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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).

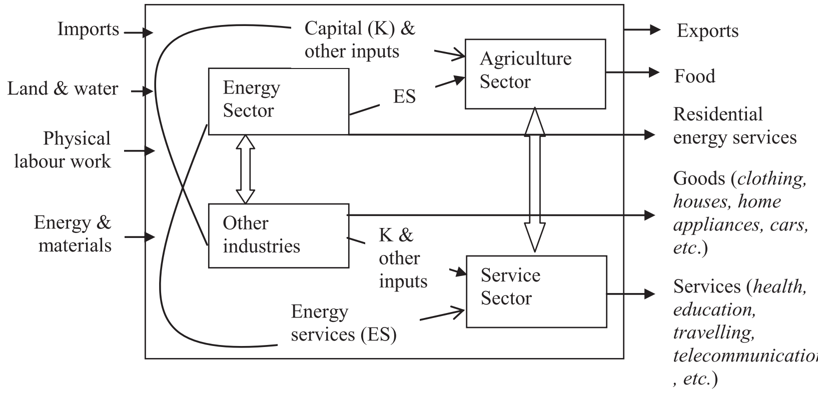

Fig. 1. The physical flows of inputs and outputs in a simplified economic system.

3. An analytical framework

3.1. The physical basic of modern economies

Recent studies into the physical and economic growth of modern economies have modelled a typical economy as a system consisting of a physical basis and a market superstructure (Lindenberger and Kümmel, 2011; Ayres and Warr, 2009). The physical basis produces goods and services by converting energy and materials into commodities while economic actors trade these commodities in the market superstructure. Fig. 1 presents the physical flows of natural resources in this simplified system. All economic activities within a single economy are categorised into four sectors: agriculture, service, energy and other industries. Inputs include land, water, raw energy, materials, and physical work performed by labour. There are interactions between the four sectors within this simplified system. The energy and industrial sectors produce energy services, capital goods (buildings, machinery, information-processing equipment, installations, etc.), and other inputs (e.g. various compounds of materials such as chemicals and fertilisers) which are used by agriculture and service sectors.

Labour is a distinct input because it contains physical work and intelligence. Physical labour work, to a significant extent, can be substituted by man-made capital such as machinery and equipment. A typical example is mechanical equipment that has replaced physical workers in car or clothing manufacturing. Human intelligence refers to the information, knowledge and management skills embodied in people, and these are primary to technological improvements. Without human intelligence, there would be no innovation and no radical improvement in resource efficiency. Labour's intelligence is the ultimate determinant of on-going improvements in resource efficiency.

Outputs consist of food produced by the agricultural sector, services produced by the service sector, residential energy produced by the energy sector and goods (i.e. clothing, cars, houses, home appliances, etc.) produced by other industries. Imports and exports can be in forms of physical labour work, raw energy/materials, energy services, services, and goods in which raw energy and/or materials are embodied.

Note that the basic function of outputs is to contribute to human welfare. Food provides us with nutrition to survive, perform physical work, study, and enjoy our lives. Home appliances help us do housework quicker so that we have more time for self entertainment, self development and family activities. Education improves our knowledge, which expands our human intelligence. Hence there are sophisticated interactions between different types of outputs, the quality of physical labour, and the intelligence of labour. These interactions also affect technological improvements.

All economic activities involve some transformations of materials and energy which are regulated by the first and second laws of thermodynamics (Ayres, 1995; Ayres and Kneese, 1969; Daly, 1992). The first law of thermodynamics states that energy and materials are separately conserved in every transformation, but the second law suggests these transformations 'destroy' the usefulness of materials and energy. One important implication of these two thermodynamic laws is that the production (and consumption) of goods and services will destroy natural resources and produce polluting emission to the environment, regardless of recycling efforts. Importantly, the two thermodynamic laws lace constraints to the sustained growth of energy and materials consumption of our modern human society.

3.2. Measuring the quantity and quality of physical flows

Mass is the common measure of physical quantity for all material substances; but it is inconvenient to keep separate accounts for all the different categories of materials (Ayres and Warr, 2009). In a macroeconomic context, they are aggregated into MFA flows to derive REIs. However, using the mass content as the common physical measurement unit for different types of resources is questionable. To deal with this problem, the literature has proposed to use exergy or emergy to quantify resource flows.

