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Analysis of resource efficiency: A production frontier approach

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ABSTRACT

This article integrates the material/energy flow analysis into a production frontier framework to quantify resource efficiency (RE). The emergy content of natural resources instead of their mass content is used to construct aggregate inputs. Using the production frontier approach, aggregate inputs will be optimised relative to given output quantities to derive RE measures. This framework is superior to existing RE indicators currently used in the literature. Using the exergy/emergy content in constructing aggregate material or energy flows overcomes a criticism that mass content cannot be used to capture different quality of differing types of resources. Derived RE measures are both 'qualitative' and 'quantitative', whereas existing RE indicators are only qualitative. An empirical examination into the RE of 116 economies was undertaken to illustrate the practical applicability of the new framework. The results showed that economies, on average, could reduce the consumption of resources by more than 30% without any reduction in per capita gross domestic product (GDP). This calculation occurred after adjustments for differences in the purchasing power of national currencies. The existence of high variations in RE across economies was found to be positively correlated with participation of people in labour force, population density, urbanisation, and GDP growth over the past five years. The results also showed that economies of a higher income group achieved higher RE, and those economies that are more dependent on imports and primary industries would have lower RE performance.

1. Introduction

Natural resources are fundamental for human welfare since they provide raw materials, land, water, energy, food, and environmental services. However, natural resources are scarce and there is increasing evidence that human society is approaching a limit to the supply of many types of resources (Allwood et al., 2011). Hence, sustainable use of natural resources is essential to the sustainability of our human welfare.

Unfortunately, the consumption of natural resources in most economies throughout the world has been increasing. The global extraction of fossil fuels, metal ores, industrial and construction minerals, and biomass increased by 65% from around 36 billion tonnes in 1980 to 60 billion tonnes in 2007 (Krausmann et al., 2009a). The extraction, processing, and consuming of energy and materials has dramatic impacts on the environment. Adverse impacts include undesirable emissions to air, water and land, and the consumption of other important ecosystem services (Allwood et al., 2011; Matthews et al., 2000). Therefore, each and every economy has to increase efficiency in using natural resources to achieve sustainable development.

Empirically, analyses of resource efficiency (RE) aim to provide useful information for the development of natural resource management and environmental policies (OECD, 2008b). The reliability of such analyses depends how appropriately RE is measured. Material flow accounting and analysis (MFA) has been established to quantify the use of natural resources in national and international contexts (Behrens et al., 2007; OECD, 2008b). The concepts and methods of MFA have been increasingly standardised and aggregate material and energy flows are now an integral part of environmental reporting systems in many countries (Steinberger et al., 2010; Eurostat, 2007). Data on these aggregate flows for many economies have been made available by different organisations (CSIRO and UNEP, 2011; SERI, 2011; EuroStat, 2011). Data have also been used to construct resource efficiency indicators (REIs) such as gross domestic product (GDP) per domestic material consumption, GDP per total material requirement, and GDP per direct material input (OECD, 2008a,b; Eurostat, 2007). Recently, several empirical studies have used these data to investigate the variations of RE across different economies (Krausmann et al., 2009a; Steinberger et al., 2010; Weisz et al., 2006; UNEP, 2011; Steger and Bleischwitz, 2011).

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Regardless of differences in the research objectives, geographic scales, and time dimensions, these studies share two important common features. Firstly, they provide strong and consistent evidence of increasing consumption of resources in most economies, even in those economies that have focused their policies on dematerialising economic growth. Secondly, these analyses confirm high variations in the levels of resource consumption across economies. However, existing REIs have two important limitations. Firstly, REIs are built on aggregate mass flows of differing materials and this is questionable because mass content fails to reflect the differing quality of a variety of materials. Secondly, REIs are not able to provide 'quantitative' interpretations. For example, analysts cannot express by how much a particular economy can improve its efficiency in using resources.

To overcome these limitations, the present study proposes to use the exergy or emergy content rather than mass content of differing resources in the MFA and integrate the MFA into the production frontier framework. The literature has argued that it is more precise to use the exergy or emergy content than to use the mass content in aggregating differing resource types into aggregate flows (Wall, 1987; Ayres, 1995; Odum, 1996). Also, the production frontier framework has been used extensively in empirical micro- and macroeconomic studies. The expected results can provide decision makers with useful information regarding how economies can improve their efficiency, given a production technology that is technically feasible and currently available to economies. By using the production frontier approach, the derived RE measures are both 'quantitative' and 'qualitative'. Interpretations from these efficiency measures are much more practically meaningful. For example, by how much can an economy reduce its consumption of resources without any reductions in the quantities of goods and services produced and consumed? These new RE measures also allow relative comparisons of efficiency performance across economies and over time.

