A REVIEW OF THE LITERATURE

BY JESSE JENKINS
TED NORDHAUS AND
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ENERGY EMERGENCE

REBOUND & BACKFIRE
AS EMERGENT PHENOMENA

BREAKTHROUGH INSTITUTE
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SUMMARY

Energy efficiency is widely viewed as an inexpensive way to reduce aggregate energy consumption and thus greenhouse gas emissions. Many national governments, the International Energy Agency, and the United Nations Intergovernmental Panel on Climate Change have each recommended energy efficiency measures as a way to reduce significant quantities of greenhouse gas emissions without substantial cost (and with potential net benefits) to economic welfare (e.g., IPCC, 2007; IEA, 2009). These recommendations have been supported and informed by several non-governmental analyses (e.g., Lovins, 1990, 2005; ASE et al., 1997; McKinsey, 2009a, b) which conclude that numerous energy efficiency opportunities are available at 'below-cost' – that is, the efficiency opportunities pay back more in net savings than they cost and represent a net improvement in total factor productivity and economic welfare. These studies assume a linear and direct relationship between improvements in energy efficiency or energy productivity and reductions in aggregate energy consumption.

Economists, however, have long observed that increasing the efficient production and consumption of energy drives a rebound in demand for energy and energy services, potentially resulting in greater, not less, consumption of energy. Energy productivity improvements over time reduce the implicit price and grow the supply of energy services, driving economic growth and resulting in firms and consumers finding new uses for energy (e.g., substitution). This is known in the energy economics literature as energy demand 'rebound' or, when rebound is greater than the initial energy savings, as 'backfire.'

This review surveys the literature on rebound and backfire and considers the implications of these effects for climate change mitigation policy. We summarize how multiple rebound effects operate at various scales, and describe rebound as an 'emergent property' with the greatest magnitude at the macroeconomic, global scale relevant to climate change mitigation efforts. Rebound effects are real and significant, and combine to drive a total, economy-wide rebound in energy demand with the potential to erode much (and in some cases all) of the reductions in energy consumption expected to arise from below-cost efficiency improvements. Consequently, rebound effects have important implications for emissions mitigation efforts. We illustrate how rebound effects render the relationship between efficiency improvements and energy consumption interrelated and non-linear, challenging the assumptions of commonly utilized energy and emissions forecasting studies. We conclude by offering a new framework for envisioning the role of below-cost efficiency improvements in driving energy modernization and decarbonization efforts.

1. INTRODUCTION

1.1. ENERGY EFFICIENCY, PRODUCTIVITY, AND DECARBONIZATION

The amount of energy required to create a single unit of gross domestic product (E/GDP) and the carbon intensity of energy supply (C/E) have both steadily declined as nations have developed. These two factors combined have driven the steady decarbonization of the economy (i.e., a decline in C/GDP) of 1.2% per year on average over the past 200 years. The bulk of this decarbonization rate has been due to reduction in energy intensity (0.9% per year) with only one quarter of the reduction in C/GDP resulting from the declining carbon intensity of energy (0.3% per year) (IPCC, 2007; Nakicenovic, 1996).

Given its historic role in decarbonizing economies, policy specialists, governments, and NGOs have understandably recommended making energy efficiency a central priority of emissions reductions strategies designed to mitigate climate change. For example, widely cited reports from consulting firms such as the Rocky Mountain Institute (Lovins, 1990, 2005) and McKinsey and Company (2009a, b) have estimated that 'below-cost' efficiency measures – e.g., efficiency opportunities that pay back more in net savings than they cost and represent a net improvement in total factor productivity and economic welfare – can reduce U.S. energy consumption 25% by 2020, single-handedly achieve America's 2020 greenhouse gas emissions reduction goals, or drive one-third of the global emissions reductions needed by 2030. Relying on similar methodologies, both the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) estimate that energy efficiency measures will be capable of driving the greatest portion of emissions reductions needed to stabilize the global climate (IPCC, 2007; IEA, 2009).[1]

These analyses are based on the underlying assumption that aggregate improvements in energy efficiency have a linear and direct effect on aggregate energy consumption and greenhouse gas emissions. The following simplified formula is useful to illustrate this assumption:

$$CO2 = GDP \times E/GDP \times C/E \qquad (1)$$

Where CO2 = total carbon dioxide emissions; GDP = aggregate economic output; E/GDP = 'energy intensity of the economy,' or energy consumption per unit of GDP; and C/E is 'carbon intensity of energy,' or carbon emissions per unit of energy consumption.[2]

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[1] The Fourth Assessment Report of the IPCC (Working Group III) projects that energy efficiency improvements will be capable of reducing global energy consumption approximately 30% below business-as-usual forecasts (IPCC, 2007). See Technical Summary Figures TS.3 and TS.10. Likewise, a climate stabilization scenario circulated by the IEA in advance of international climate negotiations in 2009 estimates that energy efficiency measures can account for 45% of needed emissions reductions by 2030, relative to business-as-usual forecasts (IEA, 2009). Pielke, Wigley and Green (2008) caution that IPCC projections actually place even greater emphasis on energy efficiency opportunities than revealed in Working Group III recommendations, as business as usual forecasts developed by the IPCC already include substantial improvements in energy efficiency. When taken from a frozen technology baseline (e.g. a forecast excluding any technical improvements in efficiency), efficiency improvements may actually account for more like 80% of emissions reductions forecast by the IPCC in various climate mitigation scenarios. A similar note of caution applies to IEA forecasts.

[2] This is a simplified version of a formula known as the 'Kaya Identity,' developed by economist Dr. Yoichi Kaya. The full Kaya formula disaggregates GDP into population (P) and GDP per capita (GDP/P) terms to indicate the role of population changes in total greenhouse gas emissions.

Studies such as McKinsey (2009a, b) aggregate engineering-level estimates of technical efficiency opportunities to determine the potential of such measures to reduce the energy intensity (E/GDP) term of our formula. Crucially, this improvement in energy intensity (perhaps better thought of as an increase in energy productivity) does not feed back into assumptions regarding economic activity or demand for energy services[3] within the economy, leading to the calculation of a direct reduction in total CO2 emissions. The implicit assumption is that efficiency improvements simply decrease the E/GDP term in our Formula 1 above, with GDP and C/E remaining constant, directly resulting in a reduction in the CO2 term.

However, these commonly utilized studies consistently ignore the potential increases in energy consumption known to result from below-cost energy efficiency improvements — what is known in the energy economics literature as energy demand ‘rebound,’ or ‘backfire,‘ when rebound is greater than 100% of projected energy savings.[4]

Given the drive to maximize profits and production, economic theory suggests that increasing the productivity of any given economic input or factor, whether labor, capital, or raw materials does not result in a simple, linear reduction in demand for that input. Rather, increased productivity will spur substitution of that input for other factors of production and/or increase economic production, output, and growth. In the language of neoclassical growth theory, ‘factor-augmenting’ improvements are not necessarily ‘factor-saving.’ Like any other factor of production, the same is true of improvements in energy productivity, including below-cost energy efficiency measures.[5]

Below-cost efficiency improvements may therefore accrue to the economy in any combination of the following three ways: first, as an increase in economic output via the more productive use of energy services (which will in turn drag up demand for energy in the economy as a whole); second, as the productive substitution of energy services in lieu of other inputs (reducing consumption of other inputs to production but increasing energy consumption); and third, as a reduction in energy consumption and expenditures required to produce a given level of energy services. In any case, truly cost-effective energy efficiency measures should be vigorously pursued, as they will lead to an improvement in general ‘welfare’ (at least narrowly construed in economic terms). However, from

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[3] The term ‘energy services’ refers to the useful work or output provided by the consumption of fuels, such as lighting, heating, transportation, or the contributions of energy to production of goods and services.

[4] McKinsey (2009a) for example only acknowledges rebound effects in a sidebar (p. 33) and notes that direct, indirect and macroeconomic rebound effects are not addressed in their research and analysis. McKinsey (2009b) likewise acknowledges (p. 27) that the study estimates technical greenhouse gas abatement opportunities “without accounting for rebound effects.”

[5] Saunders (1992) credits this key observation to Robert Solow, the pioneer of neo-classical growth theory, although Jevons (1865) and other early classical economists laid out the basics of these economic dynamics for energy and other factors of production a century earlier (see historical review in Alcott, 2008).

a climate mitigation perspective, we must be keenly aware of the precise, macroeconomic impacts of energy efficiency improvements, since only a reduction in total aggregate energy consumption will directly contribute to emissions reduction objectives. This in turn requires an understanding and analysis of the non-linear combination of impacts on economic activity, demand for energy as a factor of production, and other macroeconomic factors that are together summed up in the term 'rebound effect.'

As this literature review demonstrates, multiple rebound effects operate at varying scales and their combined effect results in a complex, non-linear interdependence among the economic activity (GDP), energy demand (E), and energy intensity/productivity (E/GDP) terms of our formula: improvements in energy efficiency do not translate into straightforward reductions in E/GDP, but rather drive multiple mechanisms that feed back into and drive corresponding changes in both economic activity and energy demand. Relying then on a linear, direct, and one-to-one relationship between below-cost energy efficiency improvements and reductions in energy demand (and thus carbon emissions), as is common in contemporary energy and emissions forecasting and analysis, will consistently produce overestimates of the net energy savings and emissions reductions potential of such efficiency measures, with potentially dangerous consequences for climate change mitigation efforts.

1.2. AN INTRODUCTION TO REBOUND AND BACKFIRE

This literature review examines efforts to quantify rebound and backfire in energy demand resulting from below-cost energy efficiency improvements and includes a growing body of empirical surveys, theoretical work, and modeling analysis. Rebound and backfire must be understood in order to accurately evaluate the potential of below-cost efficiency improvements to reduce greenhouse gas emissions (or slow the depletion of finite energy resources such as fossil fuels).

It is important to note that the scope of this review pertains only to the potential for rebound in response to *below-cost* efficiency improvements. Those improvements that do not pay for themselves or do not result in net improvements in productivity should not result in rebound (at least at aggregate macroeconomic scales)[6] because they have the effect of increasing the cost of energy services and/or have a total economic cost that depresses economic activity, reducing energy demand. Conversely, below-cost efficiency improvements by definition lower the cost of energy services, driving both

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[6] If individual energy consumers do not pay the full cost of 'above-cost' energy efficiency improvements, they may see a decrease in the implicit price of energy services, triggering rebound effects at microeconomic scales, while the net cost of the efficiency improvement at societal or economy-wide scales may still reduce overall energy use.

economic growth and greater energy consumption through substitution and income/output effects. Thus, the question is not whether improvements in energy efficiency that truly 'pay for themselves' will drive a rebound in energy consumption, but rather, how much rebound will result.

Several distinct mechanisms cause a rebound following below-cost energy efficiency improvements. Efficiency measures reduce the cost of energy services,[7] driving greater demand for such services (all else equal), referred to in the literature as 'direct rebound.' Should efficiency improvements lead to cost savings, consumers or firms will increase consumption or savings and investment, either of which increases economic output and thus energy consumption, a mechanism known as 'indirect rebound.' More broadly, the more efficient production and use of energy at a macroeconomic scale drives economic productivity overall and encourages the substitution of energy for other factors of production (e.g., labor)[8], resulting in more rapid economic growth and energy consumption ('macroeconomic rebound' effects).

To date, the bulk of empirical surveys of rebound have focused on direct, microeconomic rebound for end-use consumers of energy services in developed countries (e.g., home heating and cooling, electric appliances, transportation). However, as this literature survey will demonstrate, such surveys examine precisely the scope and location at which energy rebound is least visible.

While direct rebound for end-use energy services in developed economies appears to be small to moderate, far greater rebound can result from efficiency improvements in productive sectors of the economy (e.g., industrial and commercial firms) and in developing nations, where elasticity of demand for energy services and opportunities for substitution are both greater. For example, homeowners heating their homes may get little utility out of raising the thermostat beyond seventy degrees Fahrenheit despite having lowered their electricity costs through home weatherization, leading to little direct rebound.[9] In contrast, improvements in efficiency at a steel manufacturer may provide much greater opportunity to substitute energy services for other inputs of production

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[7] A distinction must be made here between the effective or implicit price of energy services (e.g. the cost per unit of lighting provided or heating degrees provided) and the actual or market price of energy or fuel itself (e.g. in cost per natural unit of fuel, such as cost per gallon of gasoline or ton of coal). Rebound effects are primarily driven by reductions in the effective/implicit price of energy services and can occur independently of any changes in the actual or market price of fuels. Efficiency improvements may *also* reduce aggregate demand for a particular fuel itself, leading to possible reduction in actual/market prices for that particular energy source. In this case, a 'market price effect' may drive a rebound in energy demand, as consumers respond to now-lower energy prices. If a rebound in energy demand is not sufficient, and actual/market prices for the fuel remain lower, a 'disinvestment effect' may occur in which lower market prices discourage investments in new energy supply, which may reduce overall energy demand over the long term (a kind of negative rebound effect). These market price-related dynamics are discussed in greater detail in Sections 2.3.1 and 2.3.4 below.

[8] Indeed, much of the arc of the past two centuries of economic history can be characterized by the progressive substitution of greater and greater amounts of capital and energy for human and animal labor throughout virtually every sector of the economy.

[9] Such a scenario would result in greater cost savings, however, which can fuel greater indirect rebound, and total productivity improvements and resulting rebound at a macroeconomic scale.

and/or produce more steel at a lower price, encouraging an increased consumption of steel and the many products containing it. Likewise, even though end-use demand for energy services is fairly inelastic and may be nearing saturation for many consumers in developed economies, demand for energy services is both more elastic and far from saturated throughout the world's developing nations, where much larger rebound effects have been found by the limited number of studies of developing economies to date.

More broadly, the growing body of scholarship and research into rebound and backfire reveals that increasingly large levels of rebound are found as the scope of analysis expands from surveys of direct rebound at microeconomic scales (i.e., the response of individual consumers and firms to decreases in the cost of energy services) to indirect rebound (from embodied energy and re-spending/re-investment effects) to macroeconomic effects (including price effects, composition/substitution effects, and growth/output effects). So while surveys of direct rebound in end-use sectors of developed nations have typically found limited rebound (typically 10-30%), studies encompassing a larger set of indirect and macroeconomic rebound mechanisms at national or global scales have found rebound to be significant (frequently 50% or greater), with a number of studies predicting backfire (>100% rebound), results that are entirely consistent with both neoclassical and ecological schools of economic theory.

Furthermore, particularly acute rebound or backfire is likely to occur when more efficient (and thus lower cost) energy services open up new markets or enable widespread new energy-using applications, products, or even entire new industries (a 'frontier effect') – an outcome that is quite difficult to predict in advance. Likewise, when energy efficiency improvements not only improve the productivity of energy, but also result in simultaneous improvements in other factors of production, such as labor or capital (a 'multi-factor productivity improvement'), an outsized impact on economic output and significant rebound in energy demand can arise.