Exergy refers to the usefulness of any forms of energy and materials (Wall, 1977). Technically, it is measured using thermodynamics principles as the maximum amount of work (herein after named *potential work*) that can be produced by a system or a flow of materials or energy as it comes to equilibrium with a reference environment (Szargut et al., 1988). Several studies have proposed to use the exergy contents of marketed inputs rather than input prices in optimising the input combinations to derive environmental efficiency (Hoang and Alauddin, 2012; Hoang and Rao, 2010). The relationship between exergy and economic growth has also been studied. Exergy services (i.e. *useful work* generated by exergy flows), have been modelled as an input factor in production models (Ayres and Warr, 2009; Warr et al., 2010; Warr and Ayres, 2005).

Another important strand in the literature has proposed to use emergy, defined as a common basis of solar (equivalent) energy (unit: solar emergy joules), to describe flows of matter and energy (Odum, 1996).[2] Exergy and emergy approaches differ mainly in two aspects: the goals; and the boundaries of analyses (Bastianoni et al., 2007). On the first aspect, emergy evaluation traces solar energy embodied in a product while exergy assesses the amount of resources destroyed in

[2] A comprehensive list of literature on emergy is available at www.emergysystems.org.

the production of the product. On the second aspect, emergy analysis encompasses the entire biosphere, while exergy analysts can define boundaries according to the aim of their studies. However, recent research has shown that methodological convergence has emerged (Sciubba and Ulgiati, 2005). Importantly, emergy can be expressed as a function of exergy so that resource destruction can be analysed by using the second law of thermodynamics. Similarly, recent studies have proposed to use extended exergy analysis to account for interactions between production process and biosphere. The present paper argues that, since exergy and emergy can be used to account for differences in the qualities of differing types of natural resources, both can be used in the analysis of RE.

In review, recent studies provide sound arguments to use exergy or emergy to quantify the flows of natural resources in the physical basic of economies. Importantly, it is appropriate to consider the amount of exergy or emergy contained in inputs as production factors in aggregate production functions. Being different from existing literature, the present study propose a new approach to quantifying RE in the production frontier framework.

3.3. The production frontier framework

The unique feature of efficiency measures constructed in the production frontier framework is that they are both quantitative and qualitative, making them potentially more useful than existing REIs, which are only quantitative. For example, it is desirable to interpret an RE score of 0.7 of Economy A, as that this economy has the ability to reduce its consumption of resources by 30% without affecting output quantities. Also it is desirable to use RE scores to make relative comparisons between economies; for example, Economy A is more efficient than Economy B, having the RE score of 0.6. The next section formally sets up the production frontier framework in relation to the exergy-based or emergy-based flows of resources depicted in Fig. 1.

I start with situations where there is only one output produced from many inputs. The relationship between the output and input is expressed:

$$q = f(\mathbf{x}) \quad (1)$$

where q is the single output and $\mathbf{x}$ is a vector of inputs.

Fig. 2 graphically presents the production frontier in a case of a single input and a single output. The curve CB represents the frontier: any economy can lie either on the curve (i.e. points B and C) or below the curve (i.e. point A). Staying below the frontier point A is inefficient because it can either increase output from q_A to q_B without consuming any extra input or reduce input consumption from x_A to x_C without scarifying any output. A distance from point A to either points B or C represents its inefficiency levels and there are two general ways to achieve efficiency improvements: moving from points A to B (i.e. output-orientated framework) or moving from points A to C (i.e. input-orientated framework). Formally, these two RE measures can be defined:

$$\mathrm{SRE_I}(\text{single output RE, input} - \text{orientated}) = x_C/x_A \quad (2)$$

$$\mathrm{SRE_O}(\text{single output RE, output} - \text{orientated}) = q_A/q_B \quad (3)$$

Note that these single output RE measures are dimensionless and bounded by zero and one. They are both quantitative and qualitative. A $\mathrm{SRE_I} = 0.7$ suggests that an economy can reduce the consumption of inputs by 30% without any changes in the single output, whereas a $\mathrm{SRE_O} = 0.6$ means that the economy can increase its output by 40% using the same amount of resources in the inputs. Note that $\mathrm{SRE_I} = \mathrm{SRE_O}$ when the production function exhibits constant return to scale (CRS) (i.e. increasing all inputs by a factor of a will increase the output by the same factor a).

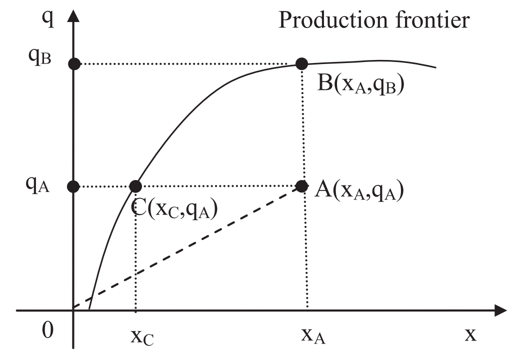

Fig. 2. Efficiency concepts in the production frontier framework.

