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Measurement of energy efficiency based on economic foundations

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ABSTRACT

Energy efficiency policy is seen as a very important activity by almost all policy makers. In practical energy policy analysis, the typical indicator used as a proxy for energy efficiency is energy intensity. However, this simple indicator is not necessarily an accurate measure given changes in energy intensity are a function of changes in several factors as well as 'true' energy efficiency; hence, it is difficult to make conclusions for energy policy based upon simple energy intensity measures. Related to this, some published academic papers over the last few years have attempted to use empirical methods to measure the efficient use of energy based on the economic theory of production. However, these studies do not generally provide a systematic discussion of the theoretical basis nor the possible parametric empirical approaches that are available for estimating the level of energy efficiency. The objective of this paper, therefore, is to sketch out and explain from an economic perspective the theoretical framework as well as the empirical methods for measuring the level of energy efficiency. Additionally, in the second part of the paper, some of the empirical studies that have attempted to measure energy efficiency using such an economics approach are summarized and discussed.

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1. Introduction

This paper reviews the developments in attempting to define energy efficiency from an economics perspective and therefore how an economic based energy efficiency indicator should be measured/estimated.[1] There is considerable debate about the contribution of energy efficiency policies in enhancing energy security and helping reduce emissions from the use of energy. However, there is no consensus on how energy efficiency is actually defined and measured. The most typical indicator used in energy policy analysis is that of energy intensity, often defined as the simple ratio of energy consumption to GDP at the state or country level or energy consumption per square meter at the residential level.

According to EIA (1995; p.vii) without a clear definition, the term energy efficiency is "a vague, subjective concept that engenders directionless speculation and confusion rather than insightful analysis" and so there is a need to adequately define and measure what energy efficiency actually is, although recognizing that this is a difficult task. Furthermore, EIA (1995) suggests that although energy intensity and energy efficiency are often used interchangeably, energy intensity does not necessarily reflect true energy efficiency given energy intensity is influenced by factors other than just pure energy efficiency. For instance, the IEA (2009) argues that using energy intensity as a proxy for energy efficiency is not appropriate given changes in energy intensity depend upon several factors such as the organization and structure of the economy and the real level of energy efficiency.

Over the past few years, some published academic papers have attempted to measure the level of the efficient use of energy based on the economic theory of production and used empirical methods for measuring productive efficiency. However, these studies have not generally provided a systematic discussion of the theoretical basis of energy efficiency. Neither have they clearly defined energy efficiency nor clearly shown how it should be empirically measured using parametric methods. The objective of this paper, therefore, is to sketch out and explain from an economic perspective the theoretical framework as well as the empirical methods for measuring the level of energy efficiency in order to try to deal with the problems highlighted by EIA (1995). Additionally, in the second part of the paper, some of the empirical studies that have attempted to measure the energy efficiency using such an economics approach are summarized and discussed.

The paper is organized as follows. The next section presents and discusses productive efficiency and its relationship to energy efficiency. Section 3 then considers the developments in the parametric

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[1] Note, that in previous works (Filippini and Hunt, 2011, 2012) in order to highlight the distinction from using energy intensity as a measure of 'true' energy efficiency, we used the term 'underlying energy efficiency' to indicate the efficient use of energy obtained from estimating a frontier energy demand function using stochastic frontier analysis. We have not used this term here, but it should be remembered that when we refer to energy efficiency this relates to the estimated economic based energy efficiency indicator obtained from the techniques discussed in this paper and ***not*** measured (or proxied by) energy intensity.

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estimation of energy efficiency as defined here and the advantages and disadvantages of various stochastic frontier analysis models that can be applied. Moreover, a discussion of the distinction between permanent and transient productive efficiency is introduced. This is followed by Section 4 that highlights some of the attempts to measure energy efficiency, followed by a short summary and conclusion in the final section.

2. Productive efficiency and its relationship to energy efficiency[2]

There is no one clear and accepted definition of energy efficiency, but according to Bhattacharyya (2011), most definitions are based upon the simple ratio of 'useful output of a process/energy input into a process'. Furthermore, Patterson (1996) identifies a number of ways in which the outputs and inputs for this ratio can be quantified. These include: i) thermodynamic indicators (energy input and output are measured in thermodynamic units); ii) physical–thermodynamic indicators (energy input is measured in thermodynamic units and output is measured in physical units); iii) economic indicators (output and input are measured purely in terms of monetary values); and iv) economic–thermodynamic indicators (output measured in monetary values and the energy input measured in thermodynamic units). Moreover, these indicators can be applied at the product, sectoral or national levels of economic activity and for primary energy consumption and secondary final energy consumption.

One of the most often used ratios in energy analysis at the macro level is the energy-GDP ratio, which is in fact the inverse of economic–thermodynamic indicators of energy efficiency identified by Patterson (1996). However, when undertaking aggregate energy efficiency analysis, this approach is arguably too simplistic and naïve and a better way to proceed is to use the definition based on the microeconomic theory of the production (see, Huntington, 1994) advocated in Evans et al. (2013) and considered further below.

