ENERGY EFFICIENCY AND CLIMATE POLICY:

THE REBOUND DILEMMA

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EXECUTIVE SUMMARY

Much of today's energy policy assumes that regulations mandating greater energy efficiency will reduce energy use. That isn't always the case and energy efficiency improvements are seldom as large as promised by engineering calculations because of "rebounds." For example, people who install lighting that is 50 percent more efficient frequently leave the lights on longer, negating some of the energy savings from greater efficiency. This is called an energy efficiency rebound. Sometimes these mechanisms even bring about net increases in energy use known as "backfires."

Rebounds have a direct implication for energy efficiency mandates and incentives. If rebounds are substantial, efficiency policies will be less effective at reducing air pollutants, for example, as any energy "saved" can easily find other uses, and energy consumption may even increase in the event of backfires. This paper explores the literature on energy efficiency rebounds and provides a framework for how to think about energy efficiency policy.

There are four basic types of rebound that might result from improved energy efficiency, defined by the markets in which their effects occur: direct rebound, indirect rebound, economy-wide rebound, and embedded energy.

- Direct rebounds are adjustments in the production or consumption of a good whose energy efficiency has increased. For example, improved vehicle fuel economy that lowers the per-mile cost of driving may motivate drivers to travel more miles than otherwise. Increased gasoline used is a direct rebound.

- Indirect rebounds are changes in the production or use of goods related in use to the activity being improved in efficiency. For example, increased fuel economy that leads to more driving also indirectly increases the demand for tires. The resulting increase in the tire industry's energy use is an indirect rebound.

- Economy-wide rebounds are the impacts of an efficiency improvement summed over all affected economic activities. If drivers are travelling more often, hotels will require additional energy to meet increased demand for rooms and services; hotel furniture manufacturers likewise increase their energy consumption to boost outputs.

- Embedded energy inputs are those that expend energy in the process of creating more energy-efficient goods. Though high-efficiency building insulation lowers annual energy use, the manufacture and installation of more efficient building materials also requires energy inputs that must be accounted for.

Direct rebounds are well documented: more than 200 studies exist on the subject. The liberal Breakthrough Institute's 2011 publication of Energy Emergence summarizes and interprets the findings of much rebound research.

Though most research on direct rebounds, however, has generally verified their existence, their magnitudes vary greatly: their values depend on the energy-using activity (e.g. cooking) under study, characteristics of the subject population, and possible biases in sampling. For example, studies have found:

- Household behaviors before and after installation of energy-efficient appliances produce wide ranges of rebounds, for example between 10 and 60 percent for electric heating in the short run.
    - As a practical example of a 10-60 percent rebound range, assume a 2000 square feet house has a 20 kw electric furnace that uses 2,434 kwh per month, and operates 4 hours a day during the heating season only (about 6 months). At a cost of $0.0698 per kwh, it costs $170 per month to heat the house with this

equipment.

  - Assume that the furnace is replaced with an electric heat pump, which consumes 1,642 kwh a month, and a heat pump fan that consumes 90 kwh per month. Energy use is decreased to 1,732 kwh and results in a bill of $120.96, assuming that there is no change in power consumption.

  - Now we can experiment with rebounds. In the range of Sorrell's figures (from Chapter 3) the gross saving of 2434 – 1732 = 702 kwh can be netted against rebound. If the rebound is 10 percent the household consumes 1,732 + .10*702 = 1,802 kwh, with a new bill of $125.79. At a high-end 60 percent rebound consumption is 1,732 + .6*702 = 2,153 kwh, with a new bill of $150.29.

- In particular, wealthy households that already own all major appliances do not reduce energy consumption after buying more efficient ones; instead, further increases in their incomes are often spent on energy-intensive services like travel.

- A high percentage of utility-sponsored conservation and efficiency programs have found that actual savings fall short of projected ones, a possible manifestation of rebounds.

- Improvements in energy efficiency can raise the productiveness of other inputs, e.g. works in a better-lit plant are more productive. These increases in non-energy productivity increase the profitable scale of production and bring higher energy use.

Economy-wide estimates of rebound use "computable general equilibrium" (CGE) models to track input-output relationships between sectors and have the ability to simulate the economy over longer durations during which capital investments in energy and energy-using equipment are taking place. Though the limited amount of CGE studies makes it difficult to draw firm conclusions, a general principle appears to be emerging: rebound effects are greater for models with more comprehensive structures and with simulations of longer duration. Over half of the available studies using CGE show rebounds that approach or exceed 100 percent. In other words, their net result is that more energy was consumed than saved.

Groups such as the Breakthrough Institute contend that if greenhouse gases are to be reduced, rebound must be overcome by direct government intervention in markets, rather than with efficiency mandates; however, in the absence of uniform worldwide policies, the ubiquitous nature of greenhouse gases would render such policies ineffective. Implementation would also require governments to identify "winner" technologies, regardless of their capability to do so.

The pervasiveness of energy efficiency rebounds illustrates that attempts to plan or direct energy policy toward desired goals will likely fall far short of expectations. Instead of imposing energy efficiency mandates, energy policy should embrace market prices and disruptive innovations to guide energy to its most valuable uses.

TABLE OF CONTENTS

1 CH. 1: INTRODUCTION
1 The Jevons Effect
2 Generalizing Jevons
3 Why Rebounds Matter Now
3 Plan of This Study
6 CH. 2: REBOUNDS: THEIR LOGIC AND DIMENSIONS
6 Introduction
9 Energy Services
11 Rebounds by Industrial Energy Users
11 Economy-Wide Effects
12 Summary
14 CH. 3: ESTIMATES OF REBOUND
14 Introduction
14 Direct Rebounds
16 Indirect Rebounds
18 Economy-Wide Effects
21 Summary
24 CH. 4: REBOUNDS AND CLIMATE POLICY
24 Introduction
25 Efficiency Policies
27 Rebound Meets Politics
28 BTI's Policy Proposals
32 Conclusions
36 CH. 5: SUMMARY AND CONCLUSIONS
36 Summary
37 Conclusions: Does Backfire Matter?

INTRODUCTION

A: THE JEVONS EFFECT

Many of today's economists know William Stanley Jevons only as a footnote in the history of their subject. His obscurity, however, is receding as he returns to take on an unexpected and important role in today's energy policy debates. His 1865 study of the British coal industry and its contributions to economic growth contains theories and presents data that have much to say about the current century's energy efficiency policies.[1] Coal facilitated the deployment of steam technologies for pumping, transportation, and metalworking that were among the foundations of Britain's world leadership in the nineteenth century. Ongoing improvements greatly increased the useful work producible by steam, and with it the demand for Britain's abundant coal supplies. Then as now, some thinkers stressed the importance of improving technological efficiency (useful work per unit of coal input) in light of coal's finiteness. By extending coal's capabilities, these improvements would help to postpone the seemingly inevitable economic decline that would follow supply exhaustion.[2]

Jevons's reading of history and his economic logic brought him to a quite different viewpoint: an early version of the "rebound effect" that embodies today's controversies over efficiency policy. Historians credit Thomas Newcomen and James Watt for inventing the steam engine, but in reality their work had many precursors, most importantly Thomas Savery's 1698 coal-fueled mine pump. The pump was functional but uneconomic:

> Savery recommended his engine for its cheap drawing of water and its small charge of coals. But, as he allowed the steam to act straight upon the water, without the intervention of a piston, the loss of heat was tremendous. Practically, the cost of working kept it from coming into use; *it consumed no coal, because its rate of consumption was too high.*[3]

Jevons's insight was a deep one: absent technological improvements, fuel gets "conserved" forever. It goes into use only if it can be cheaply converted into services that people value. If a commercially viable engine is more fuel-efficient, its diffusion into new employments can lead to more coal being burned, rather than less. Jevons believed that the consequences were straightforward. On the supply side, inventors would profit by designing engines that produced more work per unit of fuel. Producers would devise cheaper ways to build the engines and apply the engineering principles to designs usable in industries that had yet to adopt them. The increase in efficiency of fuel conversion would not only pump more mines; it would soon also power locomotives and ships, and adapt itself to manufacturing in a limitless number of industries.[4] On the demand side, steam-powered transportation and manufacturing would produce lower-priced travel and goods. As consumers spent their higher incomes, they would spur additional investment in steam technologies and still-higher consumption of coal.

The coming of better steam engines would affect both their own production costs and those of extracting coal, which would bring further incentives to devise new uses for the mineral. As a typical example, the Bessemer converter revolutionized steel production both by lowering fuel requirements and by facilitating hitherto unseen economies of scale.[5] The invention turned the steel industry from a relatively small user of coal into one of its largest. Cheaper steel cut the cost of manufacturing products that were once prohibitively costly or had to be fabricated by hand. There was one other unforeseen outcome of better steam engines and lower coal costs: the centuries-long deforestation of Britain that resulted from charcoal use by ironworkers came to an end when coal became an economical substitute for wood.[6] Jevons concluded that, *"the new applications of coal are of an unlimited character."*[7]

B: GENERALIZING JEVONS

Jevons's views and findings will hardly surprise most readers—the story of Britain's industrial transformation through coal is well-known. Its generality and lessons for energy policy, however, are less appreciated.
For generality, apply the principle to labor. In 1890, 29.4 million people (43.4 percent of the U.S. labor force) owned or worked on farms.[8] The subsequent mechanization of agriculture (including steam tractors) reduced the farm population to 3.0 million (2.6 percent of the labor force) in 1990. Tens of millions left farms as the productivities of tractors, fuels, and workers who remained on farms grew. The transitions were not always easy, but the displaced workers eventually found new skills and raised their standards of living to those of urban residents. An assertion that "jobs" are scarce is a claim that workers who left farms constituted a permanent mass of unemployment, when in reality they turned to employments that satisfied other human wants.[9] The economy transitioned from farming to manufacturing at the opening of the twentieth century, and is moving from manufacturing to services as another new century opens. If human wants are as limitless as they appear, we can be confident that those who lose employment will "rebound" to new work and often be wealthier for it.[10]

The examples of Jevons and the emigration of farm workers also shed light on today's patterns of energy consumption. In a series of publications, Jeffrey Tsao and his colleagues have assembled data on peoples' consumption of light, as measured in lumens per capita per year.[11] Their remarkable compilations span three centuries, six continents, and six types of lighting technology, from candles through incandescent bulbs to fluorescents. The range of variation in the figures is enormous. Per capita gross domestic product varies by a factor of 1,400 percent in their data, the cost of light by 4,300 percent, and per capita consumption of light by 5,400 percent.[12] Yet all of their data cluster around a common upward trend that shows no sign of slowing. Light may be a necessity of civilized life, but consumption keeps increasing as humans invent new sources of it, find new uses for the sources, and utilize them more intensively.

> [T]here is a massive potential for growth in the consumption of light if new lighting technologies are developed with higher luminous efficacies and lower cost of light. Indeed this empirical result has powerful implications on the rebound effect.[13]

Jevons would see the findings as straightforward extensions of his work on steam and coal: demands for light do not become "saturated" as people become wealthier, and the quantity of light consumed per person continues to increase as the price per lumen falls.

The examples of steam, coal, and light are about large, well-documented, and historically significant rebounds. Research on smaller and more prosaic subjects, however, also keeps finding rebounds, such as the responses of households to more energy-efficient appliances and fuel-efficient cars, detailed in Chapter III. Rebounds confound simple engineering calculations of saved energy because they reflect people's reactions to lower prices and lower costs of using it.[14] Rebounds may mean that the engineering calculations overstate savings. By itself, however, the existence of rebounds says nothing about the value of efficiency-related policies, which also requires consideration of their costs. Very large rebounds are possible, if, for example, a more efficient fuel-burning technology for using energy expands use of the fuel by more than the originally projected savings. A rebound like this one, greater than 100 percent, is often called a "backfire." Jevons's description of the massive rebound of coal use that came with steam technology is almost certainly a case of backfire.[15]

C: WHY REBOUNDS MATTER NOW

Energy policies in the United States and other nations increasingly emphasize efficiency as a "resource." One commonly hears that "the best kilowatt-hour of electricity is the one that doesn't have to be produced at all." An energy-efficient appliance can perform services without that kilowatt-hour, but uncritical acceptance of this logic can give rise to difficulties.[16] Many governments intend that regulation of automotive fuel economy and appliance energy use be a major component of their efforts to reduce carbon emissions from the burning of fossil fuels. Whatever the desirability of climate policy, cost-effective mandated efficiency could in principle reduce energy consumption without the imposition of direct taxes or other controls on its use. Designers of greenhouse gas (GHG) policies to abate carbon dioxide and methane generally reserve a major role for efficiency standards. Evaluations of such policies, however, have seldom attempted to project the emissions that are regained as a result of rebound.

There are currently several hundred estimates of different types of rebounds, either in publication or available as drafts. As will be seen in Chapter III, results are sometimes in conflict (even for simpler cases like new appliances in households), but the calculated rebounds, if correct, must be considered by policymakers. Cases that are more complex than the introduction of a new appliance carry tougher data requirements, and much of the research is so novel that there is no consensus on analytical approaches. Even more complex are economy-wide rebounds, which happen when a major change in efficiency affects prices of both goods and services, and the inputs that are used in their production. Again, calculated results vary widely but the majority of currently available estimates predict strikingly high economy-wide rebounds that sometimes achieve the status of backfires. Any informed development of climate policy will require defensible estimates of such numbers. One can no longer assume this problem away, because it is already clear that many relevant rebounds are far above zero.

D: PLAN OF THIS STUDY

This introductory chapter has provided some historical background and an introduction to the potential importance of rebounds for energy policy. Chapter II begins with an exposition of the most widely accepted way of classifying rebounds, in terms of the numbers of markets they affect. *Direct rebounds* affect a single market, *indirect rebounds* affect two or a few closely related markets, and at the limit there are *economy-wide rebounds*. It is sometimes important to treat separately the *embedded energy* that is consumed in the manufacture of durable goods ("capital goods") and the construction of buildings. Numerous other rebounds extend beyond these relatively simple varieties, including those associated with international diffusion of technologies and those that result from incentives to innovate additional uses for "saved" energy. Chapter II goes on to explain the relationships among rebounds, backfires, and the economic concept of demand elasticity. Because rebounds that involve inputs into production are very important, it also discusses some of the difficulties in estimating them for these goods and services. The chapter closes with an expanded discussion of the measurement of economy-wide effects of increased energy efficiency.

Chapter III summarizes a variety of research estimates about the magnitudes of rebounds. It starts with descriptions and findings of some "meta-analyses" that have attempted to estimate direct rebounds using data from studies that are not directly comparable. Chapter III next discusses the large number of studies that have estimated direct rebounds by surveying changes in the behavior of households that replace inefficient appliances with energy-efficient ones. Often, it will be important to evaluate responses in the short-run (before full adjustment to the change) and long-run (after such adjustments). The chapter also summarizes research on the effects of "saturation" of appliance markets in richer countries with rising incomes, which some observers believe will decrease the importance of rebounds. In reality, however, as families' incomes rise, their added consumption expenditures tend to be on goods and services (e.g., travel) that require substantial amounts of energy.

Chapter III continues with a discussion of direct and indirect rebounds by business consumers of energy. Estimates of such rebounds are heavily dependent on the range within which a business can substitute between energy and non-energy inputs into production. Here, the econometric research has reached no consensus, most importantly because increasing the productivity of energy also affects (generally increases) the productivities of other inputs. Many studies of indirect effects analyze energy saving in buildings, which account for large volumes of its use. Such studies allow researchers to estimate rebound-related trade-offs between direct energy use (e.g., for heating) and energy that is embodied in buildings through construction (e.g., insulation).

The chapter's final section is a discussion of the economy-wide effects of improved energy efficiency, including a critique of recent studies that claim to have found extensive possibilities for saving energy in the American economy but have failed to account for possible rebounds. To make further headway we must introduce readers to recently devised "computable general equilibrium" (CGE) models used to analyze the effects of efficiency policies on many distinct sectors of the economy. CGE models are new and often difficult to evaluate. The few available studies that have utilized them suggest an important attribute of rebounds: the wider the set of markets being studied, the larger are estimated rebounds, and quite often rebounds become backfires that result in more energy consumption than was originally saved.

