-Grubb debate has focused our attention on price and quantity readjustments or economy-wide effects of both direct and secondary responses to technology-induced changes in the effective price per unit of fuel. Examination of micro-level behaviors in a static context have indicated the rebound to be insignificant to moderate in size. However, when those behaviors are aggregated to contemplate total consumption and investment by both consumers and government, the effects on the composite price of energy services, especially the adjustments in fuel supply markets, could be significant (e.g., Kydes, 1997). The size of the rebound from this source, particularly since potential paths of technological change are stochastic, is highly uncertain and deserves further study (Greening and Khrusch, 1996).

Changes in technology also have the potential to change consumers’ preferences, alter social institutions, and rearrange the organization of production. We refer to these potential effects as transformational effects. However, there is no all-inclusive theory for predicting those effects, which could result in more or less energy consumption. Improvements in fuel efficiency have altered, and could continue to alter, human activity (Schipper et al., 1989; Schipper and Meyers, 1992). However, many technological advances, in addition to fuel efficiency improvements, have resulted in changes in the allocation of time. This is reflected as a change in labor force participation rates and occupational structure. These effects are difficult to identify and quantify usually because of the lack of time-series data on fuel and durable good consumption coupled with demographic detail, time use and expenditure diaries. As a result, distinguishing income effects from these other effects makes attribution of specific changes in society to increases in fuel efficiency problematic (Brookes, 1978). Furthermore, even if these detailed data were available, it is doubtful whether major

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8 The existence of diminishing returns requires that the firm’s production function exhibit constant or decreasing returns to scale (e.g., Binger and Hoffinan, 1988). These conditions ensure that both the short-run supply and demand curves describe the observed behaviors. Such conditions are typical of competitive industries, however similar effects can be shown for monopolistic industries.

9 The dual of the cost minimization problem is the output maximization problem subject to a given expenditure of total cost (Jorgenson and Lau, 1974). Under this view, the firm chooses an input combination for which the rate of technical substitution is equal to the ratio of the input rental rates, i.e., factor prices. A reduction in the price of one of the inputs relative to another will result in a change in the slope of the iso成本 line. This change in slope will reflect the greater usage of the less expensive input. This means that the direction of technical change is "biased" away from the use of the more expensive output, e.g., capital-saving and fuel-using.

To illustrate this point, the relative increase in the aggregate expenditure for other goods and services resulting from a decrease in the cost of energy services is equal to the product of the budget share for energy services and the price decrease. The secondary increase in fuel use is therefore, to a very rough approximation, equal to the product of the budget share for energy services, the price decrease for the energy service, and the fuel content of other goods and services.
transformational effects of the past caused by such innovations as the motor vehicle, refrigerator or television, or name but a few examples, could be explained in a rigorous theoretical framework. Therefore, for this discussion we have chosen to neglect transformational effects.

3. Empirical evidence for the direct rebound effect.

This section provides a review from the literature of empirical evidence for the presence and size of the rebound effect. For residential and firm energy consumption, we have drawn on either econometric or direct measurements at the micro-level. Further, we have restricted ourselves to examining the effects of improvements in fuel efficiency on a specific energy service rather than on total fuel consumption. Only at this level of detail can we identify and measure the effects of changes in effective fuel price on a given fuel-using activity. From this evidence, we see variation in the magnitude of the rebound depending on the end use. However, for all of these end uses, the magnitude for a 1% increase in efficiency is well less than unity. As a result, increases in efficiency, although partially offset by increases in consumption, will result in an overall reduction in energy consumption.

Residential fuel demand

For residential end uses, the greatest effort has been expended on measurement of the rebound with respect to improvements in fuel efficiency for space heating, space cooling, and personal automotive transportation. However, a primary issue for these residential end uses is the identification of the appropriate activity measure. For example, with space heating, should changes in the thermostat set point or thermal comfort or space heated be the appropriate measure of changes in the consumption of the heating services? Further, in the majority of end uses, data collection or end-use metering studies are lacking. The data sets that are available usually do not have some of the key variables and fuel consumption by end use. Key variables for the complete characterization of residential fuel consumption include income, other expenditure classifications, household demographics, cost of the fuel-using capital, the opportunity cost of capital, length of holding, and fuel-using stock efficiencies.