Rebound and backfire should thus be considered 'emergent phenomena,' defined here as higher order effects resulting from the complex interaction of multifold individual components and the combination of multiple non-linear and reinforcing effects. Emergent phenomena are often difficult for specialists and policymakers alike to understand because effects emergent at scale seem so different from their constituent causes. As such, technologies that may appear to be labor-saving, capital-saving, or energy-saving at a more restricted scope of analysis – e.g., at the level of individual consumers or firms – may in fact be labor-using, capital-using, and energy-using at a more expansive scope – e.g., at the macroeconomic scale of national economies or global energy systems.

I. Introduction

Over the last two centuries, policymakers and specialists have often predicted that improving the productivity of labor, capital, or materials would result in a macroeconomic reduction in demand for these inputs, when the actual result has been just the opposite. Through a variety of self-reinforcing and non-linear mechanisms, micro-level improvements in the productivity of labor, capital, or raw materials frequently result in macroeconomic increases in the demand for these factors. In the case of labor, analysts and observers have repeatedly predicted that ‘labor-saving’ devices, from the weaving loom to the ATM, would result in less demand for workers overall – varyingly sparking both fears of widespread unemployment and more optimistic visions of an imminent ‘leisure society.’ These predictions ultimately proved false, as demand for labor, capital, materials, and energy have risen in spite of, and indeed largely *because* of, improvements in the productivity of each economic factor.

In the case of energy, economists and energy historians have observed for nearly 150 years that below-cost energy efficiency improvements will drive a rebound in energy demand and could even increase rather than decrease total energy consumption in some circumstances (e.g., Jevons, 1865; see historic review in Alcott, 2008). A self-reinforcing dynamic — the substitution of energy for human and animal labor resulting in greater productivity and higher economic growth and ultimately, greater consumption of energy — is indeed the historic norm. The more efficient engines, motors, electricity generation and transmission, lighting, iron and steel production, computing, and even modern lasers have become, the more demand for each has grown.

Despite this history, in the wake of oil price spikes and in the midst of a push to construct new nuclear power plants in the 1970s, some analysts (e.g., Lovins, 1976) argued that a ‘soft energy’ path was possible in which future energy demand would be reduced, economy-wide, by the accelerated adoption of below-cost energy efficiency technologies. Economists (e.g., Brookes, 1979; Khazzoom, 1980) soon responded that such efficiency measures, if they were truly below-cost, would result in rebound or backfire, a hypothesis that would be firmly grounded in neoclassical economic growth theory one decade later (Saunders, 1992). Even so, as concerns about global climate change later mounted, the ‘soft energy’ argument would have even greater appeal to governments and agencies seeking greenhouse gas emissions reduction policies that would have little impact on the economy.

The literature on rebound surveyed in this review challenges the assumptions behind this ‘soft energy’ argument and many influential energy forecasts and policy prescriptions that have followed. For example, the IPCC (2007) concludes that substantial reductions in global carbon emissions might be achieved at zero or ‘negative’ cost (e.g., with net economic benefits) by roughly doubling historical rates of energy intensity decline through the widespread adoption of below-cost efficiency measures. In contrast, the rebound literature and both neoclassical and ecological schools of economic theory suggest that below-cost efficiency improvements are likely to result in significant rebound or even backfire, substantially eroding and in some cases negating these potential emissions reductions. Scenarios of future energy demand and greenhouse gas emissions must therefore rigorously account for rebound from below-cost efficiency in order to enable more realistic and effective climate mitigation and energy planning strategies.

While rebound and backfire may undermine the ability of below-cost efficiency measures to directly drive emissions reductions, the corollary to this conclusion is that such efforts make for excellent economic policy, as they are well suited to accelerate economic growth and modernization and expanding welfare. Furthermore, as discussed in greater detail at the end of this document, the process of both economic expansion and energy modernization, each driven in part by energy productivity improvements, can facilitate the accelerated decarbonization of the energy system. Thus, an accurate accounting of rebound effects will still likely find many strong reasons to pursue cost-effective efficiency efforts, even while such efforts can no longer be assumed to drive linear, one-for-one reductions in total, economy-wide energy consumption or greenhouse gas emissions. Below-cost efficiency opportunities should therefore be vigorously pursued, even as we reassess the potential contribution of such measures to climate change mitigation efforts. Given the largely irreversible and potentially catastrophic impacts of climate change, however, it would be prudent to view with skepticism any estimates of the ability of energy efficiency to drive global emissions reductions that do not rigorously account for the range of rebound effects discussed herein.

This review begins in **Section 2** by identifying the multiple mechanisms that drive a rebound in demand for energy services and fuel consumption after a below-cost improvement in energy efficiency, demonstrating that a variety of rebound mechanisms are operative beyond the direct, micro-scale rebound most commonly studied. **Section 3** introduces rebound effects as 'emergent phenomena' only fully visible at appropriate levels of scope and complexity, complicating efforts to quantify the scale of total, economy-wide rebound. The section then examines several methodologies used to estimate the scale of emergent rebound effects. In **Section 4**, we present a summary of conclusions and note that due to inherent challenges, even the best efforts to date are likely unable to fully capture the scale of emergent economy-wide rebound. Finally, **Section 5** discusses implications for policymaking and offers a new framework for envisioning the role of below-cost efficiency improvements in energy modernization and decarbonization efforts.

2. REBOUND MECHANISMS

Numerous mechanisms have been identified that drive increases in energy demand after an improvement in energy efficiency. Collectively known as 'rebound effects' (sometimes 'takeback effects'), these mechanisms reduce the net energy savings realized by energy efficiency improvements. A straightforward example of rebound would be a homeowner who installs new insulation to increase the heating efficiency of his home, only to take advantage of the resulting decrease in home heating costs to increase the average heating temperature, the amount of time the home is heated, or the number of rooms heated.

Rebound effects are typically expressed as the percentage of expected technical energy savings potential[10] from an efficiency improvement that are taken back or eroded by any resulting rebound in energy demand. For example, a rebound effect of 25% for a given efficiency improvement would mean that only 75% of the expected reductions in energy demand are achieved after various rebounds in energy demand are considered.

Rebound effects occur at both a microeconomic level (e.g., at the level of the individual or household, factory or firm, as in the example of the homeowner above) and at a macroeconomic level (e.g., at the level of entire market sectors or national or global economies). For example, if the widespread adoption of fuel-efficient vehicles drives a large-scale drop in demand for oil, it may translate into lower overall oil prices, which will in turn encourage a rebound in demand for the many products and services provided by oil. At the same time, any net savings in energy costs will increase consumer incomes, driving greater consumption and investment, which in turn spurs economic growth and a rebound in energy use.

Rebound effects can generally be classified as 'direct,' 'indirect,' and 'macroeconomic' rebound mechanisms (the latter are sometimes also referred to as 'general equilibrium effects').[11] When taken together, direct, indirect, and macroeconomic rebound mechanisms combine to drive total 'economy-wide' rebound. When economy-wide rebound is greater than 100% of the projected technical energy savings, 'backfire' is said to occur, and the result is a net increase in total energy consumption despite (and in fact arising from) the improvement in efficiency.

[10] Cost-effective energy savings potential is usually calculated through bottom-up engineering-economic analysis which estimates the marginal cost of buying, installing, and maintaining a more efficient device and compares these costs to the discounted stream of energy savings over the lifetime of the device (see Lovins, 2005 or McKinsey, 2009a, 2009b). These estimates ignore the various rebound effects that follow such efficiency opportunities, yet are widely used as guides for potential energy savings at micro- and macroeconomic scales. An accurate estimation of energy savings potential must subtract the effect of rebound effects from these engineering-economic estimates of technical energy savings (Sorrell, 2007, 2009).

[11] A note on terminology: there is no consistent lexicon for discussing rebound effects. Madlener and Alcott (2008) counted 28 different terms used to describe different rebound effects in their review of the literature. We therefore take liberty to utilize the terminology that seems most straightforward or explanatory (clearly a matter of opinion), since achieving consistency across the literature is ultimately impossible. Note in particular that 'macroeconomic rebound' and 'economy-wide rebound' are terms that are often used interchangeably in the literature to both refer collectively to the various rebound mechanisms operating at large aggregated scales and to describe the sum total of all rebound effects. This paper adopts 'macroeconomic rebounds' to refer to mechanisms, such as market-level pricing effects and economic output effects, operating at macro-scales, while using the term economy-wide rebound to refer to the sum total of direct, indirect, and macroeconomic rebound mechanisms at the level of an entire economy (regional, national, or global in scope).

REBOUND EFFECTS, Terms and Definitions

GENERAL TERMS

BELOW-COST EFFICIENCY: efficiency opportunities that pay back more in net savings than they cost and represent a net improvement in total factor productivity and economic welfare.

REBOUND EFFECT: an economic mechanism driving an increase in demand for energy following a below-cost improvement in energy efficiency.

TOTAL ECONOMY-WIDE REBOUND: the sum total of all energy demand increases resulting from rebound mechanisms when aggregated at an economy-wide, macroeconomic scale.

BACKFIRE: total economy-wide rebound in energy demand that exceeds 100% of projected energy savings from an efficiency improvement.

DIRECT REBOUND EFFECTS

When an efficiency improvement lowers the amount of energy required to provide an energy service, the implicit price of the energy service will fall (all else being equal), triggering direct rebound effects at the microeconomic level of an individual consumer, household, or firm. This direct rebound can be further broken into two components:

INCOME/OUTPUT EFFECTS: After the implicit price of an energy service falls, consumers may respond to the increase in apparent income by increasing demand for that energy service (an 'income effect'), while producing firms may similarly respond by increasing use of that energy service to expand their output ('an output effect').

SUBSTITUTION EFFECTS: Consumers may respond to the lower implicit price of an energy service by substituting that energy service for the enjoyment of other goods or services, while firms may similarly substitute the now-cheaper energy service for other inputs to production.

INDIRECT REBOUND EFFECTS

In addition to direct rebound effects, several indirect mechanisms drive rebound:

EMBODIED ENERGY EFFECTS: Energy efficiency technologies and investments require energy to manufacture and install, and this energy ‘embodied’ (or embedded) in the efficiency improvements themselves will offset some portion of the energy savings achieved.

RE-SPENDING AND RE-INVESTMENT EFFECTS: If direct rebound effects are small, consumers and firms will see net cost savings from energy efficiency improvements, which will increase consumer expenditures or investments in production, both of which increase demand for goods, services, and factors of production which in turn require energy to produce and support.

MACROECONOMIC EFFECTS

The aggregate impact of widespread energy efficiency improvements at a microeconomic scale can combine to drive several macroeconomic mechanisms that also contribute to total economy-wide rebound, as both producers and consumers respond to changes in energy service costs:

MARKET PRICE EFFECTS: Widespread improvements in energy efficiency can be sufficient to drive a large-scale decrease in energy demand. The resulting decrease in energy market prices will encourage greater overall use of related energy services and a rebound in energy demand.

COMPOSITION EFFECTS: Widespread improvements in energy efficiency in production processes will favor energy-intensive sectors of the economy, for which energy inputs make up a larger portion of production costs. The result should be an increase in consumer demand for energy-intensive goods and services and an overall shift in the composition of the economy towards energy-intensive sectors, driving a rebound in related energy consumption.

ECONOMIC GROWTH EFFECTS: All else equal, an overall increase in energy productivity of the economy will spur greater economic output and growth and result in an increase in energy demand.

2.1. DIRECT REBOUND EFFECTS

At the microeconomic level, when a below-cost energy efficiency improvement lowers the amount of energy required to provide an energy service, the implicit or effective cost of the energy service will fall (all else being equal). In turn, this will drive both a direct increase in demand for that service (e.g., one might drive a more efficient car more often), known as an 'income effect,' and the substitution of the now-cheaper energy service for the enjoyment of other goods or services (e.g., more affordable dish washers may substitute for hand washing, or the more efficient use of energy in a production process may allow energy services to substitute for labor at a factory), known as a 'substitution effect.' (For producers, an 'output effect' replaces the 'income effect' for consumers).

In general, direct rebounds for consumer energy services in developed nations have been found to be small to moderate in scale and can typically erode 10-30% of the energy savings from efficiency improvements, with some studies reporting higher rebounds (see Table 2.1 below; Greening and Greene, 1998; Greening et al., 2000; Sorrell, 2007; Sorrell et al., 2009).

Since energy efficiency improvements appear to consumers and producers as an effective decrease in the price of the associated energy service, the elasticity of demand for the energy service (responsiveness of demand to price) and the ability of that energy service to substitute for other inputs (e.g., capital, labor, or materials) or services are both major factors that determine the scale of direct rebound. A high elasticity of demand and/or substitition will drive greater direct rebound in response to an energy efficiency improvement and vice versa. Since energy demand is typically inelastic (less than 1.0), at least for consumers in developed nations, direct rebound effects are generally less than 100% (Greening et al., 2000; Sorrell, 2007), although opportunities for substitution of energy for other factors of production in the productive sectors of the economy may lead to much greater direct rebounds and even backfire (Saunders, 2010).

TABLE 2.1:
Scale of Direct Rebound for Consumer Energy Services in Developed Nations – Summary

Energy Service	**Range of Estimates**	**Best Guess**	**Degree of Confidence (Notes)**
Automotive transport	5-87%	10-30%	HIGH (*Unmeasured in these studies are changes in automotive attributes, particularly heavier vehicles and more powerful engines.*)
Space heating	1.4-60%	10-30%	MEDIUM (*Unmeasured in these studies are increases in the space heated and an increase in thermal comfort.*)
Space cooling	0-50%	1-26%	LOW (*Unmeasured in these studies are increases in the space cooled and an increase in thermal comfort.*)
Water heating	<10-40%	??	VERY LOW (*Unmeasured in these studies are reports of increased shower length or purchase of larger water heating unit.*)
Other consumer energy services	0-49%	<20%	LOW

SOURCE: *Greening et al., 2000; Sorrell, 2007. All values based on studies conducted in developed nations. Rebounds likely to be higher in developing nations, but studies are lacking in non-OECD countries. Degree of confidence based on availability of evidence, which can be sparse for some energy services.*

The degree to which demand for a particular energy service has been fulfilled is also a key factor in determining the scale of direct rebounds, with large rebounds possible when demand for energy services is largely unfulfilled — e.g., electricity and steel in developing nations, or heating energy for low-income households — and lower rebound when demand has been largely saturated, such as in household use of electricity or oil in developed nations (Sorrell, 2007). In a world where roughly 1.6 billion people lack access to electricity and 2.5 billion rely primarily on primitive biomass (e.g., wood and dung) for cooking and heating (Sorrell, 2007), huge pent-up demand for energy services persists, indicating potential for larger direct rebounds in developing nations (Schipper and Grubb, 2000; IAC, 2007). Sorrell (2007), for example, notes two papers examining direct rebound effects following efficiency improvements in end-use energy consumption in developing nations (Sudan and India), which found direct rebounds of 42% and 50-80%, respectively (Zein-Elabdin, 1997; Roy, 2000).

