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A CROSS-COUNTRY ASSESSMENT OF ENERGY AND CO_2 EMISSION: AN INDEX DECOMPOSITION APPROACH

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ABSTRACT

As the threat of climate change becomes increasingly acknowledged, it becomes more evident that past and current unsustainable energy consumption patterns cannot be pursued or maintained. In order to address this challenging goal for policy makers across the globe, development of decomposition techniques have been widely undertaken, regarding both variations in energy and CO_2 emissions. This study aims to promote a cross-country assessment of main energy-related emission drivers, resorting to an approach that diferenciates the contribution of RES and nuclear energy for overall carbon emissions. It resorts to a Log-Mean Divisia Index (LMDI) decomposition approach to enable disaggregation of Kaya identity function into main energy-related emission drivers. As main common emission drivers, energy intensity (Cint), affluence (Cypc) and penetration of RES (Crepe) constitute areas that require a more immediate action by energy policy decision makers. Thus, "extended" decomposition approach has enabled to identify key drivers for CO_2 emissions, accounting for the contribution of all fuel alternatives – both renewable and non-renewable, including nuclear energy.

INTRODUCTION

Energy's role to attain socio-economic development has been already historically recognized. Notwithstanding, as the threat of climate change becomes increasingly acknowledged, it becomes more evident that past and current unsustainable energy consumption patterns cannot be pursued or maintained. Both past and current trends present an excessive reliance on non-renewable energy sources, with fossil fuels accounting for 87% of primary energy supply, from which 33% of oil is allocated to transport sector, 30% of coal to electricity and industry sectors, although natural gas (24%) is increasing its share across aforementioned sectors (Banerjee et al. 2013).These figures corroborate (Timilsina and Shrestha 2009) perspective of considering these three sectors (energy; industry and transport) as major contributors to global CO_2 emissions. Effectively, according to United Nations Intergovernmental Panel on Climate Change (Eickemeier et al. 2014) latest estimates, GHG emissions have increased between 2000 and 2010, due mainly to energy supply (47%); industry (30%); transport (11%) and buildings (3%) sectors. Furthermore, as countries improve their socio-economic welfare, increasing levels of goods and services production often imply increasing energy consumption and CO_2 emissions (Banerjee et al. 2013; Lucena 2004), conditioning future energy sustainability. Therefore, given aforementioned relevance and increase in emission trends, accounting for energy related-emissions becomes imperative to promote a shift towards sustainable development. Within this context, two methodologies (Kaya Identity and Index Decomposition Analysis (IDA)) have become increasingly used to assess main influencing factors underlying variations in energy use and CO_2 emissions. Kaya Identity (Kaya, 1990) consists of an equation developed to determine main driving factors of CO_2 emissions. It has been adopted by several institutions, such as International Energy Agency (IEA 2013), to ascertain, at multiple levels, to what extent each factor impacts total CO_2 emissions. Recently, O'Mahony and Dufour (2015) further extended this equation to account for not only the impact of RES, but also that of nuclear energy. Meanwhile, although Index Decomposition Analysis (IDA) has been used in the energy sector for several decades, it has only recently- and successfully- extended its scope to environmental aspects (Ang 2004; Xu and Ang 2013). It promotes decomposition of CO_2 emissions into five main explanatory effects (activity; structure; intensity; energy mix and emission factor). However, it requires prior definition of an identity function (Ang 2004). This requirement has enabled to couple these complementary approaches, following a Log-Mean Divisia Index (LMDI) approach. Although both these techniques have been widely used at national and international level, recently developed "extended" Kaya Identity Decomposition has not been, to the author's knowledge, previously applied to promote a cross-country comparison. This complementary approach has enabled to compare a set of countries

(Portugal, Brazil and United Kingdom) characterized by substantially different energy matrix, as well as socio-economic backgrounds. While Brazil energy matrix includes nuclear and is mostly of a renewable nature, Portugal does not include nuclear, but has a higher share of RES than United Kingdom which includes nuclear but has a lower share of RES.