The variability of residential fuel demand estimates may be explained by a number of factors. Some of this variability reflects the technology used in production of the service and the level of awareness that consumers have during service consumption. For example, consumers are aware of the ambient temperature and their gas fuel bill. Since space heating represents a major share of that bill and they are also aware of thermal comfort, they will adjust their thermostat set point accordingly. The utilization of a refrigerator does not receive similar attention.

Some of the variability may be explained by the underlying assumptions regarding consumer behavior. For example, we assume that growth in consumption will be linearly proportional to total expenditures or income, i.e., energy services are a normal good. This assumption ignores the effects of satiation or the physical limitations on consumption of an energy service (i.e., even at lower costs more heat is not necessarily desired) or time constraints (i.e., consumers can only spend so many hours driving). Often, we also ignore the consumer’s double role of production and consumption of energy services. This means that every household has a different implicit price for the service (Cuijpers, 1995, 1996). Implicit prices are dependent on not only fuel prices, but also include costs of capital and household labor, and capture differences in lifestyle. Finally, many of the early estimates of the rebound at the household level failed to recognize certain important technical characteristics of energy service demand. For example, in space heating, such factors as solar gain (i.e., natural endowment) or thermal efficiency are not normally specified. Neglect of these factors, which condition demand, in empirical work result in upwardly biased parameter estimates. This is particularly true where the own-price elasticity of the energy service is elastic (Einhorn, 1982; Schwartz and Taylor, 1995).

In addition to the specification of the appropriate behaviors in a modeling framework, there is a measurement issue that should be considered when reviewing estimates of the rebound effect. Many of the early studies lacked a benchmarking or verification of the empirical results to a baseline. Fully 25% of the rebound effect reported in those early studies could be explained by the lack of proper benchmarking (Henly et al., 1987). Many of these estimates compare post-installation observed behav...
thermal comfort. For will be more involved for the end use or the lack of key explanatory variables associated with the end use, many of the measurements of rebound probably are overestimates. In the following discussion, these observations lead to a selection criterion for choosing one set of results over another. Where an econometric study existed, in which at least some of the issues we have raised, were addressed, we selected those estimates above others available. We also emphasized studies performed with panel data or household-level data. As an added criterion, we emphasized those studies performed with several years of data. Finally, the vintage of the study was considered, and values from more recent studies given more weight.

3.1.1. Residential space heating

Conditional demand analyses have indicated that residential space heating is responsible for approximately 53% of household fuel (electricity and natural gas) use in single-family households (Schwartz and Taylor, 1995). As a result, any rebound effect from improvements in this end use may be significant. Table I provides a review of some of the evidence for the existence of the rebound associated with residential space heating. The magnitude of the rebound effect varies substantially because of the definition of the activity measure and the methods used. In the case of space heating, a number of factors need to be included in the definition of an activity measure. Although measurements of changes in the thermostat set point are considered to be close to the true measure of the activity, the thermostat set is just one of the indicator measures of the service provided (Frey and Labay, 1988; Nadel, 1993). Since heating is a public good, thermal comfort is a better measure of this activity. Determinants of thermal comfort include (1) attitudes toward thermal comfort, (2) individual activity levels, (3) air temperature, (4) mean radiant temperature (heat exchange between the human body and the surrounding temperature), (5) air velocity or draft, and (6) humidity. Unfortunately, these variables are not usually collected, and as a result thermal endowment cannot be evaluated (Isakson, 1983). All of these unobserved factors affect the demand for space heating and, if uncontrolled for, result in upwardly biased estimates of price response (Quigley and Rubinfeld, 1989). Econometric estimates that include these variables produce lower estimates of thermostat net take-back (Schwartz and Taylor, 1995).