Direct rebound effects in commercial and industrial sectors of the economy have received much less study than rebounds in end-use consumer energy services. The lack of study into rebound for producing sectors of the economy is notable, because the production of goods and services consumes roughly two-thirds of global energy use.[12] Excepting one recent analysis (Saunders, 2010), evidence to date is primarily limited to single-firm energy audits, and as such only captures short-run rebound effects. These studies are therefore likely to underestimate long-run direct rebounds by failing to capture slower capital turnover effects or industry-wide effects (Greening et al., 2000).

The ease with which energy services can substitute for other inputs in industrial production greatly impacts the magnitude of direct rebound for firms (Saunders, 1992, 2000b, 2010). Overall, while some empirical estimates of the elasticity of substitution in production processes find values greater than 1.0, indicating potential for large direct rebound or even backfire due to substitution, most have shown values less than 1.0. Greening, et al. (2000) presents a respected survey of research on direct rebounds. Although the authors primarily examine evidence of rebound in end-use sectors in developed economies and note the relative absence of solid evidence for producing sectors, they briefly survey econometric estimates of substitution relationships between energy and other factors of production in various sectors, noting estimates of substitution elasticities ranging from 0.4 to 0.8, and in a few rare cases, finding values greater than 1.0. The authors thus conclude, “although the evidence is mixed, the size of the [direct] rebound from substitution effects [for firms] appears to be small to moderate” (Greening, et al. 2000).

Saunders (2010) contributes a detailed econometric analysis of historical rebound across thirty producing sectors of the U.S. economy, which provides a rigorous new methodology for analysis of rebound in commercial and industrial sectors.[13] Saunders finds long-run rebound due to substitution ranging across sectors from as low as 10% to as high as 90%, values that are roughly consistent with the range of substitution elasticities surveyed by Greening, et al. (2000).[14] Long-term rebound due to substitution effects predominately cluster between 20-50% across the thirty sectors examined

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[12] By comparison, just one-third of global energy consumption is due to end-use consumer energy services. Put differently, for every unit of energy consumed by end-use energy services such as transportation, refrigeration, or heating/cooling, two units are consumed to produce goods and services used by consumers and in refining, processing and transporting energy to end-uses (ExxonMobil, 2009, p. 5).

[13] While Saunders (2010) is still in review as this paper is written, it represents an important contribution to the study of rebound effects that fills a key void in analysis of rebound for producing sectors of the economy. The paper is therefore included in this review despite its pre-publication status. The author can be contacted for a copy of the paper at hsaunders@decisionprocessesinc.com

[14] See Saunders (2010), Table 1. Long-term rebound due to substitution effects calculated by multiplying total long-term energy-specific rebound for each sector by the share of energy-specific rebound due to substitution/intensity effects, as reported by Saunders (2010). The greatest long-term rebounds due to substitution effects are found in Electric Utilities (90%), Communications (60%), Financial Industries (58%), Primary Metals (55%) and Construction (55%).

(Saunders, 2010), indicating potential for much higher rebound in producing sectors than those observed in end-use consumer sectors (see Table 2.2).

In addition to potentially spurring substitution, increasing a firm's energy efficiency and more productively arranging factors of production (e.g. after substitution) may lower the price of that firm's product, potentially inducing greater demand for the product, driving greater output and a resulting rebound in the firm's energy consumption (an 'output effect'). Alternately, if production costs decrease, it may open up new profitable possibilities for the firm's products, allowing expanded production and increasing energy consumption, even if the firm does not pass lower prices on to consumers, as described above.

Given the relatively small share of energy in the total cost of most products (typically less than 10% according to Greening et al., 2000), direct rebound due to this mechanism is likely to be small, except in cases of very energy-intensive products with high elasticity of demand.[15] Saunders (2010) also estimates rebound for output effects in the 30 producing sectors examined, finding long-run output effects ranging from 0-15%, with four energy-intensive sectors experiencing higher rebounds of roughly 20-30% (see Table 2.2).[16]

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[15] For example, a 100% improvement in a firm's energy efficiency would cut both energy consumption and the cost of energy in production by half. If energy services contribute 10% of the firm's total production costs, the costs of the firm's products will thus fall by about 5%. Assuming perfect elasticity of demand for the product (e.g., 1.0), the firm's market share and output would increase as a result by 5%, driving a rebound in the firm's demand for energy services of just 5% (Greening et al., 2000). With the same assumptions but for a firm where energy services contribute 30% of the firm's total production costs, a doubling in energy efficiency would drive a 15% rebound in the firm's energy consumption. Thus, direct rebound is likely to be higher for efficiency improvements at firms with energy intensive production processes. Furthermore, the magnitude of this type of rebound will depend on the elasticity of demand for the firm's products (Sorrell, 2007). In the examples above, if price-elasticity for the firm's products is inelastic at 0.5, the rebound would be only half as large, whereas with a price-elasticity of 1.5, rebound would be 50% greater.

[16] Again, see Saunders (2010), Table 1. The highest long-term rebounds due to output-effects are found in Chemicals (33%), Electric Utilities (30%), Transportation (25%) and Agriculture (21%), all energy-intensive industries (see Table 2.2. herein). Note that Saunders (2010) shows output effects accumulating substantially over time, with short-term output effects much smaller than long-term effects.

TABLE 2.2: Scale of Direct Rebound for Producing Sectors

Sector	Long-term rebound	Share of rebound due to substitution	Share of rebound due to output	Long-term rebound from substitution	Long-term rebound from output
Electric utilities	120%	75%	25%	90%	30%
Transportation	59%	57%	43%	34%	25%
Services	25%	90%	10%	23%	3%
Chemicals	53%	38%	62%	20%	33%
Construction	58%	94%	6%	55%	3%
Primary Metals	66%	84%	16%	55%	11%
Agriculture	39%	47%	53%	18%	21%
Financial Industries	61%	95%	5%	58%	3%
Government Enterprises	40%	87%	13%	35%	5%
Food & Kindred Products	40%	98%	2%	39%	1%
Paper & Allied Products	44%	80%	20%	35%	9%
Stone, Glass, Clay	55%	82%	18%	45%	10%
Machinery, non-electrical	14%	71%	29%	10%	4%
Fabricated Metal	40%	96%	4%	38%	2%
Electrical Machinery	41%	95%	5%	39%	2%
Lumber and Wood	45%	89%	11%	40%	5%
Rubber & Miscellaneous Plastics	37%	93%	7%	34%	3%
Textile Mill Products	37%	89%	11%	33%	4%
Motor Vehicles	29%	97%	3%	28%	1%
Non-metallic Mining	54%	73%	27%	39%	15%
Communications	60%	100%	0%	60%	0%
Transportation and Ordinance	23%	96%	4%	22%	1%
Printing, Publishing & Allied	25%	93%	7%	23%	2%
Instruments	32%	51%	49%	16%	16%
Apparel	52%	96%	4%	50%	2%
Metal Mining	51%	73%	27%	37%	14%
Furniture & Fixtures	19%	96%	4%	18%	1%
Misc. Manufacturing	27%	95%	5%	26%	1%
Leather	30%	97%	3%	29%	1%
Tobacco	46%	70%	30%	32%	14%
OVERALL	62%				

SOURCE: *Saunders (2010).*

In general, the sum of direct rebounds (e.g., substitution and output effects) resulting from improvements in the efficiency of energy services at productive firms may be roughly 20-60%, with greater rebound possible for energy-intensive sectors where energy services are easily substituted for other factors of production (see Table 2.2; Saunders, 2010).[17] Considering the limited level of research in this area to date and the significant proportion of global energy consumed in the production of goods and services, much more study of direct rebounds for producing firms is warranted.

2.2. INDIRECT REBOUND EFFECTS

As we have seen, following an energy efficiency improvement by a given consumer, direct rebound effects drive an increase in demand from the same energy user for the same product or energy service. In addition to these direct rebound mechanisms, however, several mechanisms also indirectly drive a rebound in demand for other energy services. As these mechanisms operate at a less direct and observable scale, there is considerably more debate as to the precise scale and magnitude of these effects than in the case of direct rebound mechanisms.

2.2.1. EMBODIED ENERGY EFFECTS

Energy saving technologies and investments will require energy to manufacture and install, and this energy 'embodied' (or embedded) in the efficiency improvements themselves will offset some portion of the net energy savings achieved (Sorrell, 2007).[18] For example, thermal insulation and low-emissivity windows can reduce the energy consumption required to provide thermal comfort to a residence, but the insulation and windows will in turn require energy to manufacture, transport, and install.

The rebound in energy demand driven by this embedded energy mechanism is likely to be relatively small, given the relatively small share energy makes up of the inputs used to produce most products. Furthermore, the more the efficiency improvement saves over its lifetime, the more the scale of rebound from embodied energy effects will diminish (Sorrell, 2007).[19] In the case of thermal insulation retrofits for buildings, for example, several studies estimate that total energy savings exceed embodied energy within a few months, with the insulation lasting on the order of 25 years or more

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[17] In general, direct rebound effects (from substitution and output effects) are likely to be smaller for a firm or sector with difficulty substituting energy for other production inputs, where energy is a small share of total production costs, and with low elasticity of demand for the firm's products. Rebounds will be higher for firms or sectors with relative ease substituting energy for other inputs, where energy is a large share of production costs, and with high elasticity of demand for the firm's products.

[18] Many efficiency improvements can be understood, in economic terms, as the substitution of capital (e.g. thermal insulation, low-emissivity windows, a more costly but efficient electric motor) or labor (e.g. production and installation of efficiency technologies) for energy. Yet the provision of both capital and labor in turn requires energy to support, hence the 'embodied energy' effect described above (see Sorrell, 2007, p. 41-43).

[19] For example, if an efficiency improvement has a total cost of $1,000 and has a payback period of three years, it will save $333 in energy consumption annually. If energy makes up 10% of the cost share of inputs to produce and install the efficiency improvement, the embedded energy value of the improvement is $100. Thus, when measured on an economic value basis, the embedded energy rebound would be 30% on a short-run, one-year basis, but would diminish to just 3% over ten years or 0.4% over 25 years. The size of the embedded energy rebound thus depends on the energy intensity of production, transport and installation of an efficiency improvement, the annual energy savings from the improvement, and the lifetime of the improvement.

(Sorrell, 2007), indicating relatively small rebound due to the embodied energy effect (e.g., just 2% for a payback period of six months and a lifespan of 25 years). In contrast, window retrofits using low-emissivity, double glazed windows require up to several years for total energy savings to exceed embedded energy (Sorrell, 2007), indicating a more significant embodied energy rebound with the exact magnitude depending largely on the lifespan of windows. Studies of embodied energy in energy efficient new building construction find energy 'payback' periods ranging from as little as one year to as many as fifteen years or more, with wide variance in estimates due to differences in building types, materials, and climate conditions (Sorrell, 2007). If new buildings are assumed to have an average lifespan of about 100-years, this would indicate rebounds of 1-15% due to the embodied energy effect, alone.

Kaufman and Azar Lee (1990) performed one rare study of embodied energy in capital equipment purchases used to improve efficiency in industrial production. The authors used a relatively simplified approach to calculate that the embodied energy associated with efficiency improvements made in the U.S. forest products industry between 1954-1984 resulted in significant indirect rebounds of between 18-83% of the technical energy savings. Embodied energy rebounds were found to increase as incremental efficiency improvements were pursued over the time period examined, indicating diminishing returns in energy savings as an increasing amount of capital was required to substitute for energy inputs in order to capture the next marginal efficiency opportunity (discussed in Sorrell, 2007).

Overall, the evidence for the scale of embodied energy rebounds is sporadic at best, and given the large degree of variance from one situation to another, should be considered indicative, not definitive. In general, while likely to be small (<15%) for the most cost-effective efficiency improvements produced using little energy or having a long lifespan, the embodied energy rebound mechanism can be more significant for efficiency improvements with long economic payback periods, a short lifespan and/or energy-intensive production and installation requirements.

2.2.2. RE-SPENDING AND RE-INVESTMENT EFFECTS

If direct rebound effects are small, consumers will see a net decrease in expenditures on energy following below-cost energy efficiency improvements, which will result in an increase in real incomes. These energy cost savings will be re-allocated to purchase other goods or services, which in turn require energy. Likewise, producers who secure net energy savings from efficiency improvements (after direct rebound effects) may use the savings to increase output of one or more of their products. In addition to increasing demand for energy inputs, demand for other production inputs (capital, labor, materials) will rise, and each in turn requires energy to produce or support as well, leading to further indirect rebound in energy demand.[20] It is worth noting that there is a trade-off between indirect rebound due to the re-spending effect and direct rebound, as the total energy savings available for re-spending is lower when direct rebound is higher (and vice versa).

There has been very little effort to rigorously quantify the magnitude of these re-spending and re-investment effects (Sorrell, 2007), and the available evidence to date remains too limited to draw precise conclusions about the scale of the re-spending and re-investment effects. Several authors (Laitner, 2000; Schipper and Grubb, 2000; Greening et al., 2000) have observed that the re-spending effect will be proportionate to the share of energy consumption in marginal consumer spending and therefore quite low. In general, direct energy consumption (fuel and electricity) makes up a relatively small share of consumer purchases – roughly 10% of per capita U.S. consumer expenditures, for example (Boyce and Riddle, 2007) – indicating that the re-spending effect is fairly small. However, the embodied energy in other goods and services makes up anywhere from one-third to two-thirds of total household energy consumption and must also be considered (Sorrell, 2007). Several studies indicate that the total re-spending effect for consumers, including impacts on indirect energy consumption associated with non-energy goods and services, may therefore be more significant and could drive rebounds on the order of 5-35%, with some studies indicating higher rebounds (Sorrell, 2007).

While direct evidence is extremely limited, the re-investment effect for firms is likely to be less prevalent, since energy inputs typically make up a small portion of a firm's total costs (typically less than 10%; Greening et al., 2000). Furthermore, competitive pressures will typically encourage firms to pass on any cost savings in the form of lower prices (which may trigger direct rebounds, but will limit the scale of re-investment effects).

2.3. MACROECONOMIC EFFECTS

The impacts of widespread energy efficiency improvements at a microeconomic scale can combine to drive several macroeconomic mechanisms that also contribute to total economy-wide rebound, as both producers and consumers respond in aggregate to changes in energy service costs.

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[20] It is important to note most efficiency opportunities require substantial up-front investments (e.g. in capital and labor for installation) while recouping initial expenditures over time through reduced energy costs on an ongoing basis. While these up-front investments are related to the embodied energy rebound mechanism discussed above (2.2.1), the initial outlay will also reduce other consumer expenditure (or investment for firms), resulting in a short-term reduction in indirect energy demand associated with consumer expenditures (or investment) – a 'negative rebound' effect – that will moderate the net impact of this indirect rebound mechanism. However, energy costs will decrease more substantively in the future resulting in a larger re-spending effect going forward. To be precise, the re-spending effect should thus be broken into two components: an initial 'negative' rebound effect resulting in a short-term reduction in consumer expenditure or investment as the initial outlay is made for an efficiency improvement, with an ongoing re-spending effect as energy costs are saved over time. This on-going re-spending effect will be larger than the combined impact of both components on aggregate energy demand.