When there are multiple inputs used to produce a single output, the $\mathrm{SRE_I}$ measures are 'radial' since they refer to the contraction of all inputs by a common factor. Fig. 3 depicts this concept with two inputs, x_1 and x_2, and one output q. The isoquant curve represents all possible combinations of different quantities of the two inputs to produce the same output quantity. This curve represents the production frontier and economies staying on this curve are efficient. Point A, staying above the frontier, is inefficient and its efficiency equals the ratio OC/OB. The value of this ratio is a factor that two inputs will be reduced proportionally, while still holding the output quantities fixed.

In the empirical studies in macroeconomic literature, GDP (or GDP per capita or GDP growth) is commonly used to as the single aggregate output (q) (Ayres and Warr, 2009; Warr et al., 2010; Warr and Ayres, 2005; Bergheim, 2008). One can also adjust for differences in the purchasing power of national currencies by using purchasing power parity (PPP) GDP per capita. Given that PPP GDP per capita can be used to represent consumption-based human welfare, one can interpret the values of RE measures by how much reduction in resource consumption can be pursued without any reduction in the consumption-based human welfare. To capture the comprehensive physical flows of economic activities, the input vector $\mathbf{x}$ should include land, labour and natural resources, and all sorts of imports. Conventionally, these inputs are measured in different physical measurement units (for example hectare for land, labour force, and mass tons for natural resources). As argued above, the exergy or emergy contents of these inputs could be used. Given that physical work performed by labour is small relative to the total exergy or emergy contents of other inputs, one can normalise all other inputs by labour (i.e. the exergy or emergy divided by labour force).

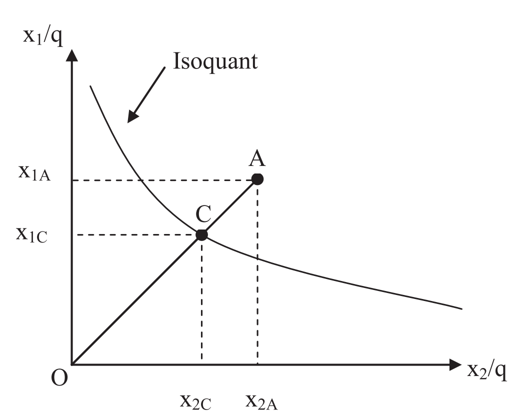

Fig. 3. A radial measure of resource efficiency in a two inputs case.

More realistically, an economy can be viewed as a multi-input and multi-output production system described by the technology set (T) using K inputs, $\mathbf{x}\in R_+^K$, to produce M outputs, $\mathbf{q}\in R_+^M$:

$$T = \{(\mathbf{q},\mathbf{x}) : \mathbf{x}\ \text{can produce}\ \mathbf{q}\} \quad (4)$$

This set consists of all vectors ($\mathbf{x}$,$\mathbf{q}$) such that $\mathbf{x}$ can produce $\mathbf{q}$. Note that the existence of such technology set (T) for the regional or global economic system depends on the assumption that economies in a region or throughout the globe share several similar technologies which have been used in the various stages of resource extraction and purification to the production of machinery and end-using products. This assumption is appropriate in modern global economy due to observed economic globalisation. Input or output distance functions are often used to derive efficiency measures (Shephard, 1953).[3] The input distance function characterises T by proportionally contracting $\mathbf{x}$ given $\mathbf{q}$. The output distance function considers a maximal proportional expansion of $\mathbf{q}$ given $\mathbf{x}$.

$$D_I(\mathbf{x},\mathbf{q}) = \max\{\rho : \rho > 0, (\mathbf{x}/\rho,\mathbf{q})\in T\} \quad (5)$$

$$D_O(\mathbf{x},\mathbf{q}) = \min\{\delta : \delta > 0, (\mathbf{x},\mathbf{q}/\delta)\in T\} \quad (6)$$

The properties of the input and output distance functions are discussed in standard efficiency textbooks (Coelli et al., 2005). Importantly, the concept of radial technical efficiency of Farrell (1957) can be used to define RE:

$$\text{MRE}_I\ (\text{multiple output RE, input} - \text{orientated}) = 1/D_I(\mathbf{x},\mathbf{q}) \quad (7)$$

$$\text{MRE}_O\ (\text{multiple output RE, output} - \text{orientated}) = D_O(\mathbf{x},\mathbf{q}) \quad (8)$$

MRE_I reflects the ability of an economy to use the minimal amount of multiple inputs to produce a given set of multiple outputs and MRE_O shows its ability to obtain maximal outputs from a given set of inputs. Their values are bounded between zero and one. If the values of D_I and D_O of an individual economy equal unity then this economy stay on the production frontier, suggesting that it is efficient. If the production technology T is CRT, $D_I(\mathbf{x},\mathbf{q}) = 1/D_O(\mathbf{x},\mathbf{q})$ for all $\mathbf{x}$ and $\mathbf{q}$.