Therefore, this work aims to promote a cross-country assessment of main energy-related emission drivers, resorting to an approach that diferenciates the contribution of RES and nuclear energy for overall carbon emissions. In order to achieve these, the paper is organized as followed. After this introductory section, in the next section an overview on energy and emission trends is presented. Section 3 briefly describes the methodology adopted and data sources used. Section 4 presents and discusses the main results obtained, while Section 5 draws the main conclusions and presents avenues for future research.

RECENT TRENDS IN ENERGY AND ENERGY RELATED EMISSIONS

This section presents a brief overview of the evolution of energy and energy related CO_2 emissions for the three countries included in the analysis. Trends and potential inter-linkages identified and their relevance will be later on ascertained through the use of decomposition approach. For Portugal, as illustrated in Figure 1, Gross Domestic Product (GDP) shows an increasing pattern until 2000, stabilizing afterwards and dropping in 2008-2009, coinciding with the beginning of the economic recession. Emissions follow closely energy pattern, having increased until 2005, following a decreasing trend until 2010. Though presenting this decreasing trend, CO_2 emissions in 2010 are still 24% higher than 1990. Population growth rate has increased slightly by (6%).

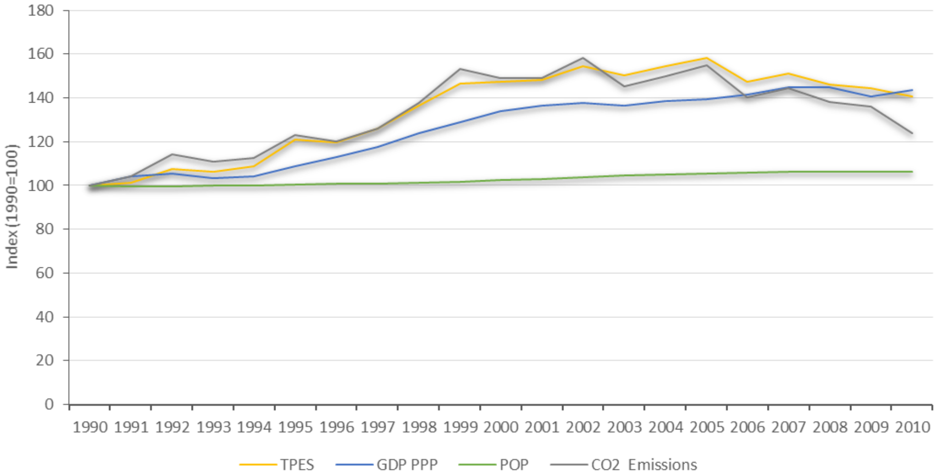

Figure 1: Energy, Population, GDP PPP and CO_2 Emissions trends for Portugal (Sources: IEA (2013b) and World Bank (2015))

Contrastingly, United Kingdom, as illustrated in Figure 2, presents an increasing GDP trend until 2008-2009 economic crisis, where it droped to increase again during 2009-2010 period. Once again emission follows closely energy trend, slightly increasing until 1995-1996, stabilizing between 1996-2008, suffering then a decrease coinciding with economic crisis. Increasing once more during 2009-2010 period. In spite of this, CO_2 emissions have decreased by 14% in comparison to 1990. Population growth has suffered a slight increase during this period (9%).