Chapter IV examines rebounds in the context of today's energy and climate policies. It begins with broad discussions of regulatory economics and the politics that often underlies it. The discussion allows us to attempt an explanation of energy efficiency's newfound popularity, and of why efficiency-related regulations seldom entertain the possibility of rebound. Moving closer to policy, the chapter then considers a recent, pioneering effort by the liberal Breakthrough Institute (BTI) to compile findings about rebounds. BTI's conclusion is that rebound carries important consequences for both the feasibility and cost of policies to reduce carbon emissions.[17] Mainstream environmentalists who expect efficiency policies to play major roles in climate policy have not welcomed BTI's findings and conclusions, since if BTI is correct there can be no "painless" climate policy. Mainstream responses, however, have thus far failed to convincingly refute much of BTI's work on rebounds.

The findings on rebound also place constraints on BTI's policy choices. These are constrained, first, by the BTI's belief that science has demonstrated a need for massive, quick, and permanent carbon reductions in order to avoid the disastrous consequences of climate change. But BTI's policy choices are also constrained by rebounds, because their existence means that efficiency policies may not significantly reduce carbon emissions and may even increase them. The two constraints effectively leave BTI to work from a menu of policies that are almost sure to fail. Despite centuries of unfavorable experience with governmental regulation of prices and technologies, such regulation is about the only tool left in their box. Much of BTI's policy program thus appears to be an undemocratic act of faith in government rather than a workable solution to climate problems as the institute perceives them. Oddly, BTI's more recent work seems to have abandoned such a vigorous policy initiative, with consequences for climate change that it has yet to describe.

Chapter V summarizes this paper's findings and draws some broad conclusions. Among these conclusions: The earlier chapters have explained the logic and pervasiveness of rebounds, linked them with economic theory, and summarized a body of quantitative studies. Very few estimated rebounds are zero, and one safe generalization is that the larger the number of economic sectors analyzed the greater the impact of rebound. One important consequence may be international: newer technologies in advanced countries may bring small rebounds as they replace older ones. Emerging nations, however, may choose to import and utilize capital goods that developed nations are retiring, increasing the potential for backfires. If rebounds are worldwide they may pose intractable problems for advocates of climate policy. Some climate change proponents have responded by denying the relevance of rebounds, quite often by devising unrepresentative and situation-specific counterexamples. Others, such as BTI, accept rebounds as important and draw an unpleasant conclusion: if carbon emissions are so important, mitigating them in the presence of rebounds will necessitate long-term intervention in markets on hitherto unseen scales.

1 W. Stanley Jevons, *The Coal Question* (Macmillan 1865). All citations are to the reprint of its Third Edition (Kelley, 1965). For a survey of Jevons's work and its impact, see Blake Alcott, "Jevons' Paradox," *Ecological Economics* 54 (2005), 9–21.

2 Until recently, most economists believed that the book's greatest contribution came in its calculations of coal reserves and the consequences of exhaustion. These matters are of secondary interest for the current study, and in any case technological developments and new fuels allowed coal's importance to end while most of it remained in the ground.

3 Jevons, 143. Italics in the original, one footnote omitted.

4 Jevons, 259–60.

5 Jevons, 386–90.

6 Nathan Rosenberg, "Innovative Responses to Materials Shortages." *American Economic Review* 63 (May 1973), 111–18.

7 Jevons, 196–97. Italics in the original.

8 http://www.agclassroom.org/gan/timeline/farmers_land.htm

9 In situations like the current economic recession, unemployment will be a higher percentage of the work force and spells of unemployment will be longer. Over the long term, the economy reverts to "normal" rates of unemployment associated with quicker transitions between jobs.

10 For more details on labor force "rebounds" to higher levels of employment, see Michael Kiley, "The Supply of Skilled Labor and Skill-Biased Technological Progress, *Economic Journal* 109 (Oct. 1999), 708–24.

11 Also see Roger Fouquet and Peter Pearson, "Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom (1300-2000)," *Energy Journal* 27 (No. 1, 2006), 139–77.

12 Jeffrey Tsao and Paul Waide, "The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six continents," *Leukos* 6 (April 2010), 259–81.

13 Tsao and Waide, 279.

14 Estimates of energy saving that do not consider economic incentives are often referred to as "engineering calculations" and that term is used in this paper. It is in no way meant to disparage the engineering profession, whose estimates are necessary starting points and important in themselves.

15 "Almost certainly" appears in the text because the changes in coal use are not compared to some hypothetical "counterfactual" that would have predicted its use absent the invention of the steam engine. This topic is discussed in Chapter III.

16 The statement cannot by itself justify efficiency policies, because it mentions neither the added costs of more efficient appliances nor the avoided cost of producing the saved energy.

17 As normally defined, greenhouse gases include carbon compounds that differ in their atmospheric effects (e.g., carbon dioxide and methane), as well as non-carbon substances such as water vapor. This paper will use "carbon" as shorthand for any compound, carbon or non-carbon, thought to be of importance for climate change.

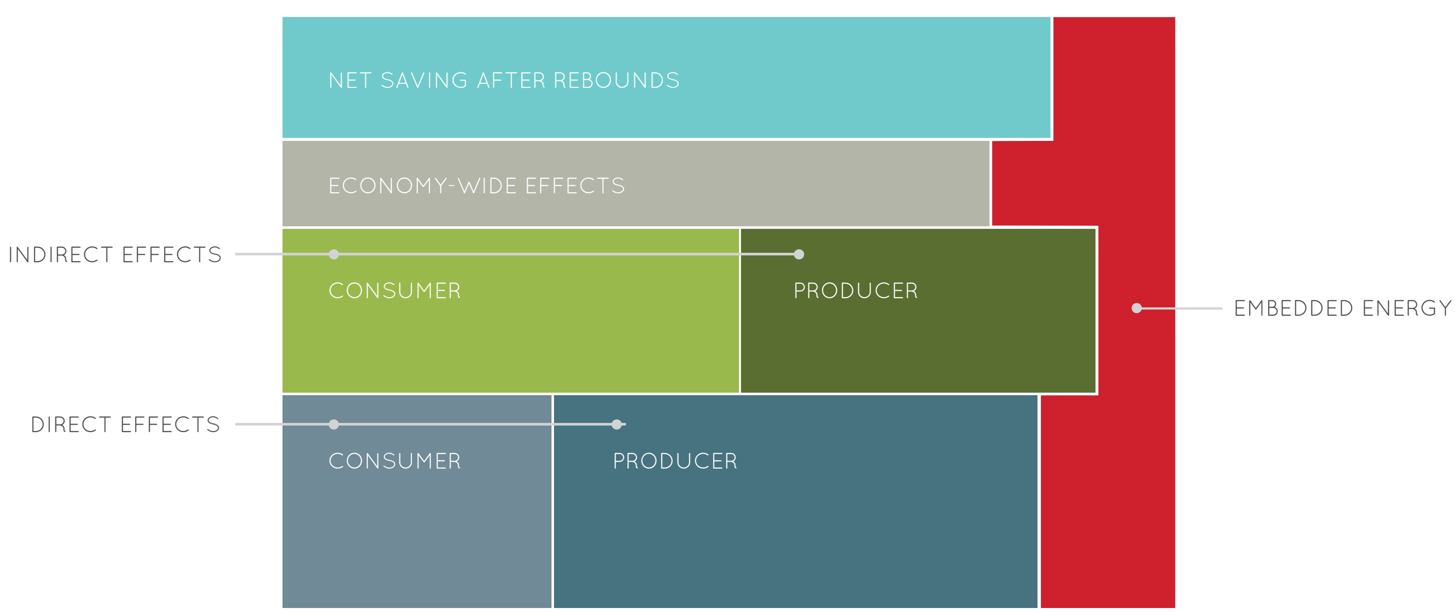
REBOUNDS: THEIR LOGIC AND DIMENSIONS

A: INTRODUCTION

Overview

There are as many definitions of economics as there are textbooks, but nearly all of them reduce to a simple pair of conditions: it is the study of self-interested people reacting to changes in their opportunities, and to changes in their surroundings that alter the costs and benefits of their reactions. A new energy-efficient technology brings new opportunities to profit from its application and extension to new areas, and a change in the price of an energy commodity changes its relative scarcity. This chapter looks at rebounds as one of many possible adjustments that households and businesses can make when their energy-related opportunities and constraints change. It explores the dimensions (time, geography, etc.) along which rebounds can occur and sets some definitions that will help readers to better understand the research findings that are presented in Chapter III.

FIGURE 1: DIRECT AND INDIRECT EFFECTS OF ENERGY-SAVING INNOVATION



Classifying Rebounds

Figure 1 illustrates a commonly used classification scheme for rebounds.[18] Assume that an engineering study of some energy-efficient appliance redesign has determined that the resulting total energy savings will be the area of the rectangle in Figure 1.[19] These are the savings if each unit of the redesigned appliance is utilized in exactly the same manner as the old, and if increased efficiency does not lead to the purchase of additional units. The area of Figure 1 is proportioned to the sizes of the various rebounds that will ensue, which are here assumed to be known and measurable for expository purposes.

Direct rebounds. These are rebounds that occur in the use or production of the good itself. Figure 1, for example, might portray a new technology that is embodied in a good such as insulation or lighting. Once it is installed, better insulation cuts the cost of obtaining additional comfort from coolness or warmth, leading to increases in energy consumption that "take back" part of the savings in the engineering calculation. The amount is the area of the rectangle labelled "Direct Effects," which can be split into those of increased use by consumers and by producers using it as an input into production of other goods.

Indirect rebounds. These are rebounds that affect goods related (in either production or consumption) to those whose efficiency has improved. Much rebound research has focused on how these improvements can raise the productivities of other inputs and spur increases in their use that increases their energy consumption. Indirect rebounds for consumers likewise can reflect increases in energy use associated with goods that are used in conjunction with the more efficient good. There may also be increases in production of those goods in response to increased demand for them. Jevons's examples show that if a new technology such as steam power affects productivities in many sectors, it will cause more substantial indirect rebounds. Figure 1 shows total indirect effects as a rectangle split between those associated with these induced increases in consumption and those associated with increases in energy use by producers.

Embedded energy. The creation, distribution, and maintenance of more energy-efficient capital goods may require the use of energy to construct them and put them in place. A step removed, additional energy will be embodied in those capital goods that will be used in more distantly related industries that are expanding in response to increased efficiency. In cases like these, however, one should also net out any reductions in energy use by less efficient equipment that is being retired.[20]

Economy-wide rebounds. A rebound can extend beyond direct and indirect effects on goods closely related to the one whose energy efficiency has improved. Fuller rebound adjustments will occur over longer spans of time (e.g., cheaper motor fuel ultimately engendered energy-using suburban lifestyles). The difference between total rebound and the sum of indirect and direct rebounds is shown in Figure 1 as the area of the rectangle labelled "economy-wide effects." (In reality the economy-wide effects subsume both direct and indirect ones. For simplicity we treat the gray rectangle is that portion of the total effect which is neither direct nor indirect.) The total is the sum of embedded energy and direct, indirect and economy-wide rebounds. Jevons's discussion illustrated several other such effects, including those of newly-engineered variants to the original technology that allow its application to other industries, and the invention of new goods that would have been prohibitively costly to produce with the inefficient earlier technology.

The net effect. In Figure 1, netting out direct effects, indirect effects, economy-wide effects, and embedded energy from the projected engineering savings yields a relatively small but positive net savings after rebounds. Energy "taken back" in rebound lies between zero and 100 percent of engineering savings. The total of the various rebounds could have also exceeded the area of the rectangle, indicating that a backfire has taken place.

The Incompleteness of Engineering Estimates

Assume engineers calculate that a new machine will reduce fuel use by 25 percent in production of good X, that X is sold in a competitive market, and that fuel accounts for 40 percent of costs. The old machine uses 10 million gallons of fuel per year. At $1 per gallon the new machine can save $2.5 million.[21] If the new machine is cheap enough, its adoption will increase producers' profits, decrease price to consumers and save energy. This engineering computation rules out rebounds, but their various effects will affect every aspect of the cost-benefit analysis. Restating and extending the above discussion of Figure 1, this calculation omits:[22]

1. *Embedded energy.* There is no mention of the "embedded energy" that must be used to produce the new technology, as described above.

2. *Direct substitution.* If fuel is substitutable for other inputs, the innovation increases the former's productivity and least-cost production of the current amount of X will use relatively more fuel and relatively less of other inputs. This rebound is a "direct substitution effect."

3. *Output or scale effects.* If an input's productivity increases, (marginal) production costs may fall at each level of output. A seller then profits by increasing output and burning more fuel. Net fuel savings may still be positive in this instance of a "direct output effect."

4. *Indirect rebound by producers.* The effects of a decrease in fuel required per unit of X are similar to those of an increase in its productivity. Under reasonable assumptions about input-output technology this input's improved efficiency can raise the productivities of other inputs. If so, use of those inputs will increase, and so will production of X, an instance of indirect rebound."[23] Production of more of those other inputs will itself generate a further indirect rebound in total energy use.

5. *Indirect rebound by producers of complements.* As X becomes cheaper, consumers wish to purchase more of it, and this effect becomes stronger as they have more time to adjust. Output of X and energy used to produce it both increase, as the same occurs for complementary goods that are consumed with X. From these effects we must subtract the fuel saved as the production of substitutes for the now-cheaper X falls.

6. *Technology diffusion.* If the new technology can be applied in sectors other than the one that produces X (or if X is itself a large industry), lower fuel use could decrease its price and indirectly affect its use in the other sectors.[24] This adjustment combines attributes of both indirect and economy-wide rebounds.

7. *Innovations.* The new X technology could suggest ways to save fuel in other industries, and possibly create incentives to invent new goods that embody variants of the technology. This is another possible manifestation of economy-wide rebound.

8. *World markets.* Direct, indirect, and economy-wide effects can all extend to the collection of economies that make up the world market and raise the total of rebounds. Effects could also include continued operation of inefficient equipment that is exported from the advanced countries rather than scrapped. Rebound effects of this type could easily become backfires.[25]

The complexities and interrelationships of these aspects of rebound tell us that a full analysis of technological innovation is not on the horizon, and that necessary data for the analysis may either be unobtainable or not collected by official sources. We must next examine methods used to estimate rebounds in more detail, prior to the discussion of quantitative results in Chapter III.

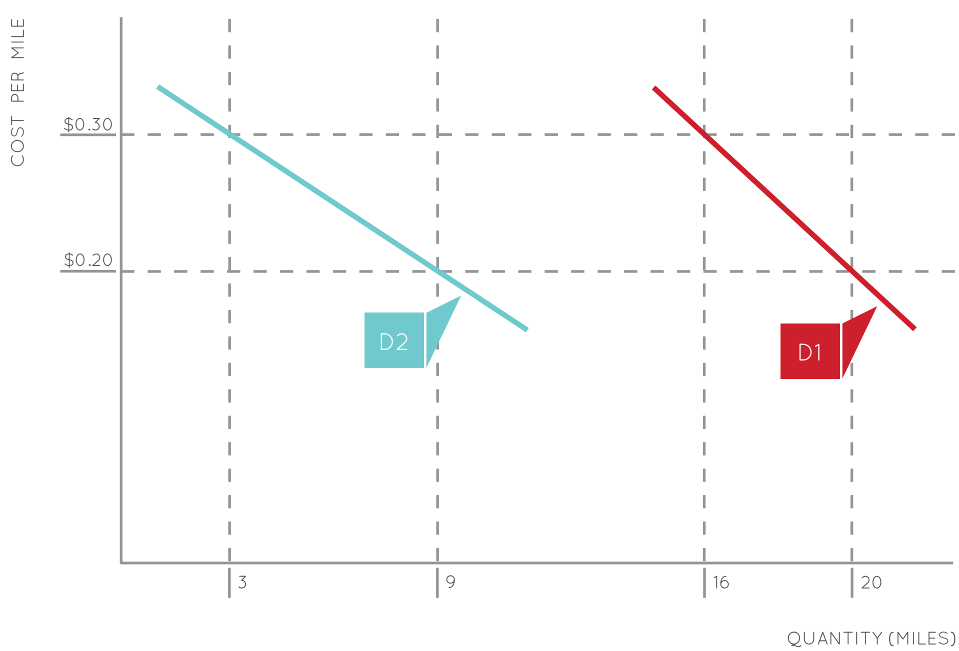
B: ENERGY SERVICES

Why "Services"

All of the definitions and examples thus far have been about adjusting the rate of consumption of some energy commodity. A fuller understanding, however, comes with the distinction between the commodity and the "services" it provides to users. Consuming an energy commodity by itself (burning heating oil outdoors because you do not own a house) produces little or no well-being for the user. Energy services are the useful output that results from consumption of the commodity in conjunction with such other goods as a furnace located in a house.[26] Burning the gas in a furnace provides the measurable service of degree-hours of heat above the ambient temperature, and burning gasoline in a car provides services measured as miles of travel. If cars A and B are otherwise identical, and A gets higher mileage than B, we say either that it produces more energy services than B or that it produces a unit of them more cheaply. Buying a more fuel-efficient car allows one to cut one's own cost of producing energy services.

