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A general equilibrium view of global rebound effects

Taoyuan Wei

Center for International Climate and Environmental Research - Oslo (CICERO), University of Oslo, P.O. Box 1129 Blindern, 0318 Oslo, Norway

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ABSTRACT

How do energy efficiency gains affect energy consumption? The effects are generally called "rebound effects" in the literature. Previous studies have extensively focused on only part of the global economy to study rebound effects, e.g. energy consumption by households, one industry, or one country. However, since the global economy is highly connected among countries, these studies may lead to misleading conclusions if the rebound effects in the rest of the economy are significant. Recently Saunders (2008) analyzes the demand side by taking the global economy as a whole. Wei (2007) also provides a general analysis by using Cobb–Douglas production functions for the global economy. The present article expands Wei (2007) general analysis to explore the rebound effects from an economist's viewpoint by taking the global economy as a whole and applying general forms of production functions. The analysis provides new insights related to rebound effects: we highlight the role of energy supply as a determinant of rebound. We show that the substitution between energy resources and other productive resources is more relevant to long term rebound. We predict that long term rebound may be lower than short term rebound. And we also discover that super-conservation can happen in both the short term and the long term.

1. Introduction

How do energy efficiency gains affect energy consumption? As put forward very early by Jevons (1865), energy efficiency gains may not reduce energy consumption, but on the contrary, increase energy consumption. The effects are generally called "rebound effects" in the literature. Previous studies have extensively focused on only part of the global economy to study rebound effects, e.g. energy consumption by households, industries, or one country. However, since the global economy is highly connected among countries, these studies (e.g. Jalas, 2002; Gardner and Joutz, 1996; Glosmsrod and Wei, 2005; Allan et al., 2007) may lead to misleading conclusions if the rebound effects are significant in the rest of the global economy, particularly in the long term.

To provide insights of the rebound effects from a global perspective, this article develops a theoretical framework where the global economy is thought of as one entity. In the framework, we do not specify the forms of production and other functions, which allow us to explore any possible values of the rebound effects. In addition, energy input to the global economy is defined as energy resources in the nature. Typical examples are unextracted or underground fossil fuels. By doing so, we simplify the analysis and highlight the key role of energy resources. This is different from previous theoretical studies (e.g. Saunders, 2008; Wei, 2007), where energy can come from a production process, e.g. extracted fossil fuels.

The main insights offered in this article are as follows:

- The supply side of the energy market is of equivalent importance to the demand side in quantitatively determining rebound. Most previous studies do not pay sufficient attention to the supply side.
- The substitution between energy and other factors is more relevant to long term rebound, but less relevant for short term rebound since other inputs are not easy to adjust.
- The theory claims super-conservation (i.e. the case that energy use is decreasing at a greater rate than an energy efficiency gain) can happen in both the short term and the long term. In the short term, super-conservation requires introducing externalities, while in the long term, it can happen without externalities, at least from the theoretical perspective.
- The theory does not automatically predict higher long-run rebound than short-run rebound. This result can be used to explain the empirical findings by Allan et al. (2007) and Turner (2009).

The present article is organized as follows. The next section explains the basic concepts of rebound effects used in this article. This is

E-mail address: taoyuan.wei@cicero.uio.no.

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followed by Section 3, which motivates the article. Section 4 introduces a general equilibrium model for the global economy. Section 5 contains the insights from the analysis deriving from the general model. Section 6 provides cautions and limitations related to the analysis. The last section concludes the article. Five appendices give a detailed description of the model and the in-depth analysis of short term and long term rebound effects.

2. Concept of rebound effects

We define the "rebound" as developed in Saunders (2000b, 2005, 2008). Assume global welfare can be represented by a numerical index Y, which can be aggregate output of global production if global welfare is proportional to output. Global welfare is a complicated function of existing resources: labor, energy resources (energy), and capital (including natural resources other than energy). Notice that energy here refers to natural resources of energy, e.g. unextracted natural stocks of fossil fuels, wind and sunlight. Since the price of wind or sunlight can be zero in the market due to free access, they can be ignored in the analysis. To simplify the notation, this article always assumes constant labor input to the global economy. We assume that energy and capital inputs to produce global welfare can be represented by aggregates E^d and K^d respectively. The superscript d indicates that these variables are quantities demanded by the production process. Hence, the global welfare function, including all the economic activities in the economy, is assumed to be of the following form and is assumed to be twice continuously differentiable

$$Y = f(K^d, \tau E^d), \tag{1}$$

where labor is ignored in the function since it is assumed to be constant and τ is an energy efficiency parameter. If energy efficiency τ increases by 1%, we can produce the same global welfare level by reducing energy input by 1% *ceteris paribus*.