4. An empirical illustration

4.1. Data description and measurement technique

This paper uses the National Environmental Accounting Database (NEAD) to construct physical flows of 116 economies in 2000 (Center for Environmental Policy, 2009).[4] NEAD contains information on natural capital stocks (soil, water, forests, and fish), mined materials (metals and fuels), and economically transformed goods and services (agricultural commodities, manufactured goods, services) from several international sources (Sweeney et al., 2007). The database reports the flows of matter and energy in the unit of solar emergy joules (sej). These emergy flows were reconstructed into several input and output terms for which Table 1 describes basic statistics.

There are four aggregate inputs: the solar emergy of organic matters contained in top soil and in water; emergy of non-renewable energy types (i.e. coal, oil, natural gas, nuclear, etc.); emergy of metals and minerals; and emergy contained in all imported commodities (i.e. raw, processed materials, energy and final products). It is crucial that emergy contents in imported commodities should reflect inefficiency levels in overseas production so that estimated RE scores for individual economies can capture inefficiencies exhibited in both domestic and foreign production. However, these aspects were not clearly present in the NEAD's dataset, which might cause additional uncertainty in the estimated efficiency results.

Table 1
Descriptive statistics for inputs and outputs.

Variables	Mean	Std. Dev.	Min	Max
Input 1: Top soil loss and water withdrawal (sej/labour force)	5.83E+13	6.57E+13	5.05E+12	5.53E+14
Input 2: Non-renewable energy (sej/labour force)	8.43E+14	2.92E+15	2.54E+10	2.92E+16
Input 3: Metals and minerals (sej/labour force)	4.93E+14	1.13E+15	3.49E+10	1.04E+16
Input 4: Imports (sej/labour force)	7.95E+14	1.05E+15	7.23E+12	7.60E+15
Output: PPP GDP per capita	9625.165	9778.397	448.614	36136.86

The physical work performed by the labour force was not available; hence the four inputs were normalised by the labour force. The present study used a single aggregate output measured in PPP GDP per capita. The use of this output helped make this study more comparable with other empirical studies using resource efficiency indicators (e.g. Behrens et al., 2007; Weisz et al., 2006). Data for labour force and PPP GDP per capita were from World Bank's World Development Indicators (WDI) database.

Data envelopment analysis (DEA) is used to estimate the production frontier and calculate RE scores using the input-orientated framework. As a nonparametric technique, DEA does not require assumptions about the behaviour of economies, the functional form of the production technology (i.e. the functional forms of Eqs. (1) or (4) or the distribution shape of RE scores. DEA does not take into account data noise, random errors in its estimation, and correlations between efficiency levels; hence, interpretations on the efficiency scores of individual economies require caution.

It is arguable to assume that there exists a production frontier for the 116 economies because of significant differences in the characteristics of economic structures of those economies. Notably, several high income economies such as Switzerland or Japan are highly reliant on imported resources while other lower income economies such as Vietnam or Brazil are reasonably rich in their own resources. Several small economies Cyprus and Belgium are driven by the service sector while other larger economies are more diversified (e.g. United Kingdom – UK or United State of America-USA). In order to deal with these differences, one can categorise these economies into different groups and then estimate the production frontiers for each group. However, doing this would reduce the sample size, which affects the quality of analysis of determinants of RE (discussed more in Section 4.3).[5]

In this empirical study, the global production frontier is assumed to exist for the 116 economies because of two reasons. First, this empirical work is to illustrate how the proposed method can be applied to calculate RE results and how the RE results can be interpreted rather than the values of estimated RE scores. Second, this empirical study also demonstrates that determinants of RE can

[3] Hyperbolic or directional distance functions (H/DDFs) can also be used to simultaneously expand outputs and contract inputs. H/DDFs are more flexible than the input and output distance functions. DDFs, however, can be subjective to the choice of directions (Fare et al., 2002; Chambers et al., 1998).

[4] At the time of writing this article, only this international data set, in which the emergy contents of inputs and output had been already computed, was available to the author. Other international data sets containing mass contents now become available; however converting mass contents into exergy or emergy contents for a large number of economies requires intensive literature review and data compilation work. The author hopes that this work can be completed in near future.