2.3.1. MARKET PRICE EFFECTS Widespread improvements in energy efficiency can be sufficient to drive a large-scale decrease in demand for a particular fuel. The resulting decrease in energy market prices will encourage greater overall use of related energy services and a rebound in energy demand. For example, widespread improvement in vehicle fuel economy in the United States – a sector responsible for a major portion of total global oil consumption – may drive down prices on worldwide oil markets, triggering a rebound in demand for the many oil-consuming energy services and products.[21]

The scale of the market price effect will be proportionate to the responsiveness of aggregate energy markets to changes in the price of energy services and fuels, including both the aggregate own-price elasticity of demand (as energy users increase consumption of energy services in response to falling prices) and the elasticity of substitution (as now-cheaper energy services substitute for other consumer products and services or production inputs).[22] While demand for energy services is typically inelastic in developed countries (Greening et al., 2000; Sorrell, 2007), indicating smaller rebound due to market price effects (Laitner, 2000), demand for even basic energy services is largely unfulfilled across much of the developing world. This indicates that where energy markets are global – as is the case for oil and increasingly for other energy commodities, including natural gas and coal – global demand elasticity may be higher, particularly over longer time periods that allow for the accumulation of substitution and other adjustment responses (Allan et al., 2007; Saunders, 2008; Hanley et al., 2009; Turner et al. 2009). Since substitution is typically constrained by the rate of capital turnover, long-run rebound due to market price effects is likely to be greater than short-run rebound (Wei, 2010). If global elasticity of demand is equal to or greater than 1.0, backfire is possible due to market price effects, and the work of Saunders (2010) indicates that the combined impact of substitution effects in response to changes in the price of energy services could be significant within producing sectors of the economy (see Section 2.1 above). Note, however, that if demand is not sufficiently elastic, final market prices may remain lower following efficiency improvements, driving a 'disinvestment effect' (discussed in Section 2.3.4 below), which may actually decrease long-term energy demand (Turner, 2009; Anson and Turner, 2009; Turner et al., 2010).

2.3.2. COMPOSITION EFFECTS Widespread improvements in energy efficiency in production processes, as well as any reductions in energy prices triggered by large-scale efficiency improvements,

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[21] For the purpose of this example, this assumes global oil markets respond in a competitive manner to decreases in demand resulting from widespread fuel economy improvements. Impacts of OPEC manipulations of oil supply have the potential to moderate declines in oil price, potentially mitigating or eliminating this rebound effect.

[22] In this way, the market price effect can be considered the macroeconomic analog of the income/output and substitution effects that make up direct rebound at a microeconomic scale.

will favor energy-intensive sectors of the economy. Since energy makes up a larger portion of total costs in energy-intensive sectors, improvements in energy productivity and/or decreases in energy prices will reduce the costs of energy intensive goods and services to a greater extent than in other sectors. All else equal, the expected result would be an increase in consumer demand for energy-intensive goods and services and an overall shift in the composition of the economy towards energy-intensive sectors, driving a rebound in related energy consumption (Sorrell, 2009). Evidence for the scale of macroeconomic composition effects is very limited.

2.3.3. ECONOMIC GROWTH EFFECTS

All else equal, an overall increase in energy productivity of the economy will spur greater economic output. Likewise, lower costs for energy services will translate into an increase in real incomes, thereby encouraging greater investment and consumption, stimulating economic growth. As economic output grows, demand for a wide variety of goods and services grow in turn, driving a rebound in total energy consumption (Sorrell and Dimitropoulos, 2007; Sorrell, 2009). Since improvements in energy productivity are equivalent to increases in the supply of fuel (both increase the supply of energy services/inputs), the magnitude of rebounds due to the economic growth effect will ultimately depend on the role energy consumption (or more accurately, the consumption of energy services) plays in overall economic growth. As there is no single accepted framework to rigorously define these dynamics, considerable debate remains over the scale and function of this macroeconomic rebound effect (Dimitropoulos, 2007; Sorrell and Dimitropoulos, 2007; Sorrell, 2007, 2009).

The conventional view (consistent with both neoclassical economic theory and endogenous growth theory) is that capital, labor, and energy inputs are considered to have *independent* and *additive* effects on economic output, with residual increases in output attributed to exogenous technical change (Saunders, 2000b; Sorrell, 2007, 2009). While increases in the supply of energy inputs are critical to support economic growth, the assumption is thus that economic growth is driven primarily by increases in the supply (or improvements in the quality) of capital and labor inputs, which make up a larger share of total macroeconomic costs than energy inputs, as well as increases in total factor productivity (due primarily to technical change). If this is the case, rebounds in energy demand due to economic growth effects would likely be small (Sorrell, 2009), perhaps as little as 0-2% (Laitner, 2000; Geller and Attali, 2005). However, the work of Saunders (2010) indicates that the cumulative impact of output effects following efficiency improvements in producing sectors of the economy could yield larger rebound on the scale of 0-15% or higher.[23]

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[23] The cumulative impact of substitution effects is likely to have a much greater impact on macroeconomic rebound, according to Saunders (2010).

The works of several ecological economists have also challenged the prevailing economic view, contending that increases in the availability of high quality energy inputs have been a primary driver of economic growth since the Industrial Revolution (see Kaufmann, 1992, 1994, 2004; Cleveland et al., 1984, 2000; Ayres, 1998; Ayres and Warr, 2005, 2006). These economists argue that capital, labor, and energy inputs have *synergistic* and *multiplicative* effects on economic output and that the increased availability of low-cost, high-quality energy sources has provided a necessary condition and key driver of most historical improvements in economic productivity (Sorrell, 2009). If these conditions prove true, rebound from economic growth effects is likely to be large, even potentially leading to backfire.

Both of these perspectives are discussed further in Section 3.

2.3.4. SUPPLY-SIDE CONSTRAINTS ON MACROECONOMIC REBOUNDS While many factors drive an increase in energy demand following an improvement in efficiency, some macroeconomic effects moderate or dampen the scale of rebound. For example, if market price and other rebound effects do *not* drive a sufficient rebound in demand for energy services, a form of negative rebound effect may occur, known as the 'disinvestment effect' (Turner, 2009; Anson and Turner, 2009; Turner et al., 2010). If energy prices fall sufficiently without an increase in demand, the return on capital in energy supply sectors will fall, spurring a shedding of capital stock. The resulting tightening of supply will cause energy prices to rise, restoring capital returns to sufficient levels but dampening rebound effects over the long run. In general, the disinvestment effect is reduced the more responsive markets are to aggregate changes in energy price (Turner, 2009; Anson and Turner, 2009; Turner et al., 2010).

Wei (2010) also highlights the importance of the supply side of the energy picture to the ultimate scale of economy-wide rebound. For example, where energy supply is constrained (as is increasingly the case in global oil products markets due to limits in production and refining capacity) or supply is finite (as is the case in the long run for all fossil fuels), potential rebound effects may be less than estimated by studies focusing only on the demand-side of the market, with important implications for the likelihood of backfire (Wei, 2010). In the extreme example, if supply is fixed, the rebound effect must be no greater than 100%, as energy saved through efficiency measures is the only 'new' energy supply available to satisfy increased demand. Thus, constraints on energy supplies could in principle limit overall rebound or prevent backfire that would otherwise occur.

3. THE EMERGENT REBOUND EFFECT AND THE SCALE OF ECONOMY-WIDE REBOUND

Given the numerous mechanisms driving rebound, the inherent complexity and scale at which these rebound effects operate, and the difficulty in drawing direct connections between microeconomic mechanisms and macroeconomic observations, the nature and magnitude of total economy-wide rebound is still a matter of debate. As such, no single, widely accepted methodology exists to quantify rebound effects at the scale of aggregation most relevant to climate and energy resource depletion concerns – e.g., total economy-wide rebound at a global scale and over multiple decades (Dimitropoulos, 2007).

Efforts to interrogate rebound effects through various methods, including reductive surveys, decomposition of macroeconomic trends, econometric analysis, and detailed modeling (Section 3.1), have proceeded apace alongside the development of more formalized economic theories of rebound (Section 3.2). As with other emergent properties in the realms of biology, physics, and culture, efforts to study and quantify rebound effects face inherent epistemological challenges, particularly at all but the simplest of microeconomic scales. Methods of empirical survey or modeling analysis must overcome these challenges, which have limited even the best inquiries into economy-wide rebound to date, as we shall see below. However, as these limits and challenges are overcome and as efforts to analyze rebound effects expand in scope and complexity – from reductive inquiries into direct rebound effects at microeconomic scales to complex macroeconomic models of the global economy – the scale of rebound observed generally becomes larger and larger.

In fact, this trend is to be expected. Rebound effects should properly be considered 'emergent properties,' as they only arise through the complex interaction of multifold economic actors and mechanisms and are observable only at appropriate degrees of scale. As the scope and complexity of inquiry expands, we therefore see the gap close between the scale of rebound captured in empirical surveys and modeling inquiries and that predicted by more generalized macroeconomic theorists. Thus, as with other emergent properties, the study of rebound at macroeconomic scales, including the scale of total, economy-wide rebound, may be properly considered the domain of theoretical inquiry. As we shall see below (Section 3.2), both neoclassical and ecological schools of economic theory predict very large rebounds or even backfire to be the norm following improvements in energy efficiency. While further development of econometric and modeling analysis of rebound may ultimately yield more applicable or definitive insights, these theoretical perspectives should strike a note of caution in the meantime.

Further complicating matters is the fact that most inquiries into rebound effects consider 'pure' improvements in energy efficiency alone. In reality however, energy efficiency improvements are rarely 'pure.' As efficiency advocates commonly note, energy efficiency improvements frequently accompany simultaneous improvements in the productivity of other factors of production, such as labor or capital. Neoclassical theorists would predict that such 'multi-factor productivity improvements' would drive significantly greater rebound, raising the specter of backfire. Likewise, a school of ecological economists challenge the conventional theory that improvements in the supply or productivity of individual factors of production are independent and additive. As noted previously, these economists instead argue that increases in the supply of 'high-quality' energy supplies have had synergistic and multiplicative impacts on other factors of production and have been disproportionately large drivers of economic growth. If such is the case, improvements in energy efficiency will have correspondingly greater impacts on economic growth, driving a much larger rebound in the consumption of energy (and other economic inputs) than otherwise predicted. Each of these complicating factors is discussed in Section 3.3.

3.1. METHODS OF INQUIRY INTO THE SCALE OF REBOUND

The contemporary rebound debate began in earnest when the early works of Brookes and Khazzoom challenged the notion that engineering estimates of individual energy saving opportunities could be aggregated to estimate energy savings potential at macroeconomic scales (Brooks, 1979; Khazzoom 1980, 1982). In so doing, the pair was among the first in contemporary times to recognize that rebound effects were 'emergent' at macroeconomic scales and would undermine energy savings projected by engineering estimates of technical efficiency opportunities. The early theoretical arguments presented by Brookes and Khazzoom would go on to be formalized by Saunders (1992) and others (see Section 3.3) prompting a number of methods of inquiry into the scale of rebound effects as efficiency advocates, researchers, and energy analysts worked to test, validate, or invalidate the arguments of Brookes, Khazzoom, and later theorists. These methods are discussed below.

3.1.1. SURVEYS OF DIRECT REBOUND

Efficiency advocates such as Lovins (1988, 1998) turned primarily to surveys of microeconomic behavioral responses to efficiency improvements in an attempt to validate or invalidate the theoretical arguments of Brookes, Khazzoom, Saunders, and others. The resulting work was expanded and summarized by researchers including David Greene, Lorna Greening, and their colleagues (Greene, 1992, 1997; Greening and Greene, 1998; Greening et al., 2000).

The most robust empirical studies of rebound effects to date have thus focused on the direct rebound effect, particularly within end-use consumer sectors of developed economies (e.g., automotive transportation, appliances, or household heating). As noted in the discussion of direct rebound above (Section 2.1) , Greening et al. (2000), Sorrell (2007) and Sorrell et al. (2009) all provide robust reviews of empirical surveys of direct rebound, while Barker and Foxon (2008) briefly survey evaluations of direct rebound resulting from UK government-sponsored energy efficiency programs. All four surveys conclude that direct rebound effects for end-use consumer energy services typically erode 10-30% of projected energy savings, although these findings are limited to developed countries.

Two studies of direct rebound in developing economies find much larger direct rebounds (42-80%), indicating the potential for much greater rebound in nations where unmet demand for energy services is strong. More study of direct rebound in developing nations is warranted, given the importance of rising affluence and energy demand throughout the developing world on global energy use and emissions trajectories – according to the IEA, 93% of projected increases in energy demand through 2035 will be driven by non-OECD, developing nations (IEA, 2010).

As Schipper and Grubb (2000) observe:

> "[I]n low-income economies, energy and energy costs are often a constraint on economic activity. … In short, the shadow of Jevons lurks [in developing nations] for precisely the same reason that more efficient use of coal [in Jevons' Britain] did not save coal: the combined effects of different rebounds are very important when energy availability, energy efficiency, and energy costs are a significant constraint to activity and therefore energy use."

With the vast bulk of energy demand growth over the next half century projected to occur throughout the developing world, we may expect direct rebound effects alone to drive much greater rebound than found in studies of OECD nations, increasing the likelihood of backfire when these impacts are combined with other rebound mechanisms and considered at more appropriate (e.g., macroeconomic) scopes.

As a method of study, empirical surveys into direct rebound are constrained by the ability to collect concrete, real-world data and are inherently time-consuming, narrow in scope, and subject to all the methodological challenges typical of such surveys.[24] Thus, to date, this kind of study has yielded only

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[24] See the broader discussion in Sorrell et al. (2009).

limited insight into the operation of direct rebound in productive sectors of the economy or in the developing world (Greening, et al. 2000).

More to the point, in reducing the scope of inquiry to a scale suitable to this kind of empirical survey, this form of 'reductive inquiry' is fundamentally incapable of offering insight into the operation of rebound effects that are only emergent at macroeconomic scales (see Section 2.3), or even the more indirect microeconomic rebound mechanisms (discussed in Section 2.2 above). As Greening et al. (2000) acknowledge:

> "Because improvements in energy efficiency, with resulting increases in the supply of energy services, alter the mix of both final and input demands, increase consumers' real income, and expand firms' production possibilities, prices throughout the economy will undergo numerous, and complex adjustments. ...[O]nly a general equilibrium analysis can predict the ultimate results of these changes."[25]

As we shall see below, the scale of rebound emergent at this macroeconomic scope is clearly larger than studies of direct, microeconomic rebound effects alone can quantify.

