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Measuring the Environmental Sustainability Performance of Global Supply Chains: a Multi-Regional Input-Output analysis for Carbon, Sulphur Oxide and Water Footprints

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Abstract

Measuring the performance of what an environmentally sustainable supply chain has become a challenge despite the convergence of the underlining principles of sustainable supply chain management. This challenge is exacerbated by the fact that supply chains are inherently dynamic and complex and also because multiple measures can be used to characterize performances.

By identifying some of the critical issues in the literature regarding performance measurements, this paper contributes to the existing body of literature by adopting an environmental performance measurement approach for economic sectors (primary, secondary and tertiary sectors). It uses economic sectors and evaluates them on a sectoral level in specific countries as well as part of the Global Value Chain based on the established multi-regional input-output (MRIO) modelling framework. The MRIO model has been used to calculate direct and indirect (that is supply chain or upstream) environmental effects such as CO_2, SO_2, biodiversity, water consumption and pollution to name just a few of the applications. In this paper we use MRIO to calculate emissions and resource consumption intensities and footprints, direct and indirect impacts, and net emission flows between countries. These are exemplified by using carbon emissions, sulphur oxide emissions and water use in two highly polluting industries; Electricity production and Chemical industry in 33 countries, including the EU-27, Brazil, India and China, the USA, Canada and Japan from 1995 to 2009. Some of the results highlights include: On average, direct carbon emissions in the electricity sector across all 27 member states of the EU was estimated to be 1368 million tonnes and indirect carbon emissions to be 470.7 million tonnes per year representing 25.6% of the EU-27 total carbon emissions related to this sector. It was also observed that from 2004, sulphur oxide emissions intensities in electricity production in India and China have remained relatively constant at about 62.8 gSOx/$ and 84.4 gSOx/$ although being higher than in other countries. In terms of water use, the high water use intensity in China (1040.27 litres/$) and India (961.63 litres/$), which are among the highest in the sector in the electricity sector is exacerbated by both countries being ranked as High Water Stress Risk countries.

The paper also highlights many merits of the MRIO including: a 15-year time series study (which provides a measurement of environmental performance of key industries and an opportunity to assess technical and technological change during the investigated time period), a supply chain approach that provides a consistent methodological framework and accounts for all upstream supply chain environmental impacts throughout entire global supply chains.

The paper also discusses the implications of the study to environmental sustainability performance measurement in terms of the level of analysis from a value chain hierarchy perspective, methodological issues, performance indicators, environmental exchanges and policy relevance.

Keywords: environmental sustainability; supply chain; value chain, performance measurement; industry-level; input-output analysis

1. INTRODUCTION

Several studies have suggested that supply chain management can contribute to solving the global sustainability challenge which has taken prominence since the publication of the Brundtland Report by the World Commission on Environment and Development (1987). Indeed, sustainability and the Triple Bottom Line (Elkington 1997) have now become part of the political rhetoric and have been integrated across disciplines. In supply chain management, business and industrial practice, the increasing influence of sustainability has even forced the redefinition of the operations function by necessitating the introduction of environmental protection as key operational and business strategies (de Burgos Jiménez and Lorente 2001). It follows that sustainable supply chain management emphasises the creation of competitive advantage through the integration of information and flow and the transformation of resources within the network of activities as elaborated by Seuring and Müller (2008) and expanded upon by Crum et al. (2011) and Ageron et al. (2012). In this paper, environmentally sustainable supply chain management (sometimes described as green supply chain management) is defined as the integration of environmental thinking into the whole lifecycle processes of supply chain activities. Haines-Young et al. (2006) emphases that measurement of environmental sustainability in terms of environmental impacts has become very important since thresholds of indicators provide the opportunity to assess whether sufficient relative or absolute decoupling is taking place to support the conclusion that more sustainable patterns of consumption and production have been achieved.

Measuring environmental performance is a challenge. Lehtinen and Ahola (2010) and Hassini (2012) have all reiterated that there exist incompatibilities between the known principles of performance measures and supply chains. Indeed, despite the fact that sustainability performance measurements remain fundamental in the shift of the operations function towards sustainable supply chains, Schaltegger and Burritt (2014) recently reported that existing methods and possible approaches to measure and manage sustainability performance of supply chains such as at the industry level are lacking although performance measurement is of great importance for effective supply chain management (Yang et al. 2011). This can be attributed to many factors; amongst them the existence of multiple and sometimes conflicting measures that characterize the performance of the supply chain (Liang et al. 2006), the focus on reporting green supply chain management initiatives implementation rather than performance outcomes (Zhu et al. 2008), the fact that supply chains are dynamic in nature (Gunasekaran et al. 2004) and that environmental problems are multi-faceted (Hubbard 2009) and the result of inconsistent methodologies as expounded upon by Font and Harris (2004).

In addition, environmental evaluations of supply chains have only recently become an issue(Hoekstra and Wiedmann 2014), especially in relation to Scope 3 emissions attributed to indirect supply chain activities which is based on the Accounting and Reporting Standard of the GHG Protocol addressing carbon leakage (Scott and Barrett 2015). As a result, they envisage a future in which such environmental sustainability assessments are implemented by companies and at the national level using consistent analytical frameworks with broad but not overlapping coverage of environmental pressures to measure performance of both operations and supply chains. This study therefore seeks to contribute to performance measurement in this regard.

Further to these, this research is motivated by the recent Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), which reported that industry-related greenhouse gas (GHG) emissions have continued to increase and are higher than GHG emissions from other end-user sectors (Fischedick et al. 2014). The need for a deeper level of understanding of the environmental performances of industries especially those considered to be heavy industry sectors across different regions and across time must be studied and fully understood. As such, in an attempt to help address global environmental sustainability issues, the paper adopts an industry-level perspective of the global supply chain and provides insight using exemplar cases of how environmental sustainability performance models can be developed and systematic measurements undertaken in key industries and regions and across a range of environmental indicators. (Gereffi et al., 2005).

This paper therefore seeks to contribute to the growing body of knowledge in this research area by addressing some of these pertinent issues. To this end, we argue that an environmental sustainability performance measurement approach based on a consistent Multi-Regional Input-Output framework implemented at the industrial level of the value chain across a range of environmental indicators over a time series addresses some of the issues identified in literature including multiple indicators and conflict between measures (Liang, Yang et al., 2006); inconsistent methodologies (Font and Harris, 2004) and performance frameworks (Gunasekaran et al., 2004, Zhu, and Sarkis et al., 2008); lack of research and possible approaches to measure and manage sustainability performance of supply chains (Schaltegger and Burritt, 2014) and lack of consistent analytical frameworks (Hoekstra and Wiedmann, 2014).

The paper reports on the MRIO model results for two heavy polluting industries; Electricity production and Chemical industry. These industries were chosen because such heavy industrial sectors received special attention in the recently published Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2014). The analyses was carried out in the following countries and categorised regions: the 27 European Union member countries (EU-27), Canada, USA and Japan and some major emerging economies or BIC nations (Brazil, India and China). The BIC nations were chosen because there are growing international concerns on the environmental damages associated with the accelerated industrial and production activities of these countries (Lai and Wong 2012). The EU-27 and G7 member countries on the other hand represent some of the most developed economies with some of these countries having very stringent environmental policies which should reflect in their environmental performance of their industries but may not always be the case. Additionally, in terms of a consumption-base perspective of performance measurement, EU-27 and G7 member countries represents economic and political blocs which are responsible for significant environmental impacts (usually in developing and industrialised nations such as BIC countries) because of the high consumer demand for goods and services in these countries.

The assessment is based on a time-series analysis undertaken over a 15-year period from 1995 to 2009 enabling the performance over time to be evaluated because country specific regulations (e.g. emission standards) evolve through time and countries do not always share the same level of technological progress in key industries e.g. coal power plants in China vs. Europe may have different operating efficiencies. Multiple sustainability performance measures for carbon dioxide emissions, sulphur oxide emissions and water usage are used. Carbon dioxide emissions, (sulphur oxide emissions and water usage were chosen as the measurable indicators because they respectively characterise different environmental sustainability dimensions of climate change, pollution and resource extraction important to the electricity and chemical industries. In addition, the indicators are consistent with the objective of "Transforming our world-the 2030 Agenda for Sustainable Development" which has been set out by the United Nations Commission's Sustainable Development Framework (United Nations 2015). The process of choosing these indicators is also aligned with the World Resource Institutes' 3-step for developing indicators aimed at measuring performance and to observe progress and trends (World Resource Institute 2015).