Also in our analysis of rebound or take-back for this activity, we considered the role of capital costs, and the horizon over which the model was estimated. Capital costs are usually ignored in econometric estimates resulting in omitted variable bias (Krumm, 1982). Further, models that estimate only fuel consumption, or direct measurements of activity changes such as the thermostat setting, capture only short-run utilization (Klein, 1985, 1987). Analyses, which model long-run behaviors, particularly those including periods of low- and high-energy prices, indicate lower elasticities of substitution for periods of unstable fuel prices (i.e., a greater propensity to invest in capital improvements exists when energy prices are high).

The results reported in Table 1 consider these various issues, and in our final analysis we relied on these studies. Other methods, such as direct measures of changes in thermostat set point, have been used in the analysis of the rebound effect (Nadel, 1993). However, many of those studies suffer from sample bias resulting from the selection techniques used for participants, and many other factors were not controlled for (Greening and Greene, 1998). The studies, we finally selected, were performed using survey instruments from different periods of time. Dubin et al. (1986) is significant, because heating and cooling were metered separately, and the results were compared to engineering estimates before and afterward.

Table 1
Recent studies for residential space heating

<table>
<thead>
<tr>
<th>Study authors</th>
<th>Method</th>
<th>Sample size</th>
<th>Indication of response</th>
<th>Presence of a control group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dubin et al. (1986)</td>
<td>Econometric analysis: Cooling was metered separately from other end uses and was accompanied by an engineering study</td>
<td>252</td>
<td>− 0.52 to − 0.81 Take-back was estimated at 8–12% below engineering estimates (winter only).</td>
<td>Yes</td>
</tr>
<tr>
<td>Hauk and Gern (1993)</td>
<td>RECS 1981</td>
<td>1028</td>
<td>− 0.35</td>
<td>No</td>
</tr>
<tr>
<td>Schwartz and Taylor (1995)</td>
<td>RECS 1984</td>
<td>1188</td>
<td>− 0.987 to − 0.96 Engineering took-back estimated at 1–3%.</td>
<td>No</td>
</tr>
</tbody>
</table>
The analyses presented in Klein (1985, 1987) are the only studies that consider the trade-offs between capital and fuel consumption. Further, Schwartz and Taylor (1995) explore the effects of both square footage and region. While, Hsueh and Gerner (1993) contemplate the technological aspects of heating, including degree days. Finally, Cuijpers (1995, 1996) explicitly contemplates saturation of this end use.

Given all of these considerations when evaluating the empirical work for space heating, we were still able to draw some conclusions concerning the magnitude of the rebound from space conditioning. For a 100% increase in fuel efficiency, values of take-back from “pure” price effects or substitution and income effects combined are between 10 and 30% of the energy consumption savings. These results suggest that any technological improvement will be between 70 and 90% effective in reducing energy consumption for space heating.

3.1.2. Residential space cooling

Air conditioning can contribute as much as 11% to a household's total electricity consumption (Hausman, 1979). As with residential space heating, the same issues concerning identification and measurement of this activity are applicable. The determinants of thermal comfort previously cited for space heating also apply to space cooling. However, the emphasis needs to be placed on levels of humidity when forecasting the effects of service price. Further, from changes in response between seasons, Dubin et al. (1986) indicates that levels of potential take-back are highly dependent on the air conditioning unit capacity utilization. Levels of price responsiveness and take-back will be lower in months when an air-conditioning unit is running at full capacity.

The number of studies available to examine space cooling is limited compared to those for space heating. Hausman (1979) and Dubin et al. (1986) provided the best measures of the potential rebound effect. However, both studies were performed on small samples from high fuel price periods. Other later studies exist, but often report anecdotal results from utility weatherization or efficiency rebate programs, or were performed from billing records without direct metering of the activity. Using Hausman (1979) and Dubin et al. (1986), we estimate a total take-back of 0%-50% for a 100% increase in energy efficiency. This suggests that any technological improvements for this activity will be between 50 and 100% effective in reducing energy consumption. This wide variation in effectiveness can be explained by the factors that affect this activity, with the primary cause being capacity utilization.

