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Integrated Resource Efficiency: Measurement and Management

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Integrated Resource Efficiency: Measurement and Management

Purpose: Drawing on the Systems Theory and the Natural Resource Based View, this paper advances an Integrated Resource Efficiency View (IREV) and derives a composite *'Integrated Resource Efficiency Index'* (IRE-Index) for assessing the environmental, economic, and social resource efficiencies of production economies.

Design/Methodology/Approach: Using sub-national input-output data, the IRE-Index builds on the Human Development Index (HDI) and the OECD Green Growth Indicators by including functions for environmental resource efficiency, energy, and material productivity. The study uses multiple regressions to examine and compare the IRE-index of 40 countries; including 34 OECD nations. The study further compares the IRE-Index to similar composite indicators such as the Human Sustainable Development Index (HSDI) and the Ecological Footprint.

Findings: The IRE-Index reveals a discrepancy between social development and resource efficiency in many of the world's wealthiest production economies. Findings also show that material productivity has been the key driver for observed improvements in integrated resource efficiency over time. The index is a robust macro-level methodology for assessing resource efficiency and sustainability, with implications for production operations in global supply chains.

Originality/Value: The IREV and IRE-Index both contribute towards advancing green supply chain management and sustainability, and country-level resource efficiency accounting and reporting. The IRE-Index is a useful composite for capturing aggregate environmental, economic, and social resource efficiencies of production economies. The paper clearly outlines the managerial, academic and policy implications of the IREV and resulting Index.

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1.0 Introduction

According to United Nations estimates, about twice the current resource capacity of the earth would be required to keep up with the global pace of production, consumption, and population growth by the 2030's (Global Footprint Network, 2015). In response to this alarming trend and other environmental cues, governments and business stakeholders are making more commitments towards tackling resource sustainability and associated challenges like global warming, soaring energy consumption, and depleting natural resources (Alblas et al., 2014, Koh et al, 2013). Resource efficiency and sustainability have thus become prominent features in today's academic and socio-political discourse. According to the European Commission, resource efficiency strives to achieve two objectives; first, to utilize natural resources sustainably without exceeding the earth's long-term boundaries; and secondly, to minimize the impact of natural resource extraction on human wellbeing and the environment (European commission, 2011).

From a policy viewpoint, key economic blocs have taken a number of commendable initiatives to promote, enshrine, and measure resource efficiency and sustainability systematically. Notable initiatives include the 'Resource Efficient Europe' framework (European Commission, 2010), the triple-R approach (reduce-reuse-recycle) towards a 'Sound Material-Cycle Society' in Japan (Takiguchi and Takemoto 2008), and the 'Circular Economy' initiative for cradle-to-cradle and closed-loop material flows in China (Yuan and Moriguichi 2006). However, some have argued that such political initiatives tend to prioritize economic growth over social development and environmental preservation (Hsu et al., 2016, Giddings et al., 2002, Hopwood et al., 2005, Hajar, 1995). For instance, Dempsey et al., (2011) highlighted the lack of a clear policy definition of social sustainability, despite recent European policy rhetoric on 'social cohesion' and 'sustainable communities'. Likewise, presenting the 2015 Work Programme to the European Parliament, the Commission's first vice president, Frans Timmermans, reiterated the commission's commitment to environmental and social issues, but argued for a "more ambitious proposal" on the circular economy with greater focus on the economy (European Commission, 2014).

Studies have highlighted the interconnectedness of the environmental and socio-economic aspects of resource efficiency across scalar, network, and regional boundaries. These studies are often underpinned by theories like the resource based view (Carter and Rogers, 2008; Sodhi, 2015), natural resource based view (Shi et al., 2012), institutional theory (Dubey et al., 2015), organisational theory (Sarkis et al., 2011), stakeholder theory (Matos and Hall, 2007, Varsei et al., 2014), and system theory (Alblas et al., 2014, Bai et al., 2012). For instance, Figge and Hahn (2004) argued that firms would readily adopt sustainable corporate practices if the overall value added by such practices outweighs the value of the best alternative forgone (the opportunity cost of sustainability). Likewise, findings from Delmas and Pekovic (2015) showed that about 10% of companies in a survey, adopted sustainable resource practices during market recessions compared to about 46% under growing market conditions. These findings support the predominant narrative of profit maximization among corporations in post-industrial economies (York and Rosa, 2003), yet, 'political ecology' and 'environmental policy' researchers suggest that sustainable development is primarily achieved through policy making and strict regulation of the socio-economic and environmental resource practices of production economies and supply chains (Conroy and Berke, 2004). Taking into account the fiduciary duties of corporations to their stakeholders, stricter laws and regulations could create conflicts of interest. On one hand, there are short-term financial implications and scalability challenges encountered in translating macro-level sustainability targets into production and operations objectives. On the other hand, social and environmental dimensions of resource efficiency could have profound impacts on the profitability and survival of businesses as 'going concerns' (Longoni and Cagliano, 2015, Duflou et al., 2012; Reinhardt et al., 2012). Pagell and Shevchenko (2014) argued that the environmental and social aspects of resource efficiency and sustainability such as green supply chain management, employee commitment, and ethical procurement practices, are rooted in old and economically viable management strategies like quality control and supplier certification. They argued that the current challenge with research and practice on resource efficiency and sustainability is "compounded by measures that do not truly capture a supply chain's impacts and methods that are better at looking backwards than forwards". Furthermore, with the prevalence of outsourcing, boundary spanning suppliers, and advanced information sharing and logistics capabilities in production supply chains, modern operations often cut across different markets and national/supra-national regulatory environments. However, Wilson et al. (2007) noted that the current macro-level indicators and metrics of resource efficiency yield varying and sometimes conflicting measures of the resource efficiency of nations.

In view of the impact of macro-level resource sustainability on production operations, and in response to recent calls for methodologies that aid the assessment of supply chain resource efficiency and sustainability from a multi-stakeholders perspective (Pagell and Shevchenko, 2014), this study aims to develop an Integrated Resource Efficiency Index (IRE-Index), taking a systems view. The IRE-Index provides a top-down approach for assessing macro-level resource efficiency, which reflects aggregate impacts of bottom-up resource practices, environmental protection, and socio-economic performance of supply chain operations in macro-economies. The study objectives include:

1. To develop an *Integrated Resource Efficiency View (hereafter IREV)* to bridge the gap between macro-economic sustainability and the environmental, economic and social resource efficiencies of production operations in sub-systems like supply chains.
2. To develop a methodology and index that integrates the three pillars of sustainability into a single measure with comparable indexes termed *the Integrated Resource Efficiency Index (hereafter IRE-Index).*
3. To verify the stability of the resource efficiency index through the construction of multiple regression models at five separate periods.
4. To validate the IRE-Index by comparing it with previous composite indicators.

