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# Drivers of stagnating global carbon intensity of electricity and the way forward

Tian Goh[a,*], B.W. Ang[a,b], Bin Su[b], H. Wang[a]

[a] Department of Industrial Systems Engineering and Management, National University of Singapore, Singapore
[b] Energy Studies Institute, National University of Singapore, Singapore

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ABSTRACT

Despite the signing of the Paris climate agreement, there is still great uncertainty regarding the world's ability to decarbonize and meet the 2 °C target. In this regard, the electricity production sector deserves particular attention. The sector has the largest decarbonization potential and its share of the world's $CO_2$ emissions from fuel combustion increased from 30% in 1990 to 36% in 2014. To better understand global trends, this study analyses the factors influencing changes in the global aggregate carbon intensity (ACI) of electricity, a measure of the level of $CO_2$ emissions per unit of electricity produced, over the last 25 years using multidimensional index decomposition analysis. It finds that global ACI barely improved since 1990 because of a shift in electricity production from developed to developing countries with higher ACIs. This geographical shift offset consistent improvements to power generation efficiency worldwide and is likely to persist in the future. To keep the 2 °C target realisable, it is imperative to enhance international cooperation to lower the ACIs of emerging economies and deepen the penetration of renewables, which have thus far performed below expectations.

## 1. Introduction

As the initial euphoria over the Paris Climate Agreement fades, the world is left grappling with the same uncertainty that plagued the pre-2015 climate talks – can global temperature rise be kept below 2 °C? To answer this question, one needs to understand the factors affecting historical trends of greenhouse gas emissions and how they will change in the future. In this regard, the electricity sector is of particular importance as decarbonization is likely to occur more rapidly in this sector (IPCC et al., 2014). Furthermore, its share of global $CO_2$ emissions from fuel combustion has been increasing, reaching 36% in 2014,[1] i.e. 11.8 gigatonnes of $CO_2$ ($GtCO_2$) out of the global total of 32.4 $GtCO_2$. In fact, electricity production is growing more rapidly than total primary energy supply. This trend is likely to continue, driven by greater electrification and substitution of direct fuel consumption in end-use sectors with electricity, a necessary step for deep decarbonization (Williams et al., 2012). The electricity sector also encompasses most of non-fossil based energy sources.

Global electricity production has increased tremendously, from 11,626 TWh in 1990 to 23,061 TWh in 2014.[2] In order to prevent $CO_2$ emissions from increasing at the same rate, efforts must be made to ensure that there is a decrease in the global aggregate carbon intensity (ACI) of electricity. ACI is defined as the average level of $CO_2$ emissions per unit of electricity produced at the aggregate level and is usually expressed in kilograms of $CO_2$ emissions per kilowatt-hours ($kgCO_2$/kWh). A lower ACI is preferred as it indicates that, on average, less $CO_2$ emissions are released per kWh of electricity produced. It is chosen as the indicator in this study as it is independent of scale (i.e. total electricity consumption), and measures the decoupling of a country's electricity demand from its corresponding $CO_2$ emissions, a desirable goal for decarbonization.

Unfortunately, $CO_2$ emissions are growing in tandem with global electricity demand. Following the 98% increase of electricity generation worldwide between 1990 and 2014, $CO_2$ emissions from electricity generation increased by 87%, from 6.28 Gt $CO_2$ to 11.76 Gt $CO_2$. This is largely due to the lack of improvements in the global ACI; it improved marginally from 0.54 $kgCO_2$/kWh in 1990 to 0.51 $kgCO_2$/kWh in 2014.

The stagnant global ACI points towards a worrying trend of rising

* Corresponding author.
*E-mail address:* gohtian@u.nus.edu (T. Goh).

[1] The share of $CO_2$ emissions from electricity production, which was 36% in 2014, is computed by apportioning the share of electricity generation from electricity plants and combined heat and power plants. Heat generated is excluded.

[2] Global electricity production is computed based on the total electricity produced by 124 countries used in this study. The electricity output from the 124 countries covers about 97% of world electricity production. The data was obtained from the IEA world energy balance database and includes electricity generated from electricity and combined heat and power plants.

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$CO_2$ emissions that accompanies the rise in electricity consumption. The factors affecting the lack of improvement in the ACI are thus of great interest. To our knowledge, there have been two studies examining the electricity sector on a global level (Ang and Su, 2016; IEA, 2016a). Our study improves on these analyses by quantifying various factors affecting changes in the global ACI across five time periods between 1990 and 2014 using multidimensional index decomposition analysis (IDA). A statistical analysis of changes in power generation efficiency and share of non-fossil based energy is also conducted to visualize the changing trends in generation efficiency and a switch to cleaner energy, two important pillars of decarbonization (Bataille et al., 2016). Based on the findings, policy implications and the outlook for the future are discussed. The framework may be adopted for international benchmarking and global stocktaking of progress in climate mitigation.

## 2. Driving factors of changes in global ACI

Although efforts have been taken globally to reduce emissions from electricity production, there has been lacklustre performance in actual emission reductions. An understanding of the factors shaping this historical trend can provide insights into the future national and global policies needed to change the current trajectory of emissions growth.