3.1.3. Other residential end uses

The evidence for other residential end uses is very limited (Nadel, 1993). Other residential end uses include residential water heating, lighting, and other appliances, e.g., refrigerators. This classification presents even more difficult issues in identifying and measuring the end-use activity. Data on physical measures for a given activity often are not collected, and as a result estimates of the rebound rely on conditional demand studies, the results of which have not been consistent (Angel Economic Reports and Applied Econometrics, 1984).

The limited results available for this category of residential energy consumption suggest the following set of conclusions. Technical improvements for residential hot water heating will be between 60 and 90% effective in reducing energy consumption for this service (Hartman, 1984). Similarly, for lighting technological improvements will be between 80 and 95% effective in reducing energy consumption, and no measurements of the direct rebound effect have been reported for refrigeration services. However, for all of the services included in this category, there is an indication that income effects could be significant. Although no measurements are available for income effects for this category, anecdotal evidence indicates that consumers may shift fuel consumption to increased consumption of durable good attributes. For example, consumers may purchase a larger water heating unit, or purchase additional features such as increased volume or through-the-door features on refrigerators.

3.1.4. Personal transportation

The direct rebound effect for personal transportation may be evidenced in three different ways: (1) an increase in the number of vehicles; (2) an increase in fuel consumption in response to increases in technical efficiency; and (3) an increase in vehicle miles traveled. However, nearly all of the evidence on the rebound effect for transportation comes from econometric analyses of gasoline demand and light-duty vehicle usage. Fuel consumption for personal transportation constitutes slightly more than 60% of US transportation energy use and light-duty vehicles comprise a little less than 60% of that value. Measures of the direct rebound from fuel consumption can easily be estimated using the own-price elasticity with respect to changes in fuel price. Estimates of the rebound are also equivalent to the negative of the elasticity of vehicle miles traveled with respect to fuel cost per mile.11 Therefore, the more elastic fuel consumption with

---

11 The effect of an exogenous change in energy efficiency, \( e \) (defined here as gallons of fuel per mile or /MPG), on the demand for \( F \), can be readily derived, making use of the identity \( F = M e \), as follows:

\[
\frac{dF}{de} = \frac{dM}{de} + M \frac{dP}{dF}
\]

\[
\beta_{P,e} = \frac{dF}{dP} = \frac{dM}{dP} \frac{dP}{dF} + eM \frac{dP}{dF} M = \beta_{M,e} + 1
\]

where \( M = \) vehicle miles traveled and \( P = \) price of fuel (Groene et al., 1998).
In 'T-fir'd, vith sric-ticity due. Juty rta.ased. ting lotal im· .d in lger. l hot Re· tion nts of nan, im· e in ts of i~•ged in facts are total lings For · ting ased rs.

Table 2

Recent estimates of the long-run direct rebound effect

<table>
<thead>
<tr>
<th>Study authors</th>
<th>Years of data</th>
<th>Indication of response</th>
<th>Type of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blair et al., 1984</td>
<td>1967-1976</td>
<td>- 0.21 (midpoint)*</td>
<td>Florida state, monthly</td>
</tr>
<tr>
<td>Mayo and Mathis (1988)</td>
<td>1958-1984</td>
<td>- 0.221b</td>
<td>US national, annual</td>
</tr>
<tr>
<td>Gately (1992)</td>
<td>1966-1988</td>
<td>- 0.09</td>
<td>US national, annual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 0.05 to - 0.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Log-linear model:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 0.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Model I linear: - 0.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Model III linear: - 0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Model I log-linear: - 0.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Model III log-linear: - 0.31</td>
<td></td>
</tr>
<tr>
<td>Jones (1993)</td>
<td>1967-1990</td>
<td>- 0.23</td>
<td>US national, annual</td>
</tr>
<tr>
<td>Haughton and Sarkar (1996)</td>
<td></td>
<td>Model F: - 0.23</td>
<td></td>
</tr>
</tbody>
</table>

*Calculated from Table 2 in Blair et al., assuming a fuel price of 33 cents/gallon ($1.967), an average fuel efficiency of 14.0 miles per gallon, and monthly miles traveled of 4.250 million. The OLS coefficient estimate of - 386.4, recommended by the authors, was used.

