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

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/107099/

Version: Supplemental Material

Article:

Acquaye, A., Feng, K., Oppon, E. et al. (4 more authors) (2017) Measuring the Environmental Sustainability Performance of Global Supply Chains: a Multi-Regional Input-Output analysis for Carbon, Sulphur Oxide and Water Footprints. Journal of Environmental Management, 187. pp. 571-585. ISSN 0301-4797

https://doi.org/10.1016/j.jenvman.2016.10.059

Reuse
This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

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

Supplementary Materials 1

Paper Reference: JEMA-D-15-03409

This supplementary material consists of Figures and a Table which supports the results output generated from the environmental sustainability performance measurement as presented in the manuscript.

Table A: Research Scope and Focus of Study

SCOPE	RESEARCH FOCUS
Sustainability Focus	Environmental
Key Performance Indicators	• Carbon dioxide, • Sulphur Oxide, • Water Use
Level of Value Chain Analyses	Industry-level
Industrial Applications	• Electricity Industry, • Chemical Industry
Country/Regional Coverage	• Brazil, India, Chinas, Canada, Japan, USA, and EU-27 countries
Time Series	15 Years (1995 to 2009)
Methodological Basis	Multi-Regional Input-Output Analyses
Accounting Perspective	Consumption-based approach
Model Outputs	• Emissions/Resource Intensities and Footprint • Direct and Indirect Impacts • Ecological/Leakage Exchanges

ADDITIONAL NOTES: RESEARCH METHODOLOGY

General Input-Output Methodology

The general input-output methodology is well documented in the literature (ten Raa 2007; Minx et al. 2009; Ferng 2009, Miller and Blair, 2009). For any economy, it can be shown that:

$$x_i = x_j = \sum_j z_{ij} + \sum_i y_i \qquad \text{Equation A}$$

Where:

$x_i = x_j$ The total sector products consumed (row total), x_i or the total industry production output (column total) x_j. Theoretically, given that the IO table is balanced, $x_i = x_j$ and the units are expressed in constant million $.

$[z_{ij}]$ The matrix representation of the intermediate consumption; that is, the amount of product (i) used as an intermediate input in the production process of industry (j). The matrix representation is given in monetary terms (million $).

y_i The final demand of products i which represents the demand by (households, government, capital goods, exports, etc) for products $\boldsymbol{i}$.

In a generalised form, Equation A can be expressed as:

$$\boldsymbol{x} = \boldsymbol{Z} + \boldsymbol{y} \qquad \text{Equation B}$$

For any economy, it can also be shown that:

$$\boldsymbol{A} = [a_{ij}] = \frac{[z_{ij}]}{x_j} \qquad \text{Equation C}$$

Where:

A Represent the technical coefficient matrix of the whole economy because it defines *the technology* of all the individual industries. It is unit-less.

a_{ij} Represent all the generic elements of the technical coefficient matrix, A. The technical coefficient matrix consists of the technology matrix for each of the industries in the economy. Hence for an industry where $j = k$ its technology matrix is given by elements of the matrix $[a_{ik}]$. These elements are all the products and services (example: raw materials, machinery, energy, goods, transport, services, etc) required from its own and all other industries in the economy which enables that industry to produce a unit of output.

Hence from Equation C:

$[z_{ij}] = \boldsymbol{A} \cdot [\widehat{x_j}]$. Where $[\widehat{x_j}]$ is the diagonalised $[x_j]$. In a generalised form: $\boldsymbol{Z} = \boldsymbol{A} \cdot \boldsymbol{x}$.

Therefore from Equation 2 where: $\boldsymbol{x} = \boldsymbol{Z} + \boldsymbol{y}$, it follows that: $\boldsymbol{x} = \boldsymbol{A} \cdot \boldsymbol{x} + \boldsymbol{y}$. Solving for x and expressing in matrix notations:

$$\underline{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y} \qquad \text{Equation D}$$

Matrix $\boldsymbol{I}$ is the identity matrix and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ known as the Leontief inverse matrix, $\boldsymbol{L}$ (Ebiefung and Kostreva 1993).