To understand this approach, it is necessary to recognize that the demand for energy is derived from the demand for outputs that can be products, services or energy services such as heating, cooling and lighting. Households and firms use energy, labor and capital to produce outputs. From an economic perspective, it is important to produce outputs in an efficient way; that is, by choosing the combination of inputs that minimize the production cost. In this context, situations where households or firms are producing outputs without minimizing the use of inputs or using an obsolete technology that does not allow them to minimize the quantity of energy, labor and capital cannot be excluded. In these situations, the input energy as well the other inputs capital and labor are used in an inefficient way and a waste of energy is observed.

Productive inefficiency in the production of energy services can be discussed using the microeconomic theory of production framework with particularly isoquants and isocosts (Chambers, 1988; Huntington, 1994). In this context, the radial definition of technical, allocative and overall productive efficiency introduced by Farrell (1957) and particularly the non-radial concept of input specific technical efficiency introduced by Kopp (1981) can be helpful to understand the concept of energy efficiency.

Fig. 1 presents the situation of an economic agent that is using capital (K) and energy (E) to produce, in this case, an energy service (ES) such as heating.[3] The situation is illustrated using a unit isoquant (IS_0) and an isocost (IC_0) line. A technically efficient economic unit uses combinations of E and K that lie on the isoquant IS_0.

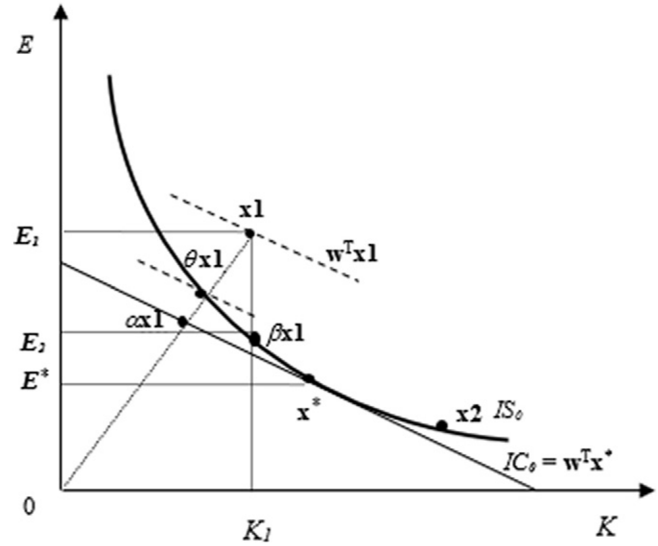

Fig. 1. Productive efficiency.

If the input price ratio, represented by the slope of the isocost line IC_0 in Fig. 1 is known, then a cost efficient input combination can be identified. An economic agent that uses a cost-minimizing input combination is illustrated by point $\mathbf{x}^*$, where the isocost line $\mathbf{w}^T\mathbf{x}^*$ is tangent to the isoquant IS_0, which reflects the production of a given level of energy services (ES^*). Thus, the minimum costs required for the production of the given level of energy services (ES^*) are $\mathbf{w}^T\mathbf{x}^*$.

If an economic agent uses a combination of inputs defined by point **x1** in Fig. 1 to produce a level of energy service that correspond to the isoquant IS_0, it is technically inefficient as the point lies above IS_0. Using a classical input oriented radial measure, the level of technical efficiency θ can be measured as the ratio between the distance from the origin to technically efficient input combination θ**x1** and the distance from the origin to input combination **x1**. This measure treats the contribution of each input to technical efficiency equally (equiproportionate).

From Fig. 1 the economic agent operating at θ**x1** is technically efficient but allocatively inefficient since it produces with higher costs. The level of allocative efficiency is measured as the ratio between the distance from the origin to α**x1** and the distance from the origin to θ**x1**. The overall productive efficiency or cost efficiency α can be obtained as the ratio between the distance from the origin to α**x1** and the distance from the origin to **x1**. To reach the optimal input combination, the economic agent has to increase the use of input K and decreases the use of input E. For example, an increase of K could be reached by installing a device on a cooling system to improve the function of the system or by substituting the single glazing windows with double glazing windows.

Note, that an economic agent that uses quantities of inputs defined by point **x1** is technically as well allocative inefficient. The economic agent could improve the level of overall productive efficiency by moving to the optimal input combination $\mathbf{x}^*$. In this case, energy consumption will decrease, as energy is substituted with capital and used in a more parsimonious way allowing the economic agent to consume less energy. This occurs for instance when a household or a firm improve the insulation of the building, change some electrical appliances, optimize the use of the heating or cooling system and the use of electrical appliances, in order to reach $\mathbf{x}^*$.

So far, a radial notion of technical efficiency has been discussed. In this case, an improvement of the level of efficiency in the use of inputs requires a reduction in energy and the other inputs proportionally. However, if researchers are more interested in obtaining an input specific technical efficiency measure, for example, as here, in terms of an energy efficiency measure, then empirical analysis should be based on

[2] This section builds on and improves upon an initial attempt to consider these theoretical issues in Evans et al. (2013).

[3] An economic unit could be a firm or a household and could refer to a wide range of energy services, such as heating, cooling, lighting, transportation, industrial processes, etc. Moreover, Fig. 1 could also represent the economy wide aggregate production function for a state or a region.

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