3.1.2. DECOMPOSITION ANALYSIS OF NATIONAL, MACROECONOMIC TRENDS

Decomposing historical, macroeconomic trends in energy intensity, energy consumption, energy prices, and economic activity may yield insights into the real-world operation of rebound effects, potentially providing a method to test or validate theoretical inquiries into rebound.

Lee Schipper and Michael Grubb (2000) attempted such an analysis for historical trends in nearly a dozen developed nations (all OECD nations belonging to the IEA) for the period 1970 to 1995. The authors focus primarily on answering the question, is energy demand lower than 'what it would have been' absent the efficiency improvements? In this sense, Schipper and Grubb (2000) test whether or not backfire occurred, and they do so by constructing a counterfactual energy use scenario that holds energy intensity levels constant to 1970 levels while scaling activity levels to 1995 levels (and controlling for personal income or GDP changes). They then compare energy usage under this hypothetical 'what it would have been' counterfactual scenario to actual 1995 levels after observed improvements in energy intensity, which fell roughly 15-20% over the period examined, finding lower energy consumption. The authors argue that this analysis provides "indirect evidence" that rebound effects "may

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[25] The econometric analysis of Saunders (2010) may offer another route to gauging the complex impacts of efficiency improvements within producing sectors of the economy on the final demand for energy inputs after multiple substitution and output effects. See Section 3.1.3.

have taken back some of the overall savings, but most remain" – e.g., that economy-wide rebound over this period was significantly less than 100% (Schipper and Grubb, 2000).

While the authors conduct an extensive examination of observed energy use, intensity and activity trends across several OECD nations, this method of analysis suffers several methodological challenges. First, while this analysis does provide indirect evidence that actual rebound levels were likely less than 100%, accurately gauging the degree of actual rebound present would require comparing observed energy usage levels to another counterfactual scenario that accounts for a 'zero rebound' scenario. Constructing such a scenario would require estimating actual technical efficiency improvements achieved in observed sectors and calculating the net change in energy intensity had no rebound occurred – e.g. if all technical efficiency gains were taken as a reduction in energy inputs per unit of economic output or activity in that sector. Actual rebound would be the relative difference between observed energy usage trends (accounting for economic activity levels) and this zero rebound scenario on the low end and the full rebound scenario on the high end.[26] Without this comparison scenario, we cannot accurately gauge how much rebound was operative or whether or not it was significantly more than zero. All Schipper and Grubb (2000) can therefore conclude is that rebound appears to have been less than 100% – e.g. that backfire did not occur, at least within a scope of analysis restricted to the specific sectors examined.

Second, the methods employed by Schipper and Grubb (2000) do not appear capable of accurately estimating any rebound due to output effects. The authors construct their counterfactual scenario by holding energy intensity levels constant, yet continue the observed increase in economic activity levels. But if energy efficiency changes underlying the observed energy intensity trends are necessary conditions for at least some portion of observed increases in energy-using activities and economic output, as would be the case when rebound due to output effects is operative, the construction of a counter-factual scenario in this manner is inaccurate (Brookes, 2000; Sorrell, 2009). In fact, measuring energy savings from a baseline scenario in this manner is quite common in studies estimating energy savings potential from efficiency measures (e.g., McKinsey 2009a, b; IEA, 2009). Yet this practice rests on the assumption that energy and economic activity measures can be scaled and adjusted independently, an erroneous assumption given the operation of rebound effects which identify the causal mechanisms that render trends in energy use, energy intensity, and economic activity mutually interdependent variables.

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[26] This method is developed by Saunders (2010), discussed below.

Third, energy intensity may also decline due to energy prices increases, as was indeed the case during much of the period examined by Schipper and Grubb (2000).[27] Such price-induced efficiency measures are not the primary concern of the rebound debate, however, which focuses centrally on the effects of non-price-induced technical change that captures cost-effective 'low-hanging' efficiency opportunities (Saunders, 2000). Thus, the presence of significant price-induced energy-saving change in the period examined by Schipper and Grubb (2000) further complicates efforts to determine the scale of rebound.

Finally, Schipper and Grubb (2000) only examine observed changes within specific economic sectors in OECD nations. This scope of analysis therefore cannot capture broader, macroeconomic interactions between sectors or nations of the global economy, effects that nevertheless remain pertinent to climate mitigation concerns. And, as the authors themselves emphasize, this analysis is restricted to mature, developed economies, and "findings cannot be extended readily to developing countries," where rebound levels are likely to be far more substantive.

The decomposition analysis employed by Schipper and Grubb therefore appears to offer some indicative evidence that rebound was less than 100% during the period observed and within a scope of analysis limited to the specific sectors of developed nation economies examined. This method of analysis faces inherent challenges however, and may be incapable of capturing the full scale of rebound effects at work within the examined historical trends.

3.1.3. ECONOMETRIC ANALYSIS OF HISTORICAL SECTORAL TRENDS

Harry Saunders (2010)[28] offers another method of analyzing historic trends in energy efficiency and use to find evidence of rebound effects, which may overcome some of the limitations of the decomposition analysis method employed by Schipper and Grubb (2000). Saunders (2010) develops four-factor Translog unit cost functions[29] for thirty different producing sectors of the U.S. economy based on econometric measurements of historic data from the period 1960-2005. Critically, the author also econometrically measures technology gain parameters for each of the four inputs to production. This allows

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[27] Price-induced technical change and substitution away from energy use is common after price shocks, such as the 1973 Arab oil embargo, and they can yield a decrease in the energy/GDP ratio. Furthermore, such changes can persist long after the initial price shock and even in the face of falling prices, both because expectations about higher future prices may continue to affect investment decisions, and because the fixed-nature of many energy-saving investments makes these changes essentially irreversible, as Schipper and Grubb (2000) acknowledge.

[28] As noted previously, Saunders (2010) is still in review as this paper is written. However, the paper represents an important contribution to the study of rebound effects that utilizes a new method of analysis that appears to overcome some of the shortcomings of prior efforts to analyze historical trends for the presence of rebound. The paper is therefore included in this review despite its pre-publication status. The author can be contacted for a copy of the paper at hsaunders@decisionprocessesinc.com

[29] Four factors of production modeled are capital (K), labor (L), energy (E) and other materials inputs (M).

Saunders to create two comparison scenarios to explore rebound: a scenario in which measured energy efficiency gains (e.g., improvements in the technology gain parameter for energy inputs) are frozen in 1980, equivalent to a scenario in which 100% rebound is experienced; and a 'zero rebound' scenario where measured energy efficiency gains are fully realized as reductions in energy consumption (e.g., where an X% increase in energy efficiency as measured by the technology gain parameter for energy inputs leads to an X% decrease in energy consumption below where it would have been without the technology gain).[30] Saunders can then compare actual measured energy trends by sector with each of these two scenarios to determine the scale of rebound experienced by these sectors.

Saunders (2010) finds that long-run rebound effects due to both substitution and output effects total 60% on a weighted average basis across all thirty producing sectors examined, although rebound effects in individual sectors range from 14% in the non-electrical machinery sector to 120% for electric utilities (see Table 2.2. above). So while rebound rates are below 100% for most sectors and energy use is thus lower following efficiency improvements than it would have been otherwise (consistent with the conclusions of Schipper and Grubb, 2000), energy use levels are significantly higher than if there was no rebound (the comparison Schipper and Grubb were unable to make). Substitution effects largely dominate the total rebound effects for each sector. As is consistent with the observations of prior works (Schipper and Grubb, 2000; Laitner, 2000; Greening et al., 2000; Saunders, 2000b; Wei, 2007), output effects are relatively small, generally less than 5% in the long run across most sectors, although larger output effects of upwards of roughly 10-30% are observed in some energy-intensive sectors (e.g. chemicals, electric utilities, transportation, etc.; see Table 2.2).

Saunders' analysis does not examine rebounds in the end-use consumer sectors of the economy, and findings cannot be extended to these sectors. The analysis is also restricted to the U.S. economy, and findings may not be readily translated to other national economies. As with the general equilibrium analysis methods discussed below, the methods employed by Saunders (2010) are also limited by all the standard assumptions of microeconomics – i.e., perfect competition, rational, profit maximizing producers, etc. Furthermore, while capable of more precise analysis than decomposition of energy intensity trends (as in Schipper and Grubb, 2000), the methods developed by Saunders (2010) still have several limitations, which are rigorously illuminated by the author. In particular, the chosen production function may not be the best possible candidate for rebound analysis, although it may be the

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[30] In technical terms, Saunders (2010) calculates this zero-rebound scenario, where all efficiency gains "take" (e.g. are converted to reductions in energy consumption) on a one-for-one basis, by assuming Leontief production technology, wherein an efficiency improvement in any one factor of production leaves economic output, output cost, and other factor uses unaltered.

best practical candidate at this time.[31] Consumer utility calculations are also made using a simple Cobb-Douglas function, which allows for easy aggregation across sectors consistent with general equilibrium theory. However, the choice of functional form may skew results (see Saunders, 2008), and more sophisticated, realistic, and generalizable general equilibrium models for rebound are possible (Saunders notes the works of Turner, 2009 and Wei, 2007, 2010). More generally, the analysis also considers the U.S. sectors as part of a closed economy without imports or exports, so may miss broader macroeconomic effects of a global, interconnected economy. The author articulates several other technical limitations ,[32] which identify ways in which this new analysis method may be productively extended and improved in future work. Overall, the method of analysis developed in Saunders (2010) appears to offer a fruitful path for further examination of rebound effects.

3.1.4. GENERAL EQUILIBRIUM MODELING The field of computable general equilibrium (CGE) modeling extends neoclassical theory to simulate and explore how various impacts in one portion of the economy diffuse throughout the rest of the economy. These models can thus be used to explore macroeconomic rebound effects resulting from aggregate efficiency improvements and a number of CGE studies have simulated such impacts at the scope of national economies (see surveys in Sorrell, 2007 and Dimitropoulos, 2007). While these studies utilize a variety of production functions and assumptions (i.e. differing nesting structures within which inputs are combined, substitution elasticities between inputs, etc.) and the results vary too widely to provide universally generalizable conclusions, it is nevertheless notable that the large bulk of these studies predict very large rebound or backfire; all but one study projects economy-wide rebound greater than 30% and the majority project rebound greater than 50%, with several finding backfire (see Table 3.1 below; Sorrell, 2007; Dimitropoulos, 2007).

These CGE simulations indicate that the magnitude of rebound may depend on a wide range of variables. In addition to the elasticity of substitution between energy and other inputs identified as a key variable by Saunders (1992, 2000b, 2010), other factors appear significant in CGE simulations as well, including elasticity of supply for labor and capital, elasticities of demand for the products in each sector, the energy intensity of a given sector, income elasticity of consumption, the scope of substitution between consumer goods, and the use of government revenues (Sorrell, 2007). In particular,

[31] More specifically, while superior to rebound-inflexible CES production functions (see Saunders, 2008), the Translog function used in Saunders (2010) is not as general as other candidate functions. However, the potentially preferable Gallant (Fourier) production form is parameter- and data-intensive and at present may not be a practical choice for rebound analysis.

[32] See extensive discussion in "Cautions and Limitations," Saunders (2010).

Turner (2009) notes that backfire is the projected outcome of efficiency improvements introduced into energy producing and exporting sectors of the Scottish economy, but rebound is more modest in other productive sectors of the economy.

It should be noted that the large majority of these studies examine energy productivity improvements in the production sectors of the economy and thus yield little insight into the impact of end-use efficiency improvements in consumer sectors. Furthermore, most of these studies simulate ‘free’ energy productivity ‘shocks’ to the economy with no assumed investment cost required to capture efficiency gains. One study (Allan et al., 2006) considers the impacts of additional up-front costs of efficiency improvements and finds that the scale of rebound is correspondingly reduced (see also Allan et al., 2007).

TABLE 3.1: Survey of CGE Simulations of Economy-wide Rebound Effect

Study	Country/ Region	Projected Economy-wide Rebound	Notes
Semboja (1994)	Kenya	170-350%	Two scenarios: 1% improvement in economy-wide energy production efficiency and end-use energy efficiency.
Dufournaud et al. (1994)	Sudan	47-77%	Three scenarios, modeling 100%, 150% and 200% improvement in efficiency of wood-burning stoves
Van Es et al. (1998)	Holland	15%	Explicit representation of efficiency improvements fed by detailed, bottom-up supply side database of energy-saving technology opportunities.
Vikstrom (2004)	Sweden	50-60%	15% increase in efficiency in non-energy sectors and 12% increase in energy sectors of economy.
Washida (2004)	Japan	35-70% (53% in central scenario)	1% efficiency improvement in all energy use in production. Sensitivity analysis reveals positive correlation between rebound and value for elasticity of substitution with energy
Grepperud and Rasmussen (2004)	Norway	Small for oil use but >100% for electricity	Two sectors see doubling in efficiency of electricity use and two see doubling of efficiency in oil use modeled as doubling of energy productivity growth rate.
Glomsrod and Wei (2005)	China	>100%	Compares BAU case to an improvement in coal-sector productivity under scenario limiting emissions with tax on coal use.
Hanley et al. (2005)	Scotland	120%	5% improvement in efficiency of energy use across all production sectors. Model looks at open region with major energy exports, identifies sensitivity of export demand is key driver of backfire.
Allan et al. (2007)	United Kingdom	30-50% (37% central scenario)	5% improvement in efficiency of energy use across all production sectors. Performs extensive sensitivity analysis. Note contrast between this study and very similar study of Scottish economy Hanley et al. (2005, 2009), indicating further evidence of importance of rebound in energy exporting sectors.
Hanley et al. (2009)	Scotland	132% for electricity and 134% for other energy	5% improvement in efficiency of energy use across all production sectors; refinement of Hanley et al. (2005) with robust sensitivity analysis and greater decomposition of results. Backfire is only found in energy supply sectors (~245% rebound) with more modest rebound (~35-41%) in non-energy supply sectors.

SOURCE: *Dimitropoulos (2007), Sorrell (2007), and Turner et al. (2009).*

3.1.5. INTEGRATIVE MODELING INQUIRIES: NATIONAL ECONOMIES Since the mid-1990s, integrating 'bottoms-up' systems engineering/technical models of key economic sectors (particularly the energy sector) with 'top-down' macroeconomic models has allowed more detailed exploration of the energy-economic-environmental impacts of energy and climate policies. Such models offer a promising way to blend appropriate observations from reductive inquiries into technical factors or microeconomic behavior with sophisticated economic modeling capable of providing insight into macroeconomic rebounds (Sorrell, 2007; Barker and Foxon, 2008). In particular, these models also provide a sufficient degree of disaggregation to begin to link together the micro- and macro-scales and explore specific causal factors. As such, these 'integrative models' may offer the best route to bridging the gap between reductive and theoretical perspectives to provide greater understanding of emergent rebound effects at various scales.