The triple bottom line approach often used in sustainability appraisal essentially reports environmental, economic, and social sustainability bottom-lines separately (Andon et al., 2015). By measuring these streams of capital in a single index, this study represents an important, proactive, and theoretical step towards unifying the fragmented research on resource efficiency and sustainability. The study also makes important policy and production operations contributions. First, it seeks to provide a decision-making methodology for supplier selection, network design, and supply chain reconfiguration. Secondly, it represents a useful systematic approach to monitoring and improving sustainability credentials, both at national and supply chain levels. The next section examines the predominant theoretical views on resource efficiency and sustainability in order to arrive at an IREV.

2.0 Integrated Resource Efficiency View: Theoretical development

The political and social debates on resource efficiency have been slightly polarised by the view that fixed trade-offs exist between sustainable resource utilization and economic competitiveness (Daly and Cobb, 1989; Griggs et al., 2013; Hertwich, 2010). This is partly because our current understanding of the complex and multi-layered interactions between resource efficiency and sustainability at micro, meso, and macro levels is somewhat fragmented. In addition, there have been very few attempts to harmonise the environmental, economic, and social capital of sustainability and resource practices. The challenge with taking a one-sided view is that sustainability requires not only reductions in consumption, environmental depletion, and pollution, but also a transformation in the way we live and use natural resources for economic gains, and to support human security, health, and social wellbeing (Griggs et al., 2013; Koh et al, 2012; McMichael et al., 2003).

Although policy makers often conceive sustainability as macro-economic phenomena, there is an invariable link between macro-level sustainability and the resource efficiency of production supply chains. As such, the Resource-Based View (RBV) of firms provides a good starting point for conceptualising resource efficiency. According to the RBV, rare and inimitable resources, supported by tacit skills and socially complex organizational processes gives firms their competitive advantage (Barney, 1991). However, the competitive advantage described in the RBV, is essentially a product of efficient and sustainable production and utilization of resources. Emergent perspectives from the RBV such as the Natural Resource Based View (NRBV) have drawn parallels between long-term socioeconomic and environmental sustainability and the overall notion of resource efficiency. The NRBV argues that the natural environment imposes a constraint on firms' ability to create long-term *sustainable* competitive advantage (Hart and Dowell, 2010). The NRBV succeeds in establishing a logical link between resource efficiency and sustainability, and has been applied in a number of studies to investigate the impact of top-down policy directives on the resource efficiency and sustainability of production operations in supply chains (see Shi et al., 2012; Koh et al., 2013; Sarkis et al., 2011). However, one limitation of both the RBV and the NRBV is that they do not conceptualize resource efficiency and sustainability beyond firm and production supply chains (De Burgos-Jiménez et al., 2013).

The ecological modernization theory on the other hand, provides a top-down view of resource efficiency and sustainability (Bailey and Caprotti, 2014, Korhonen, 2008). Rooted in the philosophy of enlightened self-interest, the theory argues that as capitalist liberal democracies evolve or "modernize", they establish the necessary institutional capacity to push for reforms that eventually give rise to positive economic and ecological outcomes (Buttel, 2000; Mol, 1997). Studies that adopt this perspective or similar are more concerned with the socio-political measures through which modernization produces positive ecological outcomes (Mol, 1997). Nonetheless, critics argue that this promotes a form of “green washing” under the guise that self-regulating corporations and societies would invest in efficient and sustainable practices and technologies (Mejías et al., 2016, Seuring and Müller, 2008). Consequently, such approaches obscure the impact of corporate and supply chains level decisions on macro-level monitoring and regulation of resource efficiency and sustainability (Tachizawa et al., 2015).

Global production chains are extremely complex and interconnected, partly due to the outsourcing of operations across national/supra-national policy regimes, industry-specific regulatory requirements, technological advancements, and boundary spanning suppliers. This suggests that the resource efficiency of countries cannot be captured without considering the production and consumption links that span across regional boundaries (Choi et al., 2011). Despite corporate investments in eco-efficiency measures, overall global resource efficiency still appears to be on the decline (Kallio and Nordberg, 2006) partly because the contributions of “corporate greening” to macro-level resource efficiency is yet unclear. Whiteman et al., (2013) succinctly summed up the key research gap on resource efficiency and sustainability addressed in this study by arguing that:

> “Despite awareness of the declining state of ecosystems, business management scholars have yet to adequately link business processes to macro-ecological processes and boundary conditions.”

A systems theory approach is therefore required to capture the socio-cultural, economic, environmental, energy, material, technical, and individual capital associated to resource practices and cycles from pre-production to post-production, for a more realistic and plausible view of resource efficiency at different scalar levels (Hearnshaw and Wilson, 2013). There are several critical regional and continental resource-interdependencies, particularly around water, minerals, and energy resources. In addition, advancements in communication and global logistics have compounded these macro-level interdependencies through global production supply chains with intercountry operational and tactical resource interdependencies (e.g. labour, expertise and technology) (Djanibekov and Valentinov, 2014). The key premise of the systems thinking is that aggregate performance of each production sector of an economy is required to assess resource efficiency, because intra-system relationships produce path dependent outcomes that affect overall performance (Richardson, 1999). Recent theories on production supply chains have also conceptualized them as ‘complex adaptive systems’ that are significantly path dependent, self-organising, and sensitive to marginal changes in initial conditions (Carter et al., 2015). Therefore, in order to capture resource efficiency adequately, a macro-level systems approach is necessary (Choi et al., 2001; Hearnshaw and Wilson, 2013).

Another important point worth considering in advancing a comprehensive macro-level index for resource efficiency is the production-consumption paradox. Polimeni et al. (2007) suggested two systems approaches for construing macro-level resource efficiency and sustainability to address this paradox. The first approach is to construct alternative views on ‘development’ in order to reduce the global focus on gross domestic product (GDP) maximization. The second option is to assume that global macro-economies are self-regulatory and capable of finding alternatives to scarce natural resources. However, Bridge (2001) argued that such post-industrial political and ecological narratives give primacy to the optimization of consumption without due regard to 'productive spaces', and fuel the predominant world view that resources hold primacy over the spaces that produce them (resource triumphalism). This has led to the proliferation of resource efficiency indicators that obscure the impacts of the production activities of consumptive economies on the resource efficiency of primary commodity-supply zones (Gouldson and Murphy, 1997, Rees, 1996). Therefore, a robust macro-level measure of resource efficiency must account for the simultaneous impact of production and consumption on the sustainability and resource efficiency of nations and their production supply chains.