In summary, the contributions of the paper are as follows (see also Table A in the Supplementary Information):

- Generate modelled outputs of carbon emissions, sulphur oxide emissions and water use in the two heavy industries; Electricity and Chemical industries in EU-27 countries, BIC nations and G7 countries are generated allowing for cross country analyses in a consistent manner.
- An environmental performance outlook of key industries (electricity and chemical) based on an assessment of a 15-year time series.
- Calculation of direct and indirect environmental impacts and their relative contribution to the total footprint across the indicators used and for the countries assessed by adopting the consumption-based environmental accounting approach.
- Insight into ecological exchanges and emissions leakage problems between countries is provided.
- The development of environmental performance model for targeted indicators, industries and countries is exemplified, along with contextual assessment and a discussions and implications of the findings.

2. LITERATURE REVIEW

2.1 Industries as part of Global Value Chains

The contemporary view of supply chain is that of a network of multiple relationships where value can be added (Horvath, 2001). These relationships can be between products, processes, firms and industries as elaborated upon by Lambert and Cooper (2000), Min and Zhou (2002) and Kemppainen and Vepsäläinen (2003) and as schematically represented in Figure 1. Within this context, it can be seen that there are reduced complexity and value added activities at the bottom of the value chain hierachy. Moving up the chain upto the industry level (Figure 1), there is increased complexity and value added activities. In effect, a supply chain can be defined as the integration of information and resource flows through a series of value added activities. Sturgeon (2001) emphasised that an industry-level analysis of economic activity that uses a 'value chain' approach works well in studies of cross boarder economic integration because it takes a significant but still manageable slice of the world economy as the object of the study.

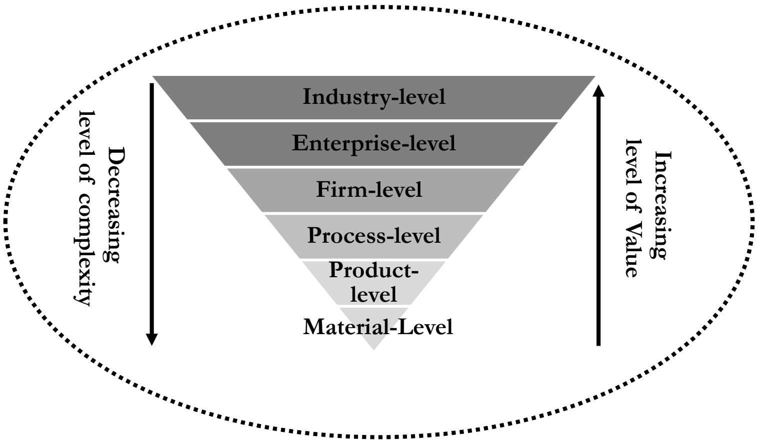

Figure 1: A hierarchal perspective of the value chain and complexity of supply chain systems

Ponte et al. (2013) have also argued that 'industry' has morphed from a localized, cluster-based concept to a value chain form that exhibits greater spatial dispersion. Following these assertions, the industrial level-perspective of the global supply chain can be described as being characterised by increased complexity but also associated with increased levels of value added activities (Gereffi et al., 2005). Through these value chains, production in primary, manufacturing, and service sectors are coordinated and organized on a global basis (Yeung and Coe 2015). Cattaneo et al. (2010) even went further to state that the industrial representation of the global value chain has become the world's economy backbone and central nervous system.

Indeed, literature on industrial clusters within global value chains has also highlighted the role of inter-firm co-operation which is further down the hierarchy presented in Figure 1 (Humphrey and Schmitz 2008; Pietrobelli and Rabellotti 2011; Gereffi and Lee 2016). In this paper, we seek to emphasise that the firm-based view (a bottom-up perspective) of global value chain analyses, although useful (Saliola and Zanfei 2009), is not wholly sufficient for the purpose of measuring the environmental performance of global value chains; so we argue for an industry-level (top-down) perspective as the level of analyses in an attempt to build on the theory and application of measurement of environmental sustainability.

2.2 Environmental Sustainability Measurements Approaches

Given the recognition of the importance of sustainability in business practices, sustainable supply chain management has become the critical next step for the operations function (Dey et al. 2011; Hassini et al. 2012). An aspect of environmentally sustainable supply chain management relates to the direct link between the accounting or measurement approaches that can be used and the application to production and supply chains/networks to measure sustainability performance. Literature has examined and explored key themes between these links including models and methods (Brandenburg et al. 2014), complex set and integration of social, environmental, technological, political and economic performance issues (Schaltegger and Burritt 2014) as well as reporting (Lodhia and Hess 2014).

Sustainability performance measurement according to Schaltegger et al. (2006) seeks to address the social, environmental and economic (performance) aspects of corporate management in general and of corporate sustainability management in particular. The path towards sustainability has led to an increasing attention to lifecycle thinking. Indeed, with regards to environmental sustainability, the general construct of lifecycle assessment is used as the basis for environmental performance measurements at the product level (Heijungs et al., 2010) which can also be applied at the industry level (Joshi, 1999). This is also a fundamental principle behind the Greenhouse Gas Protocol. Similarly, an argument for lifecycle thinking is made because even at the industrial-level, the framework considers all supply chain activities in the production and consumption processes. For instance, in the production of goods and services process, all supply chain activities including raw materials extraction, processing, transportation, etc and all activities along the supply chain where value is added are captured in the framework. At the product-level of the value chain, a bottom-up performance measurement approach offers benefits such as assessing carbon hot-spots and supply chain mapping (Koh et al. 2013). However, it is somewhat limited due to the truncation error (Feng et al., 2014a) in addition to factors such as scaling up the value chain from the product-level and the ambiguity of how effective the impact of sectorial policies can be measured. We therefore propose to address some of these limitations by undertaking the environmental performance measurements from an industry-level perspective. A top-down performance measurement such as at the industrial-level can provide a more holistic view of value chains such as the overall performance of specific industries which may present opportunities to evaluate the effectiveness of implemented policies in specific industries. Additionally, a specific industry in one country can compare its performance against other similarly structured industries in other countries and regions.

Literature also suggests that bottom-up approaches such as at a product-level as demonstrated by Glew and Lovett (2014), Koh et al. (2013), Smith (2012) have been widely assessed. However, the limited research practitioner-oriented studies (see: Network for Business Sustainability (2012), Sustainalytics (2011), Mineral Products Association (2013)) and academic and research works (refer to: Bassioni et al. (2004), Yongvanich and Guthrie (2005), Singh et al. (2007)) are typically lacking theoretical foundation and methodological robustness. More importantly, there is a lack of literature exploring how such environmental sustainability performance measurement studies undertaken at an industrial-level can inform the management of value chains as highlighted by Thoresen's (1999) attempt to answer research questions on how product, technological and operational environmental management may be aggregated to benefit industries.

Undertaking environmental performance measurement at the industrial-level and linking findings to sustainable supply chain strategies is particularly important because as Azapagic et al. (2000) point out, industrial systems are an important part of the human economy which determine the flows of materials and energy, making it a source of environmental degradation and resource depletion. Industry therefore must play a central role in identifying and implementing more sustainable options.

Generally, environmental performance measurement aims to achieve two outcomes. Firstly, it attempts to link environmental systems with business operations and in environmental sustainability reporting (Melnyk et al. 2003; Clarkson et al. 2011). Secondly it seeks to connect environmental management with business and competitive strategy (Porter and Kramer 2006; Hart and Milstein 2003; Wagner and Schaltegger 2003). As such, using appropriate analytical frameworks for model development and using results generated as a means of informing the management of supply chains is fundamental to sustainable supply chain design and management; however, studies on this are lacking. This view has just recently been reiterated by a number of authors. For instance, Taticchi et al. (2013) comments that sustainable supply chain performance measurements is an immature field of study but is growing very fast while Schaltegger and Burritt (2014) report that little research has been conducted on sustainability performance issues including existing methods and possible approaches to measure and manage sustainable supply chains. We aim to contribute to this area of study through the developments and applications and practical implications made in this paper.

A review of extant literature also suggests that there are generally two research pathways usually used in studies related to sustainability performance measurement. One such pathway suggests an emphasis on developing sustainability indicators and identifying key performance drivers; see Epstein and Roy (2001), Böhringer and Jochem (2007), Hezri and Dovers (2006), Singh et al. (2007), Shaw et al. (2010). Secondly, there is also a growing body of literature that attempts to measure sustainability performance using different frameworks and approaches (Dias-Sardinha and Reijnders 2001; Hubbard 2009; Munda 2005; Aref et al. 2005)).

Methodologies used to measure sustainability performance measurement are commonly based on the principles of lifecycle assessment (LCA) (Kissinger et al., 2011, Lake et al., 2014). Current LCA methodologies (Wiedmann and Minx 2007; Suh 2009; Kumar et al. 2014) suggests that models developed using the input-output framework (Weber and Matthews 2007; Wiedmann 2009, Ibn-Mohammed et al. 2013) provide a systematic assessment approach and an extended system boundary hence direct and indirect environmental impacts associated with activities can be comprehensively evaluated. Direct environmental impacts of an industry in this paper are defined as the impacts resulting from direct production processes of an industry and indirect environmental impacts describes the impacts resulting from the use of inputs along the upstream supply chain for the production of an industry (Yu, Hubacek et al. 2010).