Given that the study on the ESPM performance measurement focusses only on the industrial supply chains and not on the impacts that the final demand for products and services $\boldsymbol{y}$ causes, the ESPM model characterized by the Leontief inverse matrix, $\boldsymbol{L}$ which is can be expanded and defined mathematically as:

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} = A^0 + A^1 + A^2 + A^3 + \cdots \qquad \text{Equation E}$$

$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$ Therefore describes the total (direct and indirect) requirements that are needed at all tier (0, 1, 2, 3, ….) of the industrial supply chain needed by an industry to produce a unit of output.

The use of the Leontief inverse matrix in the ESPM model ensures that the characteristics of capturing direct and indirect industrial requirements provides the complete supply chain visibility; a key requirement in environmental modelling across supply chains (Sundarakani et al. 2010).

This general approach is extended to characterise the overall industrial supply chain system for each of the countries and region studied in this paper under a time series. As such, following on from Equation 5, a fully globalised Multi-Regional Input-Output (MRIO) model (see: (Davis and Caldeira 2010; Peters et al. 2011)) was developed with the analysis focussing on the technical coefficient matrix for all the EU-27 member countries and other major economies including

USA, Canada, Japan, Brazil, India and China and the Rest-of-the-World as a one region. The full technical coefficient matrix is given by:

$$A = \begin{bmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{bmatrix}$$

Hence, from Equation E,

$$L = \left(\begin{bmatrix} I & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & I \end{bmatrix} - \begin{bmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{bmatrix} \right)^{-1} \qquad \text{Equation F}$$