This approach, however, trades greater realism for greater complexity, making it time consuming and challenging to construct and operate such integrative models, especially when examining global-scale economy-wide rebound. Furthermore, by blending reductive and theoretical perspectives, these integrative models inherit some of the limitations of each. They are thus constrained by both the availability of solid findings from reductive empirical inquiries (e.g., into direct rebounds, real-world elasticities of demand, etc.) and decisions about underlying theoretical frameworks (e.g. choice of production functions for key sectors of the economy). As such, there have been relatively few examples of integrative modeling techniques applied to explore the rebound effect to date, and even the most advanced models have shortcomings. Therefore these modeling efforts as yet offer an incomplete picture of economy-wide rebound.

Two early and less sophisticated integrative modeling efforts by Musters (1995) and ETSAP (1997) employ the 'MARKAL-MACRO' model, an integrated computer model developed by the IEA in the mid-1990s that links a 'bottom-up' engineering/technical model of the energy sector (MARKAL) with a macro-model of the overall economy (MACRO) (ETSAP, 1997). On behalf of the Netherlands Energy Research Foundation, Musters (1995) uses MARKAL-MACRO to explore rebound in the Dutch economy in the year 2020, following energy-saving technical changes triggered by a modeling constraint requiring a 50% reduction in CO2 emissions. The MARKAL-MACRO results indicate an economy-wide rebound of 32.8% under this particular scenario (Musters, 1995)

ETSAP (1997) describes the use of MARKAL-MACRO to examine the rebound effect in the Swedish and Dutch economies both with and without constraints on carbon emissions. While the magnitude of the rebound effect is not quantified by the study,[33] the authors report that rebound was found in both cases, with “noticeably greater” rebound when carbon emissions were restricted. However, the results of these early efforts at integrative modeling should be interpreted with caution, as they are restricted by several over-simplified assumptions (i.e. a single assumption for the elasticity of substitution of energy and other inputs across all sectors; no international trade; exogenous fuel price assumptions; etc.) and barely begin to take advantage of empirical observations to provide key model inputs. Furthermore, they appear incapable of modeling several operative rebound mechanisms, including market price effects, embodied energy effects, and re-spending/re-investment effects.[34]

The Cambridge Center for Climate Change Mitigation Research (4CMR) has developed a more advanced integrated model to explore energy policy impacts known as ‘MDM-E3.’ Developed on behalf of the UK government, the sophisticated model combines time-series econometric relationships and cross-sectional input-output modeling with a detailed energy sector model (Sorrell, 2007).

The works of Barker and Foxon (2006, 2008) and their colleagues (Barker et al. 2007a, b) apply this model to examine rebound effects (and other macroeconomic impacts) of several UK energy efficiency policies for the period 2000-2010 (surveyed in Sorrell, 2007). After determining the impacts of these policies, indirect and macroeconomic rebounds are calculated to be 11% on average. The authors also assume a 15% direct rebound effect (averaged across sectors), which they draw from estimates of direct rebounds based on evaluations of UK government efficiency policies and programs (Barker and Foxon, 2008). The combined, economy-wide rebound effect for the UK economy is thus estimated at 26% in 2010 for the suite of UK policies examined (see Barker and Foxon, 2008). The high degree of disaggregation in the MDM-E3 model allows a finer-grained examination of rebounds in specific sectors (summarized in Table 3.2 below).

The primary source of the indirect and macroeconomic rebound effects modeled by MDM-E3 was substitution between energy and other goods by households along with increases in output by industry. Given the larger share of energy in the output of energy-intensive sectors, rebound was greater for these producers. Increases in consumers’ real income and overall economic growth were found to contribute to relatively small rebound due to re-spending and economic growth effects. Real GDP

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[33] ETSAP (1997) is focused on introducing the MARKAL-MACRO model to potential users and briefly illustrating its potential applications. Unfortunately, it does not delve into sufficient detail on any given topic, including the model’s use as a means of exploring the rebound effect.

[34] Musters (1995), for example, identifies just two operative rebound mechanisms captured by their model: direct rebounds (increased demand and substitution at the micro-level induced by lower price of energy services) and a macroeconomic growth effect (increase in economic output driven by improved energy productivity). As market prices for energy carriers and products are set exogenous to the model, market price effects are impossible to discern, and the effects of several other rebound mechanisms are not identified.

increased 0.4% resulting in an 0.2% increase in final energy demand, compared to an 8% decrease in energy demand expected from the policies, for a rebound of 2.5% due to these mechanisms (Barker and Foxon, 2008).

TABLE 3.2:
Estimates of Direct and Indirect Rebound by Sector – the MDM-E3 Model

Sector	**Direct Rebound**	**Indirect/ Macroeconomic Rebound**	**Total Economy-wide Rebound**
Energy-intensive industries	0%*	25%	25%*
Other industry	0%*	16%	16%*
Road transport	25%	7%	32%
Commerce, etc.	0%*	7%	7%*
Households	23%	7%	30%
ECONOMY-WIDE TOTAL	15%	11%	26%

SOURCE: *Barker and Foxon (2008); direct rebound at p. 29; indirect rebound at p. 47.*

** Note that direct rebounds for industry and commerce are assumed to be zero due to lack of empirical study. Actual direct rebound is likely, and appears significant (as per Saunders, 2010), so total rebound for these sectors (and entire economy) is likely underestimated here. See discussion of limitations below.*

The MDM-E3 model is a promising approach to analyzing and disaggregating various rebound effects, likely representing the most sophisticated effort to date to examine rebound effects at a macroeconomic scale. That said, this approach still has several limitations that likely lead to an underestimate of the scale of total economy-wide rebound:

- Direct rebound effects are not modeled, but fixed exogenously based on observations of prior efficiency policies. This methodology could be another limitation of the MDM-E3 since the conditions that gave rise to direct rebounds in the past may not hold true for future policies, and the magnitudes of direct rebound effects are not responsive to changes in other relevant variables.

- Direct rebound due to substitution and indirect rebound due to re-investment effects for producers are not explicitly modeled.[35] The re-investment effect is likely to be a small effect (see discussion in

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[35] While Barker and Foxon (2009) claim to not include any direct rebound for producing sectors, they do model increased industrial output due to falling product prices (from lower energy input costs) at a macroeconomic scale, so the omission of direct rebounds for firms appears limited to the substitution effects (Sorrell, 2007). However, substitution effects appear to be the most significant contributor to direct rebounds in producing sectors (Saunders, 2010), so this omission is still notable.

Section 2.2 above), but substitution effects appear to be more significant, on the scale of 20-50% and higher in some cases (Saunders, 2010), as (newly cheaper) energy services substitute for other inputs within producing sectors (Sorrell, 2007). According to the authors, however, the majority of energy efficiency savings modeled for the producing sectors correspond to the UK Climate Change Agreements (CCAs), which obligate businesses to commit to reducing energy use per unit of economic output by 2010. Hence, these efficiency improvements, modeled exogenously, should already account for substitution effects, as the net impact of any substitution on a sector's energy demand must not exceed the CCA energy intensity commitments for that sector. Assuming the CCAs are effectively binding, this omission may therefore be appropriate in the case of the specific policy measures examined in Barker and Foxon (2009). However, future modeling of energy efficiency improvements in producing sectors that do not correspond to strict energy intensity targets should include endogenous modeling of substitution effects, which may substantially increase total economy-wide rebound.

- The study of the UK economy only examines relatively short-run rebound through 2010. Rebound effects are likely to change over time as investment decisions and behavioral adjustments accumulate and as macroeconomic rebound effects each play out (see Section 2.3; Turner, 2009; Wei, 2010).

- The modeling considers 'pure' energy efficiency improvements brought about by government policy with no associated improvements in the productivity of any other factors of production (Sorrell, 2007). As discussed previously, if energy efficiency technologies are associated with improvements in the productivity of other factors, total rebounds could be significantly greater (Saunders, 1992, 2005, 2010; Sorrell, 2007, 2009).

- Finally, the model is confined to the UK economy and national energy use. As such, calculated rebound effects exclude the increased energy consumption overseas associated with increased consumption of imports, air travel, and tourism that may be driven by macroeconomic responses to energy efficiency gains (Sorrell, 2007). As these three consumption categories account for roughly 40% of the increase in GDP projected by the model, this effect could be significant, but cannot be calculated without further research (Barker and Foxon, 2008). The model's UK-focused scope also discounts embodied energy effects by only taking into account the portion of embodied energy associated with efficiency investments from within the UK economy, ignoring the embodied energy associated with any imported content in efficiency investments.

For each of these reasons, the total rebound for below-cost efficiency opportunities in the UK are likely to be higher than projected by the MDM-E3 modeling runs, perhaps on the order of 30-40%, and even higher if efficiency measures simultaneously improve the productivity of other inputs to production (e.g., are not 'pure' energy efficiency improvements).

3.1.6. INTEGRATIVE MODELING INQUIRIES: THE GLOBAL ECONOMY Barker et al. (2009) extend their integrative modeling approach to study macroeconomic rebound effects at the scale of the global economy, producing one of the only modeling efforts to explore rebound at the scope most relevant to climate change and energy resource depletion concerns. In expanding their scope from the UK national economy to that of an interconnected global economy, Barker and colleagues find a correspondingly larger rebound effect, as would be expected given the emergent nature of rebound effects.

Barker et al. (2009) model the rebound effects resulting from the global, 'no-regrets' energy efficiency measures proposed in the IEA's World Energy Outlook 2006 and incorporated into the IPCC's Working Group Three volume of the Fourth Assessment Report (IPCC, 2007). The IEA and IPCC notably ignore macroeconomic rebound effects in assessing the potential of energy saving efficiency measures. For energy efficiency measures undertaken globally in the period 2013-2020, Barker et al. (2009) estimate that total economy-wide rebound erodes 31% of the projected energy savings potential by 2020, with rebound rising to 52% by 2030, averaged across the global economy (see Table 3.3 below).

TABLE 3.3:
Estimates of Worldwide Direct and Macroeconomic Rebound by Sector

Sector	Direct Rebound		Macroeconomic Rebound		Total Economy-wide Rebound	
Year	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
Energy-intensive industries	0%	0%	20.8%	43.7%	20.8%	43.7%
Transport	9.1%	9.1%	26.9%	43.1%	36.0%	52.2%
Residential/services buildings	20.0%	20.0%	24.3%	40.6%	44.3%	60.6%
Industry	5.0%	5.0%	18.3%	40.8%	22.3%	45.8%
Agriculture	5.0%	5.0%	11.8%	36.1%	16.8%	41.1%
Weighted average for all sectors	9.4%	9.7%	22.1%	41.6%	31.5%	51.3%

SOURCE: *Barker et al. (2009).*

Barker et al. (2009) are global in their scope and thus overcome the single-nation limitations of prior studies (e.g., Barker and Foxon 2007, 2008), and the analysis is perhaps the most rigorous modeling exploration to date of rebound effects at a global scope. Despite this, there are still several reasons to believe Barker et al. (2009) underestimate total economy-wide rebound.

First, the magnitudes of direct rebound effects are again exogenous to the model and fixed based on surveys of prior empirical studies. However, little data was available to the authors on direct rebound in productive sectors of the economy, and the values selected by Barker et al. (2009) for these sectors (e.g., 0% in energy supply sectors and 5% in industry and agriculture) are likely underestimates. Saunders (2010), for example, estimates direct rebounds (due to substitution and output effects) ranging from 15-120% across sectors (see Section 2.1), with the highest rebound (actually a case of backfire) estimated for the electric utilities sector, one of the 'energy supply industries' for which Barker et al. assume no direct rebound at all. Also notable is that the same values for direct rebound are assumed for both OECD and non-OECD nations, despite the fact that direct rebound effects are likely to be much more substantial in developing nations (see Section 2.1). Finally, the value selected for rebound in transportation sectors (9.1%) appears low when compared to surveys of direct rebound in automotive transportation (e.g., 10-30% reported in Sorrell et al. 2009). Indeed, Barker and Foxon (2008) assume a direct rebound in road transportation of 25% for the UK economy.

Additionally, Barker et al. (2009) model efficiency measures as 'pure' energy-saving technical changes that do not lead to multi-factor productivity improvements. If efficiency measures tend to achieve simultaneous, 'win-win-win' improvements in the productivity of several factors (e.g., labor, capital, and materials, as well as energy), total economy-wide rebound should be much larger than presented by Barker et al. (2009), as discussed in Section 3.3 below.

Integrative studies of economy-wide rebound are limited to date; therefore generalized conclusions should be viewed with caution. Still, it is notable that while economy-wide rebound is found to be on the scale of 25-40% for the developed nations examined by the MARKAL-MACRO and MDM-E3, the scale appears much larger, on the order of 50% (or greater if the limitations discussed above are overcome) at the scope of an interconnected, global economy. As both the scope and complexity of analysis undertaken by these integrative models has expanded, so too has the scale of economy-wide rebound, a trend that is again consistent with the emergent nature of rebound effects.

3.2. THEORETICAL PERSPECTIVES

As Brookes (2000) argued, “The claims of what might be called the Jevons school” – e.g., those who argue that economy-wide rebound commonly leads to backfire – “are susceptible only to suggestive empirical support,” since deriving the macroeconomic consequences and impacts of specific energy efficiency improvements at a microeconomic scale is inherently difficult (if not impossible) (Sorrell, 2009). Yet rebound effects emergent at precisely this macroeconomic (even global) scale are of the greatest concern to those seeking to address climate change and energy resource depletion challenges, while the multi-decadal timescales of these challenges further complicate empirical study (Saunders, 2000b; Madlener and Alcott, 2008). Thus, as with many other emergent properties, theoretical perspectives may still provide a key guide to the scale of rebound effects emergent at a global, macroeconomic scope, including the perspectives of both classical and neoclassical economists.

3.2.1. CLASSICAL ECONOMIC PERSPECTIVES

Classical economists including Jevons, Smith, Say, and Malthus, all noted that improvements in the efficiency of production inputs chiefly lead to greater output for a given level of input, not less use of the input overall (they were primarily concerned in their day with labor and capital, but also noted the impacts of resource and energy efficiency; see the extensive survey of these historical perspectives in Alcott 2008). Even today, this basic rebound argument is not limited to energy and, especially in the case of labor productivity, is widely accepted as the norm. That is, we do not expect increased labor productivity to lead to mass unemployment any more today than did 19th century classical economists (Alcott, 2008; Turner et al, 2009). Classical economic perspectives would therefore expect below-cost energy efficiency measures to contribute to greater production and economic output, but have little if any impact on energy conservation.

3.2.2. NEOCLASSICAL GROWTH THEORY

As Harry Saunders has illustrated, the well-established neoclassical framework for economic growth can be used to explore rebound effects in the context of contemporary economics, and much like prior classical perspectives, neoclassical economic theory predicts large rebound or backfire in energy demand following efficiency efforts.