Settanni et al. (2011) has also highlighted the role of life cycle costing based on an input–output technological model which integrates both physical accounting and cost accounting. The input-output framework has been used by many authors in a wide variety of applications such as modelling global material flows (Wiedmann et al. 2013), supply chain analysis (Koh et al. 2013), ecological footprint (Barrett and Scott 2003), supply chain benchmarking (Acquaye et al. 2014) with the hybridized version applied at the product levels (Treloar 1997; Suh 2004). In particular, it has formed the basis for carbon (Aichele and Felbermayr 2012), ecological (Ewing, Hawkins et al. 2012) and water footprint accounting systems (Feng, Siu et al. 2012)

Even with environmentally developed input-output frameworks, two contrasting approaches generally considered in environmental assessments studies comes to the fore; a production-based perspective and a consumption-based perspective (Barrett et al. 2013; Schaffartzik et al. 2014). A production-based perspective considers only the direct impacts as defined above; thus it neglects the impacts from the upstream suppliers (Peters 2008; Boitier 2012). Hence for an industry, only environmental impacts caused directly by activities or production processes of the industry are assessed based on production-based environmental accounting approaches. In this paper, we argue that performance measures should rather be developed from a consumption-based perspective which takes a systems view and includes emissions attributed to all upstream activities including imports (Peters 2008; Boitier 2012). This is because the consumption-based measurement takes into account the whole global supply chain network; thus enabling a complete representation (in terms of the extended system boundary) of upstream activities and all associated impacts along the supply chain in addition to the direct impacts. As a result, a key principle of green supply chain management which requires complete supply chain representation is achieved (Carter and Easton 2011; Acquaye et al. 2014). Larsen and Hertwich

(2009) also report that a consumption-based accounting provides a useful and complementary indicator in performance measurements in addition to the more traditional production-based accounting because it provides a more representative all supply chain activities. Further to this, the consumption-based measurement using multiregional input-output approaches has several advantages, such as accounting for emissions embodied in international trade which may help to address emissions leakage, increasing mitigation options, and making policies such as the Clean Development Mechanism a natural part of the National Emissions Inventories. The consumption-based approach is relatively a more complex accounting system compared to the production based approach (Peters and Hertwich 2008).

This paper adopts the consumption-based approach and uses a time-series environmentally extended input-output model to generate modelled outputs at an industrial-level in different countries across multiple indicators. This forms the basis for the discussions in this paper.

3. RESEARCH METHODOLOGY

3.1 General Input-Output Methodology

The general Input-Output (IO) approach originally developed by Leontief (1936) is used as the methodological basis in used in this paper. The basic IO framework which is based on the structure of the production processes of an economy (Correa and Craft 1999) records monetary transaction representing the flows of resources (products and services) from each industrial sector considered as a producer to each of the other sectors in the economy (Jury et al., 2013). By transforming the economic flows into physical flows (in this case carbon dioxide emissions, sulphur oxide emissions and water use) under the assumption that all outputs of an industrial sector are produced with the same physical flow intensity (Miller and Blair 2009), it allows for the development of a framework to measure the environmental impacts of an industrial sector. This is consistent with lifecycle thinking as the consumption-based framework takes into account all the production processes required to produce intermediate products and services used by industries as well as the consumption of goods and services used by the final demand groups (households, government, export, etc). Indeed, Wiedmann and Barrett (2011), report that an environmentally extended input–output analysis provides an alternative, economy-wide approach making system cut-offs or truncations unnecessary because its comprehensiveness and completeness. The input–output framework can be used to calculate consumption-based emissions of a country by linking its international and domestic emissions in a multi-regional input-output (MRIO) framework given growth in final demand via global trade transactions (Feng et al 2014b; Minx et al 2009; Peters et al 2011; Scott and Barrett 2015).

Methodological details of the general input-output methodology is presented in the Supplementary Information.

3.2 Analytical MRIO Model

The Leontief inverse matrix forms the basis for the MRIO model which is used to generate results which can be used measure the environmental performance of industrial supply chains based on different indicators. The MRIO model in this paper is based on a consumption-based approach of environmental assessment (Barrett et al. 2013; Schaffartzik et al. 2014).

Let:

E_j Represent the direct environmental output for any industry j in a particular economy. As the environmental outputs in the MRIO model in this study are carbon emissions, sulphur oxide emissions and Water Use, the units of E_j is respectively 1000tonnes $CO_{2\text{-eq}}$, tonnes SO_x and $1000m^3$ of water.

Given that x_j is the total industry production output expressed in constant million \$, the direct intensity environmental impact of any industry j is given by:

$$e_d = \frac{E_j}{x_j} \qquad \text{Equation 1}$$

This represents the measurement of the performance of an industry based solely on the direct production activities of that industry. It therefore provides a measure of the direct impacts per unit dollar of an industry can be used to compare the performance of the company or industry versus the supply chain performance. The direct intensity environmental impact e_d of all industries are presented in the model as a row matrix $\underline{e_d}$.

As seen from Equation E in the Supplementary Information, given that the Leontief inverse matrix represents both the direct and indirect activities of an industry, from a consumption-based approach, the MRIO model as used in this paper is expressed as:

$$Impacts = \underline{e_d}.\boldsymbol{L} = \underline{e_d}.(\boldsymbol{I} - \boldsymbol{A})^{-1} = \underline{e_d}.(A^0 + A^1 + A^2 + A^3 + \cdots) \quad \text{Equation 2}$$

Expressing Equation 2 in structure adopted in this paper, the MRIO is specifically defined as:

$$Impacts = \underline{e_d}.L = \underline{e_d}.\left(\begin{bmatrix} I & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & I \end{bmatrix} - \begin{bmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{bmatrix}\right)^{-1} \quad \text{Equation 3}$$

It should be noted that the MRIO model uses the consumption-based approach in Equation 3 as opposed to the rather limited production-based approach in Equation 1 in the industrial-level performance measurement. A production-based perspective of performance measurements has been heavily criticized because it accounts for only the impacts that occur within the fixed boundary of a country from an industry's direct activities hence impacts for instance due to imports are truncated by the system boundary and omitted from the analysis (Jakob et al. 2014). However, a consumption-based perspective enables a complete representation of the entire supply chain, hence imported goods and services either used indirectly as inputs along supply chains located in other regions or directly as intermediate requirements of a particular industry in the reference country can be captured (Feng et al. 2014b). As a result, a key principle of green supply chain management which requires complete supply chain representation is achieved (Carter and Easton 2011; Lake et al. 2014).

3.3 Data Sources

The MRIO model was constructed using both global MRIO tables and environmental data collected from World Input-Output Database (WIOD) database (WIOD 2012). The WIOD database consist of national IO tables, MRIO tables, environmental accounts for 40 countries and one Rest-of-the-World category comprising all other countries. These 40 countries include all European Union (EU) member countries, Non-EU OECD (the Organization for Economic Co-operation and Development) countries (e.g. the USA, Canada, Japan), and some large emerging economies (e.g. Brazil, India, China). Most of countries in the Rest-of-the-World region are developing countries in Africa, Asia, and Latin America. The IO table in each country includes 35 economic sectors. The WIOD database contains time series MRIO tables from 1995 to 2011. The environmental accounts in the WIOD database contain sectorial level carbon emissions, sulphur oxide emissions and water consumption which are used for environmental performance indicators in this study. However, its environmental accounts are available only until 2009. Therefore, our analysis covers 1995 – 2009.

3.4 Limitations of the Study

The MRIO model was based on a Multi-Regional Input-Output (MRIO) framework developed using the basic input-output (IO) principles. Input-Output data are not regularly produced which might imply that current data may not reflect latest structural changes and technological progress with the economy. For example, the most recent data from the WIOD database is 2009 (WIOD 2012). In addition, IO models by nature suffer from inherent limitations (Hendrickson et al. 1998). For instance, because of data harmonization issues and to reduce complexity of infinite products available within an economy, the model assumes homogeneity by aggregating different products into a single sector classification. The homogeneity assumption which proposes that each industry classification within the model produces a uniform output using identical inputs and processes. However, this is not always the case since each sector may be a representation of many different products or services, and even for the same product, different technologies may be used in its production.

Additionally, the IO concept is based on the proportionality assumption which suggests that in any production process all inputs are used in strictly fixed proportions; as such there is a linear correlation between production inputs and outputs and consequently in environmental impacts (Baral and Bakshi 2010). However, Tukker and Dietzenbacher (2013) report that the proportionality assumption is accepted in the use of input-output frameworks mainly because of the lack of data. Hendrickson et al. (1998) also noted that the linear proportionality assumption could be sufficiently accurate even if the underlying effects are nonlinear. This is because in some cases, the best available estimate still might be a linear extrapolation.