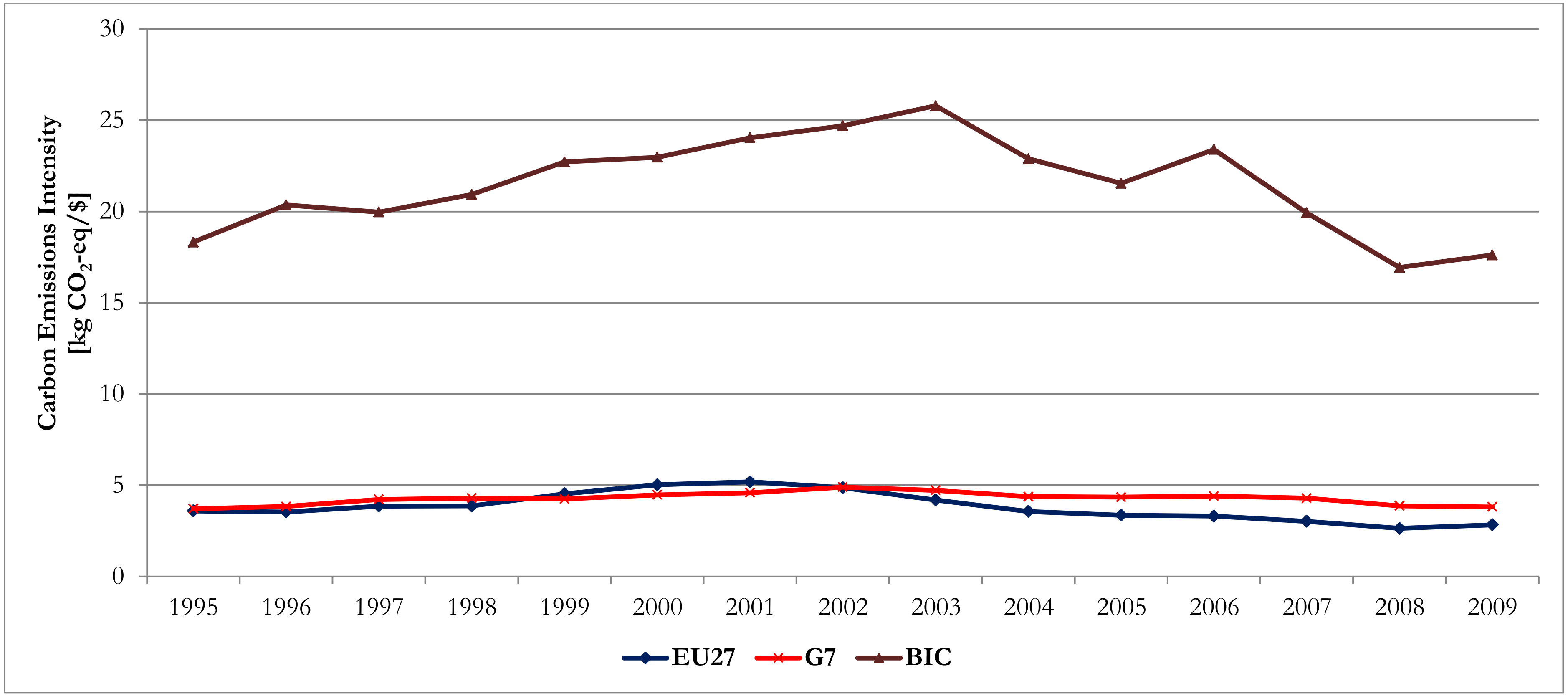

Figure A: Carbon emissions performance of electricity industries in major regions in the world