*b*The lagged dependent variable was not significant in Mayo and Mathis' VMT equation, having a value of 0.15 but a t-statistic of 0.73. Nonetheless, had this coefficient been used to estimate a long-run cost per mile elasticity of VMT that would have been - 0.25.

*These are the only two models presented by Haughton and Sarkar that included all of the statistically significant effects identified by the authors.
These results using a time series of state-level data. They found a short-run elasticity of 0.17 and a long-run elasticity of 0.22. The aggregate results presented in Table 2 imply that the number of vehicle miles traveled will increase by between 10% and 30% as a result in improvements in fuel efficiency. Therefore, activity measures do reflect the results of efficiency improvements, but the rebound does appear to be small in magnitude. However, this measure does not reflect increases in congestion and the associated effects of increased travel.

A number of econometric analyses have used household survey data to estimate the sensitivity of vehicle use to fuel price and fuel efficiency. However, these studies do not generally include vehicle age as an explanatory variable. The omission of this variable may explain the greater magnitudes from this class of model. Using data from the 1990 Nationwide Personal Transportation Survey (NPTS), a recent econometric analysis estimated an overall gasoline price elasticity of VMT of -0.51 (Walls et al., 1993). Elasticities were found to vary by household ownership level, with elasticity estimates of -0.29 for single-vehicle households, -0.41 for two-vehicle households, and -0.78 for three-or-more-vehicle households. These estimates compare reasonably well with older econometric studies by Archibald and Gillingham (1980, 1981a, b) and Train (1986). Two recent studies by Puller and Greening (1997, 1999) have made use of multiple years of consumer expenditures survey (CES) data and have also addressed the question of simultaneity in vehicle use and fuel economy. Puller and Greening (1997) obtained a fuel cost-per-mile elasticity of -0.49 based on CES data for the period 1984-1990.

When vehicle age is included as one of the explanatory variables, estimates of the rebound are much lower. Goldberg (1996) estimated a simultaneous model for vehicle choice and usage using the 1984-1990 CES data. Goldberg’s analysis, which was restricted to new vehicles, indicated that fuel costs were statistically insignificant. Greene et al. (1998) estimated separate light-duty vehicle usage models for 1-, 2-, 3-, 4-, and 5-vehicle households, using data from all six Residential Transportation Energy Consumption Surveys conducted by the US Energy Information Administration. The simultaneous equation models, which included vehicle use, fuel economy, and fuel cost, with usage of all household vehicles also simultaneously determined, produced estimates of a weighted average, long-run fuel cost-per-mile elasticity for all household vehicles of 0.23. These estimates are very much in agreement with the results of the recent aggregate econometric studies. Therefore, the results from analyses of both aggregate and household level studies indicate that technological improvements for personal transportation services will be between roughly 50 and 80% effective in reducing energy consumption.

3.2. Firms

A technical improvement in fuel use efficiency will affect a firm’s demand for energy services in two ways. First, the increased productivity of energy (resulting in the reduced cost of a per unit measure of energy services, ceteris paribus) will induce substitution in favor of energy services versus other inputs (e.g., capital, labor) during the production process. A firm’s production costs are minimized when the ratios of the marginal products of every input to every other input equal the ratios of their prices (e.g., Binger and Hoffman, 1988). Thus, an efficiency-induced decrease in the price of energy services relative to other factor prices will result in an increase in the consumption of energy services and less of other inputs. However, since fuel is only one input to the production of energy services, the increase in fuel consumption resulting from the substitution towards a greater use of energy services will not be determined purely by an increase in fuel efficiency.

Direct measurements of the take-back or direct rebound effect for commercial and industrial firms are extremely limited (Nadel, 1993; Eto et al., 1994, 1995). All of our direct evidence for the rebound comes from established facilities that have undergone energy audits or participated in similar types of programs. The short-run nature of such studies means that firms’ production technologies are relatively fixed in terms of major processes. As a result, little input substitution is likely and, since the unit of observation is a single firm, industry size effects also cannot be assessed. Given these caveats, observed levels of take-back appear to be proportional to levels of capital investment required to provide the energy service. Nadel (1993) reported take-back effects of about 2% for process fuels in industrial facilities but 30% or more for lighting programs in buildings. This very large difference in observed changes is likely to be due, at least in part, to the slower rate of capital stock turnover associated with industrial process fuel use, and the difficulties associated with making large-scale changes to the equipment used in these processes after installation. Increased lighting, in contrast, is a more easily added factor of production.