While industrial structures consist of a complex series of value added activities throughout supply chains lifecycle processes such as exploration, production, and distribution/transportation, etc, the input-output approach takes on a total macro-perspective of single-step industries and so does not provide details of such distinct processes. Methods such as Structural Path Analyses (Acquaye, Wiedmann et al. 2011; Hawkins, Singh et al. 2013), can be used to assess such individual chains by using it to decompose the production structures of an industry and individually linking it to supply chain activities.

In contemporary research employing input-output analyses, constant prices in USD as used in this study accounts for economic influences such as price changes over time within a country. In terms of price differences across countries, O'Mahony and Timmer (2009) reported that industry specific Purchasing Power Parities (PPPs) which reflect differences in output price levels across countries can be used. This price adjustment is often done by means of GDP PPPs which reflect the average expenditure prices in one country relative to another. It is however well recognised that the use of GDP PPPs, which reflect expenditure prices of all goods and services in the economy, can be misleading when used to convert industry-level output (Inklaar and Timmer, 2011).

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4.0 ANALYSIS OF RESULTS AND DISCUSSIONS

4.1 Electricity Industry's Carbon Emissions, Water Use and Sulphur Oxide Emissions

4.1.1 Carbon Emissions Intensities in Electricity Industries

With the electricity sector continuing to remain an important contributor to global industrial emissions and environmental concern, an assessment of the performance of the global industries of this sector has become even more important.

The total carbon emissions intensity for the EU-27 economic bloc, the USA and Canada and Japan, Brazil, India and China are calculated using the MRIO model in Section 3.2 is presented in Supplementary Materials 1 as Figure A. The total emissions intensity is the combination of the direct and indirect carbon emissions intensities from 1995 to 2009 and it was evaluated as a weighted average of individual countries in each region. It can be seen that for each of these regions, the emissions intensities for both the G7 and EU-27 remains relatively low compared to that of the BIC countries. In fact, it peaked at 5.18 kg/$ for EU-27 in 2001 and at 6.0 kg/$ in 2002 for the G7 countries. This is quite unsurprising given that the EU-27 and G7 countries consist of some of the most industrialized nations in the world which have electricity technologies with higher efficiencies as well as making faster progress in de-carbonization efforts of the electricity industries.

It is also evident from Figure A in the Supplementary Material 1 that the carbon emissions performance of the electricity industries in the BIC region increased steadily from 1995 and peaking in 2003 at 25.78 kg/$. The total output of the electricity sector at constant prices in the BIC countries remained relatively constant between 1995 and 2003. Hence the rise in carbon emissions intensities (and consequently a reduction in carbon emissions performance) can be attributed to among other factors, an increase in actual total carbon emissions.

A much detailed breakdown of the carbon emissions performance of the electricity industry for these nations is presented in Figure 2.

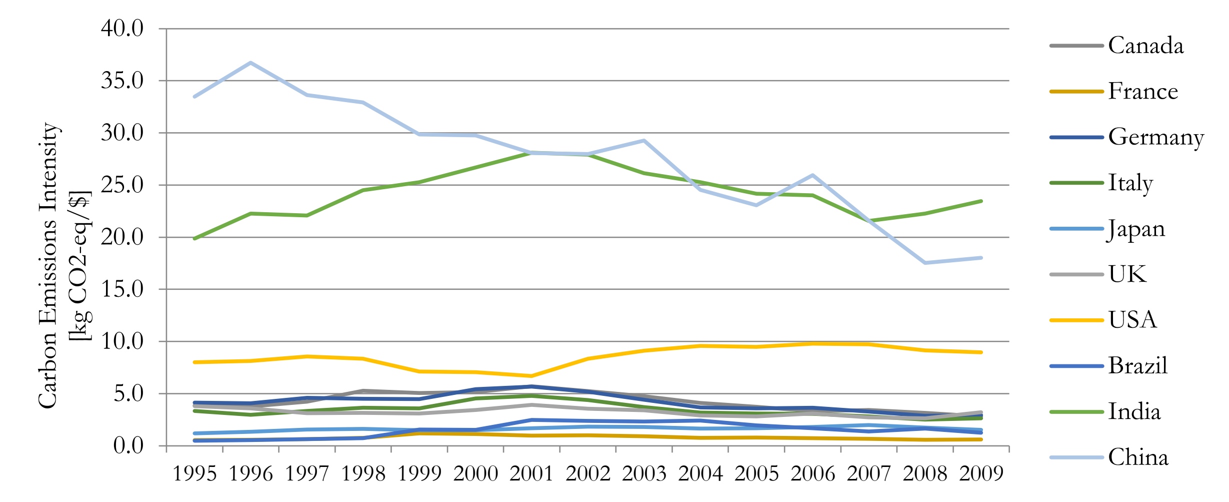

Figure 2: Carbon emissions performance of electricity industry in major countries in the world

It can be observed that, despite the fact that Brazil belongs to the BIC nations (Brazil, India and China) which together have significantly higher average carbon dioxide emissions intensity from the electricity industry (see Figure A in the Supplementary Material 1), Brazil's average carbon emissions intensity over the 15-year period of 1.54 kg/$ is only higher than France which have an average carbon emissions intensity of 0.81 kg/$. This contradicts the myth that the environmental performances of the industries in emerging economies are worse than that of developed economies. The significantly better performance measurement of Brazil's electricity industry can be attributed to two factors. Firstly, although Brazil is the 8th largest energy consumer in the world and the third largest in the Americas, behind the United States and Canada, the US Energy Information Administration (2013) recently reported that hydropower accounts for 80% of its total electricity production. Secondly, governmental policies in Brazil such as the effort to improve energy security by addressing the country's dependence on oil imports saw surplus sugar cane production being channelled to ethanol production and consumption beginning in the 1970s. As such, Brazil now ranks second largest producer and consumer of ethanol in the world after the United States (US Energy Information Administration 2013). These in addition to the fact that there is a decline in the rate of Brazil's rainforest deforestation (Mongabay 2014) which acts as carbon sink have led to the reduction in carbon emissions.

Given the globalised nature of industrial supply chains, it is important to also gain insight into how the indirect upstream supply chain affects the performance of an industry. Figure B in the

Supplementary Material 1 compares the carbon emissions from a consumption-based perspective and from a production-based perspective. This provides some insight into the effects that methodological perspectives have on the performance measurement of an industry as highlighted in Section 3.2. We compare the results of the two perspectives; the consumption-based approach on which the ESDM is developed and the production-based approach. In practice, while an industry can have direct control of its direct emissions, through collaboration and industrial de-intensification, indirect emissions (or resource use) can be reduced since industries are indirectly dependent on the performance of other industries because they indirectly require inputs from these other industries whether in the same country or in other countries. Any assumption that inefficient technologies are used in the upstream part of the supply chain is only valid under the condition that the intensity of the industry in question in the domestic country is lower than the intensity of the source of the upstream emissions in other industries from other countries.

In this analysis, the results obtained from the performance measurement of the electricity industries of all the EU-27 member countries were analysed. Firstly, the total emissions consisting of the direct industrial emissions and from the indirect upstream emissions measured from the ESDM using the consumption-based approach was compared to the production-based approach which only measures the direct industry emissions. The results for the EU-27 countries from 1995 to 2009 are shown in Figure B in the Supplementary Material 1.

It can be deduced that the electricity industry has significant embodied emissions across the EU-27 countries. On average, direct carbon emissions in the electricity sector across all 27 member states of the EU was estimated to be 1368 million tonnes and indirect carbon emissions to be 470.7 million tonnes per year representing 25.6% of the EU-27 total carbon emissions related to electricity production.. The contribution and effects that indirect upstream activities can have on an industry can therefore not be under estimated given it was more than a quarter of the total emissions. The implication of this is that, the environmental performance of an industry even in a highly developed nation which uses some of the best available technology for its direct production processes may be affected. This is because as shown from the analysis conducted on the EU-27 electricity industries, in the upstream supply chain where lower efficient technology may be used, indirect emissions contribute about a third of the total carbon emissions of the electricity industry.

4.1.2 Sulphur Oxide Intensities in Electricity Industries

The emissions of sulphur oxide (SO_x) occur as a result of fossil fuel consumption. In the electricity sector, fossil fuel consumption is generally from energy sources such as coal, crude oil, natural gas, refined oil, etc. Given that sulphur oxide emissions and carbon emissions are both the result of fossil fuel use in the electricity industry, it is envisaged that the carbon emissions performance in Section 4.2.1 will correlate positively with sulphur oxide emissions intensity. In Figure 3, the total sulphur oxide emissions intensity is presented.