Reflecting on the foregoing arguments, this study advances a novel theoretical approach aptly termed: *the Integrated Resource Efficiency View (IREV)*, underpinned by arguments from the natural resource based view and the systems theory. Unlike the top-down approach of views like ecological modernization, the main thrust of the IREV is that, nations evolve and adapt to the resource challenges and uncertainties in their production supply chains. The second premise of the IREV is that the environmental, social, and economic capital of resource practices are macro-level reflections of the aggregate resource efficiencies of sub-systems or production supply chains within industrial ecosystems (Hartmann and Moeller, 2014; Hellweg and Canals, 2014). This approach makes an important advancement over previous approaches by taking a systems view of resource efficiency to evaluate how (and if) efficient and sustainable resource practices can diffuse through production supply chains into host production economies. The IREV could also help to overcome the challenge of firms wanting to appear sustainable in response to national or regional institutional pressures, while contributing marginally to overall macro-level sustainability, as a result of boundary spanning suppliers and outsourcing of production activities (Whiteman et al., 2013) . Adopting the IREV and index would enable the alignment of 'corporate greening' strategies at supply chain level with macro-level sustainability targets. In summary, the proposed IREV approach to resource efficiency fosters improvements in the measurement and management of macro-level sustainability with academic, managerial, and policy implication.

2.1 Measuring Resource Efficiency

Resource efficiency is the ratio of outputs to inputs within system, in which optimal equilibrium is the degree to which extracted virgin resources remain relevant in an input-output product or process cycle (Polimeni et al., 2007). As a function of sustainability, resource efficiency strives to optimize the environmental, economic, and social capital of resource practices and cycles simultaneously. Korhonen (2008; p1339) noted that:

> 'actors may need to learn how to appreciate that, at times, suboptimal outcomes at the level of an individual system component can be important for optimal long-term outcomes at the level of the larger system'.

Although reducing consumption is an important system adaptation for mitigating resource shortages and perceived scarcity, as a primary system strategy (Alblas et al., 2014, Hoang, 2014), it often results in suboptimal efficiency outcomes and limited benefits for macro-level sustainability. This is largely because the environmental, economic, and social dimensions of resource capital are interrelated, and the full scope of resource efficiency must take into account the interconnected cycles of inputs and outputs across different geographical, industrial, and operational levels of the macro-economy (Brobst, 2013). Therefore, resource minimization as the objective of resource efficiency according to 'Javon's paradox' often result in increased consumption of other resources or new system inefficiencies in equally relevant input-output cycles. There are other important factors besides the Jevon's paradox, which affect resource efficiency like the 'direct rebound effect'. Direct rebound is evident in the energy industry today, where consumption has exponentially increased partly due to the 'substitution effect' of technical efficiency and progressively lower cost of production (Gillingham et al., 2015). 'Indirect rebound effects' could also impact resource efficiency; a typical example being China – an emerging economy where the growing middle-class and rising income has drastically increased the nation's production and consumption levels (Alblas et al., 2014). Thus, to account for the trade-off between the 'grow now and clean up later' approach to efficiency (UNESCAP, 2009), and the resource minimization approach, a robust resource efficiency indicator should capture economic growth alongside the energy, carbon, and material productivities of input and output cycles. In line with the forgoing the IRE-Index proposed, in this study aims to account for aspects of 'resource effectiveness'- or the degree to which resources cycles are managed to achieve desired environmental, economic, and social capital or productivity; and 'resource efficiency'- or the optimal degree of resource productivities required to improve macro-economic resource sustainability.

2.2 Quantifying Economic Resource Efficiency

Gross Domestic Product (GDP) has remained one of the most recognized global indicators of economic productivity, and the production approach is the most widely applied. It estimates the gross value added per sector by deducting gross output from immediate consumption. Although the approach is robust, GDP is somewhat incomplete because its computation relies on the final value added in each stage of production. A sustainable approach will examine the manner in which GDP is generated, ensuring that economic development and well-being is related to social progress and environmental efficiency. Therefore, in building a composite resource efficiency index, economic factors are embedded in the social and environmental resource efficiency components.

2.3 Quantifying Environmental Resource Efficiency

The OECD Green Growth (2014a, b) document provides a useful framework for computing macro-level environmental resource efficiency in economic terms. This study builds on Green Growth approach and computes environmental resource efficiency as a function of the economic capital associated to the environmental impacts of resource use. The categories of resources capital estimated in this study include:

1. Carbon resources: measured in terms of the volume of carbon emissions and expressed in kg of CO_{2e} required to generate $1 of GDP.
2. Energy resources: measured in terms of the volume of energy resources, in kt_{oe} required to generate $1 of GDP.
3. Material resources: measured in terms of the volume of non-energy resources, in kg, required to generate $1 of GDP.

The proposed IRE-Index computes carbon, energy, and material efficiencies as a function of the change in GDP generated from consuming a given volume of resources. Sustainable environmental resource efficiency would thus induce a substantial increase in GDP with minimal increases in material consumption, energy consumption and emission generation. As noted earlier, efficiency in emission, energy, and material consumption requires a holistic input-output approach with the right mix of minimization, recycling and investment in resource second life, and efficient/effective production processes.

2.4 Quantifying Social Resource Efficiency

Since the 1990's, the United Nations Development Programme (UNDP) has published a series of annual Human Development Reports (HDRs) in which the Human Development Index (HDI) is computed for each country (Sagar and Najam, 1998). This was the first mainstream recognition of 'social development' as a key measure of overall macro-economic development (Sagar and Najam, 1998). According to the HDI, three key parameters determine the state of human development and quality of life – wealth, education, and health. Taken together, these parameters constitute the social capital of a nation. By definition, social capital is the aggregate value derived from production and consumption exchanges within social networks (Chen and Hung, 2014). The human development index (HDI) is arguably one of the most widely used measures of human social capital (UNDP, 2014). It includes a number of social measures like life expectancy, education, disposable income, personal growth, security, and well-being. However, the main criticism of the HDI as an index of resource efficiency and an alternative to the GDP and GNP per capita, is the omission of environmental measures, given the importance of the environment to human wellbeing and sustainability (Neumayer, 2001, Sagar and Najam, 1998). Togtokh (2011) argued that in its current form, the HDI gives high rankings to developed nations and primary commodity zones, with little consideration to the impact of production practices and growth on the ecosystem and human social development. The Human Sustainability Development Index (HSDI) developed afterwards included 'per capita carbon emissions' as a remedy to the shortcomings of the HDI but still does not give a clear picture of resource efficiencies in terms of carbon emissions, energy, and material utilization.