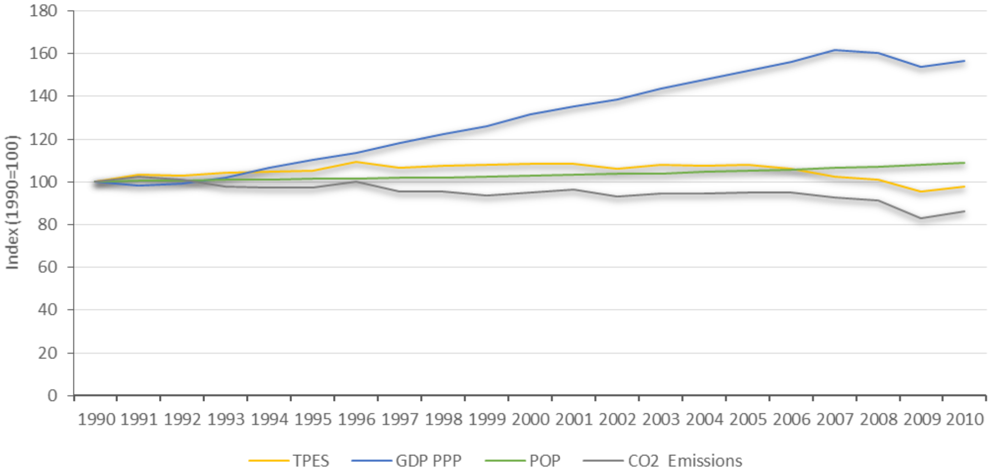

Figure 2: Energy, Population, GDP PPP and CO_2 Emissions trends for UK (Sources: IEA (2013b) and World Bank (2015))

For Brazil, emissions increased closely following energy and economic growth. Decrease in all these three indicators has coincided with economic crisis. Similarly to UK, these trends have increased again during 2009-2010 period, with CO_2 emission for 2010 increasing 101% comparatively to base year. Population growth has increased in 2010 by 30% comparatively to base year (1990).

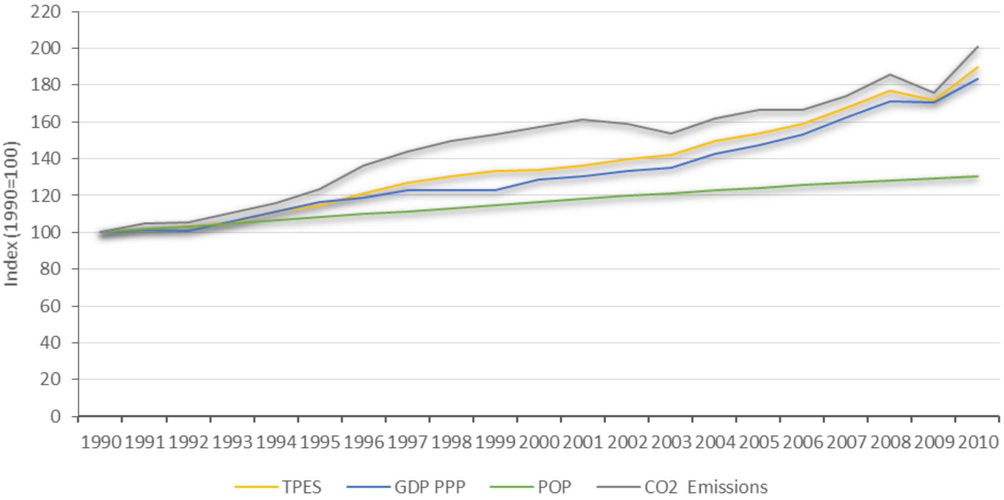

Figure 3: Energy, Population, GDP PPP and CO_2 Emissions trends for Brazil (Sources: IEA (2013b) and World Bank (2015))

DATA AND DECOMPOSITION APPROACH

In order to develop this complementary decomposition, this study follows the approach proposed by O'Mahony and Dufour (2015). The first step is to establish an identity function, in this case this equation corresponds to an adaptation of the original Kaya identity. As so, extended version encompasses the following effects:

$$C = \sum_i C_{i} = \sum_i [(C_i / FF_i) * (FF_i/FF) * (FF/FFN) * (FFN/E) * (EY) * (Y/P) * P = \sum_i F_1 S_1 S_2 S_3 IGP \qquad (1)$$

Where,
C= Total CO_2 emissions
F_1= Ci/FFi, CO_2 emission factor, for fossil fuel type i
S_1= FFi/FF, share of fossil fuel i in total fossil fuel
S_2 = FF/FFN, shares of fossil fuel in total fossil fuels plus nuclear
S_3= FFN/E share of fossil fuels plus nuclear in total energy
I= E/Y, aggregate energy intensity
G= Y/P, GDP/capita, GDP per capita or affluence
P= Population