Elasticity and Rebound

FIGURE 2: ELASTICITIES OF DEMAND FOR ENERGY SERVICES



The economist's familiar "demand curve" portrays a person's (or market's) response to alternative prices of some activity. The two curves in Figure 2 show possible relationships between the number of miles a person will wish to drive per day at various gasoline prices. If that price falls and demand is D1, a rebound will occur. If demand is D2 the outcome will be a backfire.[27] Assume that an efficient car that gets 9 miles per gallon replaces an inefficient one that gets 6. If the price of gasoline remains at $1.80 per gallon, the cost per mile has fallen from 30 to 20 cents. A simple engineering calculation implicitly assumes a vertical demand curve, that is, that better mileage does not change miles driven. The consumer with demand curve D1, however, responds to a 10 cent fall in per-mile cost by increasing weekly miles driven from 16 to 20. The elasticity of demand in this region (measured from the midpoints) is 0.56.[28] If his miles driven had remained at 16, he would have "saved" 0.72 gallons of gas (2.50 gallons – 1.78 gallons). Instead, after fuel economy increased he rebounded to drive 20 miles and consume 2.22 gallons for a "saving" of only 0.28 gallons. The rebound is the percentage of engineering savings taken back in increased consumption, equal to 0.44 / 0.72, or 61 percent. It can be shown that if elasticity lies between zero and 1 there will be a rebound, but not a backfire. To get the latter, assume that the consumer's demand is instead D2, whose elasticity calculated as above is approximately 2.5. An engineering calculation that kept weekly driving at 3 miles would show a saving of 0.17 gallons (0.5 gallons – 0.33 gallons). Higher elasticity, however, strengthens the consumer's response. He now drives 9 miles and consumes 1 gallon of gasoline. Consumption rises by 0.5 gallons rather than falling by 0.17, so the improved efficiency creates a backfire. More generally, demand elasticities in excess of 1 will invariably produce backfires.

Since most estimates of short-run gasoline demand elasticity cluster around 0.1 and 0.2, one might conclude that rebounds that accompany greater efficiency will be minor and backfires will be out of the question. In economics, however, short run is defined not as calendar time but rather as an interval during which responses to price cannot easily be adjusted. In the near future the consumer has little choice but to consume and work in the same locations and to drive the same car. Time brings with it greater awareness of substitutes and lower costs of adjusting to the higher price. The more and better the substitutes for a good, the more elastic the demand for it, and hence the rebound.

Elasticity, rebound, and backfire may be particularly large in situations with thresholds to be crossed. If the person with demand D2 drives only a handful of miles when the cost per mile is high, his best bet may be a rental car. Over the long run, a fall in that cost per mile could justify the purchase of a new car that could be driven for vacations, with effects that reach the status of backfires. A poor person who made do with a single incandescent bulb when efficient bulbs were unavailable might react to their introduction by buying enough of them to bring about a backfire. In the next chapter we will encounter effects like these in less-developed countries.

General and Application-Specific Improvements

Assume that a new type of compressor improves the energy efficiency of refrigerators (which are already owned by nearly all households), but for some reason the new design is unusable in air conditioners. Consumers value more capacious refrigerators, but above 25 cubic feet (which many already own) find little value in extra capacity. The change in a particular technology that has no applications beyond refrigerators will produce minimal rebound. The market is saturated with them, few consumers want additional capacity, and the only way to further increase energy use is to open the door more frequently.[29]

By contrast, examples like those of Jevons confirm that wide applicability of an efficiency improvement is more likely to generate substantial rebounds or backfires. If many appliances can use an improved electric motor there will probably be more unsaturated markets in which rebounds occur. A researcher using historical data on innovations to estimate rebounds has no obvious zero point from which to begin measuring the rebounds. There are usually many ways to obtain and economize on energy services, and some would likely have existed and been put to use absent the innovation.[30] Absent a "counterfactual" that provides estimates of energy use had the innovation not occurred, there is no reason to believe that (for example) declines in energy intensity per dollar of GDP since the 1970s are evidence that increased efficiency produces negligible rebounds.[31]

C: REBOUNDS BY INDUSTRIAL ENERGY USERS

Economists typically model a business firm's management as choosing the most profitable output quantity and producing that output with the lowest-cost combination of inputs. There are options for substituting among inputs, and the substitutions will favor those whose relative prices are lower. If some inputs are fixed and others are variable (the economist's "short run"), the range of substitutability will be less than if all are variable (the "long run"). Relationships among productive inputs have complexities that complicate the logic of rebounds for business decisions. There is much evidence that improved productivity for one input can often raise the productivities of others. In particular, increases in the productivity of energy-using equipment can increase that of the workers who work alongside it, as in the common example of a better-lit workplace.[32] Economists' models of business behavior generate demand curves for inputs that show how profit-maximizing input choices vary with their market prices. Like consumers' demands for goods, producers' demands for inputs are generally downward-sloping functions of their prices

As is the case for consumer behavior, demand elasticities determine the possibilities for rebounds and backfires. In economic theory, demands for inputs are "derived demands" that reflect the possibilities for substitution under different assumptions about technologies and markets.[33] Three characteristics of derived demands are relevant:[34]

1. The demand for an input is more elastic the easier it is to substitute between that input and others. That ease is measured by the "elasticity of substitution," discussed below.

2. The demand for an input is more elastic the more elastic the demand for the firm's product.

3. The demand for an input is more (less) elastic the larger (smaller) the fraction of total cost that this input accounts for.

The elasticity of substitution between energy and (for example) labor is the relative responsiveness of the producer's choice of inputs (measured by their ratio) to a change in their relative prices, holding output constant.[35] Determined by technology, this elasticity may be any number greater than zero. If one of the inputs is energy services, a higher elasticity of substitution with capital goods or labor means a greater rebound in energy use if its cost falls or its productivity rises.[36] If the elasticity of substitution between two inputs is zero (substitution is impossible), no change in their relative prices will change the input mix. Zero elasticity of substitution means zero rebound. The next chapter will discuss the many studies that have attempted to measure rebounds using econometric estimates of elasticities of substitution.

D: ECONOMY-WIDE EFFECTS

Partial and General Equilibrium

Direct rebounds are the effects of improved energy efficiency in the production of some good on the market in which that good is produced and exchanged. Indirect rebounds are measured in small numbers of markets (often just two) that are related in consumption or production. Models of direct and indirect rebounds use simplifications to make them manipulable and facilitate quantitative estimation. Because simplifications that render these systems tractable include the restriction of their effects to a handful of markets we often call them "partial equilibrium" models. There is, however, no obvious limit to the impacts of a change in energy efficiency. Improved vehicle fuel economy will affect the market for gasoline, with consequences both for its production and for energy use by oil producers and refiners. If vehicles are replaced more frequently (because they now travel more miles), automobile makers will use more energy, and so will makers of steel, aluminum and tires. Not all of the effects will be expansionary. Hotels will expand

and increase their energy use to accommodate more travelers, but industries like short-haul airlines may shrink as cars become cheaper ways to travel short distances.

Because there is no logical end to the possibilities, an estimate of economy-wide rebound will require inclusion of all relevant markets in a "general equilibrium" model. Absent rebound, improved energy efficiency in some sector in effect means an increase in energy usable by the entire economy. General equilibrium systems can track more sectors where rebound might manifest itself, as opposed to the small numbers of markets that a direct or indirect rebound analysis can study. Because some sectors might experience falls in energy consumption, more inclusive general equilibrium models may not always estimate larger rebounds than less inclusive partial equilibrium systems. The next chapter examines the findings of "Computable General Equilibrium" (CGE) models devised to perform these wider-ranging analyses.

E: SUMMARY

This chapter has outlined the basic terminology and classification of rebounds and discussed some conceptual approaches for estimating their magnitudes. In the simple case of direct rebound the researcher goes one step beyond an engineering calculation to examine the effect of an efficiency improvement on the particular market for that good. Indirect rebounds affect "adjacent" markets for goods that are closely related to that good in production or consumption. Rebound effects in durable goods and buildings can include both energy use when they operate and the "embodied energy" used in their manufacture or construction. Rebounds may manifest themselves in numerous aspects of market behavior, including effects on foreign markets and on incentives to invent goods that put "saved" energy to new uses. Often (but not necessarily always) increasing the number of affected markets one studies will increase the size of an estimated rebound, and possibly turn it from a rebound into a backfire.

For inputs used by businesses the significance of rebounds is likely to increase with elasticities of demand for them. Those elasticities are in large part determined by the possibilities for substitution between different inputs, and on their relative importance as elements of cost. The impact of an efficiency improvement is greater if it improves the productivities of inputs other than just those that directly utilize energy. There are wide applications of the increasing relationship between elasticity of demand and the likely strength of a rebound, including the analysis of threshold effects and specialized versus general technological improvements. Because ultimately all sectors of the economy are related either directly or indirectly there is no logical end to the possible effects of a given efficiency improvement. This problem is being attacked by new economic modeling methods that have been devised to estimate economy-wide rebounds.

18 For an alternative taxonomy of rebounds, see R. Madlener and B. Alcott, "Energy Rebound and Economic Growth: A Review of the Main Issues and Research Needs," *Energy* 24 (2009), 370–76.

19 Given that our only dimension is that of the energy saved, we could just as well have used a line of fixed length. Had we done so, however, some of the interrelationships between the different aspects of rebound would have been less clear.

20 Note that Figure 1 does not split embedded energy rebounds by type of rebound, although it could in principle have done so.

21 For simplicity in this example, assume that the time dimension is unimportant, so that we can treat both the capital cost and fuel costs of the new machine as single dollar payments, both made today.

22 For an alternative taxonomy of rebound "pathways," see Jeroen van den Bergh, "Energy Conservation More Effective with Rebound Policy," *Environmental and Resource Economics* 48 (2011), 43–58.

23 The terminology is not settled, and some call this another type of direct rebound. The distinction is purely terminological.

24 Several authors of rebound studies confuse shifts of a demand curve with movements along a fixed one. In this paper's example, a lower price for fuel (and possibly lower production) is the end of the story. The lower price does not generate additional sales because the demand curve is about the willingness to pay on the part of all possible users.

25 Additional theoretical arguments to rationalize the possibility of backfire appear in Steve Sorrell, "Jevons' Paradox Revisited: The Evidence for Backfire from Improved Energy Efficiency," *Energy Policy* 37 (2009), 1456–69.

26 Steven Sorrell, "The Rebound Effect: An Assessment of the Evidence for Economy-wide Energy Savings from Improved Energy Efficiency," UK Economic Research Center (2007), 12, and supporting appendices. (Subsequently cited as "Sorrell 2007") Sorrell borrows from physics and refers to this as the "useful work" that the commodity produces. http://www.ukerc.ac.uk/Downloads/PDF/07/0710ReboundEffect/0710ReboundEffectReport.pdf

27 The non-technical reader can safely avoid this paragraph and its calculations.

28 Elasticity is a calculus-based concept and is strictly defined only for extremely small changes. The calculations of the text assume that it is measured midway between the two points on the demand curve, a variant of the "arc elasticity." For more on elasticity, see Robert Michaels, *Transactions and Strategies: Economics for Management* (Cengage Learning, 2010), 89–95.

29 Recent redesigns have substantially reduced power use per refrigerator but there is evidence of some rebound, such as new features that include larger freezers and drinking water coolers.

30 For more on the necessity of counterfactuals, see Sorrell 2007, 22. Note that this problem also means that we cannot pin down a "rebound" figure for lighting on the basis of the studies of Tsao and his colleagues discussed earlier.

31 One recent study discussed in Chapter IV includes this decline in energy intensity as one of its arguments against rebound. David B. Goldstein et al., "Are There Rebound Effects from Energy Efficiency? – An Analysis of Empirical Data, Internal Consistency, and Solutions," Electricity Policy.com, May 2011. http://www.electricitypolicy.com/Rebound-5-4-2011-final2.pdf

32 A summary of research findings on how energy affects the productivities of other inputs, particularly capital, appears in Sorrell 2007 at 75.

33 For a simplified graphic treatment of consumer and producer rebounds, see UK Energy Research Center, *UKERC Review of Evidence for the Rebound Effect, Supplementary Note: Graphical Illustrations of Rebound Effects,"* Working Paper, Oct. 2007. http://www.ukerc.ac.uk/Downloads/PDF/07/0710ReboundEffect/0710SuppNote.pdf

34 A fourth characteristic is: demand for an input is more elastic the more elastic are the supplies of other inputs. It is not relevant for the discussion in this paper.

35 An intuitive discussion of elasticities of substitution can be found in George Borjas, *Labor Economics*, 4th ed. (McGraw-Hill, 2008), 126–27.

36 If input prices change, however, the firm will probably also wish to alter its profit-maximizing output, a change known as a "scale effect."

ESTIMATES OF REBOUNDS

A: INTRODUCTION

This chapter summarizes research findings on rebounds and their measurement. As of this writing, there is no authoritative count of rebound studies, but the hundreds known to be available constrain one to cover their broad conclusions rather than offer detailed critiques of individual findings. This chapter's next section summarizes the now-extensive body of research on direct rebounds. It considers both individual appliances and heating technologies, as well as effects such as those of improved insulation. The chapter also examines some "meta-studies" that have attempted to draw broad conclusions by tabulating the findings of many individual studies that are not directly comparable. Section B looks at available studies of indirect rebounds and examines the difficulties for inference that are posed by divergent estimates of elasticities of demand and substitution. Section C describes general equilibrium approaches in more detail, including the structures and limitations of CGE models. This section includes a table that summarizes the results of all CGE-based rebound studies extant as of this writing.

B: DIRECT REBOUNDS

Residential Aggregates and Appliance Use

Energy use in a range of nations and activities follows one general principle: where energy deficits are greatest, improvements in efficiency or fuel prices bring the biggest rebounds. The best available estimate of the aggregate household rebound to efficiency improvements in China is 30 to 50 percent, somewhat higher than that found in meta-studies of the U.S.[37] In the Spanish state of Catalonia (substantially wealthier than China), estimated short-term household rebound is 35 percent and long-term is 50 percent.[38] Estimates for specific activities also follow that principle. Much research has been devoted to rebounds associated with heating, but oddly not to those in cooling. Sorrell's meta-analysis of rebounds associated with more efficient electric heating found a range between 10 and 58 percent in the short run and 1.4 to 60 percent in the long. Air conditioning has greatly expanded but as of this writing there are only two publicly available rebound estimates, one at 1 percent and the other at 26.[39] For most other appliances, rebounds have yet to be calculated.