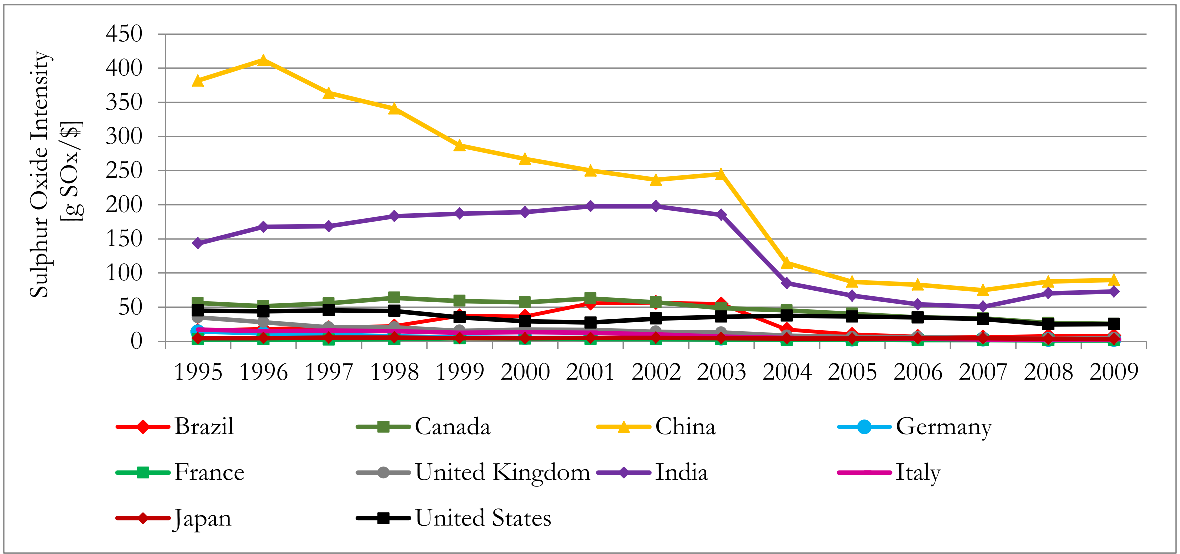

Figure 3: Electricity industry's performance measure assessed as sulphur oxide emissions intensity

It can be observed that for most countries, with the exception of India and China, the performance of the electricity industry as a measure of sulphur oxide emissions intensity remains relatively constant from 1995 to 2009. Even for India and China, it is clearly evident that, high sulphur oxide emissions intensities were recorded prior to 2005; however, from 2004 onwards, the sulphur oxide emissions intensities also remained relatively constant at about 62.8 $gSO_x/\$$ and 84.4 $gSO_x/\$$ respectively despite it still being higher than the other countries.

The correlation between the sulphur oxide emissions performance and the carbon emissions countries in the electricity industry are also presented for selected countries as shown in Figure C in the Supplementary Material 1. What is evident from Figure C in the Supplementary Material 1 is that, the sulphur oxide emissions intensity as a performance measure was historically high in the electricity industry but has recently seen a gradual decline. In fact, there is a sharp decline between 2003 and 2004 for most of these countries particularly in Brazil, India and China. This may be attributed to new technologies and regulations to manage sulphur oxide emissions in the electricity industry. From 2004, it can also be observed that there is a positive correlation between sulphur oxide emissions performance and the carbon emissions countries. For instance, in the case of Germany, the performance of sulphur oxide emissions prior to 2004 was poor compared to after 2004. However, after 2004, sulphur oxide emissions reduced from a historically high of 13.64 gSOx/$ in 1995 to an average of 2.42 gSOx/$ between 2004 and 2009. In fact, a linear regression line for sulphur oxide emissions intensity and the carbon emissions intensity between 2005 and 2009 showed an almost identical gradient of -0.19 and -0.17 respectively. It can therefore be posited that the sulphur oxide emissions performance of the electricity industry saw a sharp drop between 2003 and 2004 from a historical high and has begun to positively correlate to that of carbon emissions intensity performance.

4.1.3 Water Use Intensities in Electricity Industries

Total Water Use is calculated from the blue, green and grey water uses. According to Water Footprint Network published definitions (Aldaya et al. 2012), blue water footprint is the volume of surface and groundwater consumed as a result of the production of a good or service; green water footprint represents volume of rainwater consumed during the production process particularly of agricultural and forestry products whiles grey water footprint of a product is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain.

In what has been described as the energy-water nexus (Feng et al. 2014a), water stress and scarcity are intrinsically linked with the need for energy since the extraction and processing of fuel for electricity supply and transport requires water (Mielke et al. 2010).

By addressing the fact that indirect as well as direct water consumption forms part of the electricity industry, the paper highlights the disparities in the total water consumption intensity in EU-27, BIC and G7 member countries as presented in the spatial distribution diagram in Figure 4.

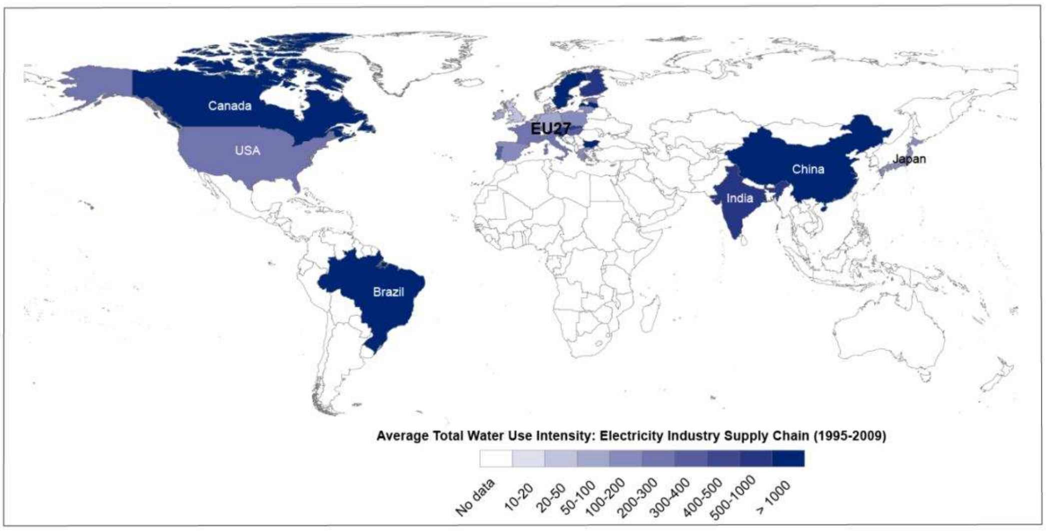

Figure 4: Water consumption intensities of electricity industries in EU-27, G7 and BIC nations

It can be seen from Figure 4 that the BIC nations produced the lowest performance measure in terms of total water intensity per dollar out of the electricity industry. Further analysis as shown in Table 1 shows that this is exacerbated by the significant indirect water use intensities. Refer to Supplementary Materials 1 for details of the results.

Table 1: A comparison of the direct and indirect water use intensities for the electricity industries in the BIC countries

BIC Country	Direct Water Use Intensity [Litres/$]	Indirect Water Use Intensity [Litres/$]
Brazil	3521.1	812.8
India	697.8	263.9
China	724.0	316.2

Of the countries assessed, Brazil had the highest indirect water use intensity (812.8 Litres/$). It is interesting to note that, while Brazil recorded one of the lowest carbon dioxide emissions intensity from the electricity industry as a result of hydropower dominating its electricity generation, the side effect of this is that its water use performance reported as total water use intensity (Figure 4) is the largest among these countries. As such, it can be posited that the distinct characteristic of an industry can both enhance its performance measurement based on a particular indicator whiles reducing the performance measurement based on another indicator.

Recently, researches started integrating water stress into the analysis of water use and impacts (Feng et al., 2014; Jiang, 2009; Lenzen et al., 2013; Pfister et al., 2011). Water stress measures total annual water withdrawals (municipal, industrial, and agricultural) expressed as a percentage of the total annual available blue water. Higher values indicate more competition among users. In study, the World Resource Institute (2015) examined at a national level, scores and ranking of future water stress—a measure of competition and depletion of surface water—in 167 countries by 2020, 2030 and 2040. In the year 2020 "Business as Usual" assessment for all industries at the national level, it observed that, for the countries considered in this study, only Brazil (score of 0.87) is considered Low Risk (score between 0-1) in terms of Water Stress. Canada (1.04), Germany (1.76) and France (1.98) for all industries aggregated together are considered Low to Medium Risk (score of 1-2). At the higher end of the scale, the US (3.17), China (3.19), Italy (3.51) and India (3.70) are considered High Risk (score between 3-4) in terms of Water Stress with a score of 4-5 assigned the maximum of Extremely High Risk.