[5] One can also use stochastic frontier analysis (SFA)- a parametric method imposing a pre-selected functional form of the production technology and the distributional shape of efficiency terms- to conduct empirical studies. SFA takes into account data noise and the differences in the economic structures in estimating the RE scores but is exposed to potential econometric problems such as misspecification.

also be analysed in this framework. Since this empirical study does not attempt to arrive at a specific characterisation of the global production technology both CRS and VRS specifications are used.

4.2. Resource efficiency results

Table 2 reports the summary of estimated RE results. When the global production technology is assumed to be CRS economies, on average, achieved an RE score of 0.618, suggesting that these countries could reduce the consumption of emergy-based resources by 38.2% without having any reductions in PPP GDP per capita. Under the VRS specification, the average RE score was estimated to be 0.679, implying that those economies, on average, could reduce the consumption of emergy inputs by 31.1%.

The results confirmed that RE varied greatly across 116 economies. RE of those economies like Jodan, Suriname, Papua New Guinea, Nambia, and Mexico were less than 20%, meaning that these economies can reduce resource consumption by a significant amount of 80%. On the other hand, there were more than 20 economies identified as being efficient (i.e. RE scores = 1). Those efficient countries include industrialised economies (i.e. Belgium, Denmark, France, Japan, Switzerland, UK, and USA) and resource-rich economies (Brazil, Kuwait, and Vietnam). The average RE scores also varied between two groups of economies: high income and lower income (using World Bank's classification). In the CRS specification, economies in the high income group, on average, achieved 20% higher efficiency levels than economies in the lower income group. This difference was, however, smaller (around 9.6%) in the VRS specification. Section 4.3 provides more discussion about the differences in RE between two groups of economies.

RE scores were used to rank 116 economies (details shown in Appendix A). A Friedman test showed no significant difference in rankings between CRS and VRS specifications.[6] Data on the domestic consumption of energy and materials reported in Krausmann et al. (2009a) were also used to rank these countries. Statistical tests, however, confirmed that rankings based on RE significantly differ from rankings based on Krausmann et al. (2009a) data.[7] Note that variations in rankings may be caused by the use of differing data sets and methods. To achieve more robust comparison results, it is desirable to apply the RE approach proposed in this study to analyse the dataset of Krausmann et al. (2009a) in the future.

4.3. Determinants of resource efficiency variations

Given significant variations in terms of resource consumption across economies, several recent empirical studies have attempted to examine the drivers of these variations by regressing the REIs on a set of explanatory variables (Steger and Bleischwitz, 2011; Krausmann et al., 2009b; Weisz et al., 2006). In the present study, a Tobit model was also estimated to examine the relationships between RE estimated from the input-orientated DEA and explanatory variables, of which descriptive statistics are summarised in Table 3.[8] Tobit models were used because the dependent variable (i.e. RE scores from CRS and VRS specifications) is bounded between zero and one, and there were a high number of RE scores of unity (Cameron and Trivedi, 2009). The inclusion of these variables was justified on several important hypotheses and empirical observations reported in the literature as follows.

Table 2
Summary of resource efficiency measures.

Samples	Specifications	Average	Std. Dev.	Min	Max
Whole sample (116 economies)	Constant return to scale	0.618	0.270	0.111	1.000
	Variable return to scale	0.679	0.271	0.120	1.000
High income economies (33 economies)	Constant return to scale	0.769	0.224	0.434	1.000
	Variable return to scale	0.739	0.226	0.410	1.000
Lower income economies (83 economies)	Constant return to scale	0.569	0.273	0.111	1.000
	Variable return to scale	0.643	0.280	0.120	1.000

Environmental Kuznets curve theorises that in the early stages of economic growth environmental degradation and pollution increase, but beyond some level of income per capita the relationship environmental degradation decreases (Stern, 2003). Hence, the average annual growth rate of GDP in the period 1995–2000 and its squared value, and a dummy variable representing the income status of economies, according the World Bank classification, were used to capture variations in the levels of economic development across economies. Other variables such as GDP per capita or PPP GDP per capita (as well as the squared values of these variables) were also included but statistical tests showed no significant correlation. Full results of these alternative models are in Appendix B.

Population growth and urbanisation have put increasing pressure on the environment (de Sherbinin et al., 2007) and increasing concerns for the environment have motivated governments to find ways to improve RE since late 1980s (Brundtland, 1987; Rayner, 2006). Therefore, variables related to population density and urban population were included. To account for variations in the human capital, the labour participation rate was also used.[9]

The share of natural resource rents in GDP was included to capture the scale of primary industries (including coal, forest, mineral and oil sub-sectors) in national economies. The share of net imports of energy in total domestic energy, and the share of imports of goods and services in GDP were used because of at least two reasons. Firstly, they were used to model the effects of dependence of domestic consumption on overseas production. Secondly, they help partly account for inefficiency levels in overseas production.