Rebound depends on both the zero point and the particulars of a user's situation. In New Zealand, improved insulation and heating technologies produced rebounds of up to 50 percent in houses in relatively cold areas, and rebounds near zero in houses that seldom needed heat.[40] Replacing inefficient furnaces with efficient ones in poor English households left their fuel consumption unchanged.[41] Other studies have shown rebounds in home heating energy use as fuel prices vary.[42] The same appears to hold in the often-studied area of automobile use. EU data from 1970 through 2007 showed a 44 percent rebound in response to a 100 percent increase in automobile fuel efficiency.[43] Analogous to findings for heating, the rebound effect of fuel efficiency is concentrated in the most economical part of the car population, and increasingly entails substitution of diesel power for internal combustion.[44] A rising opportunity cost of time may reduce time spent in cars and thereby mitigate what would otherwise be substantial rebound effects of improved efficiency. One such study covering 1966 through 2007 found short-run and long-run rebounds of 2.5 and 24.2 percent in 1985, which by 2000 had fallen to 2.2 and 10.7 percent.[45] The bulk of estimated automobile rebounds post-1990 are under 10 percent.[46] Consistent with the rising value of time, they also increase with road network and population densities.[47] One 2002–2009 estimate for Hong Kong was a striking 33 percent.[48]

If rebounds are larger when initial energy deficits are larger, the worldwide spread of electrification and other fuel-using technologies implies larger rebounds as their use spreads to poorer nations. The available research on the poorest nations is sparse but suggestive. One study found that converting from inefficient to efficient charcoal stoves in Sudan produced a 42 percent rebound.[49] Similarly, an Indian program to replace kerosene lamps with solar-charged battery lamps increased daily hours of lighting from 2 to 4. Many less efficient lamps remained in use instead of being replaced, and the estimated direct rebound was between 50 and 80 percent.[50] The developing world's growing energy use will be in important part made up of rebounds. Energy consumption in OECD and non-OECD countries was roughly equal in 2007, but from 2007 to 2035, the organization forecasts that the former will grow by 14 percent and the latter by 84 percent. Much of that will be from increases in first-time appliance purchases by residential consumers, as has been demonstrated by the growth in their power consumption in China, where the electrification rate is nearly 100 percent. By contrast, 404 million Indians do not yet receive electrical service.[51]

There are many pitfalls in consumer-based research, and few if any studies of direct rebound can avoid them completely. They include the usual difficulties of incorrect or inaccurate reporting by subjects, which may be aggravated if people shade their answers in hopes of eliciting approval by showing an interest in conservation and the environment. In addition, participants in such surveys may not be representative of the general population. For example, buyers of more efficient furnaces may value comfortable temperatures more highly than others and be more likely to rebound after acquiring an efficient furnace. The "simultaneity" between the choice of an efficient appliance and the likelihood of rebound may mean that estimates of rebound based on this nonrandom sample of the public will be biased upward.[52] The simultaneity appears in a more general context. One comparison between Arizona homes with and without the U.S. Department of Energy's "Energy Star" efficiency credentials found that the former were generally larger and on average consumed 12 percent more energy than the latter.[53]

Meta-Studies

Engineering estimates of energy savings from increased efficiency are often on the high side because they fail to account for changes in the economic incentives of consumers. American regulatory agencies commonly require utilities to undertake and report on the results of efficiency programs. The typical utility engages in a number of programs, but heterogeneity makes the results difficult to compare (and data is often kept confidential). Two available meta-studies, however suggest significant rebound. In one of the studies, economists Paul Joskow and Donald Marron estimated that 75 percent of a large sample of utility initiatives failed to achieve engineering projections of savings.[54] In the other, a consulting firm audited the California Public Utilities Commission's over-200 appliance-related conservation programs in effect in 2004, and concluded that as a group they delivered only 74 percent of expected savings.[55] Figures like these are consistent with appliance rebound studies discussed above, where rebounds are frequently in the 20 to 30 percent range.

As noted in Chapter II, rebounds from efficiency programs will be greater the more elastic the demands for energy or energy services. If the elasticity estimates are reliable we can forecast the associated rebounds. One meta-analysis of econometric estimates of household demand elasticities for electricity calculated average short-run rebounds at 20 to 35 percent (again consistent with estimates derived by different methods) and long-run rebounds at 80 to 85 percent.[56] Another meta-analysis of vehicle fuel demand elasticities found a long-run rebound range of 30 to 64 percent.[57] Because of differences in data and methods used in the individual studies, any firm inferences should be made only with great caution. One potentially important difference stems from differences in measures used to operationalize the long run. Conceptually, in the long run people can adjust all aspects of their energy use, including replacement of appliances. In reality, the available data from (for example) surveys may correspond only weakly with the concept. If we tentatively accept the 85 percent long-run electricity rebound it indicates that changes in household behavior alone (before consideration of adjustments in the business sector) may nearly suffice to produce backfires. A high estimated rebound partially supports the oft-cited "Khazzoom-Brookes Postulate," which asserts that if energy prices remain constant any technological improvement in efficiency will be more than lost in backfire.[58]

C: INDIRECT REBOUNDS

Households

Indirect rebounds are the effects of improved efficiency in some economic sector on energy use by producers and/or consumers of related goods. Ultimately all economic sectors are related, but "indirect" customarily refers to close substitutes or complements and to inputs into production of the sector's good or service. Indirect effects are usually harder to measure than direct ones because they require estimates of the degree to which goods are related—for example, how closely consumers view two goods as substitutes.

Several researchers have published estimates of how efficiency improvements affect consumption spending and its allocation among sectors. Such estimates aid in the evaluation of claims that growth in per capita GDP will make rebounds less significant as the public approaches satiation in direct expenditures on electric lights, televisions, and other appliances. Available estimates, however, do not strongly suggest that growth will reduce rebounds. Rather, prosperity may induce more spending on services (e.g., travel) and higher quality goods that embody more indirect energy. One study of Sweden estimated that 20 percent improvements in the efficiency of personal transport and space heating would bring backfires of 120 and 170 percent of the saved energy.[59] Another examined mass adoption of a 15 percent reduction in food expenditures. It found that if people spent the saved money according to existing patterns there would be a larger increase in the economy's energy consumption than the amount saved by changing the mix of food purchases.[60] Much research remains to be done in this area.

Indirect rebounds may also be triggered by consumer responses to improved energy efficiency. A household that replaces an inefficient air conditioner may choose to keep temperature lower and spend more time at home, but this direct rebound need not be the end of the story. The occupants of the house might choose to engage in more energy-intensive activities (electronic games, cooking elaborate meals, etc.) that could replace ones (outdoor recreation) that use less energy. Greater energy efficiency lowers the relative costs of goods that utilize energy more intensively in both their production and consumption. An important efficiency improvement may also produce what economists know as an "income effect" that further increases energy use. More efficiency allows a given income to purchase more goods and services, which may consume additional energy. No available study has tracked such complications or attempted to estimate their aggregate effects.

How Do Businesses Respond?

A questionable application of some economic logic purports to show that direct and indirect rebounds in production will typically be minor.[61] Assume that energy accounts for 15 percent of good A's total cost (empirically an exceptionally high amount), and that improved efficiency brings a rebound that increases output of A by 20 percent. This rise will entail only a 3 percent increase in energy purchases (15 percent of the 20 percent), and even that small figure must be netted against the energy savings at the former output level. Producers of A may also adjust by purchasing more capital equipment, raw materials, and so forth, but the size of any associated rebounds depends on the particulars of the situation. More efficient capital goods, for example, could consume less energy in operation while their production requires more embodied energy.

Such reasoning neglects important aspects of the economic theory of production that, when accounted for, could imply considerably larger rebounds. First is that the reasoning assumes that changes in prices and productivities will induce only changes in the scale of production and not substitutions among the inputs such as were examined in Chapter II's discussion of elasticities of substitution. Empirical estimates of those elasticities show that the possible scope for substitution is wide enough to frequently bring small rebounds, and in some cases backfires are possible.[62] Rebounds and backfires are generally reinforced by "scale effects" that lead more energy-efficient producers to seek higher profits by choosing to increase output and their corresponding consumption of energy. Estimating the sizes of such effects from available data continues to be a major econometric problem, and there is little agreement on the sizes of substitution elasticities in various industries.[63]

The second neglected aspect of production economics is its treatment of interrelationships among the productivities of various inputs. Unlike uncertainties about elasticities of substitution, econometric estimates of production technologies often conclude that inputs behave as complements, for example, an increase in the productivity of energy services raises the productivities of other inputs. These improvements further increase energy consumption, strengthening the case for rebound.[64] Energy's small direct share in total production costs cannot be taken as a reliable indicator of rebound size.[65] Unfortunately, the econometric estimation of production relationships becomes particularly difficult when energy is one of a large number of inputs, and this research has yet to reach firm conclusions.[66]

Paradoxically, some energy analysts who believe rebounds are minimal nevertheless accept that energy raises the productivity of other inputs, apparently failing to realize that complementarity means that rebounds will be larger. Instead, those analysts neglect rebounds while arguing at the same time that businesses that conserve energy can increase profits. A 1997 study by the Rocky Mountain Institute, for example, purported to show that improvements in lighting quality and the comfort that resulted from energy-efficient architecture could improve labor productivity by as much as 16 percent.[67] Since payroll costs often exceed energy costs by a factor of 20, the increased productivity would mean that adding more workers would increase profits. Adding more workers, however, will surely bring some energy rebounds that would not happen absent the increase in worker productivity.[68]

Measurement of Indirect Effects

There are few "direct" studies of indirect effects detailing the paths by which improved energy efficiency affects a firm's choices of input and output quantities. In part this may reflect the difficulties of investigating matters that may be important elements of competitive strategy. One such study examined the effects of a switch to energy-efficient capital goods on the U.S. forest products industry.[69] Its authors estimated substitution elasticities between energy and capital goods, and used those estimates to derive actual and embedded energy consumption of the new capital goods. They showed that the new upstream capital goods consumed between 18 and 83 percent of the direct energy that superficially appeared to have been saved downstream. The findings are for a single industry, but they show that downstream efficiency can bring increased upstream energy use, and that we cannot simply assert that upstream rebounds will be minimal.

There have also been a large number of studies that compare the actual amounts of operating and embodied energy (e.g., in insulation, glass, and so forth) used in buildings with different rated efficiencies in energy use.[70] One survey found that embodied energy is between 9 and 46 percent of total life-cycle energy used in low-energy buildings and between 2 and 38 percent in conventional buildings. These results suggest rebound, but they cannot provide usable estimates because they do not consider construction and other operating costs that are needed to compute the full rebound effect. Other research on European Union building directives has found that if builders are in compliance with them the associated investments in embodied energy cannot pass standard tests of cost-effectiveness.[71]

D: ECONOMY-WIDE EFFECTS

Modeling Total Rebound

Comparing the above discussions of direct and indirect rebounds makes clear that problems of estimation increase disproportionately with the number of variables to be analyzed, as potential interactions and potential sources of error multiply. Effects of important efficiency policies (e.g., new standards for widely used electric motors), however, can spill out over the entire economy and possibly also overseas. Macroeconomic models that aggregate economic activity into such broad classifications as "consumption" and "investment" will not suffice because they assume away many of the complexities that must be acknowledged in an analysis of rebounds. Such models usually assume that all of the economy's capital goods are identical regardless of their labor requirements, energy requirements, location, or durability. Rebounds, however, are about shifts among types of capital and changes in the mixes of inputs that individual industries employ.

The two most important recent studies on the economy-wide consequences of improved energy efficiency both followed similar strategies. They chose to mention rebounds in passing and then presented their estimates of saved energy without factoring in the quantitative effects of those rebounds. McKinsey & Company's 2009 report "Unlocking Energy Efficiency in the U.S. Economy" produced impressive estimates of low-cost energy savings in numerous sectors and concluded that efficiency was a "vast, low-cost energy resource for the U.S. economy." Specifically, $520 billion invested among the sectors between 2009 and 2020 would yield savings of $1.2 trillion and reduce energy consumption by 23 percent of the amount expected under a "business as usual" scenario.[72] Oddly, McKinsey included a page with citations to research that found significant rebounds, but "rebound" does not appear elsewhere in the report.[73] The American Council for An Energy-Efficient Economy used different modeling techniques in its 2012 study of potential savings. Under a business-as-usual scenario, ACEEE projected a rise in aggregate energy use from 100 quadrillion BTUs ("quads") in 2010 to 122 quads in 2050. Implementing policies somewhat more stringent than McKinsey's would reduce the total in 2050 to 70 quads, 42 percent below business as usual. Like McKinsey, ACEEE noted the likelihood of rebound, but acknowledged that its model "is not presently set up to answer this question" and they "are exploring ways to incorporate such feedback."[74]

CGE Models

First devised by economists for other research applications, "computable general equilibrium" (CGE) models stake out a middle ground between unimplementable ideals and studies like McKinsey's that disregard rebound and other sectoral interactions. A CGE model numerically solves a large system of equations that incorporate the determinants of economic choices made by consumers and producers of the economy's goods and services. Researchers may use empirical data and choose their assumptions about economic magnitudes and behavior. The CGE model can then estimate the economy's outputs, the inputs that it will use, and prices for the inputs and outputs. CGE models are based on "neoclassical" economics that assumes consumers and producers make rational choices. Unlike macroeconomic models, markets in CGE systems always "clear," with no shortages or surpluses or unemployment.[75]

The seeming realism still falls short of reality's complexities, and CGE computations depend directly on the researcher's data and assumptions. CGE is at best an approximation, but it is increasingly used to provide rough evidence on the consequences of alternative policy choices.[76] Sometimes the most useful predictions are about the directions of change rather than their magnitudes. CGE-based studies of energy efficiency follow the same general methods as others. Research begins with a "base case" calculation whose assumptions and data are "calibrated" with known data to produce an outcome thought to resemble reality. Then come comparison runs that examine the effects of changes in the base case assumptions. A CGE analysis of energy efficiency will generate findings on input use, output levels, and prices in all of the economy's sectors. With these and the base case results in hand, one can estimate rebounds in the individual sectors and add them up to find the full consequences.

Some CGE Results

Currently only a relatively small number of CGE-based rebound studies exist. Comparisons are difficult (and sometimes impossible) because of differences in data (nations and years), economic assumptions, and computational methods. Oddly, there are at present no available CGE rebound studies for the United States. Table 3-1 presents the results of all studies known as of this writing.[77] Some contain results from multiple calculations, in which case the table shows an average.[78]

The small sample, the diversity of modeling approaches, and the wide range of results render any inferences problematic. Of the eleven studies, five (including one variant of Japan 2008) claim rebounds of over 100 percent, that is, backfires that ultimately induce more energy use than was saved. With the exception of U.K. models that analyze disinvestment in energy, almost all of the rebounds exceed 50 percent, even for brief simulation periods. There is some positive association between shorter simulation periods and smaller rebounds but not enough for rigorous inference. The small rebounds found in two of the U.K. studies probably follow from their assumptions of mandatory energy-use reductions, which make rebounds impossible in certain industries. Most economists would expect to see estimates of economy-wide rebounds that are larger than those for direct and indirect ones. Analyzing only a small number of markets means disregarding all but a handful of prices and outputs. Economy-wide rebounds may become even larger if we take a step beyond the usual notion of the "long run," which assumes full adjustment of the economy but no changes in technology. If energy becomes more productive, history often shows that new energy-using technologies and business models will follow. Oil in the United States (kerosene) was first marketed as an alternative source of light and heat, but the subsequent spread of the internal combustion engine changed consumption and production by far more. Rebounds went on to entail more than travel, as the automobile ultimately gave rise to suburbs that further increased the use of oil. Questions that go beyond the normal definition of the long-run will bring us back to Jevons in the concluding chapter.