3.0 Methodology

The quantitative approach used to develop and evaluate the IRE-Index draws on the philosophical assumption that reality can be quantitatively determined, but boundary conditions like the level of analysis, region, or industry affect how the resulting quantitative estimates are interpreted (Flynn et al., 1990). The traditional approaches for measuring resource efficiency may vary significantly depending on the level of enquiry.

For macro-economic analysis, the indicators often used include resource scarcity, resource depletion, economic costs, and ecological footprint among others. In contrast, production supply chains use industry standards, balanced scorecards, and corporate social responsibility indicators (Bina, 2013; Whiteman et al., 2013). This study places the boundary condition for assessing the resource efficiency at the country-level, using a sample of thirty-four OECD and six other nations. The IRE-Index uses top-down estimates of bottom-up processes to account for resource efficiency and social wellbeing. As shown in Figure 1, the development of the IRE-Index follows similar steps to the ones used by Zhou et al. (2006) in developing the Composite Environmental Index (CEI). The IRE-Index combines social and economic measures from the HDI with measures of material, energy, and carbon productivities, estimated in economic resource capital terms or the unit of resources produced or consumed for every $1 of GDP.

[Insert Figure 1 here]

3.1 Data

The data used were obtained from the Human Development Index, and the OECD Green Growth Indicators. These indicators enable countries to assess and compare their sustainability performance, and integrates features of green growth with the 'pressure-state-response model' and standard accounting principles (OECD, 2014a). Other composite indexes exist, like the Inequality-adjusted Human Development Index (IHDI), and the Multidimensional Poverty Index (MPI). However, the HDI and Green Growth indicators were chosen over others because they are comparatively straightforward in their analysis, methodologically rigorous, widely adopted, reliable sources with frequently updated data, and policy relevant (OECD, 2014c). Moreover, the HDI is one of the few composite indicators of socio-economic capital with sufficient records and country coverage to enable robust cross-country comparisons of resource efficiency over time (OECD, 2014b). Table 1 provides a description of the variables and the data composition from 1990-2010, used to compute the IRE-Index for the 40 countries sampled in this study. Most of these published variables are updated annually, except the *mean education attainment*, which is updated every 5 years (Barro and Lee, 2013), and the *expected education attainment* updated periodically (UNESCO, 2013). The Green Growth indicators cover four key areas:

- Resource Productivity – the efficient uses of carbon, energy and material resources
- Maintenance of the Natural Asset Base – the levels of depletion of renewable and natural resources including freshwater, biodiversity, animal and plant species
- Benefit to Society – the benefit to people from improvements in the environment such as waste treatment, water sanitisation, and reductions in air pollution
- Economic Opportunities – the economic benefits from pursuing environmental sustainability, including environmental research and development investment and environmental taxes.

This research focuses on the indicators of resource productivity and the maintenance of the natural asset base because (a) the OECD's evaluation of the Green Growth agenda showed that the Resource Productivity indicators were the most developed of the four key areas (OECD, 2014c), and (b) the socio-economic aspects are covered by the HDI used in formulating the IRE-Index. As such, this study represents an initial attempt at developing composite environmental resource efficiency indicators with measures of socio-economic wellbeing, estimated in resource capital terms or the units of resources produced or consumed for every $1 of GDP generated. The 40 countries covered includes the thirty-four OECD nations and six others (Brazil, China, India, Indonesia, Russia, and South Africa). This produced a dataset that includes the main production economies and covers six continents. Table1 shows the sample demography.

[Insert Table 1 here]
[Insert Table 2 here]

3.2 Metric components

Our measure of environmental resource efficiency compares countries based on their productivities in carbon, energy, and material utilization. As shown in table 2, the correlation coefficient between carbon and energy productivities and energy and material productivities respectively are statistically significant at the 0.05 level. With the exception of carbon and energy in 1990, the correlation coefficients do not exceed $|r|>0.7$, which indicates a sufficient level of independence among the variables. A comparison of the correlation coefficients between carbon emissions and energy over time revealed a decline (a reduction from $r= 0.744$ in 1990 to $r=0.527$ in 2010), which points to some degree of de-coupling between energy use and carbon emissions. Due to the limited self-reporting of firm-level environmental management practices (De Burgos-Jimenez et al., 2013) this study used available and reliable macroeconomic data to construct the environmental resource efficiency index. Two functions were required for this computation:

Step 1: The index for each component of resource efficiency (x) shown in Equation 1 below:

Equation 1: Index Calculation Formula:

$$x\ index = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{1}$$

Where x = the component of resource efficiency being measured, min(x) = minimum value of x over the observed period, max(x) = maximum value of x over the observed period

Any changes in x over time indicates absolute progress in the given component.

Step 2: The aggregate environmental index in line with the HDI approach as shown in Equation 2:

Equation 2: Environmental Resource Efficiency Index

$$EREI = \sqrt[3]{CPI \cdot EPI \cdot MPI} \tag{2}$$

Where EREI = Environmental Resource efficiency Index; CPI = Carbon Productivity; EPI = Energy Productivity Index; MPI = Material Productivity Index

3.3 Constructing the Integrated Resource Efficiency Index

The HDI explicitly covers two of the three dimensions of sustainability, including two social indicators (education and life expectancy), and an economic indicator (per capita income), therefore it measures both social resource efficiency, and economic resource efficiency (García-Sanchez et al., 2015). As noted, the HSDI advanced the HDI by including an environmental indicator (per capita CO_2 emissions) to downplay the ‘celebration’ of ‘gasguzzling' nations and those that outsource material and energy intensive production activities (Bravo, 2014). The IRE-Index proposed here extends this approach by incorporating new dimensions to capture energy and material productivity in addition to carbon productivity. This index examines and compares the units of carbon, energy, and material resource utilization required to generate \$1 of GDP in each country, as opposed to the Bravo (2014) approach of measuring CO_2 emissions per capita. To ensure consistency in the economic data used to test the IRE-Index, we adopted the income index methodology from the pre-2010 human development index. This gives an index that is unit-less, with values ranging from zero (resource inefficient and unsustainable) to one (resource efficient and sustainable). Equation 3 below shows the functions of the IRE-Index:

Equation 3: IRE-Index

$$IRE\_Index = \sqrt[6]{CPI \cdot EPI \cdot MPI \cdot LEI \cdot EI \cdot AII} \quad (3)$$

Where: CPI = Carbon Productivity; EPI = Energy Productivity Index; MPI = Material Productivity Index, LEI = Life Expectancy Index, EI = Education Index, AII= Pre 2010 Income Index

3.4 Verification of the IRE-Index

The IRE-index was verified using five, multiple linear regression models estimated at different periods. Using the multivariate analysis function in SPSS (version 19), random intercepts were fitted and regression models created, with the IRE-Index as the outcome variable. In the first analysis, five regression models were built, filtering the country records over a 5 year period, to produce one model for each year of available data (1990, 2000, 2005, 2008, and 2010), where N = 40 for each regression model. In the second analysis, a regression model was built using all observed points in a panel analysis (40 countries with a 5 year period, N=200). The dependent variable in both models is the IRE-Index, and the independent variables include the carbon component, energy component, material component, income component, life expectancy component, and education component. β coefficients were estimated to identify the relative strengths of each component within the regression models. R^2 statistics showed the amount of variation in the IRE-Index explained by variations in its underlying components, and the direction of change over time.

3.5 Validation of the Index

The IRE-Index was compared with existing composite measures of sustainability; including the ecological footprint, environmental performance index (EPI) (SEDAC-CIESIN, 2016), the HDI, and the HSDI; and the most recent available estimates (2008) were used for all variables. Table 3 shows that the measures chosen cover environmental resources (EPI); social and economic development (HDI), and measures that combine these approaches to varying extents (HSDI and EF). The IRE-Index measures per country were correlated with these composite measures of resource efficiency and sustainability. A positive correlation is required however; it is preferable not to have perfectly correlated measures in order to demonstrate that the proposed IRE-Index extends the existing measures of sustainability.

Table 4 shows a comparison of the IRE-Index indicators developed in this study against other sustainability indicators.

[Insert Table 3 here]
[Insert Table 4 here]

As shown, the IRE-Index moderately correlates with the human development index (r=0.443), the environmental performance index (r=0.583), the human sustainable development index (r=0.465), and the ecological footprint (r=0.374). The correlations are statistically significant at the 0.05 level, but have minimal practical significance, since less than 35% of the variation in the IRE-Index is explained by variation in the three sustainability indicators (where r^2 = 0.19; 0.34; 0.22; 0.138 respectively). Correlations between the individual components also show how the EREI is moderately correlated with the Environmental Performance Indicator (r=0.542), and much weakly correlated with the Human Development indicator (r=0.256), whilst the reverse is true for the SREI (r= 0.393 and 0.672 respectively). These results indicate that the EREI and SREI are broadly measuring environmental and social aspects of sustainability, but are not simply replicating previous research.

Evaluating the associations between the EREI, SREI, IREI demonstrate that the IRE-Index generates results that are broadly comparable with previous approaches for measuring sustainability, but substantially extends previous methodologies by integrating both environmental and social sustainability measures, which are comprised of economic components. The novelty of the IRE-Index lies in its ability to assess sustainability and resource efficiency with measures of environmental, social, and economic productivities that are interpretable at different scales.

By accounting for carbon emissions, material productivity, and energy productivity per unit of GDP in its computation, the IRE-index is more suitable for evaluating industrial sustainability performance than the previous measures such as the HSDI, which only computes carbon emissions per head (Bravo, 2014). The IRE-index is an improvement on the EPI and EF in terms of practical applications. These indicators are an agglomeration of numerous detailed and specific underlying sustainability components and require large data for computation at scales below country level, whereas the IRE-Index's six components can be replicated using locally collected data. It addition to its potential for scalability, the IRE-index is a step towards overcoming the biases in previous measures towards either ecological or economic indicators.

4.0 Results and Findings

[Insert Table 5 here]
[Insert Table 6 here]

Results of the regression analyses presented in tables 5 and 6 show the variations in the efficiency and productivity components of the IRE-Index for the years 1990, 2000, 2005, 2008 and 2010. The adjusted R^2 statistic ranged between 0.395 and 0.478, implying that approximately 60% of the variations observed in the IRE-Index over the period cannot be explained by variations in the six underlying components. A comparison of the β coefficients shows that the material component and life expectancy are statistically significant at the 0.05 level in the 2000 model and becomes progressively more important, while the income component declined in importance from the 1990 model. Taking each country's results for each of the 5 years as different points in the overall model, the observed pattern continues, signifying a dominance of material consumption and life expectancy.

Furthermore, between 1990 and 2010, increases in material consumption efficiency, led to improved integrated resource efficiency as expected. This suggests that relative improvements in the productive processes and materials management of firms operating within the countries examined was perhaps a key driver of the overall environmental performance in the sampled countries over the observed period. By contrast, relative increases in life expectancy was associated with declining integrated resource efficiency, which appears counter-intuitive considering the arguments on social sustainability. This somewhat indicates that greater resource consumption is required to improve life expectancy in highly socially developed countries. However, it is noteworthy that further research is required to establish the relationships and interactions among the underlying components of the IRE-Index over time.

The 40 countries estimated are somewhat highly ranked on the Human Development Index; thus, one could argue that there is a lack of true variation in the relative social development levels across these countries. In addition, macro-level factors like the current and historical national and supranational sustainability policies and regulations may have influenced the pace of social development in these countries. Thus, variations in the different environmental indexes indicates that perhaps, aggregate micro and meso level activities affect the observed variations in integrated resource efficiencies in these countries. Speculating beyond the data, the otherwise obscured impact of outsourcing, production practices, global supply chains, and boundary-spanning suppliers, which are less obvious with other measures, become more evident with the IRE-Index.

4.1 Country ranking based on the IRE-Index

Table 7 presents the ranking of countries by IRE-Index, and figure 2 shows a scatterplot of environmental resource efficiency index against social resource efficiency index for 2010. The results show that in the top 10 countries by integrated resource efficiency, the environmental resource efficiency measures are lower in comparison to social measures. The correlation between these two indexes was relatively low but positive (r=0.318), implying that a wide discrepancy does exist between social and environmental sustainability in OECD countries.