Table 4 reports the results of two Tobit models in which RE scores from CRS and VRS specifications were used as the dependent variables. The models fit the data reasonably well and most of the explanatory variables (except the share of total natural resource rents in GDP and urban population share and five years GDP growth) were statistically significant (at a common 10% LOS).

The labour participation rate was positively correlated with RE, suggesting that economies with higher proportion of population aged 15 and above participating in economic activities also show a higher level of resource efficiency. Population density and urbanisation were positively related with RE. One possible explanation for these two

[6] Test statistics = 0.9372, suggesting that there is high agreement in the ranks using RE scores under two respective CRS and VRS specifications.

[7] Friedman tests were used and p-values were 0.2397 and 0.1468 respectively for tests between rankings based CRS RE scores and Krausmann et al. (2009a) domestic material consumption per capita and domestic energy consumption per capita.

[8] Many other explanatory variables were included (i.e. openness measured by the ratio of total import and export values to GDP, average growth rate of population during 1995–2000, share of household consumption in GDP, enrolment in primary education per capita, consumption of food per capita, shares of agriculture, industry and services in GDP) but their coefficients were not statistical significant (at the 10% LOS) and chi-squared tests did not reject the preference of simpler models as reported in Table 3.

[9] Due to data unavailability, various aspects of human intelligence were not present in the Tobit models. The World Bank's WDI database has several statistics on education enrolment in schools, colleges and universities, patent registrations, and research and development expenditure, etc which can be used to capture the human intelligence. Unfortunately, data were available only for a small number of economies.

Table 3
Descriptive statistics of explanatory variables.

Explanatory variables	Mean	Std. Dev.	Min	Max
Labour participation rate (% of total population ages 15+)	62.24	9.66	41.70	88.80
Population density (people per sq. km of land area)	98.62	129.2	1.55	995.6
Urban population share (% of total population)	57.37	21.20	10.80	98.20
Share of natural resource rents in GDP (coal, forest, minerals, and oil)	11.22	24.37	0.004	214.5
Imports (% of GDP)	40.52	19.46	9.53	100.6
Net import of energy (% of energy use)	−40.28	224.5	−1619.2	97.93
Five years GDP growth (annual growth rate)	0.84	0.75	−2.62	3.72
High income economies (dummy)	28.40%			

Source: World Bank's Development Indicators Database.

Table 4
Results of the Tobit model.

Variables	Constant return to scale		Variable return to scale	
	Coef.	*p*-Value	Coef.	*p*-Value
Constant	−0.5760	0.010	−0.5988	0.019
Labour participation rate	0.0164	0.000	0.0201	0.000
Population density	0.0010	0.000	0.0010	0.001
Urban population share	0.0033	0.013	0.0017	0.253
Share of natural resource rents	−0.0012	0.389	−0.0020	0.222
Imports	−0.0044	0.000	−0.0038	0.007
Net imports of energy	−0.0003	0.028	−0.0004	0.015
Five years GDP growth	0.0512	0.184	−0.0584	0.271
Five years GDP growth (square)	0.0051	0.755	0.0375	0.090
High income economies	0.1710	0.003	0.1895	0.004
LR chi2	74.480	0.000	66.850	0.000
Pseudo *R*-square	0.7180		0.5134	

observations is that higher population and more people in the working force could be highly correlated with greater amount and better quality of human capital which helps deliver higher efficiency.

The results reported a positive correlation between RE and GDP growth and a negative relationship between RE and the squared value of the GDP growth in the CRS specification but these relationships were not statistically significant. Opposite relationships were detected in the VRS specification, leaving us an inconclusive interpretation about the Kuznets hypothesis. However, one important implication from this finding is that the scale of production at the aggregate national economy level matters in the analysis of RE variations.

A positive correlation between RE and the income status of economies was in line with common expectation and also consistent with Table 2 where higher income countries were more efficient than lower income counterparts. The magnitude of the relationship between RE and explanatory variables (i.e. the absolute value of the coefficient) was strongest for the income status. This finding supports an argument that better transfer of technology and knowledge from groups of high income countries to groups of lower income countries is crucial for RE improvement at the global level.[10] Importantly, developed economies, by simply shifting production to less developed economies without deploying state-of-the-art technologies and environmental management knowledge in production facilities (especially those located in less developed economies), will not help the global economy achieve sustainable production. However, to promote faster technological diffusion, governments in both home and host economies should put in place consistent policies.