To assess the magnitude of the rebound from substitution and increases in industry output, we must examine econometric estimates of elasticities of substitution and increases in productivity. The size of the shift toward energy services will depend on the elasticity of substitution of energy for other factor inputs. As Robert Solow is reported to have said (Saunders, 1992) “... it all depends on the elasticity of substitution, compared with one”. If the elasticity of substitution of energy is less than 1.0, then technical efficiency improvements will result in a

\[ 12 \text{The marginal product is defined as an increase in output due to a one unit increase in a specified input.} \]
will always be ting in services. energy during this are inputs of their efficiencies relative in the inputs. The variation in the contribution of a unit of fuel to the production of a unit of output may be explained by a number of different factors. The majority of these estimates have been performed with aggregate data, and depending on the level of aggregation may combine industries with significantly different underlying production relationships. Depending upon the industry groupings used to estimate this relationship, the substitutability of fuel for other factor inputs may be over- or under-estimated. Further, depending on the functional specification, the industries included, and the time period represented, the magnitude and sign of the estimated relationship between energy and other factor inputs also varies (Greening and Greene, 1998).

To illustrate the wide variability of estimates of the relationships between fuel and other factor inputs in the literature, the following are cited as examples. By no means do these represent a complete review, but they do illustrate these points. Using a constant elasticity of substitution (CES) specification, Manne and Richels (1992) estimated a substitution elasticity of 0.4 between energy and a nesting of capital and labor. Other estimates using the same functional specification have been as high as 0.8 (Kemfert, 1998), which still implies energy savings from technical efficiency improvements. Several studies have estimated negative elasticities of substitution between energy and capital implying complementarity, or as the input of capital increases the input of energy decreases (e.g., Hudson and Jorgenson, 1974; Berndt and Wood, 1975; Magnus, 1979; Prywes, 1986). Further, substitution elasticities greater than 1.0 have been estimated by Chang (1994) and Hazilla and Kopp (1986). However, these larger estimates are rare, and the most recent estimates of substitution between energy and other factor inputs are all less than 1.0 (Kemfert, 1998). Therefore although the evidence is mixed, the size of the rebound from substitution effects appears to be small to moderate.

Since increased energy productivity increases total factor productivity, reducing the real resources required to produce a unit of output should also reduce the price of goods and services produced by an industry. Provided that the good in question is a normal good, the demand for industry’s output should increase. In response to this increase in demand, consumption of energy services should also increase. The expansion in energy service consumption will be approximately equal to the product of the increase in industry size and the cost share of energy services as a share of total production costs. Typically, this is less than 10%. Thus, a doubling of energy productivity, with other inputs held constant, would reduce total costs by only about 5%. If market demand for output were unit elastic, this would increase industry size by about 5%, thereby increasing demand for energy services by 5%, and fuel use by 2.5% of the original amount. Once again although there is some rebound effect resulting from increases in industry output, the magnitude appears to be small.

4. Secondary and economy-wide effects

Because improvements in energy efficiency, with resulting increases in the supply of energy services, alter the mix of both final and input demands, increase consumers’ real income, and expand firms’ production possibilities, prices throughout the economy will undergo numerous, and complex adjustments. Only a general equilibrium analysis can predict the ultimate result of these changes. However, if the technical energy efficiency improvement does ultimately shift the supply curve for energy services to the left or upward (i.e., greater supply at every price level), world energy prices should fall, instigating a greater demand for energy. However, these shifts of the supply curve are dependent upon the cost structure of energy services (i.e., the underlying production function). As a result of this shift of the supply curve, greater levels of energy consumption are expected, with the exact effect levels depending on the price elasticities of energy supply and demand.