In accordance to LMDI I method (considered by Ang and Liu (2001) a simpler LMDI formulae), each of these components can be further decomposed as:

$$Cemf = \exp(\sum_i wi * \ln(\frac{F_1^t}{F_1^0})) = \exp(\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - C_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(F_1^t/F_1^0)) \qquad (2)$$

$$Cffse = \exp(\sum_i wi * \ln(\frac{S_1^t}{S_1^0})) = \exp(\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - C_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} * \ln(S_1^t/S_1^0)) \qquad (3)$$

$$\begin{aligned} Cnepe &= \exp(\sum_i wi * \ln(\frac{S_2^t}{S_2^0})) \\ &= \exp(\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - C_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} \\ &* \ln(S_2^t/S_2^0)) \end{aligned} \tag{4}$$

$$\begin{aligned} Crepe &= \exp(\sum_i wi * \ln(\frac{S_3^t}{S_3^0})) \\ &= \exp(\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - C_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} \\ &* \ln(S_3^t/S_3^0)) \end{aligned} \tag{5}$$

$$\begin{aligned} Cint &= \exp(\sum_i wi * \ln(\frac{I^t}{I^0})) \\ &= \exp(\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - C_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} \\ &* \ln(\frac{I^t}{I^0})) \end{aligned} \tag{6}$$

$$\begin{aligned} Cypc &= \exp(\sum_i wi * \ln(\frac{G^t}{G^0})) \\ &= \exp(\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - C_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} \\ &* \ln(\frac{G^t}{G^0})) \end{aligned} \tag{7}$$

$$\begin{aligned} Cpop &= \exp(\sum_i wi * \ln(\frac{P^t}{P^0})) \\ &= \exp(\sum_i \frac{(C_i^t - C_i^0)/(lnC_i^t - C_i^0)}{(C^t - C^0)/(lnC^t - lnC^0)} \\ &* \ln(\frac{P^t}{P^0})) \end{aligned} \tag{8}$$

Where w_i represents the weight function, each one of these equations represents a factor that contributes to change in total C. Decomposition of changes in total CO_2 emissions in multiplicative form can be represented as illustrated bellow:

$$\text{Ctot} = \text{Ct/C0} = \text{Cemf Cffse Cnepe Crepe Cint Cypc Cpop} \tag{9}$$

In this equation Cemf stands for emission factor effect, and togheter with Cint, energy intensity effect, they constitute intensity effect; Cffse represents fossilfuel substitution, contributes along with Crepe to structural effect; Cypc and Cpop constitute scale effects.

Regarding decomposition approach, given that this study's database covers a large dataset, from multiple countries in a consistent manner and over a considerable period of time (1990-2010) an annual chaining perspective was undertaken, similarly to Baležentis, Baležentis, and Streimikiene (2011) and Mahony (2013). Furthermore, accessability issues to a more detailed emission database has rendered impossible initial intention of assessing emissions at sectoral level. Nowithstanding, the use of primary energy has its advantages, allowing to portray improvements from the suplly side that would otherwise pass unnoticed from a final consumption perpective (Banerjee et al. 2013). For empirical analysis, a database was built from a combination of two main data sources: International Energy Agency (IEA) and World Bank (World Development Indicators series). Most energy and socio-economic (population and GDP) data were collected from a single source (IEA) improving data comparability. Furthermore, by opting for an economic indicator (expressed in Purchasing Power Parities (PPP) at constant prices for 2005), this study avoids distortion of energy intensity values by disregarding differences amongst countries prices (Banerjee et al. 2013; Henriques and Kander 2010). Both primary energy and CO_2 emissions data contemplate fossil fuel contributions (coal, oil and natural gas) and has been assembled in internationaly standardized World Bank database.

RESULTS

Results from cummulative annual chained decomposition between 1990 and 2010 are summarized in this section. In order to facilitate result interpretation (Henriques and Kander 2010) a classification criteria was adopted. It is a three level criteria where 1.00 equals no change; values below 1.00 contribute to decrease total emissions, whereas values above 1.00 contribute to increase total emissions.