The share of natural resource rents in GDP, the share of imports of goods and services in GDP, and the share of net energy import in total domestic energy consumption were negatively correlated with RE, delivering several important implications. Firstly, those economies with a bigger scale of primary industries do not necessarily exhibit more effective experience in managing natural resources. Secondly, it is possible that the primary industries of many economies are on the path of decreasing return to scale; hence reducing the scale of primary production could help achieve higher RE. Thirdly, international prices of goods and services are much below the actual marginal social costs (i.e. after taking into account negative environmental externalities). Hence economies importing goods and services do not pay for the actual social costs and this international market failure leads to overconsumption in importing economies.

[10] Appendix B shows that the correlations between the squared value of PPP GDP per capita with RE in both CRS and VRS specifications are positive (significant at 10% in the VRS specification), implying that marginal changes in RE is increasing with respect to changes in the levels of income.

5. Conclusion

This article has proposed an integration of material/energy flow analysis into the production frontier framework to measure resource efficiency. Particularly, the paper used the emergy content (rather than mass content as done in MFA) contained in various inputs to aggregate them into several input terms. In an input-orientated framework, the new RE measure is derived by contracting all exergy/emergy-based aggregate input terms given the fixed level of a single aggregate output measured in PPP-adjusted GDP per capita. The defined RE measure are qualitative and quantitative: one can use this RE to express the potential of efficiency improvement and to make comparisons across economies.

For the purpose of illustrating the applicability of the proposed framework, the present paper utilised the international emergy dataset of 116 economies in 2000. Results showed that these economies, on average, have an RE level of 0.618 (CRS specification of the global production technology) and of 0.679 (VRS specification). These figures suggest that those economies, on average, could reduce the use of natural resources by 38.2% (or 31.1% for VRS specification) without scarifying any consumption-based welfare (i.e. PPP GDP per capita). Consistent with recent empirical studies, the results also showed high variations in RE across economies. Particularly high income economies, on average, obtained higher level of RE than lower income economies.

Analysis of RE variations yielded several important findings. Those variables related to labour force, population density, urbanisation, GDP growth were positively correlated with RE. Those economies which relied on primary industries or imports of goods, services and energy and of lower income group had lower RE. Faster diffusion of technologies and knowledge from highly developed to less developed economies could help improve global RE levels. Failure to internalise environmental externalities in exporting economies could encourage overconsumption of resources (via overconsumption of goods, services and energy) in importing economies. Also, it is important to have more international investigations in the primary industries, as this study has shown that economies with more dominant primary industries are not necessarily more efficient in managing natural resources.

There are several directions for future research. Analysts could apply this new framework into several international data sets that are currently available so that comparisons of results can be made. More advanced techniques (including bootstrapped DEA and stochastic frontier analysis) in analysing determinants of RE variations also can be deployed to provide more robust results.

Appendix A
Rankings based on resource efficiency scores.