We have been unable to find any global general equilibrium assessments of the effect of energy efficiency improvements on world energy markets. Some indication of the potential magnitude of economy-wide effects, however, is presented by Kydes’ (1997) analysis using the National Energy Modeling System (NEMS). Kydes compared nine scenarios, including a reference case in which the overall energy intensity of the economy declined 17.5% by 2015 and an accelerated technology case with a 24% decline in energy intensity. The additional 6.5% decrease in energy intensity caused a 5% decrease in overall energy demand. GDP increased by 0.4%, while world oil prices fell by 13.7%. However, the Kydes analysis assumes technological change only in the US. Had technological changes occurred globally, energy prices would have fallen farther and energy consumption would not have declined as much.

Growth theory offers another avenue for assessing economy-wide impacts of energy service augmenting technological change. Saunders (1996) has demonstrated...
that growth models using Cobb-Douglas production functions will always predict that technological progress will result in increased, rather than decreased energy consumption. Models using CES production functions, however, demonstrate that this is not necessarily the case. The impact of energy efficiency gains depends on the elasticity of substitution between fuel and other factor inputs in the production of energy services. As noted above, if the elasticity of substitution of fuel for capital and labor (jointly) is less than 1.0, technical efficiency improvements will reduce overall energy use. The Cobb-Douglas function is incapable of producing this result, since the elasticity of substitution in a Cobb-Douglas production function is always unity (Varian, 1992). As we have also noted above, the evidence on this point is mixed. Therefore, substantial additional research is warranted on the economy-wide effects of fuel efficiency improvements.

5. Conclusions

Table 3 presents an overview of our review of over 75 estimates of the rebound in the literature (Greening and Greene, 1998). Estimates, derived from both econometric studies and direct measurements, were only available for

<table>
<thead>
<tr>
<th>Economic actor</th>
<th>End use</th>
<th>Potential size of the rebound*</th>
<th>Comments</th>
<th>Number of studies*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumers</td>
<td>Space heating</td>
<td>10–30%</td>
<td>The unmeasured part of this effect includes an increase in space conditioned and an increase in comfort.</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Space cooling</td>
<td>0–50%</td>
<td>The unmeasured part of this effect includes an increase in space conditioned and an increase in comfort.</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Water heating</td>
<td>&lt; 10–40%</td>
<td>Reports of increased shower length or the purchase of increased water heating unit size indicate some indirect effects, which cannot be measured.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Residential lighting</td>
<td>5–12%</td>
<td>An indirect effect in terms of an increase in operating hours was reported.</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Appliances (&quot;White Goods&quot;)</td>
<td>0%</td>
<td>Indirect effects in terms of the purchase of larger units with more features were reported.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Automotive transport</td>
<td>10–30%</td>
<td>The unmeasured part of this effect includes changes in automotive attributes, particularly the shifts toward attributes such as increases in weight, horsepower and acceleration.</td>
<td>22</td>
</tr>
<tr>
<td>Firms</td>
<td>Process uses (Short-run)</td>
<td>0%–20%</td>
<td>Although increases in output occurred for less than 20% of the study participants, no values were reported.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Lighting (Short-run)</td>
<td>0–2%</td>
<td>Changes in output were not reported. However, labor productivity probably improved.</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Long-run aggregate impacts</td>
<td>&lt; 100–0%</td>
<td>Changes in output show a great deal of variability in the literature.</td>
<td>Any number of studies with a variety of conclusions.</td>
</tr>
<tr>
<td>Economy-wide effects</td>
<td>Change in total output growth</td>
<td>0.48%</td>
<td>Postulated effects include an increase in standard of living and consumption of more energy-consuming &quot;luxury&quot; goods.</td>
<td>1</td>
</tr>
</tbody>
</table>

*These estimates are expressed as a percentage increase in consumption estimated to result from a 100% increase in energy efficiency (i.e., the estimated elasticity of demand times — 100%).