As illustrated in Figure 4, total carbon emission (Ctot) trend for Portugal presents a highly fluctuating behavior, though with a decreasing trend. Energy intensity (Cint), affluence (Cypc) and penetration of renewables (Crepe) seem to play a key role regarding total carbon emission in Portugal. Highest CO_2 emission was verified in 1998-1999 period, main factors contributing for this increase were energy intensity (Cint), affluence (Cypc) and decreasing penetration of renewables (Crepe). These factors were opposed by fossil fuel substitution effect (Cffse). On the other hand, greatest reduction was verified during 2005-2006 period. Main effects contributing for this reduction were energy intensity (Cint), and penetration of renewables (Crepe). These decrease has been opposed by affluence effect. The impact of population growth has kept unaltered during considered timeframe.

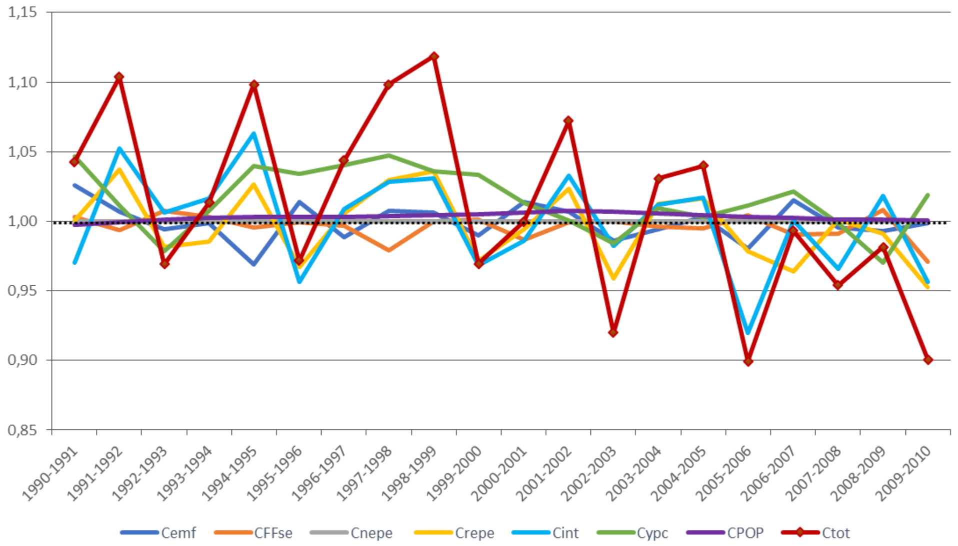

Figure 4: Cumulative Decomposition of CO_2 Emissions for Portugal (Sources: IEA (2013b) and World Bank (2015))

In spite of annual volatitlity, total carbon emission (Ctot) trend for UK, presents a steady trend. Energy intensity (Cint) and affluence (Cypc) were most relevant effects regarding CO_2 emissions for United Kindgom, illustrated in Figure 5. Highest emissions were reached in 2009-2010 period, associated with energy intensity (Cint), affluence (Cypc) and decreasing penetration of renewables (Crepe) and nuclear energy penetration effect (Cnepe). This increase was opposed by fossil fuel substitution (Cffse). Main reduction was reached during 2008-2009 period, influenced by energy intensity (Cint), affluence (Cypc), decreasing penetration of renewables (Crepe) and nuclear energy penetration effect (Cnepe). These effects were counteracted by emission factor effect (Cemf). It is also possible to see that the impact of population growth has been essentially marginal during the timeframe under analysis.