The industry-level analysis in this study complements the country-level WRI assessment. For instance, while Brazil (4333.92 litres/$) and Canada (3140.16 litres/$) both have very high water use intensity in the Electricity industry (72% and 64% of electricity is generated from hydroelectric respectively), they are however respectively considered Low and Low to Medium Risk in terms of Water Stress according to the WRI ranking due to high water availability in both countries. On the other hand, high water use intensity in China (1040.27 litres/$) and India (961.63 litres/$) in the electricity industry is exacerbated by a national-level ranking of High Water Stress Risk by the WRI.

4.2 Chemical Industry's Assessment: Carbon Emissions, Water Use and Sulphur Oxide Emissions Performance Measurement

4.2.1 Carbon Emissions Intensities in Chemical Industries

The carbon emissions intensity performance of the chemical industries is presented in Figure 5.

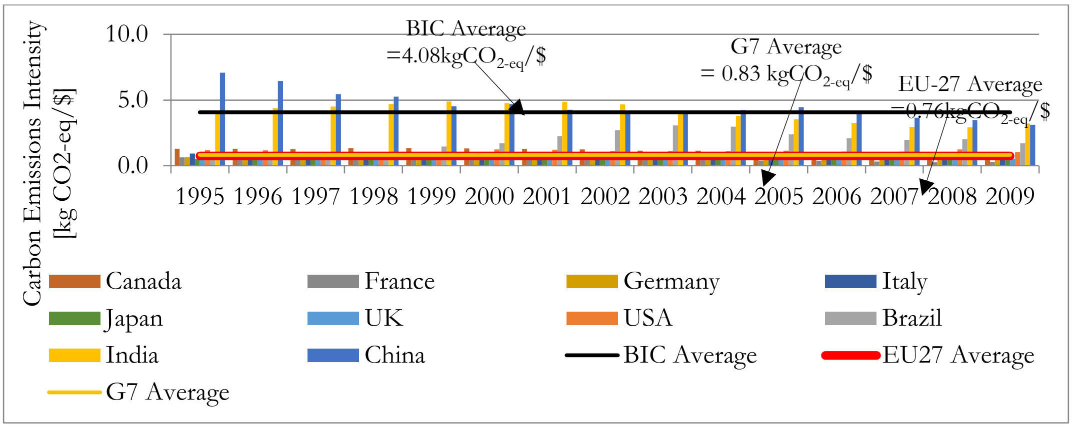

Figure 5: Chemical industry's performance measure assessed as carbon emissions intensity

The highlights of Figure 5 show the disparity between the average carbon emissions intensity performance in the EU-27 (0.76kg$CO_{2\text{-eq}}$/\$) and G7 (0.83 kg$CO_{2\text{-eq}}$/\$) countries and that of the BIC nations (4.08kg$CO_{2\text{-eq}}$/\$). Given the differences in emissions intensity, it is important to highlight the role of different legal regulations in the various countries. Specifically, within the European context, the EU Emissions Trading System has been highlighted as an example of a promising policy tool for reducing greenhouse gas emissions in industry and supporting the transition to greater energy efficiency (Kopidou, Tsakanikas et al. 2016). Comparing the performance of the electricity (Figure 2) and chemical industry (Figure 5) in terms of carbon emissions intensity as presented in the Supplementary Materials 1 as Figure D, it is interesting to note that in France, Brazil and Japan, the carbon emissions performance of the chemical industries is to a large extent comparatively similar to that of the electricity industry. Interestingly, these countries have the three best industry level performance assessed in terms of carbon emissions intensity. We can therefore argue that, in countries where there is relatively very good carbon emissions intensity performance in the electricity industry, this good performance is also reflected in the carbon emissions intensity performance of other industries in that country.

4.2.2 Sulphur Oxide Intensity in Chemical Industries

Manmade sources of sulphur oxide emissions (SO_x) includes chemical manufacturing, combustion of fossil fuel, etc and can combine with rain to produce acid rain which can damage forests and crops, change the acidity of soils, etc as well as affecting human health. Although sulphur oxide can also come from natural sources such as volcanoes and geothermal hot springs, about 99% of the sulphur dioxide in air for comes from human sources.

Indeed, the US EPA (2014) reports that the largest sources of sulphur oxide emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Given that fossil fuel combustion at power plants is mainly used to generate energy such electricity in power plants, in the analysis of the chemical industry, the sulphur oxide performance is compared against that from the electricity sector to determine if any insight can be gained (See Figure F in Supplementary Material).

It can generally be inferred from Figure F in Supplementary Material 1 that the sulphur oxide intensities of the chemical industries is lower than in the electricity industries. It can also be observed that although the sulphur oxide intensity of the electricity industries has been historically much higher than the chemical industries. In recent times *circa* 2004, the sulphur oxide intensity of the electricity industries have dropped significantly and has started to converge towards that of the chemical industries. The largest source of sulphur oxide in the atmosphere is the burning of fossil fuels (US EPA 2016) which is a commonality in both power plants and other industrial facilities such as chemical plants and so this explains the convergence sulphur oxide intensity of the electricity and chemical industries. Furthermore, national policies are gradually influencing fuels switching from fossil fuel and regulatory actions such as National Air Quality Standards on Sulphur Oxides which has been implemented in many countries. We therefore hypothesize that the performance measurement of the chemical industries measured in terms of sulphur oxide intensity has been historically lower than that of the electricity industries. However, there is evidence of the sulphur oxide intensity of the electricity industry converging towards that of the chemical industries.

4.2.3 Water Use Intensity in Chemical Industries

Faced with global water scarcity concerns (Hoekstra 2014), there is a growing concern for industries such as the chemical industry which includes producers of commodity chemicals like organic and inorganic chemicals and industrial gases, and speciality chemicals such as pharmaceutical products, detergents, pesticides and essential oils to reduce their water use and efficiency.

National governments and international bodies have set up programs to address water consumption challenges in industries. In the EU for example, the European Commission recently reported on a complete approach to sustainable industry in which it is envisaged that the benefits of increasing water efficiency at chemical production plants will flow into other industries (European Commission 2014). Such a sustainable approach should however go beyond the various chemical production plants making up the chemical industry to looking at the supply chain in its entirety. This is because as shown in Table B in the Supplementary Materials 1, the average indirect water use intensities which is upstream of chemical production plants which may occur in some country contributes significantly to the total water use intensities. This reinforces the need for consumption-based approach to performance measurement as previously explained.

A spatial distribution map highlighting the total water intensity for the EU-27, G7 and BIC nations is presented in Figure D in the Supplementary Materials 1. This highlights the disparities in the water consumption intensity [Litres/$] in EU-27, BIC and G7 member countries.

4.3 Ecological Exchanges between Countries

The emergence of globalisation in international trade has meant that global production networks spans different countries. The implication of this is that, resources from different countries are used for intermediate and final production of goods and services but are consumed in another country. When resource deficits get created as a result of this production and consumption phenomenon, it creates an imbalance in the ecological exchange between countries. This has been described as ecological unequal exchange (Yu, Feng et al. 2014; Jorgenson 2016). The tendency is that, if this unequal exchanges are not considered, a false decoupling of a country's environmental performance is created in which the consumption trend of goods and services is consistently not aligned to the resources and energy used to produce the goods and services. As such, the true picture of a country's environmental impacts within the global context becomes distorted.

Similarly, the issue of carbon leakage introduced by separation of production and consumption activities (Chen, Chen et al. 2013; Prell 2016) undermine climate mitigation efforts because when companies move their production processes to other countries with less ambitious climate measures, there is an indirect leakage arising from this shift and so can lead to a rise in global carbon emissions. The carbon leakage problem then becomes a negative externality which is not accounted for in the current supply chain management practices of global industries and necessitates reforms on environmental policies to capture these exchanges. Accounting for these exchanges in performance measurements therefore becomes important. Within the context of this study, the consumption-based MRIO model presented is used to establish the exchanges (carbon emissions in this case) that occurred between two respective countries. This exchanges relates to the carbon emissions occurs in a country but can be attributed to the Chemical Industry in another country. This is assessed in the two extreme time periods of this study; 1995 and 2009. The analyses between the two time periods is done to examine the changes that may have occurred over the 15-year time period. Refer to Supplementary Materials 2 for further details.

Table 3: Carbon emissions [1000 tonnes $CO_{2\text{-eq}}$] exchanges between one country and chemical industry in another country in 1995.