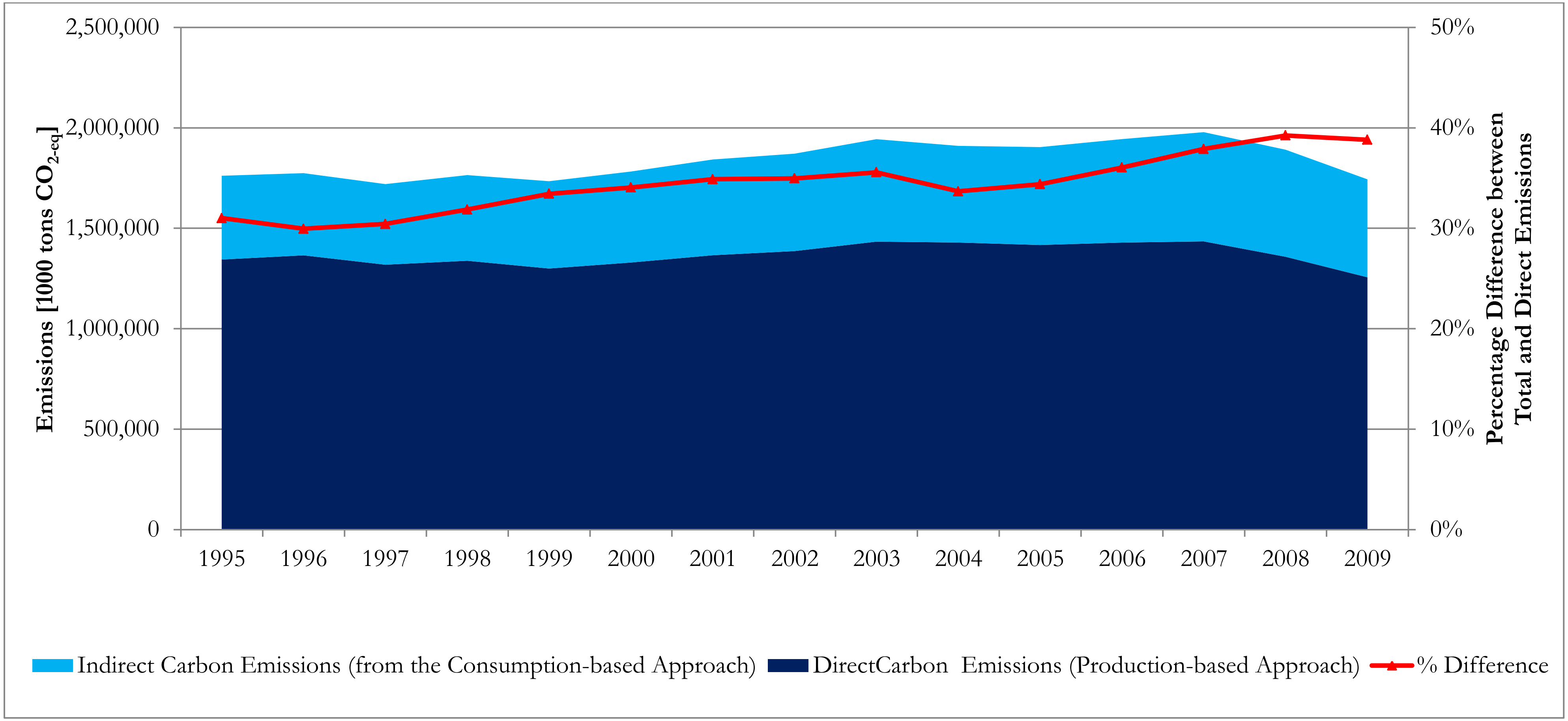

Figure B: Comparison of consumption and production-based approaches to measuring carbon emissions of electricity industries in EU-27 member countries