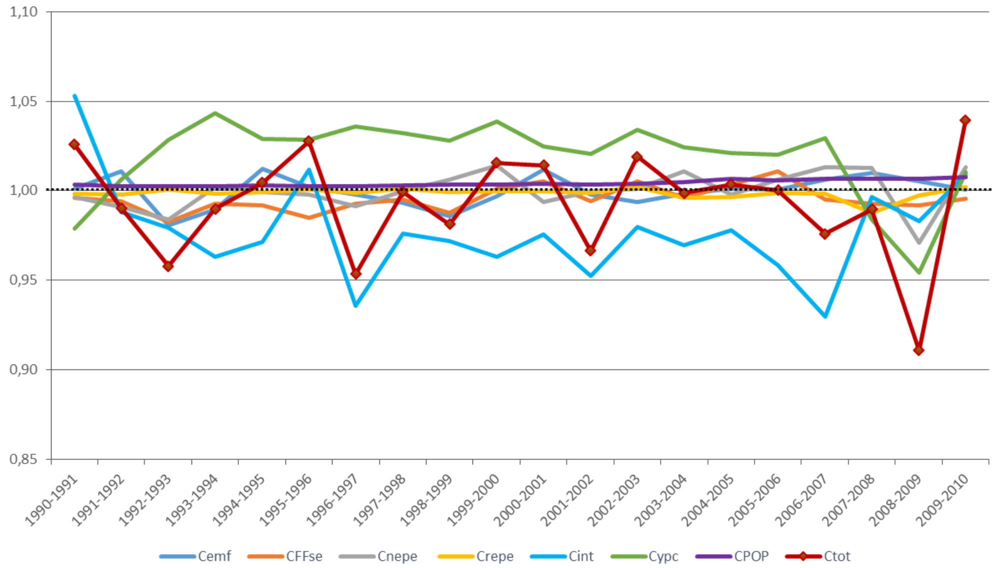

Figure 5: Cumulative Decomposition of CO_2 Emissions for United Kingdom (Sources: IEA (2013b) and World Bank (2015))

Total carbon emission (Ctot) trend for Brazil, presents a fluctuating behaviour, though with an increasing trend. Main influencing factors regarding total CO_2 emissions in Brazil were Energy intensity (Cint), affluence (Cypc) and penetration of renewables (Crepe), as illustrated in Figure 6. Upmost emissions were reached during 2009-2010 period, resulting from contribution of energy intensity (Cint), affluence (Cypc), decreasing penetration of renewables (Crepe) and nuclear energy penetration effect (Cnepe). These effects were offset by emission factor effect (Cemf). Minimum emissions were reached during 2008-2009 period, influenced by energy intensity (Cint), affluence (Cypc), decreasing penetration of renewables (Crepe), fossil fuel substitution (Cffse) and nuclear energy penetration effect (Cnepe). These effects were offset by emission factor effect (Cemf).