FIGURE 3: ESTIMATES OF ECONOMY-WIDE REBOUNDS

COUNTRY	STUDY YEAR	CHANGES STUDIED	REBOUND	PERIOD ANALYZED
CHINA[i]	2005	Effects of cheaper coal cleaning technology	Over 100%	25 years
JAPAN[ii]	2004	1 percent efficiency increase in all sectors	53%	Unspecified
JAPAN[iii]	2008	Improvements in efficiency, differ among sectors	27-115%	Unspecified
NORWAY[iv]	2004	Oil or electricity efficiencies doubled in 6 sectors	Over 100%	50 years
SCOTLAND[v]	2005	5 percent increase in energy efficiency in all sectors	132%	50 years
SPAIN[vi]	2010	5 percent energy efficiency increase in all sectors	177%	Unspecified
SWEDEN[vii]	1957-62	Efficiency up 15% in nonn-energy, 12% in energy	50-60%	5 years
U.K.[viii]	2000	5% efficiency increase, all production sectors	30-55%	Unspecified
U.K.[ix]	2000	5% energy efficiency increase, all sectors	23-59%	Unspecified
U.K.[x]	2000-10	All planned U.K. climate policies go into effect	26%	10 years
WORLD[xi]	2013-20	Implement all current IEA policy proposals	31.5-51.3%	17 years

i Solveig Glomsrød and Wei Taoyuan, "Coal Cleaning: A Viable Strategy for Reduced Carbon Emissions and Improved Environment in China?" Energy Policy 33 (2005), 535–42.

ii Toyoaki Washida, "Economy-Wide Model of Rebound Effect for Environmental Efficiency," unpublished 2004, http://www.webmeets.com/files/papers/ERE/WC3/991/w3c-washida.pdf

iii Kenichi Mizobuchi, "An Empirical Study of the rebound effect considering capital costs," *Energy Economics* 30 (2008), 2486–16. Assumes 20 percent improvement in efficiency of electricity and motor vehicles, 10 percent in natural gas, and 3 percent in oil, A rebound of 27 percent occurs if capital investment has fully adjusted to the improvements, and 115 percent if there has been no such adjustment. The model is run until certain of its solutions converge, which takes place over various time spans that cannot be equated with years.

iv Sverre Grepperud and Ingeborg Rasmussen, "A General Equilibrium Assessment of Rebound Effects," *Energy Economics* 26 (2004), 261–82.

v Hanley, Nick, et al., "Do Increases in Energy Efficiency Improve Environmental Quality and Sustainability," *Ecological Economics* 48 (No. 3, 2009), 692–709. Rebound is 132 percent for electricity and 134 percent for other energy sources.

vi Ana-Isabel Guerra and Ferran Sancho, "Rethinking Economy-Wide Rebound Measures: An Unbiased Proposal," *Energy Policy* 38 (2010), 6684–94. The figure is for assumed elasticities of substitution of 1 everywhere.

vii Peter Vikstrom, "Energy efficiency and Energy Demand: A Historical CGE Investigation on the Rebound Effect in the Swedish Economy 1957, unpublished 2004, http://www.iioa.org/pdf/Intermediate-2004/440.pdf

viii Grant Allan et al., "The Impact of Increased Efficiency in the Industrial Use of Energy: A Computable General Equilibrium Analysis for the United Kingdom," *Energy Economics* 29 (2007), 779–98. Long-run rebound is 30 percent, short-run 55 percent. Difference reflects assumption that lower energy use results in a fall in the price of domestically produced fuels and subsequent disinvestment in their production. Model runs through 25 periods of simulation that are not identifiable with years, long-run outcome is said to be "conceptual."

ix Karen Turner, "Negative Rebound and Disinvestment Effects in Response to an Improvement in Energy Efficiency in the U.K. Economy," *Energy Economics* 31 (2009), 648–66. Like other 2000 U.K. study, lower long-run rebound reflects disinvestment in domestic fuel industry.

x Terry Barker et al., "The Macro-Economic Rebound Effect and the UK Economy," *Energy Policy* 35 (2007), 4935–46.

xi Terry Barker et al., "The Macroeconomic Rebound Effect and the World Economy," *Energy Efficiency* 2 (2009), 411–27. The 31.5 percent rebound occurs in 2020 and the 51.3 percent in 2030.

E: SUMMARY

Rebounds are relatively easy to classify and very difficult to quantify, even in relatively straightforward cases. The common finding of relatively small direct rebounds cannot be taken as strong evidence that rebounds at other levels are minor and do not greatly alter engineering estimates of the benefits of efficiency policies. Moving from direct rebounds to those that affect more sectors often raises estimated rebounds, and effects on the entire economy may be even stronger if one accepts the findings of the relatively small number of CGE studies. Treating rebounds as international phenomena that also affect less-developed countries may raise calculated rebounds above those found using CGE models.

Indirect rebounds among small numbers of markets are harder to estimate than direct rebounds, owing to the complexity of the interactions, particularly when one uses more appropriate models of the production side. With those models, it becomes impossible to dismiss rebounds on the grounds that energy is often a small part of total costs. This reasoning fails on two grounds. First, the consequences of substitutability between energy are likely to include larger rebounds (or backfires) than calculations based on cost percentages. Second, complementarities between inputs mean that increasing the amount of one input (energy) will raise the productivity of another (labor). If so, a firm's most profitable response will be to further increase both energy and labor use. Looking at household behavior, there is little factual support for claims that "saturation" of energy-using appliances in wealthy nations is decreasing the quantitative importance of rebounds.

The authors of two recent studies that claim great benefits from increased energy efficiency both acknowledge that their studies did not estimate or otherwise account for rebounds. This disregard becomes even more untenable in light of CGE estimates of economy-wide rebounds whose values are generally greater than those calculated for models with fewer intersectoral relationships. CGE models are tool kits that allow researchers to compare the estimated effects of more fully specified policies in more detail than has hitherto been feasible. the number of CGE studies is still small but their results so far suggest an important lesson: The more complex the economy and the longer the time that can elapse, the greater will be the rebounds that follow improvements in energy efficiency.

37 Jinlong Ouyang et al., "Rebound Effect in Chinese Household Energy Efficiency and Solution for Mitigating It," *Energy* 35 (2010), 5269–76.

38 Jaume Gonzalez, "Empirical Evidence of Direct Rebound Effect in Catalonia," *Energy Policy* 38 (2010), 2309–14.

39 Sorrell 2007, 32–36.

40 Philippa Howden-Chapman et al., "Warm Homes: Drivers of the Residential Demand for Heating in the Residential Sector in New Zealand," *Energy Policy* 37 (2009), 3387–99. On the other hand, changes in energy policy and fuel prices have not led to any significant change in home thermostat settings in the U.K. between 1984 and 2007. Michelle Shipworth, "Thermostat Settings in English Houses: No Evidence of Change Between 1984 and 2007, *Building and Environment* 46 (2011), 635–42.

41 Sung Hong et al., "The Impact of Energy Efficient Refurbishment on Space Heating Fuel Consumption in English Dwellings," *Energy and Buildings* 38 (2006), 1171-81.

42 Hugo Hens et al., "Energy Consumption for Heating and Rebound Effects," *Energy and Buildings* 42 (2010), 105–10.

43 Amela Ajanovic and Reinhard Haas, "The Role of Efficiency Improvements versus Price Effects for Modeling Passenger Car Transport Demand and Energy Demand—Lessons from European Countries," *Energy Policy* 41 (2012), 36-46.

44 Wenzel Matiaske et al., "Modifying the Rebound: It Depends! Explaining Mobility Behavior on the Basis of the German Socio-Economic Panel," *Energy Policy* 41 (2012), 29-35.

45 Kenneth Small and Kurt Von Dender, "Fuel Efficiency and Motor Travel: The Declining Rebound Effect," *Energy Journal* 28 (No. 1, 2007), 27–51.

46 David Greene, "Rebound 2007: Analysis of U.S. Light Duty Vehicle Travel Statistics," *Energy Policy* 41 (2012), 14–28, tables at

17–18. Estimates for adjacent but less densely populated Canada center around 20 to 30 percent. Philippe Barla et al, "Travelled Distance, Stock and Fuel Efficiency of Private Vehicles in Canada: Price Elasticities and Rebound Effect," *Transportation* 36 (2009), 389–402.

47 Qing Su, "A Quantile Regression of the Rebound Effect: Evidence from the 2009 National Household Transportation Survey in the United States," *Energy Policy* (2012), in press.

48 H. Wang et al, "Direct Rebound Effect for Passenger Transport: Empirical Evidence from Hong Kong," *Applied Energy* 92 (2012), 162–67.

49 Eiman Zein-Elabdin, "Improved Stoves in Sub-Saharan Africa: the Case of Sudan," *Energy Economics* 19 (1997), 465–75.

50 Joyashree Roy, "The Rebound Effect: Empirical Evidence From India," *Energy Policy* 28 (No. 6, 2000), 433–38.

51 Catherine Wolfram et al., "How Will Energy Demand Develop in the Developing World?" *Journal of Economic Perspectives* 26 (Winter 2012), 119–38.

52 There are econometric methods to mitigate these problems of selectivity bias, but few rebound studies have acknowledged and attempted to account for them. One that does is Scott Kelly, "Do Homes That Are More Energy Efficient Consume Less Energy? A Structural Equation Model of the English Residential Sector," Energy 36 (2011), 5610–20.

53 Jeffery Harris et al., "Towards a Policy of Progressive Efficiency," in *People-Centered Initiatives for Increasing Energy Savings*, ed. Karen Erhardt-Martinez and John Laitner (American Council for an Energy-Efficient Economy, 2010), 60–79.

54 Paul Joskow and Donald Marron, "What Does a Negawatt Really Cost? Evidence from Utility Conservation Programs," *Energy Journal* 13 (No. 4, 1992), 41–74. The outcome could also be subject to measurement errors.

55 Megdal and Associates, *Overview of the Evaluations of California's 2004-2005 Efficiency Programs*, http://www.megdalassociates.com/pubs/IEPEC_2005-005.pdf Utility reports claimed an average of 91 percent of projected savings.

56 John Espey and Molly Espey, "Turning on the Lights: A Meta-Analysis of Residential Electricity Demand Elasticities," *Journal of Agricultural and Applied Economics* 36 (Fall 2004), 65–81.

57 Phil Goodwin et al., "Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income," *Transport Reviews* 24 (May 2004), 275–92. A predecessor report is discussed by Sorrell 2007 at 28–29.

58 J. Daniel Khazzoom, "Economic Implications of Mandated Efficiency in Standards for Household Appliances," *Energy Journal* 1 (No. 4, 1980), 21–40; Leonard Brookes, "Energy Efficiency Fallacies Revisited," *Energy Policy* 28 (No. 6, 2000), 355–66.

59 Sorrell 2007 (at 49) lists a number of such estimates, whose different findings are hard to reconcile. Thirty percent of Australian household energy consumption was indirect, as opposed to fifty-four percent for Dutch households. One-third of energy consumption of poor Norwegian families was indirect, but that of rich families was two-thirds was indirect.

60 Runnar Brannlund et al., "Increased Energy Efficiency and the Rebound Effect: Effects on Consumption and Emissions," *Energy Economics* 29 (No. 1, 2007), 1–17.

61 For a fuller exposition, see Lee Schipper and Michael Grubb, "On the Rebound? Feedback between Energy Intensities and Energy Uses in IEA Countries," *Energy Policy* 28 (No. 6, 2000), 367–88.

62 Alternative formulations of the relationship between output and inputs (known in economics as "production functions") imply different percentage rebounds in response to increased energy efficiency. The commonly used "Cobb-Douglas" function has an elasticity of substitution equal to 1, and can be shown mathematically to always produce 100 percent rebound. A "constant elasticity of substitution" function (whose elasticity can be specified as any positive number) produces rebounds below 100 percent if its elasticity is below 1, and backfires if it is above 1. For mathematical formulations and derivations of these results, see Harry Saunders, "Fuel Conserving (and Using) Production Functions," *Energy Economics* 30 (2008), 2184–235.

63 For a summary of estimates and their difficulties, see UK Energy Research Centre, UKERC Review of Evidence for the Rebound Effect, Technical Report 3: Elasticity of Substitution Studies (Working Paper, Oct. 2007). http://www.ukerc.ac.uk/Downloads/PDF/07/0710ReboundEffect/0710Techreport3.pdf

64 There are, however, many case studies that document these complementary effects and the associated rebounds. A list appears in Sorrell 2007 at 70. The most advanced econometric work thus far is in Harry D. Saunders, *Historical Evidence for Energy Consumption Rebound in 30 US Sectors and a Toolkit for Rebound Analysts*, unpublished, 2010. This material is on-line but has not yet undergone peer review. http://thebreakthrough.org/blog/Historical%20Evidence%20Article%2011-11-10.pdf

65 Extension of this reasoning leads to models of "ecological economics" that are not yet amenable to rebound analysis. They

currently center on arguments that the productivity effects of increased energy quality (for example, electricity has greater energy density and is more directable than coal) are as important or more so than those of improved energy-using technologies. If this reasoning is correct, it casts doubt on claims that the once generally agreed-upon link between energy and GDP was actually severed by the market developments of the 1970s. See, for example, Robert Kaufmann, “A Biophysical Analysis of the Energy / Real GDP Ratio: Implications for Substitution and Technical Change,” *Ecological Economics* 6 (No. 1, 1992), 35–56.

66 The facts that estimation is difficult and data do not correspond perfectly to theoretical constructs have been used to argue against econometric estimates of rebound. Critics who reject econometrics, however, cannot simply claim as they do that intuition and casual examination of some correlations suffice to justify the rejection. See “Bombshell: Energy Experts Call on Breakthrough Institute to Retract or Fix Its Deeply Flawed Energy Rebound Report” and references therein, at http://thinkprogress.org/romm/2012/01/20/408087/co2-scorecard-breakthrough-institute-retract-or-fix-its-deeply-flwed-energy-rebound-reports/

67 Amory Lovins and L. Hunter Lovins, “Climate: making sense and making money,” Rocky Mountain Institute, 1997. http://www.rmi.org/rmi/Library/C97-13_ClimateSenseMoney

68 Compare Hunter Lovins’s recent assertion that “[y]ou typically pay 100 times for salaries what you pay for energy, so if you can get a 1 percent increase in [worker] productivity, that dwarfs all the energy savings.” “Convincing Even the Skeptics to Go Green,” *New York Times*, Feb. 2, 2011. The above text considers only the activities of a single business. The economy-wide effects of such productivity improvements are discussed in the next section.

69 Robert Kaufmann and I. G. Azary-Lee,“A biophysical analysis of substitution: Does substitution save energy in the U.S. forest products industry?” in *Ecological Economics: Implications for Forest Management and Practice*, ed. D. P. Bradley and P. O. Nilsson, (Swedish University of Agricultural Sciences, 1991), 111–23.

70 A summary appears in I. Satori and A.G. Hestnes, “Energy Use in the Lifecycle of Conventional and Low-Energy Buildings: A Review Article,” *Energy and Buildings* 39 (2007), 249–57. These authors do not examine the significance of their findings for analysis of the present value of returns from investments in greater embodied efficiency.

71 Xavier Garcia-Casals, “Analysis of Building Energy Regulation and Certification in Europe: Their Role, Limitations, and Differences,” *Energy and Buildings* 38 (2006), 381–92.

72 McKinsey Global Energy and Materials, *Unlocking Energy Efficiency in the U.S. Economy* (July 2009), Executive Summary at v. Savings are calculated on a net present value basis. http://www.mckinsey.com/en/Client_Service/Electric_Power_and_Natural_Gas/Latest_thinking/~/media/McKinsey/dotcom/client_service/EPNG/PDFs/Unlocking%20energy%20efficiency/US_energy_efficiency_full_report.ashx

73 McKinsey 2009, 33. McKinsey has not released any documents that detail the report’s calculations of costs and savings.

74 ACEEE, *The Long Term Energy Efficiency Potential: What the Evidence Suggests*, Report No. E121 (Jan. 2012), 58–60 and 64. http://www.aceee.org/research-report/e121

75 A fuller but still readable introduction to CGE models appears in Sorrell 2007 at 51–54.

76 Abstraction is necessary, but researchers must strike a balance with realism. As an example of a poor balance, there are widespread concerns that California’s pending carbon control policies will aggravate its already high unemployment rate. The CGE model that the California Air Resources Board uses to evaluate the policy’s effects is mathematically structured to be incapable of producing increases in unemployment.

77 Some of these are unpublished and have yet to be peer-reviewed.

78 Some of these are listed in Table 4.1 of Sorrell 2007, and I have used his estimates of central tendency.

REBOUNDS AND CLIMATE POLICY

A: INTRODUCTION

Both the discovery of a new resource and an increase in the productivity of an existing one can bring benefits that did not previously exist. Both enrich the world because resources "freed up" by the change can now satisfy other wants. Economists often see the finiteness of a resource not as a barrier but as a challenge that if met will produce widespread benefits. Some environmentalists find this a disturbing perspective with potentially disastrous consequences for health, ecosystems, and the world economy. One appeal of efficiency policies has been the possibility that they can simultaneously reduce resource use and maintain standards of living. But if rebounds are large and pervasive, this happy compromise will be fleeting as "saved" energy commodities find other uses.