[Insert Table 7 here]

[Insert Figure 2 here]

Given the relatively high levels of social development in the countries examined (with India having the lowest social index of 0.61), variations in the IRE-Index are primarily driven by changes in the environmental resource efficiency index in each country, from 0.1 in China to 0.87 in Switzerland. Using IRE-Index, managers could rank regions by their integrated resource efficiencies to inform production-outsourcing decisions and supply chain reconfiguration. Opting to source for suppliers or build capacity in resource efficient countries could improve supply chain sustainability and contribute towards improving the combined environmental and socio-economic sustainability of countries.

The IRE-Index further reveals that the former soviet states, and less developed countries have lower levels of environmental and social resource efficiency in comparison to highly developed nations. Consistent with the findings from Bravo (2014), the IRE-Indexes countries heavily dependent on fossil fuels is significantly affected by poor energy efficiencies. For example, the rankings of Australia and USA on the IRE-Index dropped to 31st and 19th respectively, compared to a ranking of 2nd and 4th respectively on social resource efficiency. What appeared rather surprising is the low rankings of Denmark and Sweden, notable for their environmental credentials. Yet in both countries, material productivity was below the sample average of the 40 nations studied. Denmark's material and CO_2 productivity in 2010 stood at \$2.25 per kg of non-energy material, and \$3.82 per kg of CO_2 emitted, which is close to the average recorded (\$2.30, and \$3.45 respectively). Sweden ranked even lower on material productivity at \$1.79 per kg of non-material resources. This along with poor energy efficiencies, reduced the overall IRE-Index scores for both countries, and has implications for policy makers, corporate entities and supply chains operations and configuration.

China recorded the lowest IRE-Index score in 2010 due to the sharp increase in the nation's underlying CO_2 and energy productivities between 1990 and 2010. However, in the same period, China's material efficiency improved by 67%. If China continues to grow at the projected pace, and investments are made in efficient production processes in line with the circular economy initiative, the country could move up significantly in global sustainability rankings. This has implications for companies sourcing from China. At present, the environmental and socio-economic resource efficiencies associated to sourcing from China is low and this has business and policy implications for the resource efficiency of China's major customers in North America and Europe. However, if China continues to invest in sustainable infrastructure and social development, perhaps partly driven by emerging global initiatives, the country's integrated resource efficiency is likely to improve, as well as the sustainability and competitiveness of production operations in China.

5.0 Discussion

The IREV articulated in this study argues that sustainability and resource efficiency require the productive use of material and energy resources, minimised carbon emissions, and socio-economic capital. On this premise, the study examined country level sustainability by determining the environmental, economic and social resource efficiencies of countries estimated in terms of unit of resource inputs or outputs required to generate \$1 of GDP. As such, the IRE-Index provides a decision support framework for supplier selection, outsourcing production, and supply network design. Furthermore, it contributes towards overcoming the limitation of corporate-level resource efficiency accounting with little consideration to the overall capitalized impact of production efficiencies, including the remote impacts associated to operations in primary commodity zones.

The IRE-Index further demonstrates that resource efficiency is a composite function of economic growth, material productivity, energy productivity, and carbon productivity. A good measure of resource efficiency should account for changes in material, energy, and carbon productivities in order to assess the sustainable development of nations and corporate entities. The ranking of OECD countries based on the IRE-Index highlighted how improvements in production supply chains contributed to improved material productivity and overall environmental sustainability over the observed period. Although the analysis centres on resource efficiency at the country level, it highlights the practical drawbacks of taking a purely top-down or bottom-up perspectives to resource efficiency. The IRE-Index is important for managers of global supply chains because resource efficiency and sustainability is shaped by non-linear and complex global interactions that link the activities and accountability of firms and supply chains to the nation states where they operate (Whiteman et al., 2013).

Other composite measures have estimated resource efficiency either as a percentage of GDP, or in terms of carbon emissions per capita such as the HSDI; however, such approaches are limited because they essentially capture the sustainability of countries, without considering the impact of resource efficiency within global and interconnected production and consumption supply chains. By determining the amount of energy and materials required to produce $1 GDP, the overall resource efficiency of countries based on the IRE-Index reflects the productivities of both local and outsourced activities that contribute to a country's GDP. Where detailed developments for composite measures of sustainability are available, such as the EPI, the applications beyond simply ranking countries and monitoring over time appear limited due the large number of variables included in the calculation of each measure. The IREI (and its underlying composite parts) provides an overview of resource efficient sustainability with lower computational requirements. The reputable nature of the resources used in the development of the IRE-Index (OECD and UN Development Programme), combined with the simplicity and transparency in quantifying resource efficient sustainability serves as a useful measure of a complex, and difficult phenomenon (Moldan et al., 2004). This summarization and synthetisation of environmental, social, and economic data in a transparent manner provides essential information for decision-making, both internally and to justify to stakeholders (García-Sanchez et al., 2015).

A comparison of the social and environmental resource efficiencies of the 40 countries sampled in this study revealed that the two spheres of resource efficiency are not as aligned as previous indicators might suggest. Despite the relatively high levels of social resource efficiency in OECD countries, the IRE-Index indicated varying material, energy, and carbon resource efficiencies across these nations. As noted, the IRE-Index could help supply chain leaders and policy makers to identify the most resource efficient regions to build/outsource production operations in order to achieve simultaneous economic, environmental, and social performance. For policy makers, the study demonstrates through the IRE-Index, the potential impact of policy decisions on the economic competitiveness and sustainability of nations and corporate entities. There is scope for future research to quantify the relationship between resource efficiency at supply chain level from pre-production to pros-production, and the integrated resource efficiency of countries.