Saunders (1992, 2000b) used neoclassical growth theory and common production functions to show that backfire is the projected outcome following ‘pure’ improvements in energy efficiency (e.g., a technical change that improved the productivity of energy inputs, but did not affect other inputs), thus driving greater energy consumption, not less.[36] When decomposed into constituent mechanisms, substitution and price effects are found to be the greatest drivers of rebound under this theoretical framework, with economic growth effects found to be a smaller contributor to rebound (Saunders, 2008). Further theorists, including Wei (2007, 2010), reach similar conclusions.

While Saunders (2000b) readily acknowledges that his findings are theoretical in nature and that his work does not prove that backfire should be the norm, his work does demonstrate that large rebound or backfire is fully consistent with contemporary neoclassical economic theory and would be predicted given certain admittedly-simplified, yet commonly-utilized assumptions about how the economy operates.[37] While the works of Saunders, Wei and other economic theorists operate with all the inherent abstractions and limitations of economic theory,[38] if neoclassical growth theory is accepted as a broad guide for economic decision-making, as it commonly is today, then these theoretical perspectives should at least prompt skepticism about the ability of energy-saving technical change to achieve major decreases in total energy consumption or related emissions.

3.3. COMPLICATING FACTORS AND BACKFIRE RISK – MULTI-FACTOR PRODUCTIVITY IMPROVEMENTS, ECOLOGICAL ECONOMICS, AND FRONTIER EFFECTS

The theoretical works of Saunders, Wei and others (see Section 3.2), as well as the CGE and integrative modeling efforts discussed above (See Section 3.1), typically examine 'pure' improvements in energy efficiency.[39] In reality, however, technologies that improve energy efficiency and productivity often have more complex and synergistic impacts on the productivity or supply of other factors of production as well, driving more complex and ultimately greater impacts on energy demand. In some cases, if energy efficiency improvements are substantial, they may also open opportunities for newly

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[36] Howarth (1997) challenged Saunders on this finding, arguing that Saunders (1992) failed to distinguish between the consumption of energy and energy ***services***, which Howarth claimed led to an overestimate of the rebound effect. Saunders (2000a), however, showed that neoclassical theory would still predict backfire from 'pure' efficiency gains when a production function was used to model the provision of energy services. Saunders (2008) extends his prior work and shows that the projected magnitude of rebound depends almost entirely on the choice of the underlying production function, demonstrating that analysts and theoreticians must take care when exploring the impacts of efficiency measures to select functions sufficiently sensitive to rebound. In particular, Saunders demonstrates that several production functions commonly used to derive demand equations are effectively useless in studying the rebound effect, as they produce results indifferent to the choice of several key parameters (Saunders, 2008). Saunders (2008) recommends the use of Gallant (Fourier) or Generalized Leontif/Symmetric Generalized Barnett cost functions as the most "rebound flexible" choice of production function for rebound analysis. Saunders also shows that both the commonly used CES (Solow) and Translog production functions are possible candidates, but are only sensitive to rebound in particular forms (CES) or under specific circumstances (Translog). Since the CES function is commonly used in energy-economic models and the Translog function is common in empirical studies, Saunders' results problematize the outcomes of these studies, as they are likely incapable of accurately simulating rebound effects (Sorrell, 2009).

[37] Typical assumptions include: ease of substitution; technology improvements come 'free'; there are constant returns to scale in production; markets are fully competitive; there is always full employment; etc.

[38] See the broader discussions in Sorrell (2007) and Dimitropoulos (2007)

[39] Saunders (2005) actually uses numerical simulations to explore rebound effects for simultaneous improvements in productivity for multiple inputs, demonstrating the potential for much larger rebounds in these cases, as would be expected.

profitable uses of energy—as yet unforeseen new energy-using applications products, enterprises, or even whole new industries emerge. These complicating factors are a prime example of the emergent nature of rebound effects. They are rarely captured in modeling and analysis of rebound effects and when operative, significantly increase the risk of backfire resulting from energy efficiency improvements. Several perspectives on these more complex impacts are discussed below.

3.3.1. MULTI-FACTOR PRODUCTIVITY IMPROVEMENTS AND BACKFIRE RISK – As discussed in Section 3.1, neoclassical growth theory predicts large rebound in energy demand to result from 'pure' improvements in energy productivity. This observation informs much of the CGE and integrative modeling efforts utilized to explore macroeconomic rebounds to date (see Section 3.2). However, neoclassical growth theory predicts that 'pure' improvements in the productivity of capital, labor, and other materials will drive a rebound in energy consumption as well. The clear implication is that a *simultaneous* improvement in the productivity of energy and one or more other inputs to production (e.g., a 'multi-factor productivity' improvement) would drive even larger rebound than any 'pure' improvement in energy productivity alone, increasing the likelihood of backfire in such cases (Saunders, 1992, 2005, 2010; Sorrell, 2009).

This is a key observation, as advocates of the cost effectiveness of energy-saving efficiency measures frequently cite the multiple benefits of efficiency measures. Lovins (2005), for example, writes:

"Improved energy efficiency, especially end-use efficiency, often delivers better services. Efficient houses are more comfortable; efficient lighting systems can look better and help you see better; efficiency motors can be more quiet, reliable, and controllable; efficient refrigerators can keep food fresher for longer; efficient cleanrooms can improve the yield, flexibility, throughput, and setup time of microchip fabrication plants; … retail sales pressure can rise 40% in well-daylit stores … Such side-benefits can be one or even two orders of magnitude more valuable than the energy directly saved. …[I]n efficient buildings, … labor productivity typically rises by about 6-16%. Since office workers in industrialized countries cost ~100x more than office energy, a 1% increase in labor productivity has the same bottom-line effect as eliminating the energy bill – and the actual gain in labor productivity is ~6-16x bigger than that."

While the multi-factor productivity improvements Lovins describes greatly improve the economic case for energy efficiency upgrades, they simultaneously raise the specter of significantly greater rebound in energy demand than if the improvement in energy productivity were considered alone (as is common in the inquiries discussed in prior sections). If the economic impact of labor productivity improvements from efficient buildings is several orders of magnitude greater than the simultaneous savings in energy consumption, for example, then the rebound due to economic growth/output effects alone should also be several orders of magnitude greater than would be predicted if the energy savings were considered alone.

An illustrative case is provided by Saunders (2010), who uses econometrically derived estimates of technical improvements in multiple factors of production (e.g. capital, labor, materials, and energy) to calculate impacts on energy consumption and total rebound effects across thirty producing sectors of the U.S. economy for the period 1960-2000. According to this method, historic improvements across all factors of production drove a long-term rebound in energy consumption of 172% during this period (weighted average for all sectors) – in other words, leading to significant backfire, from an energy use perspective. While these historic improvements in multiple factors of production occurred concurrently in the examined sectors, these gains may not have been associated specifically with energy efficient technology improvements and are not direct evidence of rebound due to energy efficiency measures (e.g. improvements in the productivity of labor may have occurred concurrently but independently from improvements in energy productivity within a given sector). However, the significant backfire estimated by Saunders (2010) clearly indicates that large-scale rebound or even backfire can easily result when energy efficiency efforts do increase the productivity of other factors of production.[40]

3.3.2. ECOLOGICAL ECONOMICS PERSPECTIVES As noted in the discussion of economic growth effects (Section 2.3) above, a school of ecological economists challenge the conventional neoclassical school's assumption that energy inputs play a relatively limited role in economic growth (see Kaufmann, 1992, 1994, 2004; Cleveland et al, 1984, 2000; Ayres, 1998; Ayres and Warr, 2005, 2006).[41] These authors argue that the increasing availability of 'high-quality,' more productive energy inputs, particularly electricity, has been a primary driver of economic growth in the past two centuries and note that these inputs may have more complicated, synergistic impacts on the productivity of other factors of production than is typically accounted for in conventional economic theory. While these economists do not study rebound directly, Steve Sorrell (2007, 2009) notes that the implications of ecological economics are notable for those concerned about rebound effects.

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[40] Saunders (2010) also clearly demonstrates the potential for progressive improvements in the productivity of any factor of production to drive increases in the demand for energy and energy-using services. Increases in energy demand following improvements in labor productivity or capital productivity, for example, are thus commonplace and significant drivers of energy demand over time, with notable implications for climate mitigation efforts and energy demand forecasting.

[41] These works are briefly surveyed in Sorrell (2007, 2009) and reviewed in considerable detail in Sorrell and Dimitropoulos (2007).

Cutler Cleveland and his colleagues (Cleveland et al, 1984), Robert Kaufmann (1992, 1994, 2004), and others argue that most attempts at causal analysis of energy inputs and economic growth use simple physical or heat measures of energy inputs (i.e., tons of oil-equivalent, BTUs, etc.), ignoring the increasing availability of 'high quality' energy inputs capable of delivering greater levels of useful work (e.g., the successive shift from wood and biomass to coal to oil to natural gas and the increasing use of electricity). For example, after factoring in structural shifts in the economy[42] as well as improvements in the quality of energy inputs,[43] Kaufmann (1992) is able to account for all of the observed improvements in 'energy intensity' (e.g., the ratio of primary energy inputs measured in terms of heat content to real GDP) in France, Germany, Japan, and the UK for the period 1950-1990 *without* including any assumed energy-saving technical change – e.g., technical improvements in energy efficiency. Kaufmann (2004) conducts a similar but more complex causal analysis and finds consistent results for the United States.

The primary implication of this analysis for Kaufmann and his fellow ecological economists is that there are likely to be fundamental limits to the ability of economic growth to be decoupled from the consumption of energy inputs (e.g., through substitution of capital and labor for energy in the form of energy-saving technical change), as trends driving structural shifts in the economy and the increasing availability of higher-quality fuels cannot be assumed to continue *ad infinitum*. Furthermore, while they do not specifically examine the rebound effect, these studies would also imply that rising energy productivity – whether through the provision of more versatile and productive energy sources, like electricity or oil, *or* the more efficient and productive use of such fuels – is a much more important driver of economic growth than assumed by neoclassical or endogenous growth theory. If this is true, improvements in energy efficiency and resulting productivity gains are likely to drive much greater rebound (through an enhanced economic growth effect) than would be expected in conventional economic theory (Sorrell, 2009).

It should be noted that the implications of ecological economics are consistent with the works of Sam Schurr (1982, 1983, 1984, 1985) who studies and decomposes trends in U.S. energy consumption, energy productivity, and total factor productivity throughout the 20th century to highlight the importance of increasing energy quality to productivity growth. Schurr found that the technological improvements driving output growth actually depended critically on the increasing availability of higher quality energy sources (oil and electricity), which helped enable changes in industrial process-

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[42] Notable structural economic shifts examined by Kaufman include: a decrease in the share of household income spent on direct fuels as incomes rise and consumption of goods and services increases; and changes in the portion of economic output derived for energy-intensive manufacturing sectors.

[43] Measured as an increase in the share of total energy from oil and primary electricity.

es and organization (notably electrification and the widespread use of electric motors) and new consumer products (e.g. electric appliances, automobiles) that drove much greater output growth (Schurr, 1982; discussed in Sorrell, 2009). If the trends and dynamics identified by Schurr prove to be widespread across other sectors and periods of time (an empirical question), improvements in the efficiency at which high quality fuels (including electricity) are converted to energy services should have a similar synergistic and multiplicative effect on the productivity of other factors of production (capital and labor) driving much greater economic growth than pure improvements in energy productivity alone would imply. Under these conditions, rebound due to the economic growth effect is likely to be large, perhaps large enough to generate backfire (Sorrell, 2009).[44]

Likewise, ecological economists (notably Ayres, 1998; Ayres and Warr, 2005, 2006) have developed several alternatives to conventional (neoclassical and endogenous) economic growth models that do not assume the productivity of each input is proportionate to the share of each input in the value of economic output (as is typically assumed in conventional economic theory). Instead, these models derive the productivity of each input directly from a production function to accurately reproduce historical trends in economic growth without relying on the time-driven technical change variables that are commonly assumed to be major drivers of output growth neoclassical models. Under these models, the marginal productivity of energy inputs is found to be roughly ten times greater than would be derived from the cost share of energy in economic outputs (Sorrell, 2009). Again, even though these studies do not examine the rebound effect directly, the implication of these results is that improvements in energy productivity (e.g., efficiency improvements) could have as much as an order of magnitude (10x) greater impact on economic growth, and thus rebounds in economy-wide energy consumption, than assumed under conventional theory.

3.3.3. FRONTIER EFFECTS, GENERAL-PURPOSE TECHNOLOGIES, AND BACKFIRE

Many of the most clear-cut cases of backfire involve improvements in energy-using technologies that have opened up entirely new and unforeseen opportunities for the profitable application of the technology, enabling large new markets or enabling widespread new energy-using applications, products, or even entire new industries to emerge. Historical examples of this dynamic include the widespread new applications of Watt's improved steam engine, which was at the heart of Jevons' original 19th century treatise on rebound and backfire, as well as the many new applications of modern electric motors that feature prominently in the work of Sam Schurr (which in turn informed the observations of Leonard Brookes). In these cases, the 'production-possibility frontier' for an energy-using technology

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[44] Note that this is precisely the observation – e.g., that energy plays a large role in economic growth – that underlies much of Brookes arguments for the likelihood of backfire (see Brookes' discussion in Sorrell [2009] p. 1466).

expands significantly, opening up unforeseen opportunities for substitution and potentially significant impacts on economic activity and the composition of the economy. Whether this should be considered a distinct rebound effect – perhaps dubbed a 'frontier effect' – or simply an extreme case of severe rebound due to the combined impact of multiple other rebound mechanisms (i.e., the combined macroeconomic impact of direct output and substitution effects, economic growth effects, etc.) is unclear. What is clear is that in such cases, backfire is the most likely outcome.

In another striking example, Tsao et al. (2010) have shown that since the 1700s, new applications of increasingly efficient lighting technologies have consistently offset the energy efficiency gains from new lighting technologies almost exactly, leaving the portion of global GDP devoted to lighting essentially unchanged over hundreds of years despite significant improvements in 'luminous efficacy' (e.g., energy use per unit of light provided) over several successive generations of lighting technologies. New lighting applications have continually arisen that offset energy consumption reductions due to lighting efficiency gains for more than 300 years and across three continents. Tsao et al. (2010) analyze these empirical lighting trends using a simplified energy-economics framework and, extrapolating into the future, predict similar backfire if luminous efficiency gains due to the widespread adoption of solid-state lighting (e.g., light-emitting diodes or LEDs) are realized. The authors note that the future clearly may not continue historical trends – e.g., societal demands for lighting may change or materials and production constraints may limit the uptake of new lighting technologies despite demand. But unless a clear argument is made as to why future lighting trends are likely to differ from three centuries of historical trends, the wise bet is that continued improvements in lighting efficiency will continue to generate unforeseen new ways of consuming and utilizing lighting services, corresponding improvements in human productivity and welfare, and continued backfire in energy demand.