This chapter begins by placing efficiency policies in the regulatory taxonomy of command-and-control measures and market-based institutions. Doing so allows us to evaluate them in light of common rationales for regulation. This is followed by an examination of the forces that are currently making efficiency an important determinant of policy. We follow these points with a discussion of *Energy Emergence*, a February 2011 report by the Breakthrough Institute (BTI's) on rebound and its consequences.[79] Like the present document, BTI's report summarizes the state of knowledge about rebounds and its potential importance for climate policy, BTI's work quickly elicited criticism from researchers who believe that their own work shows the unimportance of rebounds and the value of efficiency mandates. BTI sees rebounds as requiring a reorientation of climate policy. First, they provide a rationale for publicly supported research into carbon mitigation technologies. Second, there will be a need for market oversight and related policies that discourage rebound behavior and encourage the use of technologies such as nuclear.

BTI thus challenges more established environmentalists whose carbon policies rely on efficiency mandates that are superficially cheap to implement and politically acceptable. The environmentalists' resistance is understandable: if both rebound and climate change are real, there are only two workable policies: (1) Direct controls, which will be politically problematic to implement and enforce; and (2) Investment in carbon-free sources (such as nuclear power) that challenge their basic vision. BTI, however, sees rebound as a rationale for stronger carbon policies, some of which involve governmental setting of market prices and directing investments. Absent rebound, the policy task would be considerably more manageable. Unfortunately, BTI's preferred policies will probably not be workable even under its own optimistic and self-contradictory assumptions. This chapter closes with a discussion of some recent changes in BTI's policy outlook and their likely consequences for rebound analysis.

B: EFFICIENCY POLICIES

Two Types of Policy

Most environmental and energy policies can be viewed as either direct controls or market-based systems.[80] Energy efficiency measures often combine aspects of the two. We begin with a general discussion direct controls and market-based methods that will set the stage for a discussion of efficiency-related regulations.

Direct controls intend to achieve some objective either by setting technological standards or by directly regulating certain activities. Examples include requirements that power plants use certain pollution-capture devices that might improve health and outright prohibitions against certain discharges into the environment. Over half of the states currently have "renewable portfolio standards" (RPS) that specify power sources that utilities must use to meet legislated quotas of "renewable" power. An RPS points up important inefficiencies often associated with direct controls. Whatever its political value, there is little economic case for requiring power from renewable technologies. If the goal is to reduce atmospheric emissions, it is generally better to allow any type of plant that meets emission criteria than to restrict the range of allowable technologies.[81] Alternatively, if the goal is to improve renewable power's commercial viability, this might better be done with targeted research support than by a more costly RPS, which can give utilities perverse incentives.[82]

Market-based regulations are formulated with the intent of achieving certain objectives at lower cost by incentivizing behavior that furthers those objectives. One familiar example is the system instituted by the Environmental Protection Agency's (EPA) that allows power generators to buy and sell rights to emit "criteria pollutants" such as oxides of nitrogen and sulfur.[83] To simplify, EPA sets a "cap" on allowable emissions and then allocates rights to emit ("allowances") using administrative proceedings or auctions. Holders may choose to use their allowances or sell them. Allowing resale improves efficiency by encouraging those with lower abatement costs to reduce emissions and sell their allowances at a profit. The profit motive might further encourage innovation in more cost-effective control technologies.[84]

Policies that promote energy efficiency can take on aspects of both direct controls and market-based systems. Direct controls can include restrictions on the design of energy-consuming devices, such as the California Energy Commission's size limits on west-facing windows in new houses.[85] Market-oriented policies can include those that set limits on energy consumption without limiting ways in which compliance can be achieved. Federal light bulb regulations specify maximum power consumption per unit (lumen) of light, but allow the production of halogens, compact fluorescents, LEDs, and future technologies that meet the standard. Regulators occasionally impose "technology forcing" standards, intended to induce the development of currently nonexistent technologies by guaranteeing successful inventors a market for their work.[86]

The Economics of Efficiency Requirements

Efficiency requirements are often viewed as regulations akin to those for pollutants, but environmental rationales for them are not as airtight. As previously noted, indirect control of emissions by design mandates will likely be less cost-effective than direct regulation of pollutants. Pollution, however, is not the only "market failure" that efficiency policies are said to address. Two broad rationales have been suggested.

The first is that an efficiency mandate can induce research efforts to solve a so-called "public goods" problem of underinvestment in research. If a manufacturer or engineering firm succeeds in designing a more efficient piece of equipment, its competitors may be able to copy it. A manufacturer who anticipates the copying risk might choose not to invest in the research, and too little valuable inventive activity will take place. It is important to note that this scenario depends on an implicit assumption that patent protection is either unavailable or unenforceable. It is hard, however, to see any reason why intellectual property might be more problematic in energy efficiency than in other policy areas. Further, an efficiency requirement expands the size of the market for the new technology but does not attack the original problem of unauthorized infringement on the inventor.[87]

The second market failure stems from difficulties that consumers allegedly encounter in acquiring and processing information about energy. For a typical example, assume that an energy-efficient appliance has higher upfront ("capital") costs than an inefficient one, but that consumers typically fail to properly account for the difference in the present (discounted) value of monthly energy bills over the life of the appliance. A number of studies have estimated substantial degrees of such consumer myopia.

Consumers who rationally evaluated their future energy cost savings would buy more efficient appliances, even if they had to borrow at credit card interest rates to finance them. On this reasoning, mandatory efficiency standards are in consumers' best interests because the true saving makes them wealthier. Beyond arguments against paternalism, there are additional problems. The reasoning disregards subjectivity of preferences (some dislike the quality of light from fluorescents), assumes that all consumers use the appliance in the same time pattern, and does not recognize option value that can give rational consumers incentives to defer the purchase of more energy efficient models.[88] However one views this anomalous behavior toward energy, there is abundant evidence that consumers act quite rationally when making other large transactions whose effects extend over the future, such as mortgages.[89]

The Politics of Efficiency Requirements

Justification of a proposed efficiency standard requires more than a presumption that households and businesses cannot make rational choices. It also requires a presumption that a government citizens elect has the knowledge and motivation to make better choices than they do. Regulations, however, are the end products of the interactions of interest groups, and are more likely to reflect the politics of the moment rather than any underlying "public interest" that transcends politics. Efficiency regulations are in no obvious way different.[90] Many entities have financial and emotional interests in expanding efficiency mandates, and others have similar interests in the status quo. Information provided by both sides is likely to biased and incomplete, and the dollars at stake for an individual so small that it is not worthwhile for a person to evaluate a given proposal in detail. There is likewise no reason to presume that government appointees and employees act with any deeper interests in mind.

Today's politics makes energy efficiency a fertile ground for regulation. In an era of high energy prices, proposals to increase energy efficiency are unlikely to gather substantial organized opposition. A public with a limited attention span and little directly at stake from a given regulation might easily accept advocates' claims that efficiency offers a "free lunch" of lower bills for the same "energy services." The basic logic of economic models of regulatory politics is that regulation will concentrate benefits in the hands of political supporters (sources of funds) and distribute costs as diffusely as possible among the remainder of the electorate.[91] In effect, regulation offers an alternative to taxation, with the added advantage that regulators can distribute costs and benefits in patterns that might never achieve legislative majorities. Politics further makes it likely that once in place a regulation will be difficult to eliminate, even after its failure or perverseness becomes obvious.[92] Efficiency programs often entail the phase-in of higher standards whose full consequences will be hard for members of the losing coalition to appreciate at the time of enactment.[93]

Until recently, efficiency regulations were virtually exempt from political criticism. Some, such as refrigerator standards, succeeded in substantially reducing residential power consumption with little impact on price and little discernible rebound. Happy stories like these may be less common in the future for two reasons. The first is that as "easy" sources of energy savings become more scarce, the price consequences of additional efficiency may bring consumer reaction. The second comes with the growing awareness of rebound, which means that the energy savings from even the easy sources will be less than promised. Rebound means that efficiency standards must be raised farther and earlier for equipment that has higher costs of saving energy. If rebound adds to the political controversy over efficiency regulations, supporters of activist climate policy will have few choices beyond explicit taxes and more direct controls on energy use.

C: REBOUND MEETS POLITICS

The BTI Report

Energy efficiency regulations began in the "energy crises" of the 1970s, in the mistaken hope that they could postpone the exhaustion of fossil fuels and buy time to transition to new technologies. Since then, policies such as decontrol of natural gas prices helped move such concerns well down the public's priority list. Efficiency regulations, however, have continued to proliferate and are now rationalized as components of climate policy. Engineering calculations have long been important justifications for such regulations, under an implied assumption that rebounds will be minor. Almost unnoticed during the 1980s and 1990s, however, research that found significant rebounds of many types began to appear. If the findings held up, efficiency would no longer provide a "free lunch" and policy makers would need to extend engineering calculations to factor in rebounds and backfires.

The findings finally made their impact in February 2011 with the release of *Energy Emergence*: *Rebound and Backfire as Emergent Phenomena*, written by Jesse Jenkins, Ted Nordhaus, and Michael Shellenberger of the nonprofit Breakthrough Institute (BTI).[94] *Energy Emergence* classified rebounds, described individual studies, compiled summary estimates, and concluded that rebounds warranted far greater attention than they had received. If rebounds indeed existed, reduced emissions due to efficiency would likely be short-lived, as temporarily underutilized energy sources found new uses and new users.

BTI's compilation is quite thorough and serves well as the basis for their conclusions about the relevance of rebounds for policy. Rebounds may indeed be relevant, but the precise policies they might suggest are not obvious and will in any case depend on the politics of those who choose them. For BTI, climate dwarfs all other issues, but related problems such as pollution and resource depletion remain salient.[95] *Energy Emergence* carries a simple message to efficiency enthusiasts: rebound means that well-intentioned efficiency programs are far less likely to reduce carbon emissions to climate-ameliorating levels. With the passage of time most or all of the avoided emissions will reappear. For any resource, efficiency abhors a vacuum—innovators will devise new and valuable uses for "saved" energy, just as they have for "redundant" labor through the centuries. BTI's preferred policies will be discussed, after a quick look at environmentalist reaction to *Energy Emergence*.

The Environmentalist Response

BTI attempts to distinguish its "product" from those of other environmental organizations, but there are few substantial differences (e.g., reconsidering nuclear power) to differentiate its preferred programs. Most observers might expect reaction from the political right (where it has gone unnoticed), but BTI has instead drawn fire from both the left and the environmentalist center. The critiques include a series of blog posts on *Climate Progress* by individuals including its editor, Joe Romm; Stanford University economist James Sweeney; and the Rocky Mountain Institute's Amory Lovins.[96] William Steinhurst, a frequent expert witness for environmental interveners, produced a critique under the aegis of his affiliated consulting firm.[97] These comments have primarily taken the form of rhetoric rather than research that could produce a numerical showing that would vitiate BTI's conclusions.

Non-peer reviewed critiques have appeared, one by David Goldstein of the Natural Resources Defense Council (NRDC) and another by Shakeb Afsah and Kendyl Salcito of the CO2 Scorecard Group.[98] BTI and its supporters have responded on justifiable grounds that include: (1) the fact that Goldstein's examples center on direct rebound by end-use consumers, which BTI and others have long known are among the smallest rebounds;[99] (2) Goldstein's claims that such trends as the declining energy intensity of GDP and the long-term near-constancy of California per capita power consumption refute rebound. (Both of these are of no inferential value without counterfactuals that estimate the trends had rebound not happened[100]) (3) Goldstein's references are few, dated, and unrepresentative, and his discussion of Jevons is at best incomplete.[101]

The hostile reaction of environmentalists is hard to explain, since both they and BTI favor aggressive action to reduce carbon. One possible reason is that BTI's expectation of rebounds and continued technology improvement could mean additional industrial activity in non-energy areas that would trouble environmentalists. A second is that rebound confounds the environmental vision of a "steady-state" world, made all the worse because future rebounds arrive unpredictably as the byproducts of technologies whose emergence cannot be predicted. Third, experience with technologies such as wind tells us that dependable power in volume from renewable sources (if possible) will be as environmentally disruptive as conventional energy unless efficiency policies can permanently cut resource use, that is, unless rebounds are minimal. Rebound by contrast turns energy efficiency into a finite resource, and increases the burden that renewables will place on the economy and the environment.[102]

Countering the environmentalists, BTI criticizes their failure to acknowledge that "today's renewable energy technologies are, by and large, too expensive and difficult to scale to meet the energy needs of the nation, much less a rapidly growing global population."[103] Rebound complicates almost every generally held environmentalist position:

> The deep problem here is that rebound means one cannot have it both ways: one can no longer simultaneously claim [as NRDC does] that "energy efficiency provides a solution that allows us to reduce energy consumption" and that this can be done "without stifling the standard of living for many poor and developing populations around the world." This is an extremely seductive conclusion—we would all like to believe this—but unfortunately rebound makes it problematic. Blindness to rebound effects means we risk over-reliance on efficiency measures to reduce climate risks and conserve energy resources, and in so doing, condemn future generations to the consequence of our false hopes.[104]

D: BTI'S POLICY PROPOSALS

Prices and Direct Controls

No one today can identify the technology (if indeed one is coming) whose rebounds will mirror those of the steam engine and once again transform the economy. BTI acknowledges this reality, and the accompanying reality that direct controls on new technologies may fail to limit rebounds. Likewise, there are also costs of mistakenly suppressing valuable inventions, and suppression itself requires an assumption that other nations will not take the initiative to invent and deploy them. These views might lead the reader to assume that BTI's preferred policies would favor markets over planning. Such is hardly the case. *Energy Emergence* makes clear that BTI intends to control and administer prices in ways that go beyond other climate literature.

> …. [t]o fully avoid rebound effects, energy price increases must be sufficient to keep the final price of energy services constant despite improvements in energy efficiency, eliminating any net productivity gains from the efficiency measures. It is important to also note that achievement of deep reductions in energy demand and associated carbon emissions through price-induced efficiency will likely require substantial and rising energy prices over time and sustained over the multi-decadal periods relevant to climate policy, such that rising energy prices keep pace with the improvements in energy productivity. Furthermore, if revenues collected through carbon pricing, energy taxes, or other efforts to raise energy prices are reinvested into economically productive ends, macroeconomic rebound effects may result, so the precise use of revenues will determine the efficacy of these policies in curbing rebound. Thus, carbon pricing policies (e.g., carbon taxes or cap and trade systems) and energy taxes offer potential tools to mitigate some or all of the energy demand rebound resulting from efficiency improvements, although implementing such policies faces practical challenges and will invariably encounter the political difficulties inherent to policy efforts that seek to impose energy price increases that will result in loss of economic welfare (ignoring potential benefits of avoided economic externalities)[105]

These are not prices as commonly understood in economics. In market economies, prices change with demand conditions, production costs, and expectations of the future. They transmit information about abundance and scarcity that guides market participants to economize on costlier goods and to invest in industries that produce more valuable outputs. Prices are informative, set in markets whose participants enjoy the benefits of wise choices and bear the costs of unwise ones. BTI's prices will be set by governments, often intentionally to countermand market indicators of scarcity and abundance. At least one contemporary commentator on the Jevons effect has articulated what BTI only implies: that coping with larger rebounds requires increasing the degree and scope of direct intervention into technology and markets.[106] Rebound provides a novel and pervasive rationale for market interventions of types and scopes that would be difficult to justify in its absence.

What are prices? Without using the term, BTI justifies its proposals on grounds of "market failure." The market fails because the harm that today's carbon emissions impose on future generations is not paid for by today's consumers in market prices. Thus, too much energy will be consumed unless some policy increases its price by the dollar value of the climate cost, and if taxes or cap-and-trade does not do the job, then more onerous (and probably more inefficient) direct controls will be necessary. Rebound further complicates the pricing problem because the prices of energy commodities will also have to include both the value of climate-related harm caused by direct users and the additional future damage caused by rebound-induced increases in their use as their productivities increase. BTI does understand that the price-setting problem will be perpetual, because as energy efficiency continues to grow, so too must the prices that will only discourage rebound behavior if they are high enough. The effective and efficient control of rebounds will also require monitoring and possible adjustment of at least some non-energy prices.[107] Monitoring and adjustment will be further complicated because technologies change discontinuously and rebounds are impossible to predict with any accuracy. The information problem facing price regulators worsens if rebounds are large and affect many sectors, but those cases are the ones for which BTI would probably see as creating the greatest need to control outcomes.

