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Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts

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A R T I C L E   I N F O

A B S T R A C T

This article presents a detailed econometric analysis of historical energy efficiency rebound magnitudes in the US economy by sector and in aggregate. The results strongly suggest that energy consumption forecasts that ignore rebound effects will systematically and significantly understate energy consumption. Accompanying this article is a toolkit that allows any analyst to conduct a comparable analysis for any country, or sector, for which the data are available.

1. Introduction

Energy consumption forecasts, especially those used to inform climate change mitigation policy, must explicitly account for projected technology improvements in energy use efficiency. While nearly all do, such projections often fail to take account of rebound effects, whereby energy consumption may not be reduced on a one-for-one basis with energy efficiency gains.

For example, The Intergovernmental Panel on Climate Change (IPCC) of the United Nations projects that by 2030 energy efficiency gains will provide a substantial part of the remedy for climate change by reducing global energy consumption approximately 30% below where it would otherwise be—nearly sufficient to offset projected economic growth-driven energy consumption increases.[1,2] Like the IPCC report, the widely-cited [58] report is seen by many as reflective of current best thinking on the question of future energy consumption trends. The Stern report, relying on projections made by the International Energy Agency (IEA), offered that the "technical potential for efficiency improvements to reduce emissions and costs is substantial," and cited the IEA finding that "energy efficiency has the potential to be the biggest single source of emissions savings in the energy sector."[3] This conclusion is supported by several analyses that project comparable energy reduction benefits arising from deploying visible "below cost" energy efficiency technologies.[4]

However, these studies fail to take account of rebound effects, either altogether or (generously) in any significant way.

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[1] IPCC Fourth Assessment Report, Technical Summary Figures TS.3 and TS.10.

[2] [59] argue that reductions due to energy efficiency gains projected by the IPCC are actually more like 80% owing to the assumed technology gains already embedded in the IPCC's baseline scenario.

[3] The specific IEA projections used by Stern are not specified in the Stern reference cited here, but more recent [60] projections claim that energy efficiency gains will contribute 40% to carbon emissions reductions by 2020 (see Fig. 3, page 18).

[4] For example, McKinsey & Company, "Pathways to a Low-Carbon Economy" (2009). Lovins [31–34] has advanced similar claims for several decades.

This article quantitatively examines the consequences of ignoring such effects by analyzing empirical evidence for rebound found in the historical record for the US economy. The results indicate that so-called direct rebound magnitudes in the productive part of the US economy (about two-thirds of the energy economy, annual energy consumption-wise) were substantial over the period examined. The productive part of the economy is that portion involved in the creation and movement of goods and services—agriculture, industry, wholesale and retail commerce, commercial transport, finance, and government enterprises.

Especially when taken alongside the potential for energy efficiency rebound arising from other "indirect" sources not considered here, the results provide a strong argument in favor of explicitly accounting for rebound effects in energy consumption forecasts.

A key implication is that, to the extent conventional forecasts that provide a basis for climate change mitigation policy ignore or improperly treat rebound, there is less time than is commonly assumed to devise climate change solutions.

2. Background

While the scholarly treatment of rebound effects goes back a century and a half to [26], it was Brookes [5–11] who brought Jevons' work to the attention of modern economists. Brookes and Khazzoom [29] are generally credited with establishing the modern awareness of rebound phenomena.

Saunders [39] contains the earliest attempt to cast the rebound phenomenon in a formal theoretical framework. Seminal articles on empirical measurement include [12,19,20,37]. The collection edited by Schipper [47] contains articles by several early contributors.

The first efforts to cast the rebound effect in a general equilibrium context can be found in Dufournaud et al. [14] and Grepperud and Rasmussen [21].

More recent contributions include Sorrell [49], Sorrell and Dimitropoulos [50], Tsao et al. [52], Fouquet [17], Fouquet and Pearson [18] and the collections by Evans and Hunt [15] and Herring and Sorrell [24].

Contributions to the theory are found in Saunders [40–43], and in Wei [56,57], while Allan et al. [1], Hanley et al. [22,23], Barker et al. [3,4] have more recently advanced both the theory and the quantitative measurement of rebound effects. An innovate approach to consumer behavior-related rebound effects is found in Safarzynska [38].