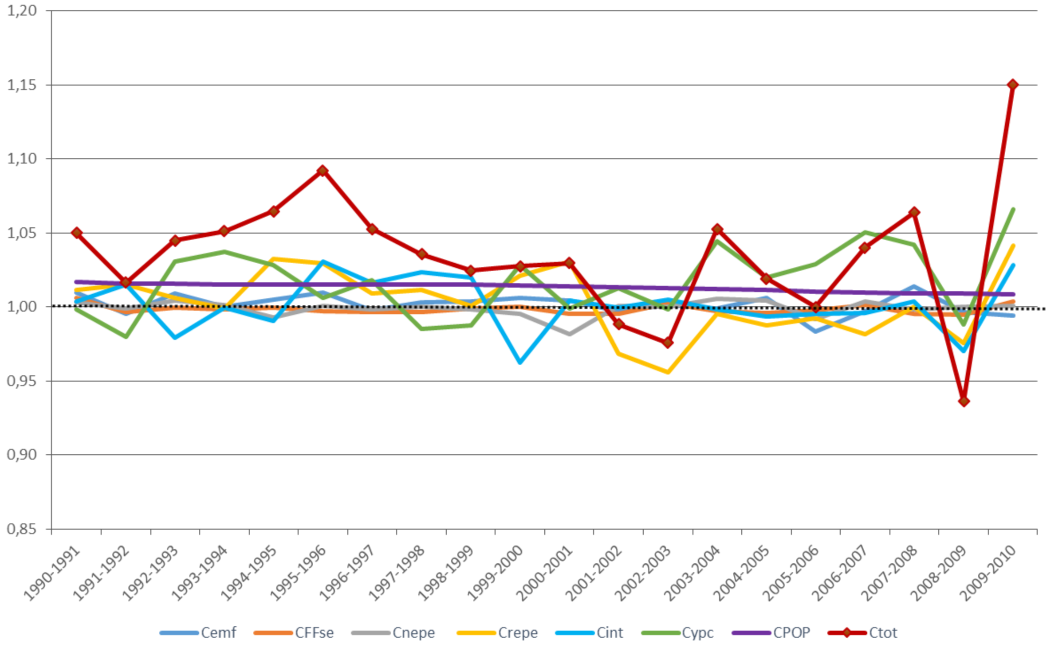

Figure 6: Cumulative Decomposition of CO_2 Emissions for Brazil (Sources: IEA (2013b) and World Bank (2015))

CONCLUSIONS AND FURTHER RESEARCH

Extended decomposition approach has enabled to identify key drivers for CO_2 emissions, accounting for the contribution of all fuel alternatives – both renewable and non-renewable, including nuclear energy. Based on this approach a cross-country comparison was developed highlighting main common and diverging drivers associated to emission trends.

Overall, for all countries energy intensity (Cint) and affluence (Cypc) have been the most influencing common factors, contributing for most accentuated fluctuations in overall carbon emissions. Contribution of RES penetration (Crepe) though consistent for Portugal and Brazil, has become more relevant for UK in recent years. Changes in affluence effect (Cypc) seem to be more significant at a yearly basis than changes in population growth (CPop). Shifts in population growth rate at yearly basis are not significant within timeframe considered, maintaining population effect praticaly unaltered. Despite this, based on obtained results, human-emission interactions should be more focused rather than population growth by itself. Furthermore, new approaches to emission assessment have emphasized the need to incorporate consumption patterns and technology when considering CPop (Rosa and Dietz 2012). As a result of GDP per capita, this effect (Cypc) is closely related to energy intensity of the economy (Cint), and together they have contributed for upmost or minimum carbon emissions in all countries. Based on its definition, upmost emissions being associated with lower energy efficiency (e.g. Portugal and Brazil), while decreases have been associated with higher energy efficiency (e.g. UK). According to decomposition results, United Kingdom should prioritize RES deployment, while Portugal and Brazil should focus more on energy efficiency improvements. Notwithstanding, this factor has made a decisive contribution towards diverging final emission trends. Contribution of increasing RES penetration (Crepe) has been evidenced during this period. However, it has been found that intermitancy associated with increasing RES deployment can contribute to amplify emissions instead of mitigating them. This result exposes simultaneously main advantages and disadvantages from RES deployment. If, on the one hand, a greater CO_2 emission reduction is promoted, on the other hand, uncertainty of energy supply is increased. This trend converges with Mahony and Dufour (2015) findings, where hydropower as acted as the main barrier for increasing contribution of other RES towards CO_2 emission reduction in Spain. Subject to a similar weather pattern variability, Portugal (nuclear free) presents more accentuated fluctuations than Brazil or UK (nuclear bound), although contribution of other effects has been considered less significant during the timeframe considered. Therefore, further debate regarding the future of nuclear energy should be undertaken. Especially given uncertainty brought on by Fukushima incident in Japan (Nachmany et al. 2014). Thus, "extendend" decomposition approach has allowed to identify main drivers for CO_2 emissions, while promoting a cross-country comparison. It has also contributed to assess the evolution of each effect's behaviour (including nuclear energy) along considered timeframe of twenty years. As main common emission drivers, energy intensity (Cint), affluence (Cypc) and penetration of RES (Crepe) constitute areas that require a more immediate action by energy policy decision makers. Futher efforts should be developed in determining main CO_2 emissions from a more holistic perspective, by allying, for example, decomposition approach to Life Cycle Assessment (LCA).

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