Can government set prices? If government is to choose prices rationally it will require data that is unavailable now and unlikely to become available in the future. At the top of the list are dollar estimates of climate-related damage, which will themselves require forecasts of future climate change. Both adherents and opponents of anthropogenic global warming theories would probably agree on a lack of consensus. Once-confident predictions are increasingly at odds with the data, and models that were once gold standards have turned into baser metals. Consensus on climate, however, is only the start of the estimation problem. Even with reliable long-term forecasts, planners will need to estimate damages due to climate change, separate them from the effects of ordinary weather, and factor in human activities that can mitigate these effects. Without trustworthy forecasts and credible estimates of harm, climate policy acts blindly, and may do more harm than good.

The value of carbon abatement. Considering these uncertainties, it is hardly surprising that one recent summary of over 200 damage estimates turned up credibly researched figures that ranged from below zero (thanks to CO2-caused increases in crop yields) to over $1,600 per ton of carbon, but with a modal value of only $14.[108] The variation reflects differences in research approaches, data used, and differing assumptions about the process and impacts of climate change. We do know that with the passage of time some of the more extreme disaster scenarios have been discredited, and that the average of later damage predictions is considerably lower than that of earlier ones.[109] Beyond weeding out more unlikely and extreme scenarios, some studies include estimates of savings that are possible if humans take already-known steps to adapt rather than exclusively devoting their efforts to the reduction of emissions.[110] Finally, investments in carbon abatement or adaptation are alternatives to other uses of the nation's capital. Making the choice among them requires the use of "discount rates" that measure opportunity costs of alternative investments, but there is no consensus on the rate that should be applied to investments in carbon abatement or adaptation over the more distant future, particularly when compared to others such as (for example) public health projects in underdeveloped countries that might be "crowded out" by increased spending on climate policy.[111]

Rebounds and Policies

Energy Emergence summarizes available knowledge on rebounds and follows this with policy recommendations. Nowhere between the two does one find a discussion of the uncertainties that pervade climate research, and there are no explanations of how its authors arrived at a conclusion that their chosen policy mix was superior to plausible alternatives. The missing material on the problems of policy making under uncertainty is quite at odds with its discussions about the uncertainties of predicting rebounds and their magnitudes. Here, too, BTI's apparent inability to understand the functions of prices leads it to simply assume away the very real problems that their regulatory agency would face. Prices of all goods (including carbon) will change over time, and with them the costs and benefits of controlling rebounds. Instead of facing these uncertainties head on, the authors implicitly assume that carbon and climate regulators will have superior foresight. Specifically, they will have the knowledge to set prices for energy commodities that are high enough to manage rebounds, but they will somehow be able to do so in a world where rebounds are unpredictable in size and can occur in many industries.

Believers in the importance of rebounds seem to agree with nonbelievers on one point: that "general purpose" technologies such as Jevons's steam engine are more likely to generate rebounds than technologies with idiosyncratic applications. How one identifies such technologies in advance is never made clear, and even if a technology appears ripe for large rebounds regulators will have to guess where the effects will appear (including other nations) and their sizes. If they cannot do so, any expectation that they can adjust prices to achieve their carbon goals will be in vain. Yet BTI admits to exactly this knowledge problem in its discussion of the historical rebound examples of the steam engine, electric motors, and lighting. "What use would econometric estimates of the substitution possibilities for Newcomen's steam engine have been to Jevons, for example, before the advent and many new applications of Watt's improved engine?"[112] Even if BTI's regulators can forecast some rebounds and set some prices correctly, they must also be able to recognize policy errors and correct them, in the process destroying the expectations of investors who made decisions on the basis of the prices now declared to be in error.[113]

There is yet another reason to expect futility from BTI's proposed policies to identify rebounds early and adjust prices: some of the most historically important rebounds have come from technologies that do not directly use energy. One of the largest ongoing ones started in the mid-twentieth century with a most unlikely invention: the shipping container. The now-familiar "box" did more than increase energy use in world shipping, whose volume doubled in the twenty years after its introduction.[114] It expanded markets so that manufacturers and consumers located inland were no longer at any important disadvantage relative to those near oceans. Other rebounds took the form of energy-intensive installations for transferring containers, along with the added trucks and locomotives that facilitated the growth of the markets. The box also became a major factor in the vertical de-integration of production and the growth of international specialization, both of which probably use more energy than if integrated – trade in components of consumer goods has grown much faster than trade in the goods themselves.[115] It appears likely that there are many analogues to the shipping container, and equally clear that most of them will not be spotted in advance by BTI's regulators.[116]

Ancillary Policies

BTI's pricing and rebound mitigation proposals are complex enough in themselves. Those difficulties, however, are compounded by a recommendation that certain mandated efficiency programs whose rebounds will be small should also be in effect. The authors understand that the choice of programs to implement should be made with care, since they could carry risks of large rebounds or backfires. Nevertheless, they recommend that "truly cost-effective energy efficiency measures should be vigorously pursued" if they ultimately reduce emissions.[117] Here again, BTI attributes an unlikely degree of foresight to regulators as they evaluate alternative programs, and here too there are two directions of error—approving a mandate that backfires or disapproving one that would have produced a net saving. Political realism says that a backfiring mandate may be impossible to reverse or repeal, and, in any case the final effects on emissions will depend on what happens in other nations that American regulators cannot control.

BTI apparently sees areas beyond climate and rebound as subjects worthy of policy concern. It also advocates some efficiency policies because they can help achieve goals quite distant from climate mitigation.[118] The well-known "Environmental Kuznets Curve" shows that pollution levels change predictably with the state of a nation's economic development. Poor economies devoid of industry have low pollution levels, which rise as development proceeds and then fall with the adoption of modern technologies and abatement methods. Accordingly, BTI argues that efficiency policies in the U.S. will cut pollution in poorer nations as they modernize their capital goods and production techniques. This is an odd argument, because the most rational choice for such nations may be the "obsolete" energy-intensive capital goods that advanced countries are replacing. Inexpensive labor may more than make up for higher energy bills. When that equipment filters down into these countries there is a near-certainty that the net effect will be rebounds or backfires, because two machines are operating where only one did previously. The outcome will happen in parts of the world that U.S. policy cannot reach, and the effects will be more acute in the event that BTI's proposed regulators succeed in raising energy prices in the United States but not elsewhere. The United States gets two injuries for the price of one: the offshore rebound will nullify a substantial part of the domestic carbon reduction, and the "leakage" of produced goods these countries will export to the United States (where production costs are now higher) promises additional macroeconomic and financial complications.

Economics and Politics

Historically, government agencies have seldom shown high abilities to process information and craft forecasts based on it, a process further complicated by the interests of elected officials. Citing no historical precedents, BTI nevertheless sees a government with extensive knowledge, plus abilities to process ongoing information that will allow it to set prices (and with them the fortunes of households and businesses) that will control carbon optimally. BTI never specifies the political institutions that must underlie its program, but clearly they must differ drastically from today's, and in predictable ways. As stated in the quotation above, BTI notes that its program for setting prices and mandating efficiency must be "sustained over the multi-decadal periods relevant to climate policy."[119] The only institution that comes to mind is an autocratic and self-perpetuating bureaucracy that is somehow above politics and whose interventions into market activity will generate no extended regulatory proceedings or litigation. Consensus on climate and climate policy may well change unpredictably with politics and events. If BTI's regulators are appointed when the public mood is activist, what happens when that mood changes? Presumably, they will need to change their policies in response, unless the old ones can be kept in force by some unspecified institution that supersedes democratic governance.[120]

Any hope for genuine impartiality from these regulators is likely misplaced. BTI never acknowledges that its proposal is in every dimension a political one, or that there are major differences of opinion regarding such proposals. Its regulators cannot possibly be insulated from political influence on their decisions—and should not be. If an election turns the legislative and executive branches into opponents of the regulations, their departments can be closed. Above, BTI acknowledged that the regulators will "invariably encounter the political difficulties inherent to policy efforts that seek to impose energy price increases that will result in loss of economic welfare."[121] The regulators, however, will not be without powers of their own, since *Energy Emergence* appears to envision them receiving and spending revenues collected from "carbon pricing, energy taxes, or other efforts to raise energy prices."[122] One can only conjecture about the likelihood of such an outcome.[123] What is clear is that BTI's policy vision is far from a breakthrough, and is better described as politics-as-usual.

E: CONCLUSIONS

BTI's policy recommendations could equally well have been written by someone who had seen none of the material on rebounds summarized in *Energy Emergence*. If carbon is a serious problem and rebounds complicate it even further, the consequences for climate policy will be more complex than ever. Instead, BTI suggests selfless regulators who have access to all relevant information, flawless abilities to process it, near-dictatorial powers to control markets at will, similar abilities to influence the rest of the world, and are apparently immune from politics. *Energy Emergence* wasted an opportunity to examine the real policy significance of rebounds and instead gave its readers a wish list with no budget and no legislation attached.

It is possible that BTI is on the road to rethinking the comprehensive policy proposals of *Energy Emergence*. The three authors of that February 2011 study are now among the fourteen authors of *Climate Pragmatism: Innovation, Resilience and No Regrets* (July 2011), published by the U.K.'s Hartwell Group, an association of policy scholars.[124] The document starts with an acknowledgement that the grandiose United Nations climate process has in fact failed, and that we are left with an international deadlock. This new reality hardly bodes well for the elaborate price control plans and the associated bureaucracies proposed in *Energy Emergence*. *Climate Pragmatism* instead proposes a far more modest (and pragmatic) program whose effects on climate will come as by-products rather than being specific objectives. The pragmatism centers on three areas: energy technology innovation, improving resilience to extreme weather, and "no regrets" reductions of non-carbon pollution. Initiatives will be implemented by individual nations or *ad hoc* alliances, and the elaborate institutions of *Energy Emergence* are nowhere to be found. "Rebound" does not appear in the document, despite the near-certainty that many new technologies will be accompanied by national and international rebounds.

Climate Pragmatism has produced a range of comments, but few of them directly address the likely consequences of BTI's drastic decentralization of its planned policies.[125] Among others, Michael Levi of the Council on Foreign Relations finds interesting in itself the idea of climate amelioration as a side effect of pragmatic policies that do not directly target climate, but concludes that even if some innovations are successful the plan "is likely to leave us with some really big climate problems."[126] Time headlined its article on the report "Fighting Climate Change by Not Focusing on Climate Change."[127] BTI's longtime critic Joseph Romm of *Climate Progress*, attempts a full refutation based on his belief that BTI misunderstands nearly all of the relevant history and science.[128] Romm further notes the virtual uniqueness of *Climate Pragmatism* in today's policy literature. It contains none of the usual data on CO2 concentrations, no quantitative statement of policy objectives, and no discussions of the urgency of immediate action.

Climate Pragmatism contains none of the policy activism of *Energy Emergence*, and appears to disregard the once-paramount importance of carbon reductions at the top of all policy goals. Now, we get three topics as priorities for international collaboration, all of which might be useful initiatives even if climate totally vanished as a policy concern. But now the urgency is also gone, and it is not clear why. Nations can take their own steps or form agreements for particular projects as they please, but this should be an evolutionary process rather than even a partial exercise in planning.

The contrast between two documents published only five months apart is graphic, and one can only conjecture about the reasons behind the change. One possibility is that BTI has consciously chosen to abandon climate as the linchpin for its otherwise liberal policy preferences. The last three years have not been good to climate alarmism, and whether or not the world is actually warming much of climate's former political salience is gone. Realists, pragmatists, and even some idealists now understand that even if climate is a serious problem the chances for coordinated large-scale international cooperation are effectively nil. *Climate Pragmatism* could be the vehicle for BTI's biggest breakthrough: to be the first left-side think tank to abandon climate as a pretext for policies it favors on ideological grounds. It will be a lot easier to be the first of them than the last.

79 Jesse Jenkins, Ted Nordhaus, and Michael Shellenberger, *Energy Emergence: Rebound and Backfire as Emergent Phenomena* (February. 2011). Subsequently referenced as “BTI” or “*Energy Emergence*.” http://thebreakthrough.org/blog/Energy_Emergence.pdf

80 Almost every name for either type of policy carries normative overtones. Thus, this paper uses “direct controls” instead of “command-and-control,” and “market-based policies” instead of “governmentally contrived markets” or similar terms.

81 For more on this reasoning, see Robert Michaels, “A National Renewable Portfolio Standard: Politically Correct, Economically Suspect,” *Electricity Journal* 21 (April, 2008), 9–28.

82 For example, regulated utilities facing RPS quotas might prefer to use established generator designs rather than risk being out of compliance because they have invested in newer but riskier designs.

83 These are often called “cap and trade” regimes. Recent court decisions have, in effect, suspended some of them, for legal rather than economic reasons.

84 Taxes on emissions have some aspects of a market-based system because they incentivize those with the lowest abatement costs to reduce their emissions by relatively more than those with higher costs.

85 California Energy Commission, 2005 Building Energy Standards (Title 24) limits the area of west-facing windows “to a maximum of five percent of the conditioned floor area.” This limitation applies in all but coastal climate zones. http://www.builditgreen.org/attachments/wysiwyg/22/Passive-Solar-P1.pdf

86 For examples in the control of pollution by vehicles, see Andries Nentjes, “Technology-Forcing Through Environmental Regulation,” *European Journal of Political Economy* 23 (Dec. 2007), 903–16.

87 A similar public-goods issue, according to some experts, also arises if more stringent efficiency standards reduce the rate of extraction of domestic fossil fuels. They feel that the reduction may allow prolongation of a longer-term transition to renewable supplies, as well as helping with peripheral issues, such as security of supply. The difficulty is an unstated assumption that government’s knowledge is superior to that of the private sector and that government’s choices will necessarily be more foresighted. The record of U.S. energy policy leads many to question this assumption.

88 Gilbert Metcalf and Donald Rosenthal, “The ‘New’ view of Investment Decisions and Public Policy Analysis: An Application to Green Lights and Cold Refrigerators,” *Journal of Policy Analysis and Management* 14 (1995), 517–31.

89 This suggests a related rationale for mandates: the amounts at stake for many consumers are too small for their minds to process, but are large in the aggregate. One apparent adherent of this view is Energy Secretary Steven Chu, who recently explained that mandatory light bulb standards should remain in place because “[w]e are taking away a choice that continues to let people waste their own money” (*Wall Street Journal,* July 9, 2011). He did not specify to whom “we” referred.

90 Many environmental regulations have in retrospect proven to be farsighted (and many the opposite). It is meaningless to say that the former express the public interest and the latter special interests. Some of the former would have been desirable well before their enactment, but the necessary coalition of interests was not in place until later.

91 The major manufacturers of compact fluorescent bulbs (General Electric, Philips and Sylvania) strongly supported the ban on incandescent bulbs, which would advantage their already-large presences in the former. By contrast, most of the public has only recently become aware of the ban and the increased costs and decreased choices that will be imposed by it.

92 Thus, only recently have we seen a general awareness that ethanol subsidies have been a waste on both environmental and “energy independence” grounds. The awareness has grown with its scale. Now that 40 percent of the U.S. corn crop goes to ethanol its impacts on food prices are becoming more obvious to consumers.

93 If a future requirement is seen as impossibly costly, the reaction may come earlier. Auto manufacturers immediately opposed regulations requiring extremely high gas mileage 15 years in the future, claiming that development of the necessary technologies is vifrtually impossible given today’s knowledge.