Exported Emissions from country's Chemical Industry	1995	Canada	France	Germany	Italy	Japan	UK	USA	Brazil	India	China
	Canada		118.51	227.43	81.68	539.10	158.51	6363.90	130.47	35.40	178.38
	France	137.60		2188.06	1189.44	589.24	1152.26	1492.93	183.78	66.27	166.44
	Germany	197.71	1870.01		1621.32	1133.69	1517.13	2524.57	378.24	155.31	324.64
	Italy	91.87	935.89	1401.16		373.47	505.53	1107.16	147.36	68.64	168.81
	Japan	211.00	335.79	705.55	223.24		373.65	3345.10	121.31	132.77	953.48
	UK	163.54	998.27	1280.78	598.98	515.14		1648.29	114.59	68.07	141.86
	USA	3925.99	1453.19	2286.10	887.15	4450.12	1646.44		1283.63	393.39	1393.70
	Brazil	33.82	62.31	124.31	59.35	156.18	61.85	414.01		18.85	34.84
	India	140.76	305.53	660.49	452.86	926.83	507.05	1746.57	117.61		300.50
	China	1642.79	1662.73	4028.36	1337.77	10511.56	2447.68	16827.14	476.47	711.66	

Table 4: Carbon emissions [1000 tonnes $CO_{2\text{-eq}}$] exchanges between one country and chemical industry in another country in 2009.

		Emissions Imported into Country.									
Exported Emissions from country's Chemical Industry	2009	Canada	France	Germany	Italy	Japan	UK	USA	Brazil	India	China
	Canada		189.52	229.98	65.19	226.67	126.34	6026.81	114.87	112.67	427.60
	France	185.57		1026.71	746.13	345.33	631.13	1300.81	149.64	73.81	378.18
	Germany	445.47	2407.56		1818.79	915.70	1628.95	3860.15	625.02	297.93	1534.06
	Italy	106.67	668.43	793.50		245.04	356.99	898.34	116.15	75.70	309.69
	Japan	315.02	438.99	748.91	296.07		380.12	3232.74	215.71	249.73	4101.03
	UK	230.55	834.55	1186.20	485.12	356.53		2567.90	156.59	75.72	348.90
	USA	4593.67	2016.92	3107.47	957.50	2245.52	1588.19		1297.29	800.88	3607.45
	Brazil	59.94	78.74	178.32	70.77	99.01	87.81	453.96		45.35	278.69
	India	321.82	349.12	636.76	305.97	340.29	499.34	3112.12	331.54		798.97
	China	817.65	2757.07	4979.97	1938.52	7572.13	2917.54	21254.68	1693.12	3755.49	

A common hypothesis of ecologically unequal exchange that is usually posited is that, low and middle income developing nations maintain an ecological deficit with wealthy developed nations (Moran, Lenzen et al. 2013). It can be deduced from Tables 3 and 4 that the carbon emissions in the developed economies that are attributed to the Chemical Industry in the emerging economies are higher than vice versa. For instance, in 2009, the carbon emissions in the UK which is attributed to the Chemical Industry in China was 2917.54 [1000 ton $kgCO_{2\text{-eq}}$] as against the 348.90 [1000 ton $kgCO_{2\text{-eq}}$] that occurred in China but is attributed to the UK Chemical Industry (a deficit of 2568.64 [1000 ton $kgCO_{2\text{-eq}}$]). This was also consistently so for India and China and the other developed countries in both 1995 and 2009.

It was however opposite in the case between the developed countries and Brazil. Here, carbon emissions in the developed economies that are attributed to the Chemical Industry in Brazil are lower than the carbon emissions in Brazil that are attributed to the Chemical Industries in the developed nations. The implication is that the hypothesis suggesting that less developed nations maintain an ecological deficit with wealthy developed nations is very much industry dependent and not generalised fact.

As exemplified by Figure 6, in the case of China's chemical industry, net carbon emissions exchanges are also compared between the two time periods; 1995 and 2009. It can be deduced that while in some countries (for instance USA, US, Italy and France), the net deficit exchanges increased between 1995 and 2009, in some countries (Japan, Germany, Canada), it indeed decreased.

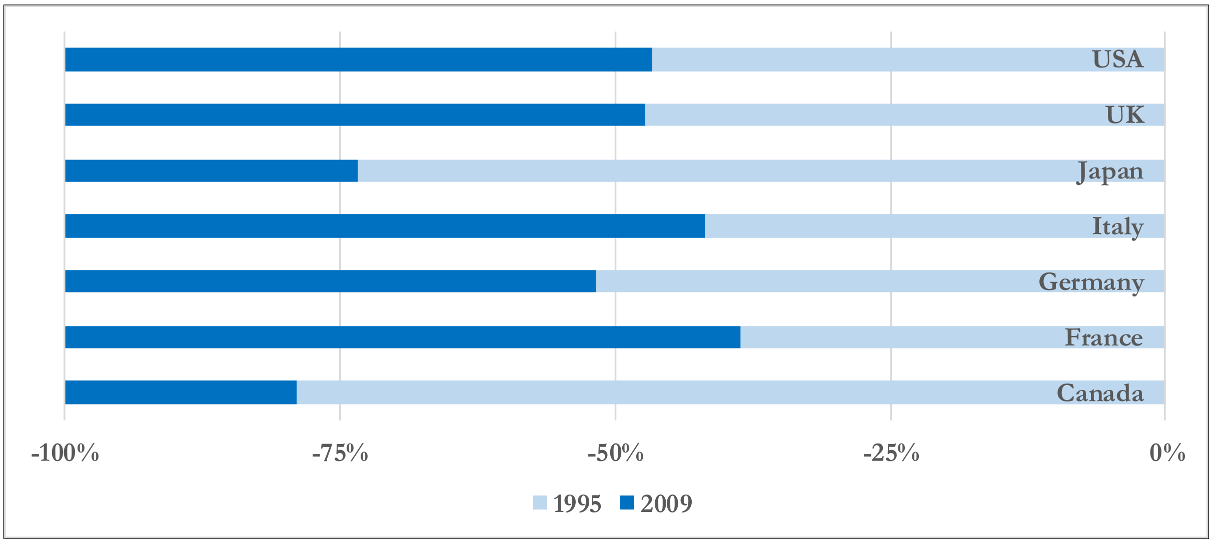

Figure 6: The ratio of net carbon emissions exchanges between China's chemical industry and some developed economies between 1995 and 2009.

This may suggest that depending on factors such countries and industries involved, ecological deficits between developed and emerging or less developed countries may in fact be improving (that is, deficits are decreasing) over time.

4.4 Implication of Study to Supply Chain Sustainable Performance Measurement

Measuring the performance of supply chains can be undertaken at different levels of the value chain, that is, at the product, process, firm, and industry-levels; akin to "slicing up the global value chain" as elaborated upon by Timmer et al. (2014). As mentioned in the previous sections, a wide body of literature has been developed to deal with these issues with recent developments addressing sustainability dimensions; see (Hassini, Surti et al. 2012; Estampe, Lamouri et al. 2013; Stefan Schaltegger, Varsei et al. 2014). This process can be inherently challenging because of the complex and multi-tier nature of production and supply networks that can be represented within the system and the existence of multiple measures that can be employed to keep track of the performance of the supply chain. The complexity of all global industries highlighted by the interdependence of dispersed and infinite supplier networks at multiple supply chain tiers from different industries and different countries means that identifying specific supplier linkages by activity becomes very challenging. This is despite the fact that attempts have been made to use methodologies such as Structural Path Analyses (Acquaye et al, 2011, Hawkins et al, 2013) to assess individual supplier network activities.

The study also reveals that any performance measurement based on a production-based approach is methodologically limited and goes against the inherent characteristic of supply chains; that is failing to achieve the holistic perspective that sustainable supply chain management should strive to achieve. This is because supply chains encompass activities and processes far beyond the focal firm and industry. However, adopting a consumption-based perspective as demonstrated by the application of the MRIO model in this study shows that impacts associated with different tiers of the supply chain can be assessed. The MRIO therefore supports the view that although products and services are produced within a country's economic system, the actual supply chains transcend many countries within a network of inter-dependent global industries (Coe and Yeung 2015; Johanson and Mattsson 2015). The implication is that the performance of a country's industry is indirectly affected by the performance of other industries in other countries through the upstream supply chains. As highlighted in this study, to address the leakage problem, ecological exchanges between countries and industries must be individually assessed since exchanges between different countries and industry can tell different stories which are against the commonly cited hypothesis that low and middle income developing nations always maintain an ecological deficit with wealthy developed nations.

Supply chain collaboration is important in addressing the leakage problem because it is not just needed at the firm level to deliver competitive advantage as has been widely reported (Cao and Zhang 2011; Mellat-Parast and Spillan 2014) but the paper argues that it also needs to be forged at the industry level. This suggests that countries have a role to play from supply chain management perspective; an area of study and practice that has traditionally been reserved for business and firms.

In terms of policy relevance, global supply chains are important in generating sector-specific information supporting policies as they point toward hotspots within global supply chains and thus provides focus points for interventions. It also provides tools for managing global supply chains, something that multinationals are increasingly doing. In addition, benchmarking of companies against sector averages can be undertaken through such global supply chain analyses. Finally, it provides information for demand side management and consumer driven policies (which relates to the large literature of consumption-based accounting and also specifically eco-labelling). In addition, drawing on the advantages that top-down policies from the global supply chain offers in terms of scalability (Scinocca, Kharin et al. 2016) and diffusion (Faehn and Isaksen 2016), insight from historical trends (15-year time series in this case) can provide a basis for gaining insight into the historical trends and cross-country analyses of the environmental performance of assessed industries.