The remaining parts of the present article are structured into four sections. Section 2 reviews the relevant empirical studies in the field of material efficiency. Section 3 proposes an analytical framework to derive a new RE measure. Section 4 illustrates an empirical application using a dataset of 116 economies in 2000. Section 5 concludes the paper.

2. Literature review

The MFA is useful in quantifying the use of natural resources (OECD, 2008b; Weisz et al., 2006). The mass contents of different types of materials and energy are used in aggregating differing material/energy flows into aggregate flows. These aggregate flows are then used to derive resource efficiency indicators (REIs). The official REIs link macroeconomic output indicators (such as GDP or value added) to economy-wide material flows and are constructed to provide information about the material productivity or intensity of national economy or economic activity sectors (OECD, 2008a). Three common REIs are GDP per domestic material consumption, GDP per total material requirement and GDP per direct material input (OECD, 2008a,b; Eurostat, 2007). These REIs are 'qualitative' in the sense that one can use them to compare the relative degrees of efficiency among economies. Data on the material flows and REIs for many economies have been made available by different organisations (CSIRO and UNEP, 2011; SERI, 2011; EuroStat, 2011).

Weisz et al. (2006) investigated the differences in the levels of domestic consumption of twelve different types of materials among 15 countries of European Union (EU) from 1970 to 2001. This study found out that domestic material consumption per capita varied significantly ranging between 12 tonnes per capita in Italy and the United Kingdom, and 37 tonnes per capita in Finland. This study revealed that national income and energy consumption had significant impacts on the level of material consumption but could not fully account for the observed differences. The consumption level of biomass, industrial minerals, ores, and fossil fuels were determined largely by the structure of economic sectors within the economy rather than by national income. The consumption of construction minerals was less determined by the economic structure and more by industrialisation and economic growth.

UNEP (2011) studied the patterns of material consumption of 59 economies in the Asia–Pacific region from 1970 to 2005. This study reported that domestic material consumption per capita accelerated from less than 3.2 tonnes to more than 8.6 tonnes due to high population density and population growth. This increasing trend was opposite to the decreasing trend observed in other regions of the world. Importantly, this study warned that the decreasing trend taking place in developed countries was due to the displacement of production from these economies to the Asia–Pacific region. This warning was consistent with Behrens et al.'s (2007) argument about the continuous outsourcing of primary commodities from industrialised countries to developing countries, which explained the relative decoupling trend in industrialised countries.

UNEP (2011) also reported significant variations of material consumption across countries in the Asia–Pacific region. Using an *IPAT* identity (i.e. $I = P \times A \times T$),[1] this study found that GDP per capita was the main driver of material consumption. Steinberger et al. (2010) also used the *IPAT* identity to investigate the highly unequal distributions of resource consumption among 175 countries in 2000. This study reported that population level was the most significant determinant of variations across different countries.

In review, these empirical studies have revealed two important facts: (1) the consumption of materials and energy in most of economies had kept increasing; and (2) there were high variations in the levels of material consumption across economies. However, the use of REIs exposes these studies to several possible limitations as discussed below.

There are two important properties that useful efficiency measures should have: being quantitative and qualitative (Heijungs, 2007). The quantitative property of an efficiency measure expresses the relative performance in relation to the maximum potential. For example, it is useful to infer an efficiency score of 0.7 with an opportunity for 30% for improvement. Qualitative property allows relative comparisons between different economies. For example, it is desirable to say that an economy with an efficiency score of 0.8 is more efficient than other economies with efficiency levels of less than 0.8. Majority of existing REIs are qualitative but are not quantitative. In addition, the use of mass contents to construct aggregate material or energy flows is questionable due to natural distinctions between materials as disparate as hydrocarbons, crops, inert construction minerals, toxic metals and reactive chemicals (Ayres and Warr, 2009). The present paper attempts to overcome these two limitations in two ways. Firstly, by firstly using exergy or emergy values (rather than mass content) in aggregating differing resource types (i.e. a variety of materials and energy) into aggregate flows. Secondly, by using the production frontier approach to derive qualitative and quantitative RE measures.

[1] *IPAT* was a common framework that conceptualises the total impacts on the environment (*I*, i.e. total domestic extraction of materials) as the product of population (*P*), the level of affluence of that population (*A*, i.e. gross domestic product (GDP) per capita), and a technological coefficient (*T*) (Ehrlich and Holdren, 1971).