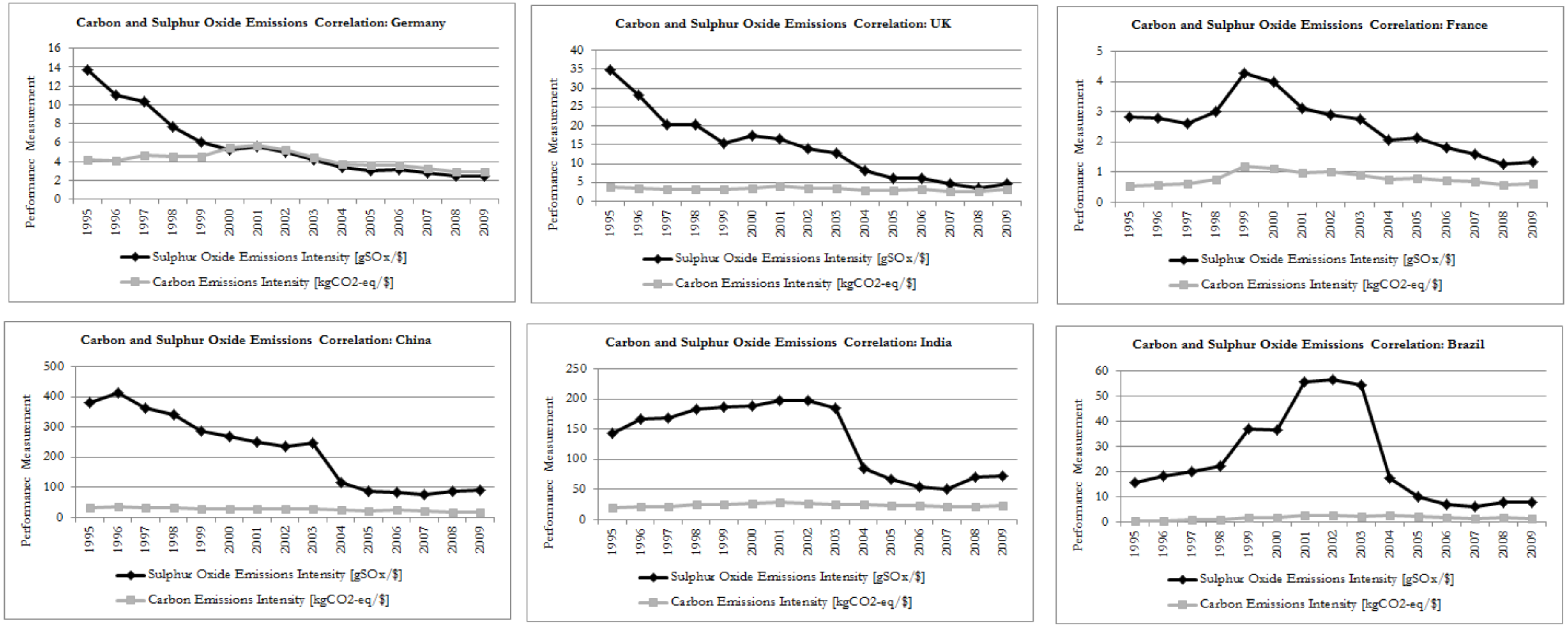

Figure C: Correlation between carbon and sulphur oxide intensities in the electricity industry

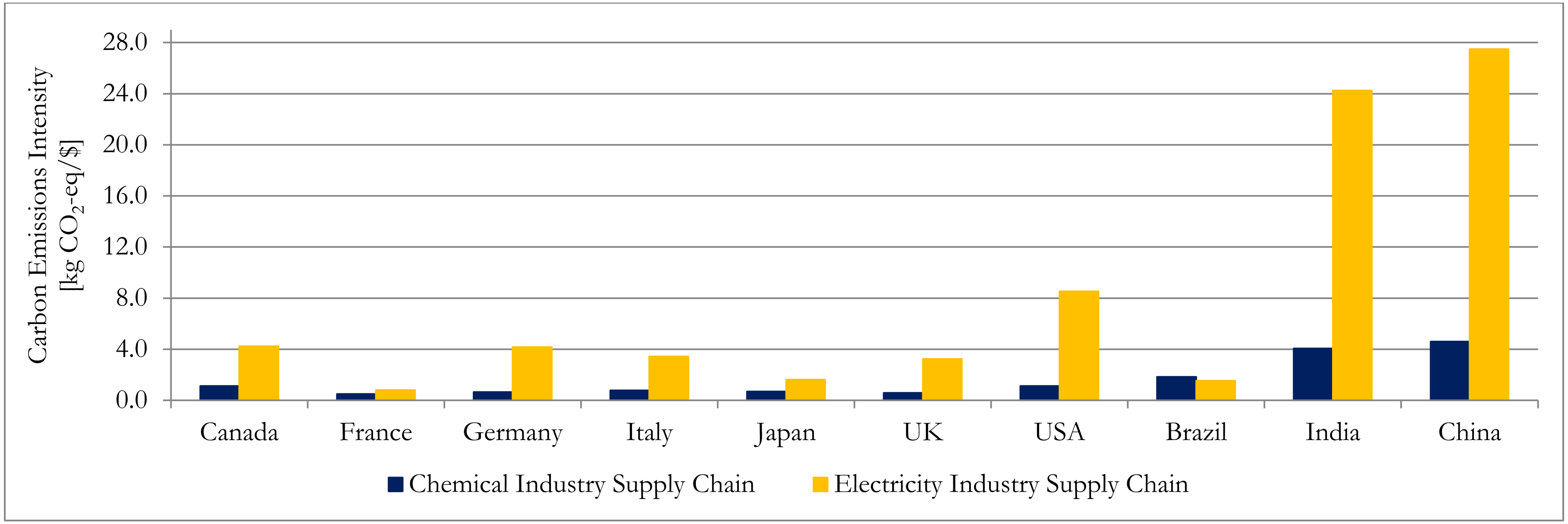

Figure D: Comparison of electricity and chemical industries carbon emissions performance

Table B: Direct and indirect water intensities in the Chemical Industry in EU-27 countries