IDA can be used to quantify the impact of driving factors on change in the global ACI based on the following decomposition identity (Ang and Su, 2016). The ACI, denoted by $V$, is broken down into five driving factors:

$$V = \frac{C}{G} = \sum_{j,i} \frac{G_j}{G}\frac{Q_j}{G_j}\frac{Q_{ij}}{Q_j}\frac{F_{ij}}{Q_{ij}}\frac{C_{ij}}{F_{ij}} = \sum_{j,i} s_j p_j m_{ij} u_{ij} e_{ij} \quad (1)$$

where $s_j = G_j/G$ is the electricity production in country $j$ as a share of global electricity production, $p_j = Q_j/G_j$ is the proportion of electricity produced from fossil fuels in total electricity production, $m_{ij} = Q_{ij}/Q_j$ is the share of electricity produced from fossil fuel $i$ in total electricity output from fossil fuels, $u_{ij} = F_{ij}/Q_{ij}$ is the generation efficiency of fossil fuel $i$ and $e_{ij} = C_{ij}/F_{ij}$ is the emission factor for fossil fuel $i$ which is taken as a constant in this study due to lack of further disaggregated data.[3]

The change in global aggregate carbon intensity between two years is then given by

$$\Delta V_{tot} = V^T - V^0 = \Delta V_s + \Delta V_p + \Delta V_m + \Delta V_u + \Delta V_e \quad (2)$$

where each term corresponds to the respective effects mentioned earlier. The formulae based on additive LMDI-I is given in Ang and Su (2016).

A more in-depth decomposition of the global ACI can reveal more details on the contributions of various attributes to the five driving factors. In this study, the contributions of three attributes, (i) country, (ii) fossil fuel type (namely coal, oil and natural gas) and (iii) non-fossil energy source, to the five factors are quantified for five time periods. The first attribute provides information on the key players in global climate mitigation efforts, the second attribute pinpoints the progress made by individual fossil fuels in terms of generation efficiency and a switch to cleaner fuels, and the third attribute quantifies the contribution of individual renewable and nuclear energy sources to the change in the proportion of electricity produced from non-fossil based energy.

The third attribute can be quantified by attributing the fossil share effect, $\Delta V_p$, to various non-fossil based energy sources using the two-step decomposition detailed in Xu and Ang (2014). The equivalent equation is as follows,

$$\Delta V_{p,k} = \left[\left(\frac{R_k^T}{G^T} - \frac{R_k^0}{G^0}\right)\Big/\left(\frac{R^T}{G^T} - \frac{R^0}{G^0}\right)\right] \times \Delta V_p \quad (3)$$

where $\Delta V_{p,k}$ is the fossil share effect attributed to non-fossil energy source $k$ and $R_k$ is the electricity output of non-fossil energy source $k$. The small-value approach is used to handle zero values (Ang and Liu, 2007). The decomposition is conducted over five time periods, namely 1990–1995, 1995–2000, 2005–2010, 2010–2014, to understand the trends over time in greater detail. 1990 is selected as the first year as it is the common base year for emission levels and 2014 is the year where the most current data is available. The results are chained to obtain the total contribution between 1990 and 2014. The raw data are taken from IEA World Energy Balance statistics database[4] and 124 countries were included in this study.[5] Only three category of fossil fuels are considered - coal, oil and natural gas.[6]

## 3. Detailed decomposition results for the global ACI

The global aggregate changes in each effect based on the chained decomposition results of this study are indicated by the diamond and round points in Fig. 1. At the aggregate level, they draw the same conclusions as that in Ang and Su (2016). The primary factor offsetting improvements in the ACI is the geographical shift effect ($\Delta V_s$); a shift in relative terms in electricity consumption from countries with lower ACIs to countries with higher ACIs nearly negated improvements due to an increase in the share of non-fossil based energy ($\Delta V_p$), improvements to the fuel mix ($\Delta V_m$) and power generation efficiency ($\Delta V_u$).

Greater details on the contribution of various attributes, such as countries and energy sources, to an effect can be quantified. The chained decomposition results are displayed by top countries' contributions in Fig. 1(a) and by contributions of attributes, namely (i) country, (ii) non-fossil based energy and (iii) fossil fuel, to each factor in Fig. 1(b). ROW represents the rest of the world. Detailed numerical results and ranking of countries by the magnitude of their contribution to each effect are shown in Table 1. The results in Fig. 1(a) show that China, the United States (USA) and the European Union-28 (EU)[7] are the main contributors to changes in the ACI. This is generally in line with their share of total $CO_2$ emissions from electricity production worldwide. In 2014, China, the USA, India and the EU were the top four emitters from the electricity generation sector, accounting for 67% of total emissions from electricity generation. Growth trajectories, as well as climate and electricity policies in these major economies, will affect the global ACI now and in the future.

The decomposition results by time period are shown in Fig. 2. They illustrate the change in trends across effects over time. Besides the magnitude of the effects, one can gain a better understanding of the contributors over time by ranking the top three positive and negative contributors to each effect for each time period, as shown in Table 2. A negative contribution leads to a decrease in the global ACI and is a desirable development. It is noteworthy that while some countries contribute consistently to some effects throughout the years, the contributors to other effects are more varied over time. For instance, China and India were consistent contributors to a positive geographical shift

[3] The emission factors are 3.99 for coal, 3.08 for oil and 2.33 for natural gas in tonnes of $CO_2$ per tonne of oil equivalent. The emission factor effect is not shown in the results as it is zero.

[4] In some countries, while there is zero output of electricity for a particular fuel type, the fuel input is non-zero. If such a scenario is encountered, the corresponding fuel input is set to zero to avoid an unexplainably large generation efficiency effect.

[5] Countries with incomplete data and Gulf Cooperation Council (GCC) member countries were excluded from this study. GCC countries were excluded as they use combined water and power plants where desalination and electricity are produced together and there is insufficient information to estimate their electricity generation efficiencies.

[6] As data on emission factors for waste differ widely based on the type of incineration used, and data is not readily available, emissions from waste are taken as zero in this study. This does not affect the general conclusions drawn from the study due to the small amount of waste used for electricity generation.

[7] Each EU member state is treated as a separate country in the decomposition and the results for the EU-28 are a sum of the 28 EU member states.