94 At http://thebreakthrough.org/blog/Energy_Emergence.pdf

95 Politically, Nordhaus and Shellenberger state that they founded BTI in 2003 “to modernize liberal-progressive-green politics.” http://thebreakthrough.org/about.shtml

96 “Rebound Effect: The Breakthrough Institute’s Attack on Clean Energy Backfires,” *Climate Progress*, Feb. 15, 2011. http://thinkprogress.org/romm/2011/02/15/207530/the-breakthrough-institute-attack-energy-efficiency-clean-energy-backfire-rebound-effect/; “Energy Efficiency and the ‘rebound effect’,” Climate Progress, Feb. 23, 2011. http://thinkprogress.org/climate/2011/02/23/207558/energy-efficiency-and-the-rebound-effect; “Bombshell: Energy Experts Call on Breakthrough

Institute to Retract or Fix Its Deeply Flawed Energy Rebound Report," *Climate Progress*, Jan. 20, 2012. http://thinkprogress.org/romm/2012/01/20/408087/co2-scorecard-breakthrough-institute-retract-or-fix-its-deeply-flwed-energy-rebound-reports/

97 Synapse Energy Economics, "The Jevons Paradox and Energy Efficiency," Synapse Energy Economics, Inc., Feb. 2, 2011. http://allpdfdocs.com/join.asp?PID=e5bd7faf-f480-4b6e-b563-70ecb4d8d845&jstyle=2&lbd=1&lang=EN&ts=6/27/2011%20 11:04:40%20PM&q=synapse,%20jevons%20paradox&cr=1

98 David B. Goldstein et al., "Are There Rebound Effects from Energy Efficiency? – An Analysis of Empirical Data, Internal Consistency, and Solutions," (May 2011); Shakeb Afsah and Kendyl Salcito, "Energy Efficiency is for Real, Energy Rebound a Distraction," CO2 Scorecard Group (Jan 11, 2012). http://www.electricitypolicy.com/Rebound-5-4-2011-final2.pdf and http://co2scorecard.org/home/researchitem/21

99 Roger Pielke, Jr., "Collateral Damage from Not Knowing What You Are Talking About," Breakthrough Blog, Jan. 12, 2012. http://thebreakthrough.org/blog/2012/01/collateral_damage_from_not_kno.shtml; Jesse Jenkins, "Energy Efficiency, Rebound and the Rise of the Rest," Breakthrough Blog, Feb. 10, 2012. http://thinkprogress.org/romm/2012/01/20/408087/co2-scorecard-breakthrough-institute-retract-or-fix-its-deeply-flwed-energy-rebound-reports/; Jesse Jenkins, "Hot Topic: Does Energy Efficiency Lead to Increased Energy Consumption," Making It Magazine Blog, June 16, 2011. http://www.makingitmagazine.net/?p=3460

100 The "counterfactual" difficulty appears frequently in the rebound literature, and must be attacked indirectly if at all. For example, a statement that steady per capita power consumption in California refutes rebound must compare actual levels of power consumption with those that would have been seen had there been no rebound (the counterfactual). Thus, it is possible that, absent a rebound, consumption would have been significantly lower. But rebound cannot easily be separated from the data.

101 These critiques are expounded in more detail by rebound experts at BTI's blog, "Rebound and Rigor: NRDC's Entry into Rebound Effect Debate Stuck in the Past," June 6, 2011. http://thebreakthrough.org/blog/2011/06/rebound_and_rigor_nrdcs_entry.shtml#more

102 Matt Ridley, "A Green Dark Age," *The Spectator*, May 21, 2011, The following paragraphs are reversed from their actual sequence.

"The industrial revolution, when Britain turned to coal for its energy, not only catapulted us into prosperity … but saved our landscape too. Forests grew back and rivers returned to their natural beds when their energy was no longer needed. Land that had once grown hay for millions of horses could grow food for human beings instead."

"Welcome to the neo-medieval world of Britain's energy policy, in which highland glens are buzzing with bulldozers damming streams for miniature hydro plants. in which [scenic landscapes will be covered by windmills], in which Heathrow is to burn wood trucked in from Surrey and Yorkshire wheat is being turned into motor fuel. We are going back to using the landscape to generate our energy. Bad news for the landscape."

103 BTI, *Post-Partisan Power* (Oct. 2010), 5. http://thebreakthrough.org/blog/Post-Partisan%20Power.pdf This document is discussed in more detail below.

104 See "Rebound and Rigor: NRDC's Entry into Rebound Effect Debate Stuck in the Past," June 6, 2011, http://thebreakthrough.org/blog/2011/06/rebound_and_rigor_nrdcs_entry.shtml#more

105 *Energy Emergence*, 52–53, (3 footnotes omitted).

106 Blake Alcott, "Jevons' Paradox," *Ecological Economics* 4, (2005), 9–21.

107 For a more rigorous discussion of the pricing and taxation problems (not in the context of climate), see, for example, A. B. Atkinson and Joseph Stiglitz, "The Design of Tax Structure: Direct Versus Indirect Taxation," *Journal of Public Economics* 6 (July 1976), 55–75.

108 Richard S. J. Tol, "the Social Cost of Carbon: Trends, Outliers, and Catastrophes," *Economics: The Open-Access, Open-Assessment E-Journal* 2 (2008), and "The Economic Effects of Climate Change," *Journal of Economic Perspectives* 23 (Spring 2009), 29–51.

109 Ibid., 36. This type of finding also casts doubt on the usefulness of the so-called "precautionary principle" as a guide to policy. That principle roughly states that: if there are risks of environmental harm from a policy, then the burden of proof that it is worth undertaking should be placed on the policy's proponents. The problem is that there are costs of action and costs of inaction, so a presumption in favor of inaction is at best a partial rule and at worst an incoherent one. See Cass Sunstein, *Laws of Fear: Beyond the Precautionary Principle* (Cambridge University Press, 2005).

110 If people have the power to mitigate environmental effects (and new technologies can increase that power), then BTI's quoted statement about the need to fully avoid rebounds is in error. Barring extreme scenarios, one wants to balance the costs of rebounds against their benefits to maximize net benefits. Climate change can impose costs, but other costs result from needlessly raising prices and suppressing the productive uses of resources whose benefits are large relative to costs of additional carbon emissions.

111 Along with the discount problem, which is in part a matter of values, any proposal to invest in carbon abatement or climate mitigation will inescapably be based on dollar estimates of the value of human life and health. The U.S. government is currently required to do this as part of a required cost-benefit analysis of new health or safety regulations, but it has not yet analyzed the values of lives to be saved or extended through climate policies.

112 *Energy Emergence,* 48.

113 BTI never considers the costs of being late to adjust prices that remained low enough to allow rebounds, and investments to exploit them. Delaying the adjustment of prices means that the profits expected from those investments will vanish, through no fault of either the investors or those who purchase the relevant product. This is the equivalent of expropriation risk, which will both chill incentives to invest in general, and possibly lead investors to prefer sectors that are under less threat of rebound.

114 Marc Levinson, *The Box: How the Shipping Container Made the World Smaller and the World Economy Bigger* (Princeton University Press, 2006).

115 David Hummels et al., "The Nature and Growth of Vertical Specialization in World Trade," *Journal of International Economics* 54 (June, 2001), 54–76.

116 Climate policy can incorporate rebounds at the direct, indirect or economy-wide level, and the incomplete treatment of rebounds in several mitigation proposals almost surely leads to overoptimistic conclusions about their likely success. See Anders Arveson et al., "Considering Only the First-Order Effects, How Simplifications Lead to Unrealistic Technology Optimism in Climate Change Mitigation," *Energy Policy* 39 (2011), 7448–54.

117 *Energy Emergence*, 6; also see discussion at 11.

118 *Energy Emergence*, 53–54.

119 *Energy Emergence*, 52.

120 There is a small but growing literature that favors programs of indoctrination or "nudging" intended to change the public's preferences and make it reluctant to behave in ways that increase the likelihood of rebounds when efficiency increases. See *People-Centered Initiatives for Increasing Energy Savings,* ed. Karen Erhardt-Martinez and John Laitner (American Council for an Energy-Efficient Economy, 2010), 325.

121 *Energy Emergence*, 53. The authors append to this sentence a parenthesized phrase: "ignoring potential benefits of avoided economic externalities." This presumably means the climate- and environment-related benefits if carbon control under the plan is successful.

122 *Energy Emergence*, 53. The authors do not further discuss the meaning of "other efforts to raise energy prices."

123 One possible model is the emerging federal Consumer Financial Protection Bureau, which may legally be able to perpetuate itself by spending fines and other income it receives.

124 http://thebreakthrough.org/blog/Climate_Pragmatism_print.pdf Although published by the Hartwell Group, it is available from BTI. Hartwell describes itself as an "informal, international network of scholars and analysts dedicated to innovative strategies that uplift human dignity through mitigation of climate risk, enhancement of disaster resilience, improvement of public health, and the provision of universal energy access."

125 For a sample, see http://www.aib.org.uk/climate-change-cop-out-or-pragmatic-approach/

126 Michael Levi, "Is Climate Pragmatism a Climate Strategy" (Council on Foreign Relations, July 26, 2011) http://blogs.cfr.org/levi/2011/07/26/is-climate-pragmatism-a-climate-strategy/

127 *Time,* July 26, 2011. http://www.time.com/time/health/article/0,8599,2085220,00.html#ixzz1TRQ517IA

SUMMARY AND CONCLUSION

A: SUMMARY

W. S. Jevons, like many thinkers of his time and ours, saw his nation's power and prosperity threatened by the inevitable exhaustion of fossil energy—in his case, coal. He saw the exhaustion problem as aggravated by the paradoxical abilities of energy-efficient technologies to induce the consumption of additional energy. His work centered on the epochal consequences of steam engines and ironworking technologies that used coal. Today we know that rebounds and sometimes backfires are pervasive and seemingly inescapable, but important aspects of energy policy continue to be formulated in disregard or ignorance of their consequences. This study has defined and described rebounds, summarized some numerical estimates of their strength, and discussed the growing significance of their implications for energy and climate policy.

Chapter I introduced rebounds and Chapter II set down some of their most important dimensions. It provided distinctions between direct rebounds, indirect rebounds, economy-wide rebounds, embedded energy, and backfires. From these building blocks, it is possible to particularize the definitions to particular goods (productive inputs versus outputs of goods and services) and to wider questions such as how rebounds interact with incentives to engage in inventive activity. Chapter II also presented some technical preliminaries necessary for an understanding of various rebound measures discussed in Chapter III. It explained the relationships between rebounds, backfires, and demand elasticities. It then went on to discuss how rebounds affect and are affected by the behavior of producers, most importantly explaining the significance of differing degrees of substitutability between energy and other inputs. Following that came a discussion of the importance of alternative assumptions about interrelationships between the relative productivities of different inputs.

Chapter III summarized research findings on various types of rebounds. It began with descriptions of how meta-analyses of collections of studies have convincingly shown that rebounds are usually well in excess of zero. It then looked at studies of "direct" rebounds that compared consumers' responses to appliances with differing energy efficiencies, again providing evidence for rebound. Other research shows that "saturation" of markets for appliances in wealthier countries has not been accompanied by a decrease in rebounds affecting people who have accumulated many such appliances. Chapter III's discussion of possible rebound behavior by businesses as users of productive inputs pointed up the wide range of possible rebounds that might exist, and the problems associated with economists' difficulties in measuring degrees of substitutability among inputs and interactions among their productivities. It is in the important area of business behavior that estimates of rebounds are fewest in number and most heavily plagued by problems of measurement. Surprisingly, tools are available in the form of computable general equilibrium (CGE) models that can help us to predict economy-wide rebounds, but no comparable tools exist for analysis of more closely interrelated markets in which many indirect rebounds take place. There are still only a small number of CGE rebound studies in print and CGE models themselves are continually being developed and refined. Nevertheless, one tentative conclusion from those models is that economy-wide rebounds will generally be substantially larger than direct and indirect ones, and backfires are very real possibilities.

Chapter IV probed the relationships between rebounds and policies intended to promote energy efficiency. After a discussion of regulatory objectives and characteristics of regulation, this chapter attempted to put efficiency regulations into those contexts. It found that such regulations are often needlessly costly ways to achieve goals that are themselves sometimes questionable, but the underlying politics renders the regulations relatively easy to enact. This discussion motivated the subsequent discussion of the Breakthrough Institute's compilation of rebound research and its associated policy recommendations. BTI's point was to show that rebounds greatly complicate climate policy because reductions in energy use due to improved efficiency seldom persist. BTI, however, also believes that the reduction of atmospheric carbon is a critical problem that must be attacked vigorously and immediately. If efficiency produces rebounds and carbon is critical, BTI has few choices but to recommend a policy of price and technology regulations that will pervade the economy, all on a scale that has never before been implemented with even modest success. Its discussion of the details is sketchy and incomplete at best, but later publications may indicate that BTI no longer believes in the priority of climate policy or in the need for long-term coordination of international actions.

B: CONCLUSIONS: DOES BACKFIRE MATTER?

W. S. Jevons was the first to give economists an understanding of how increased energy efficiency could produce rebounds in the production and consumption of energy. His real concerns, however, were macroeconomic. *The Coal Question* was primarily about his nation's growing dependence on coal and the consequences he expected to follow from coal's finiteness.[129] Many of the arguments had analogues in works such as 1972's *The Limits to Growth*, with its discussions of the developed world's dwindling resources and tightening environmental constraints.[130] We still sometimes call today's rebounds and backfires "Jevons effects." This terminology is odd, because much of the growth in coal consumption that he described was *not* the product of rebounds as we know them today. *The Coal Question* is about events that were taking place beyond the time spans that today's researchers use to delineate long-run adjustment of an economy to a "stationary state."

The true long run is not an eternity of unchangingness. It is a continuing era of invention and innovation, aptly described by Jevons but missing from much present-day work on rebound. Particular inventions are notably hard to predict, but as a general principle, inventors are motivated to alleviate scarcity and exploit abundance. Jevons was most definitely not analyzing an economy with unchanging technologies and markets in long-term equilibrium. Rather, he saw efficiency as disruptive:

> Coal thus saved [by efficiency] is not spared—it is only saved from one use to be employed in others, and the profits gain soon lead to extended employment in many new forms … Economical inventions are what I should look forward to as likely to continue our rate of increasing consumption [of coal].[131]

Innovation was an integral part of Jevons's economy, and it drove increases in coal use that today's rebound research methods cannot capture. Coal drove the growth of new industries as new coal-burning technologies were developed. Railroads grew both because coal was a superb fuel for locomotives and because they satisfied demands of both producers and consumers for a cheap mode of shipment. Coal made British iron cheap, and Britain supplanted continental nations as Europe's bridge builder. Coal did not directly advance textile manufacture, but the iron that it smelted made possible new generations of looms and ended that industry's dependence on falling water as a motive source. Jevons believed that coal was ultimately responsible for the canals that facilitated its movement and that of numerous other goods.[132] "[U]ntil coal supplied the *purpose* there was not spirit enough in this country to undertake so formidable a work as a canal."[133] Downstream, coal cheapened consumer products and gave rise to innovations in them.[6] Jevons would hardly have been surprised to see coal take on future roles in the manufacture of plastics and dyes.

This extended narrative points up the most fundamental difficulty in contemporary rebound analysis. There are no rules that define the point at which rebounds stop, and no rule for determining when other consequences of an efficiency improvement should either be disregarded or given different names. Magnitudes that contemporary rebound researchers treat as constants (e.g., the algebraic forms of relationships that transform inputs into outputs) are anything but constant under Jevons's vision of the grander sweep of rebounds. Even our categorization of industrial sectors as unchanging is a holdover from steady-state analysis that over time becomes grossly inconsistent as Jevons-style rebounds transform markets and the things traded in them. Both statistical and conceptual problems pose peculiar difficulties for economic research on rebounds, yet studies generally find that rebounds are strong and pervasive. Jevons's vision says that they are stronger still, and his is the vision that can best guide energy policy.

128 Joseph Romm and Stephen Lacey, "Been There, Tried That: 'Climate Pragmatism' Pushes Failed Strategy, *Grist* Blog, July 27, 2011. http://www.grist.org/climate-policy/2011-07-27-climate-pragmatism-report-pushes-failed-strategy1

129 Less emphasized by many students of Jevons, but much in the same vein, was his vision of the future of Britain's iron industry, which he believed had exhausted almost all of its domestic ore supplies. Jevons, 403.

130 Donella Meadows et al., *The Limits to Growth* (Universe Books, 1972).

131 Jevons, 155 and 156.

132 Jevons, 125 and 129.

133 Jevons, 121. Italics in original

134 Jevons, 140. Jevons was far from perfect in his predictions. He thought coal was unsuitable for electricity generation (then only in its infancy), and he expected that coal gas would power automobiles because the world contained very little petroleum. Jevons, 146–52.