Country	CRS	Rank	VRS	Rank	Country	CRS	Rank	VRS	Rank	Country	CRS	Rank	VRS	Rank	Country	CRS	Rank	VRS	Rank
Albania	0.61	53	0.71	51	Denmark	1.00	1	1.00	1	Lebanon	1.00	1	1.00	1	Senegal	0.59	56	0.60	65
Algeria	0.47	74	0.48	87	Ecuador	0.76	41	0.85	44	Libya	0.60	55	0.69	52	Serbia	0.71	46	0.78	47
Argentina	0.80	37	0.86	43	Egypt	0.39	93	0.49	85	Lithuania	0.75	43	0.87	41	Slovak	0.62	50	0.76	48
Armenia	0.42	89	0.60	67	El Salvador	0.38	95	0.42	98	Malaysia	0.30	102	0.32	104	Slovenia	0.57	60	0.60	63
Australia	0.77	40	0.84	45	Eritrea	0.39	94	1.00	1	Mexico	0.16	112	0.17	113	South Africa	0.43	87	0.43	96
Austria	0.84	31	1.00	1	Estonia	0.35	98	0.45	92	Moldova	0.34	99	0.35	103	South Korea	0.84	32	0.91	38
Azerbaijan	1.00	1	1.00	1	Ethiopia	0.96	25	1.00	1	Mongolia	0.20	111	0.22	111	Spain	0.50	67	0.50	81
Bangladesh	1.00	1	1.00	1	Finland	0.45	81	0.45	93	Morocco	0.42	88	0.43	97	Sudan	0.83	35	0.88	39
Belarus	0.47	75	0.48	88	France	1.00	1	1.00	1	Mozambique	0.75	42	1.00	1	Suriname	0.12	115	0.12	115
Belgium	1.00	1	1.00	1	Gabon	0.82	36	0.97	36	Namibia	0.14	113	0.15	114	Swaziland	0.86	30	1.00	1
Benin	1.00	1	1.00	1	Germany	0.86	29	0.88	40	Nepal	1.00	1	1.00	1	Sweden	0.60	54	0.61	61
Bolivia	0.36	96	0.39	100	Ghana	0.45	79	1.00	1	Netherlands	0.96	24	0.98	35	Switzerland	1.00	1	1.00	1
Botswana	0.62	51	0.68	53	Greece	0.52	62	0.53	77	New Zealand	0.70	47	0.71	50	Syrian Arab	0.43	85	0.50	81
Brazil	1.00	1	1.00	1	Guatemala	0.48	70	0.52	79	Nicaragua	0.21	109	0.21	112	Tanzania	1.00	1	1.00	1
Bulgaria	0.26	106	0.27	107	Honduras	0.29	104	0.29	106	Niger	0.43	84	0.66	59	Thailand	0.49	68	0.54	75
Cambodia	0.79	38	1.00	1	Hungary	0.43	83	0.43	94	Nigeria	0.48	71	0.56	71	Togo	0.29	103	0.67	57
Cameroon	0.88	27	1.00	1	India	0.73	45	0.75	49	Norway	0.78	39	1.00	1	Trinidad & Tobago	0.41	90	0.55	72
Canada	0.58	58	0.58	69	Indonesia	0.66	48	0.68	54	Oman	0.48	73	0.49	84	Tunisia	0.28	105	0.30	105
Central African	1.00	1	1.00	1	Iran	0.43	85	0.48	86	Pakistan	0.31	101	0.41	99	Turkey	0.44	82	0.47	90
Chile	0.48	71	0.59	68	Ireland	1.00	1	1.00	1	Panama	0.49	68	0.54	73	Turkmenistan	0.23	108	0.24	109
China	0.87	28	0.87	41	Israel	1.00	1	1.00	1	Papua New Guinea	0.13	114	0.67	55	Ukraine	0.24	107	0.26	108
Colombia	1.00	1	1.00	1	Italy	0.47	75	0.47	89	Paraguay	0.59	57	0.60	62	UK	1.00	1	1.00	1
Congo, Rep.	1.00	1	1.00	1	Jamaica	0.46	78	0.67	56	Peru	0.90	26	1.00	1	USA	1.00	1	1.00	1
Costa Rica	0.35	97	0.37	101	Japan	1.00	1	1.00	1	Philippines	0.45	80	0.46	91	Uruguay	0.56	61	0.57	70
Cote d'Ivoire	0.84	34	1.00	1	Jordan	0.11	116	0.12	116	Poland	0.57	59	0.60	65	Venezuela	1.00	1	1.00	1
Croatia	0.75	44	0.81	46	Kazakhstan	0.46	77	0.49	83	Portugal	0.51	65	0.52	80	Vietnam	1.00	1	1.00	1
Cuba	0.21	110	0.22	110	Kenya	0.40	91	0.52	78	Romania	0.66	49	0.66	58	Yemen	0.40	92	0.43	95
Cyprus	1.00	1	1.00	1	Kuwait	1.00	1	1.00	1	Russia	0.84	33	0.92	37	Zambia	0.52	64	0.60	63
Czech	0.52	62	0.53	76	Latvia	0.33	100	0.36	102	Saudi Arabia	0.51	66	0.54	74	Zimbabwe	0.62	52	0.65	60

Appendix B
Alternative Tobit models.

Variables	Constant return to scale		Variable return to scale	
	Coef.	*p*-value	Coef.	*p*-value
Constant	−0.43184	0.05900	−0.45600	0.08000
Labour participation rate	0.01499	0.00000	0.01853	0.00000
Population density	0.00097	0.00000	0.00081	0.00400
Urban population share	0.00207	0.19200	0.00055	0.76100
Share of natural resource rents in GDP	0.00002	0.98900	−0.00071	0.57100
Imports	−0.00419	0.00100	−0.00312	0.02500
Net imports of energy	−0.00024	0.07400	−0.00039	0.03000
PPP GDP per capita	0.00001	0.45100	−0.00001	0.64100
PPP GDP per capita (square)	0.00000	0.84400	0.00000	0.15500
LR chi2	73.79000	0.00000	70.17000	0.00000
Pseudo *R*-square	0.7114		0.5389	

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