6.0 Conclusions

This paper addressed the research challenges encountered in measuring sustainability and resource efficiency building from previous theoretical approaches. Specifically, we propose an IREV and a corresponding index, to extend the operationalisation of sustainability and resource efficiency beyond measures of carbon emissions, to incorporate material and energy productivities, as well as socio-economic indexes. Furthermore, the study identified and addressed a critical gap in previous research, by developing and validating an index with multiple scales, which is applicable at multiple levels. It considers the efficient consumption of natural resources to generate economic growth, in relation to impacts on human health, as opposed to measuring the economic, social, and environmental sustainability in isolation. This contributes towards advancing the fields of green supply chain management, and corporate responsibility by developing resource efficiency indicators at a macro level, which account for the aggregate effect of micro- and meso-level practices. Findings show that material productivity is the key driver for improved integrated resource efficiency, and that there is a discrepancy between social development and IRE in many of the world's wealthiest nations. In addition to the outlined theoretical contributions, this study also has implications for practice and policymaking. It provides a holistic framework for policy makers and supply chain managers to aid decisions on the selection of sustainable regions to operate and expand supply networks, supplier selection decisions and corporate/regional sustainability accounting. As with all empirical studies, there are some limitations associated to the scale of measurement. While logical deductions regarding supply chain resource efficiency were made based on theory and macro-level IRE-indexes, the study does not directly explore the impact of macro-level IRE-Indexes on supply chain resource efficiency and vice-versa. Industry level analysis would prove directional for future studies aimed at applying the IRE-Index developed to company and supply chain-level analysis. Hybrid input-output and life cycle analyses could be used to quantify relevant material, energy, and emissions cycles associated to production operations in supply chains.

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Table 1 Data sources used in this research

Original Data Source	Organisation	Published Variables	Description	Year(s)	Frequency of Update
OECD (2014)	OECD (2014)	Carbon Productivity	Production based CO2 productivity is measured by GDP generated per unit of CO2 emitted.	1990 - 2010	Annual
		Energy Productivity	Expressed as GDP per unit of total primary energy supply (TPES) in ktoe	1990 - 2010	Annual
		Material Productivity	Material domestic consumption productivity is expressed as the amount of economic output GDP generated for a unit of material consumed. The focus is on non-energy materials, which include biomass for food and feed, wood, construction minerals, industrial minerals, and metals.	1990 - 2010	Annual
		GDP (U$ 2005 Prices)	In national currency, in current prices and constant prices (national base year, previous year prices and OECD base year i.e. 2005) - and for comparative purposes in US $ current prices and constant prices (using exchange rate and PPPs). Expressed in millions and in indices.	1990 - 2010	Annual
		Total Population	Data for total population may be compiled following two basic concepts: – "Present-in-area population" or de facto, i.e. persons actually present in the country on the date of the census. - "Resident population" or de jure, i.e. Persons regularly domiciled in the country on the date of the census.	1990 - 2010	Annual
Barro and Lee (2013)	Research	Mean Education Attainment	Average number of years of education received by people ages 25 and older, converted from education attainment levels using official durations of each level.	1990-2010	5-Yearly
UNESCO (2013)	United Nations	Expected Education Attainment	Number of years of schooling that a child of school entrance age can expect to receive if prevailing patterns of age-specific enrolment rates persist throughout the child's life.	1990 - 2010	Sporadic
UNDESA (2013)	United Nations	Life Expectancy at Birth	Number of years a newborn infant could expect to live if prevailing patterns of age-specific mortality rates at the time of birth stay the same throughout the infant's life.	1990-2011	Annual

Table 2: Correlation Coefficients between Green Growth Indicators

	1990			2000			2005			2008			2010		
	Carbon	**Energy**	**Material**	**Carbon**	**Energy**	**Material**	**Carbon**	**Energy**	**Material**	**Carbon**	**Energy**	**Material**	**Carbon**	**Energy**	**Material**
Carbon	1	0.748**	0.220	1	0.677**	0.320*	1	0.573**	0.261	1	0.495*	0.263	1	0.527**	0.227
Energy	0.748**	1	0.368*	0.677**	1	0.388*	0.573**	1	0.353*	0.495*	1	0.398*	0.527**	1	0.401*
Material	0.220	0.368*	1	0.320*	0.388**	1	0.261	0.353*	1	0.263	0.398*	1	0.227	0.401*	1

* indicates statistical significance at the 0.01 level

** indicates statistical significance at the 0.05 level

Table 2 Alternative Composite Indicators of Sustainability

Original Data Source	**Organisation**	**Published Variables**	**Description**
UNDP (2014)	United Nations	Human Development Index (HDI)	Index describing a country's progress by taking into account Gross National Product per Capita; Mean and Expected Educational Attainment; and Life Expectancy at Birth
SEDAC (2016)	CIESIN	Environmental Performance Index (EPI)	Measures progress towards environmental sustainability of 142 countries
Bravo (2014)	Research	Human Sustainable Development Index (HSDI)	Human Development Index with additional component of Index of Carbon Emissions per Capita
Global Footprint Network (2014)	Global Footprint Network	Ecological Footprint (EF)	Estimates the burden on natural systems of consumption processes. Measured in global hectares.

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Table 4 Regression Analysis for Multiple Years of Data

	1990 Model		**2000 Model**		**2005 Model**		**2008 Model**		**2010 Model**		**Overall Model**	
	β	**t-statistic**	**β**	**t-statistic**	**β**	**t-statistic**	**β**	**t-statistic**	**β**	**t-statistic**	**β**	**t-statistic**
Carbon Component	-0.105	-0.533	-0.073	0.377	-0.70	0.414	-0.006	-0.039	0.001	0.007	0.04	0.087
Energy Component	0.051	-0.257	-0.057	-.317	0.005	0.033	-0.027	-0.186	-0.049	-0.336	-0.024	-0.637
Material Component	0.251	1.509	0.406	2.595**	0.410	2.606**	0.546	3.464**	0.550	3.652**	0.204	5.801**
Income Component	0.287	1.369	0.103	0.478	0.094	0.461	-0.055	-0.268	0.020	0.102	0.006	0.080
Life Expectancy Component	-0.515	-3.480**	-0.610	-4.692	-0.555	-4.340**	-0.597	-4.754**	-0.665	-5.234**	-0.445	-9.582**
Education Component	-0.170	-0.919	-0.160	-0.952	-0.236	-1.486	-0.225	-1.436	-0.279	-1.852*	-0.011	-0.009

** indicates statistical significance at the 0.05 level

* indicates statistical significance at the 0.1 level

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Table 5 Regression Model Statistic

	1990 Model		2000 Model		2005 Model		2008 Model		2010 Model		Overall Model	
	Value	**F-statistic**	**Value**	**F-statistic**	**Value**	**F-statistic**	**Value**	**F-statistic**	**Value**	**F-statistic**	**Value**	**F-statistic**
Adjusted R^2 Statistic	0.395	5.525**	0.412	5.552**	0.393	5.212**	0.440	6.112**	0.478	6.957	0.413	24.33**

** indicates statistical significance at the 0.05 level

* indicates statistical significance at the 0.1 level

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Table 6 Comparison of Resource Efficiency Sustainability Index against existing indicators of sustainability