A recent literature review can be found in Jenkins et al. [25]. Saunders [44,45] contains an undergraduate-level treatment of the theoretical foundations. Saunders [46] provides a quick, high-level introduction to the rebound effect in video format.[5]

3. Methodology, briefly

The analysis considers only so-called "direct" rebound effects. Recent rebound taxonomies and descriptions of other effects not considered here can be found in Sorrell [49], Jenkins et al. [25], Turner [55].

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[5] Available at http://www.youtube.com/watch?v=oTV-aBy5A3I&feature=player_profilepage.

Appendices A through D (Appendices are posted online beside this article) explain the methodology in detail, but in very basic terms, for each of 30 US sectors each year's new vintage of productive capacity is first characterized by its output and factor magnitudes and, using factor and output prices, by the incremental factor value shares. (The dataset used is due to [28].[6]) This enables econometric measurement of a four-factor (K, L, E, M) Translog unit cost function for each new increment of capacity, including measured technology gain parameters for each factor. These measured cost functions are of the form:

$$\ln c = \ln c_0 - \mathbf{a}\boldsymbol{\lambda}^T t + \mathbf{a} \ln \mathbf{p}^T + \frac{1}{2} \ln \mathbf{p} \cdot \mathbf{B} \cdot \ln \mathbf{p}^T - \boldsymbol{\lambda} \cdot \mathbf{B} \cdot \ln \mathbf{p}^T t + \frac{1}{2} \boldsymbol{\lambda} \cdot \mathbf{B} \cdot \boldsymbol{\lambda}^T t^2 \tag{1}$$

where time indices are suppressed for clarity, $\mathbf{p}$ is the vector of factor prices, $\mathbf{B}$ is the core Hessian matrix, and $\boldsymbol{\lambda}$ is a vector of technology gains (λ_K, λ_L, λ_E, λ_M). As described in Appendix B, this is a modification of the standard Translog unit cost function to accommodate technology gains that are factor-augmenting of the form $\tau_i = e\lambda_i^t$, an approach that is mathematically dual to introducing such factor-augmenting technology gains into any production function that is CRS. As the λ_i are treated as constants, the assumption is that technology gains grow at a constant rate over the time horizon.[7] In each year, the new vintage realizes a technology gain equal $\tau_N = e^{\lambda_N^t}$, where N is the year in question. All prior vintages have already "chosen" their production technology and so are not affected by subsequent technology gains.

The parameter λ_E is referred to throughout this article as the "energy efficiency gain" because τ_E depicts, in a dual production function formulation, the conversion rate of physical energy into energy services and thus directly reflects the technical energy efficiency that is realized in engineering terms. While other researchers sometimes define "energy efficiency gain" as a decline in energy intensity (the ratio of physical energy input to economic output, or often, GDP), a subsequent section shows that energy intensity is determined by numerous drivers unrelated to technical energy efficiency improvements. Comparable considerations apply to the other λ_i.

With this framework in place, for each sector multiple different investment model variants and variants of utilization rates across vintages are tested to see which among them delivers econometric measurements of new vintage factor and output capacity characteristics that provide the best statistical match to actual factor *uses* and actual *observed* output over the time horizon. This provides the basis for evaluating what

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[6] Throughout this article, the phrase "Jorgenson et al." is used to designate both the data set (available at Dale Jorgenson's website http://scholar.harvard.edu/jorgenson/data) and the econometric approach developed by Jorgenson and his colleagues. The approach can be found in Jorgenson [27,28].

[7] A distinction is often made between technology gains that are "autonomous" and those that are "price-induced." The technology gains econometrically measured here are agnostic as to their source and will reflect both types to the extent both have occurred over the time horizon. Nonetheless, the assumption of constant technology gains is limiting in two ways: one, if technology gains actually do occur autonomously, it is unlikely that they are of the same magnitude year-to-year; and two, to the extent factor prices vary over time price-induced technology gains will likewise vary year-to-year.