Let η denote the elasticity of energy use w.r.t. energy efficiency gains, which measures the percentage change of energy use if energy efficiency gains change by 1%. In the global economy, we have

$$\eta = \frac{dE}{E}\frac{\tau}{d\tau},$$

where E is market equilibrium quantity of energy, which coincides with energy use E^d at the equilibrium. *Rebound* coefficient R is defined by

$$R = 1 + \eta. \tag{2}$$

The definition comes from the meaning of zero rebound. If energy use is reduced at exactly the same rate as the energy efficiency gains, this is called zero rebound, i.e. $R=0$, which corresponds to $\eta=-1$. By this definition, five rebound conditions can be stated as:

$R>1$ or $\eta>0$ backfire
$R=1$ or $\eta=0$ full rebound
$0<R<1$ or $-1<\eta<0$ partial rebound
$R=0$ or $\eta=-1$ zero rebound
$R<0$ or $\eta<-1$ super-conservation.

Backfire means energy use is in fact increasing given improved energy efficiency. In this case, energy efficiency gains induce more energy use than before. *Full rebound* means no change of energy use even though there is technical progress. *Partial rebound* represents the case where energy use is decreasing but does not decrease at the same rate as the improvement in the technology. *Super-conservation* then implies that energy use is decreasing at a greater rate than the technology gain.

3. Motivation

The modern macroeconomic theory on rebound effects can be traced back to Jevons (1865). Jevons (1865) observed that England's consumption of coal increased considerably after James Watt introduced his improvements to the steam engine. Jevons argued for backfire, i.e. increased efficiency would tend to increase the coal use.

Modern theory has proved that backfire is not the only possible outcome. In the modern theory, the so-called Khazzom–Brookes postulate, named after Khazzoom (1980) and Brookes (1990), states that increased energy efficiency can paradoxically lead to increased energy consumption. The Khazzoom (1980) analysis is by its nature a partial equilibrium analysis since aggregate income and output are taken as given. Brookes (1990) began to develop the argument in a macroeconomic context. Later, Saunders (1992, 2000a,b, 2005, 2008) extends this by applying a neoclassical growth approach. However, Saunders' analyses implicitly ignore the constraints of limited energy supply in the market by assuming constant energy prices. Wei (2007) notices this drawback in the theory and introduces a theoretical general equilibrium model to internalize the energy price, using production functions of the Cobb–Douglas form. However, this specific Cobb–Douglas functional form restricts the interpretive power of the general equilibrium analysis. Hence, the present article extends the general equilibrium analysis by applying a completely general form of the production function. In doing so, we put the details of human activities aside and focus on the key issues related to rebound effects. In addition, energy input to the global economy is defined as energy resources in the nature. Typical examples are unextracted or underground fossil fuels. This simplifies the analysis and highlights the key role of energy resources.

According to a recent review provided by Dimitropoulos (2007), the theoretical understanding of economy-wide rebound effects is quite poor and the existing theory is not fully supported by the empirical studies. For example, according to Gardner and Joutz (1996), the short-run rebound effects are negligible and long-run rebound effects are considerable; both, however, are significantly less than the theoretical results in Saunders (2000a,b) and Wei (2007). On the contrary, Allan et al. (2007) and Turner (2009) show that both short-run and long-run rebound effects are considerable, and surprisingly short-run rebound effects may be greater than long-run effects, which seems to contradict previous theoretical studies on rebound effects (e.g. Saunders, 2008; Wei, 2007). New theory is necessary to explain these contradictions.

The methods applied by empirical studies are various. They can be roughly classified into three types: econometric methods, computable general equilibrium (CGE) modeling, and hybrids of the previous two. CGE models seem more suitable for studying the economy-wide rebound effects since it offers insights to how energy efficiency gains diffuse within an economy. So far, most studies on rebound effects using CGE models focus on one single country, which may not suitable for the study of long term rebound due to the relatively simplified assumptions on international trade and the ignorance of rebound effects in the rest of the world. An interesting study on rebound effects can be done by a global CGE model (e.g. GRACE model developed by Aaheim and Rive 2005, GEM-E3 by DG 2005, and WEM-ECO by IEA 2008. Even though there are many empirical studies using CGE models, the general equilibrium theoretical foundation of rebound is still not fully developed. The present article is a response to this theoretical gap.

4. Theoretical framework

An ideal framework to study rebound effects would consider the global economy as one entity within a general equilibrium framework. In the framework, the behavior of all industries, countries and