Sorrell (2007, 2009) observes that backfire due to this 'frontier effect' dynamic is most likely to arise for 'general-purpose technologies' which have "a wide scope for improvement and elaboration, have potential for use in a wide variety of products and processes, and have strong complementarities with existing or potential new technologies." Besides steam engines, electric motors, and lighting, other examples of 'general-purpose technologies' could include gas turbines, semiconductors and computing technologies, lasers, robotics, radio transmitters, and perhaps many others.[45] As Sorrell (2009) observes, backfire is most likely to result after energy efficiency improvements in these general-purpose technologies, "particularly when these are used by producers and when the energy-efficiency

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[45] Huber and Mills (2005) survey many of these technologies, their many applications, and their propensity to trigger backfire as efficiencies are steadily improved and new applications for each technology unfold.

improvements occur at an early stage of development and diffusion of the technology. The opportunities offered by these technologies have such long-term and significant effects on innovation, productivity, and economic growth that economy-wide energy consumption is increased."

These emergent 'frontier effect' dynamics may prove particularly challenging for energy analysts to forecast or account for in modeling efforts, as they necessarily involve unforeseen and unpredictable applications of new and improved technologies. Econometrically derived estimates of substitution and output effects may be possible for energy-using technologies with long historical records of continually expanding production-possibility frontiers (as in Tsao et al., 2010's treatment of lighting), but for other emerging technologies, it may be all but impossible to model the operation of these frontier effects. 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? Energy analysts should therefore exercise caution in estimating likely rebound effects for technologies with the 'general-purpose' characteristics described by Sorrell (2009), as total rebound effects may ultimately prove much larger than historically-derived elasticities and other econometric estimates may indicate.

4. CONCLUSIONS

This paper surveys a variety of mechanisms that, following a below-cost improvement in energy efficiency, drive a rebound in energy consumption at both micro- and macroeconomic scales (Section 2). As this survey indicates, these rebound mechanisms are real and are not insignificant. Moreover, they combine to drive a total economy-wide rebound effect that undermines the ability of below-cost energy efficiency measures to reduce total energy consumption or related greenhouse gas emissions.

While evidence of the scale of economy-wide rebound is not conclusive, several methods of inquiry offer key insights into the likely impact of rebound effects (Section 3). Inquiries focused on micro-scale behavioral responses to efficiency improvements have yielded robust estimates of direct rebound effects in specific contexts, primarily end-use efficiency savings in developed economies (Section 3.1.1). These inquiries find that in such contexts, the direct rebound effect alone can erode 10-30% of projected technical energy savings before any other indirect and macroeconomic rebound mechanisms are accounted for. Direct rebound effects are likely to be greater in developing economies and also appear to be more significant in the productive sectors of the economy (e.g., industry and commerce), where direct rebounds may range from 20-60% or higher, particularly for energy-intensive sectors where energy services are easily substituted for other factors of production (Section 3.1.3).

The full scale of the emergent rebound effect is only visible at greater scope and complexity, and both computable general equilibrium (CGE) and integrative modeling approaches have been used to explore rebound at these macroeconomic scales. A number of CGE modeling studies are surveyed above (Section 3.1.4), which typically find macroeconomic rebounds across a relatively wide range of national economies to be on the order of 30-50% or greater, with a surprising number projecting backfire (rebound greater than 100%). While these CGE studies depict relatively simplified models of national economies and face numerous limitations, they do identify a number of factors that are likely to influence the scale of economy-wide rebound effects and are indicative of the much greater magnitude of rebound at this macroeconomic scope. Integrative modeling techniques offer a somewhat more complex portrayal of the economy, particularly of key sectors such as energy production. Although only a few such studies have examined rebound effects to date and generalized conclusions should thus be viewed with caution, these integrative modeling studies of national economies have found economy-wide rebound to be roughly 25-40% for the developed nations studied (Section 3.1.5).

At the global scope most relevant to climate change and energy resource depletion concerns, the integrative modeling efforts of Barker, Foxon, and colleagues in the UK have yielded perhaps the most robust picture of global economy-wide rebound to date. This analysis projects that global efforts to capture ‘no-regrets,’ below-cost energy savings opportunities will trigger rebound effects that collectively erode more than half (52%) of projected energy savings potential by 2030 (see Section 3.1.5). The implications of these conclusions are hugely significant for energy and climate policymaking, and it is remarkable that rebound mechanisms remain almost entirely ignored in projections of energy efficiency’s ability to drive lasting reductions in energy use or greenhouse gas emissions. Yet even these sophisticated integrative modeling efforts are inherently restricted by the availability of empirical data and the challenge of developing detailed models capable of approximating the complexity of interconnected national or global economies. Even these robust modeling efforts are therefore likely to have underestimated the potential for economy-wide rebound, given that they are currently restricted by exogenous assumptions about the scale of direct rebound and other key factors and are limited to modeling ‘pure’ energy productivity improvements without considering the potential for multi-factor productivity improvements from energy-saving technologies to trigger even greater rebound or even backfire.

In the end, rebound effects are ‘emergent phenomena’ resulting from the complex interaction of multifold economic actors and mechanisms. Reductive inquiries into individual rebound effects in particular contexts (e.g., direct rebound for end-use energy services in OECD nations) are thus incapable of telling us much about the full operation of rebound effects that are only emergent at macroeconomic scales. Additionally, it is easy for even the best CGE and integrative modeling efforts to exclude particular rebound mechanisms for lack of available data or due to an inability to accurately model these complex effects. The results of these inquiries should thus be viewed with an asterisk next to any quantification of the rebound effect; total, economy-wide rebound at a global scale will likely be somewhat larger than even the most sophisticated global integrated models are able to project.

The general trend, however, is that as analysis expands in both scope and complexity over time, larger rebound effects are discovered, and the gap between the scale of rebound quantified by empirical study and detailed modeling analysis and the large-scale rebound or backfire predicted by economic theory narrows. Overall, as the scope of analysis has moved from microeconomic analysis of direct rebounds to macroeconomic modeling of national economies and again onto the global scope critical to climate objectives, more of the emergent rebound effect comes into view.

Likewise, as more complex views of the impacts of below-cost energy efficiency improvements are developed, the scale of likely rebound effects appears larger still. In particular, very large rebound or backfire is likely the norm in cases of 'win-win' efficiency opportunities, where energy-saving technical changes simultaneously improve the productivity of other factors of production (Section 3.3.1). Similarly, if improvements in the supply or productivity of high-quality energy inputs have synergistic and multiplicative impacts on the productivity of other factors of production, as ecological economists argue, efficiency measures should be expected to be major drivers of economic growth and related rebound or backfire in energy use (Section 3.3.2). Finally, backfire risk is significantly increased for technologies, such as lighting, engines, motors, computing, and other 'general-use technologies' for which efficiency improvements may unlock unforeseen new energy-using applications, products, or even whole new industries – a dynamic potentially deserving of designation as a distinct rebound effect that could be called a 'frontier effect' (Section 3.3.3). In each of these cases of more complex, emergent rebound effects, energy efficiency measures may prove quite valuable in driving greater economic welfare, but would have limited direct impacts on climate and energy security objectives.

Finally, while the work of theorists ultimately relies on contested economic frameworks and may never prove conclusive, theoretical inquiries into rebound effects consistently indicate that when energy efficiency measures are aggregated over the global scale and multi-decadal timeframes that matter most to climate and energy security objectives, total economy-wide rebound is likely to be quite large, even leading to backfire in certain circumstances (Section 3.2).

5. DISCUSSION AND IMPLICATIONS

We are then left with the following question: do rebound effects collectively erode *much* or *all* of the technical energy savings potential of energy efficiency measures? The implications of this remaining question should be unsettling to energy and climate policymakers, to say the least, and the continued ignorance of rebound effects in contemporary policymaking may prove dangerous. While truly cost-effective energy efficiency measures should be pursued as no-regrets policies with benefits for economic welfare, if rebound effects are not rigorously considered in energy and climate analysis and policymaking, climate mitigation efforts are likely to over-rely on efficiency measures, while underestimating the need for new, affordable low-carbon energy supplies. The result could be climate mitigation efforts that routinely fall short of emissions reduction objectives.

While the insight into rebound effects first proffered by Jevons is widely considered a paradoxical notion, this survey indicates that we have reason to be skeptical of the ability of below-cost energy efficiency to drive real and lasting reductions in total energy consumption and thus, the ability of efficiency measures to significantly contribute to climate and energy security objectives directly. Relying on a linear, direct, and one to one relationship between below-cost energy efficiency improvements and carbon emission reductions, as is almost universally the case in contemporary policymaking, is very likely to lead nations and the world on a dangerous path. Efforts to reliably reduce greenhouse gas emissions or dependence on depleting fossil fuels would be prudent to avoid the risk of overreliance on energy efficiency measures. Such efforts should therefore focus primarily on shifting the means of energy *production* (rather than end use), relying on zero-carbon and renewable energy sources to diversify and decarbonize the global energy supply system..

What then, might be said about the appropriate role for energy efficiency in global and national efforts to address climate change or slow the depletion of fossil fuel supplies? The first important observation of note is that below-cost efficiency improvements are not the only path to greater energy efficiency. There is no shortage of opportunities to improve energy efficiency that are not cost-neutral or below-cost. While these measures come with a price tag, in many cases the costs are reasonable and such efforts may be well justified given the long-term threat, economic and otherwise, that global climate change represents.

Moreover, price-induced efficiency improvements, whether in response to exogenous energy price increases or successful policy efforts to price carbon emissions, should not be expected to result in significant rebound.[46] However, to fully avoid rebound effects, energy price increases must be

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[46] In such a way, energy efficiency improvements could potentially be used to 'accommodate' the adoption of higher-priced low-carbon energy supply technologies, while keeping the implicit price of energy services fairly constant.

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.[47] 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[48] – 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).

The second important observation is that there are very good economic reasons to accelerate the adoption of below-cost energy efficiency improvements even though such measures may be unlikely to result in a significant reduction of long-term global energy demand or associated carbon emissions. While rebound or backfire may indicate that the pursuit of below-cost energy efficiency improvements does not make for particularly efficacious climate policy, the corollary to this conclusion is that such efforts probably make for very good economic policy. Accelerating the adoption of below-cost efficiency improvements is likely to result in greater economic productivity and growth.

Indeed, by some accounts, rising energy productivity has been the primary driver of economic growth over the last two centuries (see Section 3.3.2), which brings us to a third important observation: future rates of energy intensity decline, driven in no small part by technical efficiency improvements, may be quite determinative of future rates of economic growth. In this manner, future energy intensity trends may be less directly determinative of the rate at which future energy demand expands than of the rate at which the global economy grows given the cost and availability of energy resources. A wealthier world, using energy more efficiently and productively, is a world with greater

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[47] For example, if below-cost efficiency measures reduce energy intensity by 30%, fully eliminating rebound effects and securing a lasting 30% decline in net energy consumption would require the imposition of policy measures – e.g. energy taxes or carbon pricing policies – sufficient to increase functional energy costs by 30%.

[48] It must be noted, however, that applying economy-wide pricing mechanisms, such as carbon pricing, will be a blunt tool to counteract the impact of efficiency improvements that will likely vary quite significantly from sector to sector. That is, technical efficiency opportunities may be far larger in one sector than another, leading to varying degrees of efficiency gains; yet economy-wide pricing signals will affect each sector equally, making it difficult to precisely counteract rebound effects utilizing such tools.

resources to devote to both decarbonizing its energy supply and adapting to those impacts of climate change that cannot be avoided. This point, in and of itself, is a strong argument for accelerating efficiency gains even if those measures do not linearly result in a direct decrease in energy demand or carbon emissions.

Fourth, there is the larger process of energy modernization and the ways in which economic growth, energy intensity, and the carbon intensity of energy supply are highly correlated and interconnected. Rising energy productivity has arguably been a critical driver of both long-term economic growth and decarbonization of energy supply. Higher rates of economic growth typically lead to higher rates of energy intensity decline, as growth drives a more rapid increase in energy demand and accelerates the turnover of existing capital stock, both of which typically accelerate the adoption of newer energy technologies that are more efficient and often less carbon intensive.

In a similar fashion, energy modernization drives both a diversification of energy supplies and a proliferation of the ways in which energy is used. Both of these phenomena drive the decarbonization of economies, as different fuels and processes are used to provide energy in highly specialized form for highly specified uses (e.g., gasoline for transportation, electricity for manufacturing processes, natural gas for heating). Such differentiation and specialization of energy carriers results in declines in both economy-wide energy intensity and carbon intensity, as more expensive, lower carbon fuels and processes find specified uses for which they are economically optimized. While this process of transition from an economy fueled by biomass and then coal and then more modern and specialized fuels including petroleum, natural gas, and various sources of electricity (e.g., hydro, nuclear, and renewable power) has progressed significantly in much of the world's developed economies, this broader process of energy modernization will continue for much of the coming century in the world's developing economies – the parts of the world where both large rebounds are most likely and where greater economic wealth can more rapidly enable energy modernization and decarbonization.

Finally, there is the well-established relationship between societal affluence and investment in non-economic amenities, specifically ecological amenities (a concept pioneered by Kuznets). Wealthier societies are more capable and willing to pay higher costs for cleaner energy supplies, and rising demand in modernizing societies for ecological amenities, specifically cleaner air, has been a major driver of the decarbonization of energy supply over the last century or more.

For all of the reasons elaborated above, below-cost energy efficiency improvements can contribute to both the decarbonization of energy supply and, more generally, efforts to mitigate climate change.

However the mechanisms through which this is accomplished are, in every case, indirect. Such mechanisms may be unsatisfying to many analysts and policymakers as they do not promise the kind of direct, immediate, inexpensive, and certain reductions in carbon emissions that some have long assumed might be achieved through the pursuit of below-cost efficiency opportunities. Nonetheless, a more realistic and nuanced understanding of the complicated and non-linear relationships between energy intensity and productivity, economic growth, and decarbonization will, in the long run, serve policymakers best.

In summary, below-cost improvements in energy efficiency are likely to trigger significant rebound in energy demand. While pursuing below-cost efficiency opportunities will result in wealthier economies that use energy more productively, such efforts are unlikely to result in economies that use significantly less energy. However, fast growing economies that use energy ever more productively are capable of more rapidly decarbonizing the energy supply system, as they have greater resources to invest in advanced energy technology that is both highly efficient and less carbon intensive. Such economies also value ecological amenities highly and are more willing and able to spend more money for cleaner energy. Ultimately, the primary implication of this survey is that there is no substitute for the difficult work of decarbonizing the global energy supply. Below-cost efficiency measures, while contributing indirectly to this effort, do not themselves offer a shortcut toward that objective, nor do they appear to offer a quick and easy means to reduce carbon emissions in the interim.

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About the Breakthrough Institute

The Breakthrough Institute is a leading, independent think tank developing climate and energy policy solutions for America and the world. Since 2003, Breakthrough has been a pioneering advocate of an innovation-centered approach to national and global energy and climate challenges, calling for major federal investments to make clean and low-carbon energy technologies cheap and abundant, strengthen America's economic competitiveness and energy security, and slow global warming.
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ENERGY EMERGENCE

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