**Grading system used for the quality of estimate:
• All estimates assume a 10% increase in efficiency of fuel consumption.
a limited number of end uses at the microlevel. During our review, we restricted ourselves to examining the effects of fuel efficiency on a specific energy service rather than on fuel consumption. Our review indicated that there is variation in the magnitude of the effect depending on the definition or the class in our typology, but the size of the rebound is well less than unity. Because of the identification and measurement issues, and the limited number of studies, this conclusion is not definitive at the microlevel. Even less work has been performed on the macroeconomic implications of the rebound. Any conclusions on the effects of the rebound at the economy-wide level are even more tentative.

Our review of the literature suggests a series of conclusions for the research community. Definitions of the rebound effect vary in the literature and among researchers. Depending on the boundaries used to describe the effect, the measured size of this behavioral response will vary. Therefore, one of the primary tasks for further research will be to reach a common view of the definition. In terms of empirical work, more effort has been directed towards measurements for residential end uses, especially space heating or cooling and personal automotive transportation, than for either commercial or industrial end uses. However, the majority of econometric analyses of residential end uses suffer from incomplete specification of residential fuel consuming behaviors, omitted variable bias, and lack of explicit recognition of capital attribute choice behaviors. The lack of availability of data sets that include a direct measure of an activity, socioeconomic characteristics, detailed descriptors of fuel-using stock, and other household expenditures has hampered the analysis. Currently available measurements of the rebound for residential end uses suggest a range of responses of 0–50% for a 100% increase in energy efficiency, with much of the size of the response depending upon consumer awareness during consumption of the service.

Levels of take-back by firms in the industrial and commercial sectors depend on the ability to substitute fuel for other factor inputs. Direct measures of take-back by establishments in these sectors include the consumption of additional fuel and increases in output. However, these direct measurements are short-run measures, and relatively few studies of individual establishments exist. For commercial firms, participating in lighting efficiency programs, the direct or pure price effect appears as a slight increase in the hours of operation. Studies of industrial process fuel improvements report small increases in output for some establishments. In the long-run, estimates of the rebound must be inferred by examining econometrically estimated elasticities of substitution and measures of productivity during various world fuel price regimes. The available evidence does indicate that in the majority of cases, technical efficiency gains result in fuel savings, which are only slightly eroded by increases in demand.

Extending the definition of the rebound effect to include economy-wide and transformational effects presents an array of new issues. Both the existence and size of economy-wide effects of specific fuel conservation policies have a high degree of uncertainty because of current forecasting tools. Various behaviors by consumers and producers may offset each other. Since the availability of investment capital is key to addressing this problem, we need to be able to evaluate the role of fiscal policy and other drivers of technological change. We can make some limited inferences about economy-wide effects through the use of growth theory, and various modeling techniques. But any conclusions drawn from these sources are highly uncertain and inconclusive. Extension of the rebound definition to include transformational effects is conceptually possible but not analytically practical since both theory and data for such predictions are lacking. Attempting to assign causal linkages between changes in society and changes in energy efficiency, without addressing all of the potential confounding factors, would likely lead to unsupported and incorrect conclusions.

This set of conclusions from our literature review indicates that we have a number of issues to address. The definitional issues are relatively easy to clarify. Estimation of the magnitude of the rebound effect, however, is not and will continue to require further analysis. More empirical work is required for the United States to estimate the size of the rebound effect for a variety of end-use improvements, including housing shell efficiency enhancements, windows, and appliances. More analysis is also needed on other modes of personal transportation besides automobiles. Models for all end uses need improved specification, and in particular the effects of saturation of the service and trade-offs with other expenditures need to be incorporated. However, because of the lack of data for some of these end uses, this may not be possible.

For the energy sectors of the US economy for which studies are available, we can conclude that estimates of the rebound are very low to moderate. The upper estimates, however, indicate a rebound effect that is not insignificant. Even these upper bound estimates, though, indicate that most or all of any reductions in energy use or carbon emissions are not lost to changes in behavior. This leads us to the conclusion that the rebound is not high enough to mitigate the importance of energy efficiency as a way of reducing carbon emissions. However, climate policies that rely only on energy efficiency technologies may need reinforcement by market instruments such as fuel taxes and other incentive mechanisms. Without such reinforcements, a significant portion of the technologically achievable carbon and energy savings could be lost to the rebound.
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