Indeed, the MRIO model presents a case for supply chain performance measurements to be undertaken over a time series using the same consistent methodology and assumptions. This presents the opportunity for an in-country and cross-country analysis of industries to be undertaken including providing insight into changes in performance over time and an industrial outlook for the future. In addition, since the technical and technological progress of industries and countries do not remain constant through time, a time series performance measurement enables the effects of any regulations (e.g. Emission Standards or National Air Quality Standards) on industries to be evaluated.

One of the main challenges of performance measurements in field of supply chain management is the use of a model that can be consistently applied to different supply chains. As demonstrated in this paper, the MRIO represents such a model that can be used to model the environmental performance in different industries. Despite this, as articulated by Genovese et al (2013b), the selection of performance indicators is a crucial problem, as there is no "one size fits all" approach to the issues. As such appropriate set of relevant indicators should be carefully chosen noting the unique characteristics of the industry being studied. For instance, for the agricultural industry, land use and methane may be an appropriate set of indicators compared to sulphur oxide which is more relevant to the heavy industries like chemical and electricity industries as used in this paper.

As shown in Figure 7, the MRIO can produce performance measures for an industry across a range of multiple indicators. In the radar diagram, the closer a country's indicator is to the origin, the better is performance measure for that indicator.

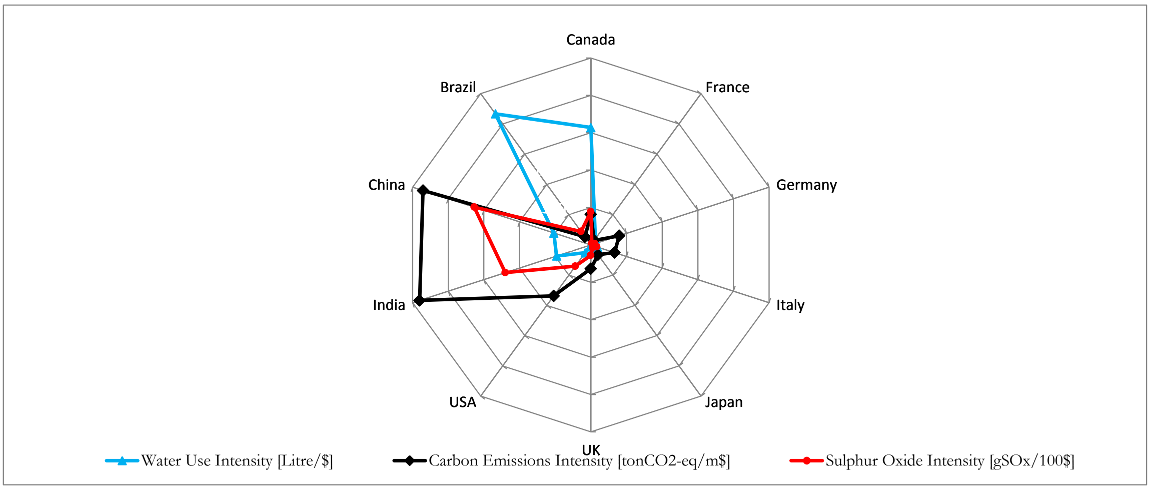

Figure 7: Average performance measurement of electricity industries across multiple indicators in different countries from 1995-2009. Note: To ensure a good presentation of Figure 6, the following radar value axis was used as scales. Carbon Emissions Intensity: 1unit=5000*tons$CO_{2\text{-eq}}$/m$; Water Use Intensity: 1 unit=1000*Litres/$; Sulphur Oxide Intensity: 1unit=5000*(gSO_2/100$)

The challenge with the use of multiple indicators in the performance measurement of supply chain management lies in how a single composite value can be created from the multiple indicators, by employing appropriate aggregation methodologies. This is because on one indicator, a supply chain may achieve good performance but relatively have a worse performance on another indicator when compared to another supply chain. However, it should be noted that as with all sustainability criteria measures in all fields of human endeavours, the local context in which the performance measurement takes place will be different from another. The over-riding aim therefore is to make consistent progress towards improving the sustainability performance measure over time.

5. CONCLUSIONS

Significant progress has been made since the initial attempt to integrate sustainability into supply chain management. This has led to the convergence of the underlining principles of sustainable supply chain management. Despite this, measuring the performance of what for instance an environmental sustainable supply chain is has become a challenge; amongst the reasons because of consistent methodological issues, the complexity of supply chains and the existence of multiple measures that characterize the performance of the supply chain. The paper therefore makes a case in taking an industry-level perspective of the global supply chain when it comes to environmental sustainability model development, measurements and analyses because of its value added activities.

This study contributes to research and the existing body of literature on supply chain performance measurement by demonstrating using industries in the global value chain as the unit of analyses, how the environmental performance measurement of global industries is undertaken using a developed model based on the already established general multi-regional input-output (MRIO) methodological framework. Described as an environmental sustainability performance measurement (MRIO) model, the study generates empirical measurements of carbon emissions, sulphur oxide emissions and water use in the two heavy industries; Electricity and Chemical industries in EU-27 countries, BIC nations (Brazil, India and China) and G7 countries (Canada, France, Germany, Italy, Japan, UK and USA) allowing for cross country analyses in one consistent study. The paper also makes the case for sustainable performance measurements framework to be undertaken over a time series. Given that the study was based on a 15-year time series, it showcases the basis for providing an environmental performance outlook of key industries and an opportunity to report progress made as a result of technical and technological changes as well as the impacts of regulations.

The consistency of the MRIO framework enables the same analytical framework to be applied in different industries and in different countries thus providing a basis for in-country and cross-country analysis. In addition, the MRIO analytical framework is based on a consumption-based approach to impacts assessment thus it enables both direct and indirect industrial-level supply chain activities and impacts to be measured; thus ensuring a complete representation of industrial activities.

The MRIO model provides the basis to gain insight into important measurement outputs such as Emissions/Resource Intensities and Footprint, Direct and Indirect Impacts and Ecological/Leakage Exchanges. By drawing on the strengths of the consumption-based accounting system adopted, the study provides some understanding of the direct and indirect environmental impacts in terms of their relative contributions to the total footprint across the indicators used and for the countries assessed. It terms of addressing the issues of ecological unequal exchanges and emission leakages, the paper was able to establish that the commonly cited hypothesis that low and middle income developing nations maintain an ecological deficit with wealthy developed nations is not a valid generalised statement because the direction of ecological deficit is dependent on the countries involved and the characteristics of the specific industry being assessed and not just on the mere fact that one country is wealthy and developed and the other less developed.

Using real data, the MRIO model also shows how a model can be consistently applied to different industries to measures multiple measures that characterize the performance of the supply chain. In this study three such indicators relevant to the electricity and chemical industries were chosen; carbon emissions, sulphur oxide emissions and water use. It was shown how the distinct characteristic of an industry (such as the dominance of hydropower technology in Brazils electricity industry) can both enhance its performance measurement based on a particular indicator (such as carbon emissions intensity in Brazil's electricity industry) whiles reducing the performance measurement on another indicator (such as water use intensity in Brazil's electricity industry). We also hypothesize on how the performance measurement of an industry's which has been historically high can start to converge and correlate towards the performance measure of the same indicator but in a different industry (example: sulphur oxide intensity in the electricity industry to sulphur oxide intensity in the chemical industry). This can provide insight into the co-management of such impacts using the same regulatory frameworks.

The paper finally highlights the difficulty in adopting multiple performance measurement indicators in the context of sustainability given that on one indicator may achieve good performance but relatively have a worse performance on another indicator when compared to another industry. This reinforces the need for supply chain performance measurement to be based on a time series where progress made to improve the sustainability performance for an indicator can be monitored over time. Despite the numerous advantages of industry-level assessment which has been highlighted, the paper also emphasises its drawbacks in terms of not been able to determine individual linkages and chains such as specific supply chain activities associated with an industry (example, raw material exploration for electricity generation). This is so despite attempts at decomposing the production structure of an industry using methods such as Structural Path Analyses.

It is envisaged that this study will contribute to environmental sustainability performance measurement literature and in particular the future prospects of developing analytical tools and models on performance measurement to include relevant social performance measures.

In terms of scope for further research which will build upon this work, it was observed that there are peaks and troughs in the environmental sustainability performance of some countries (for instance; sulphur oxide emissions in France, Brazil and sharp declines in some instances (for example decline in carbon emissions intensity in the electricity industry in BIC countries between 2003 and 2005 and then between 2006 and 2008). It is suggested that further research that can employ techniques such as Structural Decomposition Analyses to evaluate the underlying causes can be undertaken.

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