	EREI	SREI	IREI	HDI	EPI	HSDI	EF
EREI	1	0.318	0.964**	0.256	0.542**	0.290	0.201
SREI	0.318	1	0.534**	0.672**	0.393*	0.620**	0.635**
IREI	0.964**	0.543**	1	0.443**	0.583**	0.465**	0.374*
HDI	0.256	0.672**	0.443**	1	0.500**	0.986**	0.835**
HSDI	0.542**	0.393*	0.583**	0.500**	1	0.526**	0.427**
EPI	0.290	0.620**	0.465**	0.986**	0.526**	1	0.779**
EF	0.201	0.635**	0.374*	0.835**	0.427**	0.779**	1

* indicates statistical significance at the 0.01 level

** indicates statistical significance at the 0.05 level

Where EREI = Environmental Resource Efficiency Indicator; SREI = Social Resource Efficiency Indicator; IREI = Integrated Resource Efficiency Indicator; EPI = Environmental Performance Index; HDI = Human Development Index; HSDI = Human Sustainable Development Index, EF = Ecological Footprint

Table 7 Resource Efficiency Index (2010)

	EREI	SREI	IREI
Switzerland	0.87	0.87	0.87
United Kingdom	0.75	0.85	0.80
Greece	0.68	0.86	0.76
Japan	0.65	0.90	0.76
Netherlands	0.63	0.89	0.75
Luxembourg	0.60	0.92	0.75
France	0.60	0.90	0.74
Italy	0.63	0.87	0.74
Norway	0.57	0.90	0.72
Germany	0.56	0.90	0.71
Spain	0.60	0.82	0.70
Ireland	0.53	0.89	0.68
Denmark	0.52	0.88	0.68
Austria	0.50	0.91	0.67
Israel	0.50	0.87	0.66
Sweden	0.50	0.88	0.66
Portugal	0.47	0.81	0.62
USA	0.41	0.90	0.61
Belgium	0.43	0.86	0.61
Slovenia	0.44	0.83	0.60
Hungary	0.44	0.80	0.59
Korea	0.37	0.88	0.57
Slovakia	0.39	0.83	0.56
Czech Republic	0.35	0.85	0.55
Mexico	0.38	0.77	0.54
New Zealand	0.33	0.86	0.54

Canada	0.29	0.90	0.51
Turkey	0.37	0.68	0.51
Poland	0.30	0.80	0.49
Australia	0.26	0.91	0.48
Brazil	0.29	0.74	0.46
Finland	0.25	0.86	0.46
Iceland	0.23	0.88	0.45
Estonia	0.20	0.83	0.41
Russia	0.19	0.75	0.38
Indonesia	0.21	0.67	0.37
Chile	0.17	0.80	0.36
India	0.21	0.61	0.36
South Africa	0.17	0.63	0.33
China	0.10	0.76	0.28

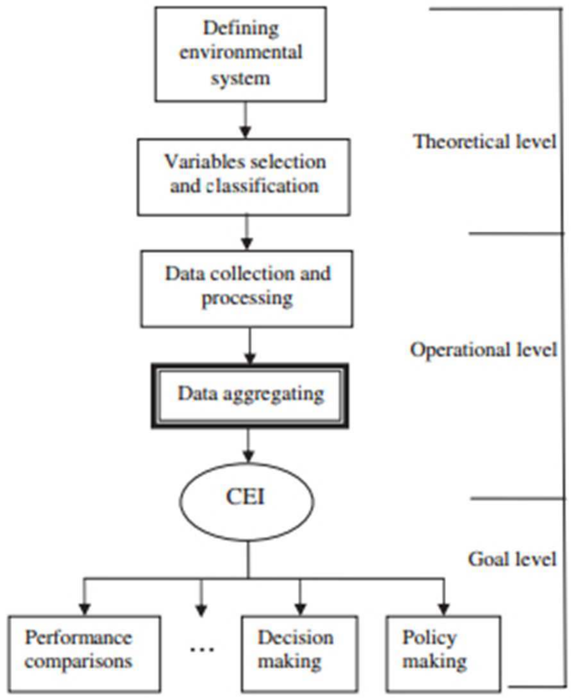

Figure 1 Constructing a Composite Environmental Index (Source: Zhou et al. 2006)

94x110mm (96 x 96 DPI)

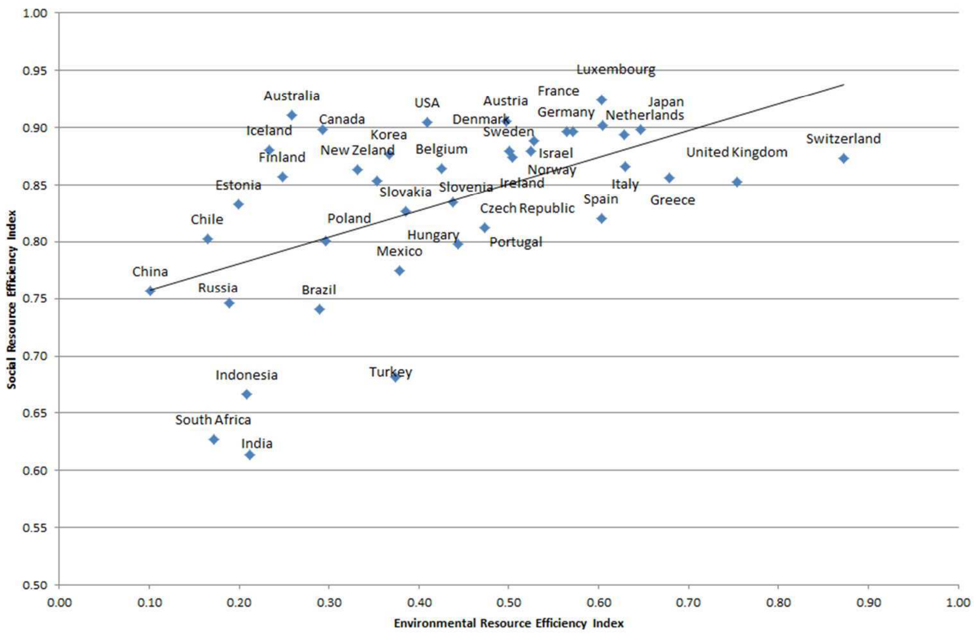

Figure 2 Comparing Environmental and Social Resource Efficiency Indices (2010)

258x177mm (96 x 96 DPI)