EU-27 Countries	Direct Water Intensity [Litre per $]	Indirect Water Intensity [Litre per $]
Austria	11.09	70.75
Belgium	24.38	53.94
Bulgaria	5857.37	2085.04
Cyprus	1.39	82.46
Czech Republic	10.82	95.56
Denmark	0.87	45.51
Estonia	0.82	165.68
Finland	19.75	84.32
France	18.81	43.06
Germany	14.57	40.37
Greece	1.65	64.16
Hungary	118.11	261.91
Ireland	4.43	25.25
Italy	14.33	68.34
Latvia	131.68	195.26
Lithuania	2.53	132.89
Luxembourg	0.40	26.51
Malta	1.19	65.86
Netherlands	3.42	64.51
Poland	395.81	121.00
Portugal	10.70	60.78
Romania	408.86	1580.70
Slovak Republic	21.65	106.64
Slovenia	49.27	111.67
Spain	4.33	61.94
Sweden	8.48	57.08
United Kingdom	1.95	36.93

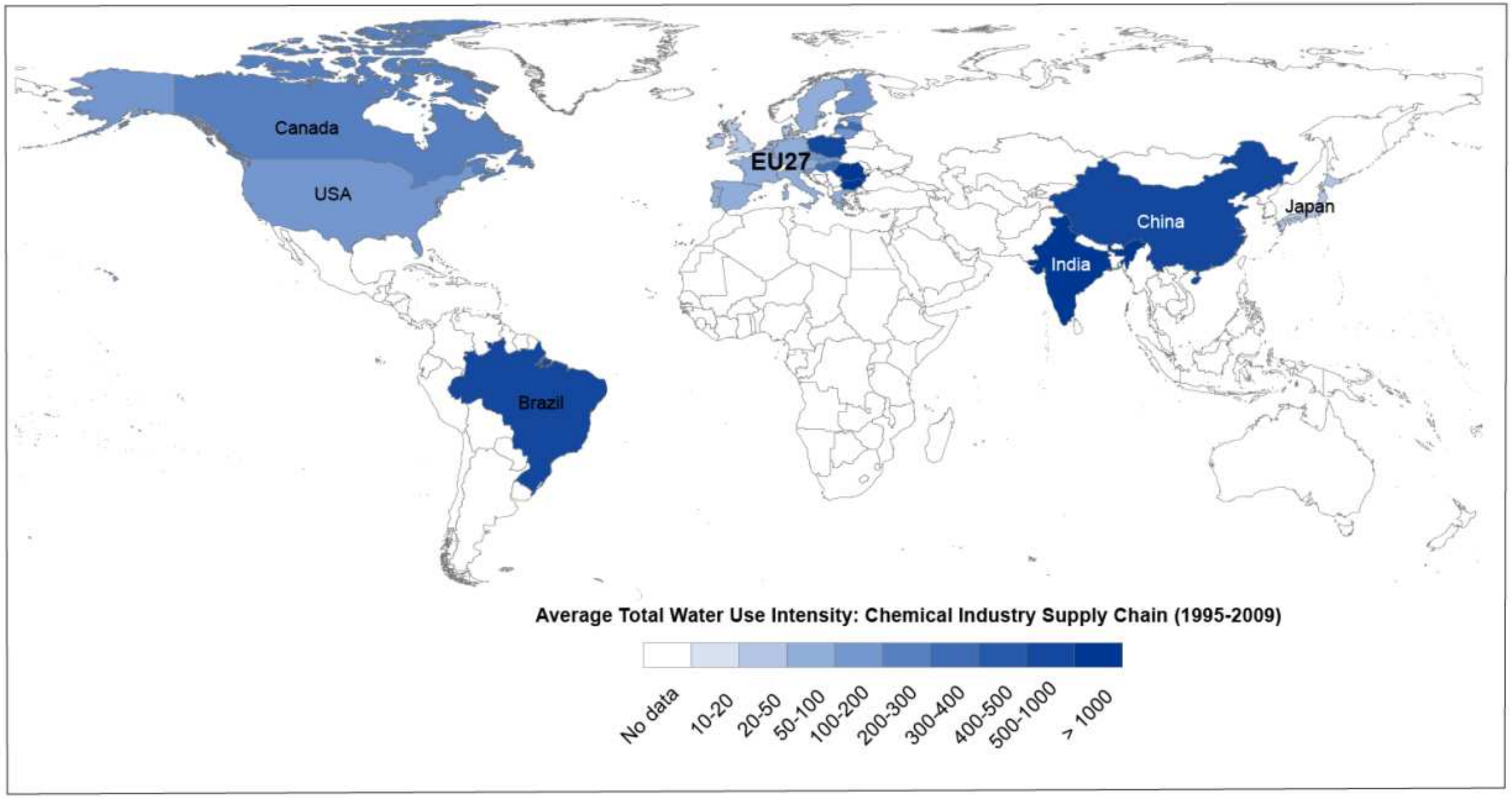

Figure E: Water consumption intensities of chemical industries

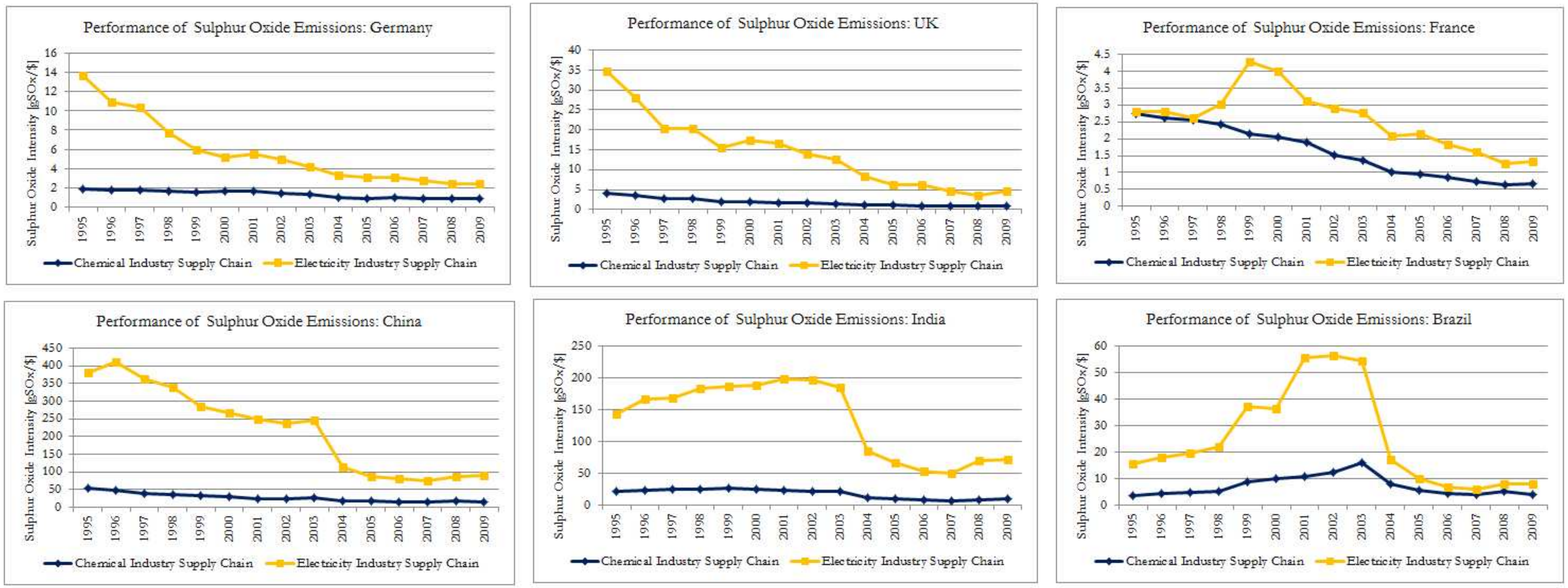

Figure F: Correlation between sulphur oxide intensities in the chemical and electricity industries