CO_2 emissions and causal relationships in the six largest world emitters

Ortega-Ruiz G.[a], Mena-Nieto, A.[b,c], Golpe, A.A.[c,d], García-Ramos, J.E.[a,c,e,*]

[a]*Department of Integrated Sciences, University of Huelva, 21071 Huelva, Spain*
[b]*Department of Electrical and Thermal Engineering, Design and Projects, University of Huelva, 21071 Huelva, Spain*
[c]*Centre for Advanced Studies in Physics, Mathematics and Computation, University of Huelva, 21071 Huelva, Spain*
[d]*Department of Economics, University of Huelva, 21071 Huelva. Spain*
[e]*Carlos I Institute of Theoretical and Computational Physics, University of Granada, Fuentenueva s/n, 18071 Granada, Spain*

Abstract

This paper aims to analyse and compare the driving forces of the carbon dioxide emissions of the six highest emitters of the world, namely, China, the United States of America, the European Union, India, Russia, and Japan, which are responsible for more than the 67% of the emissions, during the period 1990-2018. The analysis is based on an enlarged Kaya-LMDI decomposition, considering five driving forces and a Granger causality study. Both techniques allow us to disentangle the relationship among the different driving forces and how they change from country to country.

The main conclusion from the Kaya-LMDI analysis is that economic growth has been the main driving force that increases CO_2 emissions, and to a much lesser extent, the increase in population in most of the six analysed economies. On the other hand, energy intensity is the main factor for decreasing CO_2 emissions. Surprisingly enough, the end-use fuel-mix term seldom contributes to the decrease of the emissions, which proves that the use of renewable energy still should be largely promoted. It is worth highlighting the different behaviour observed between the four developed countries and the two most populous developing ones, China and India.

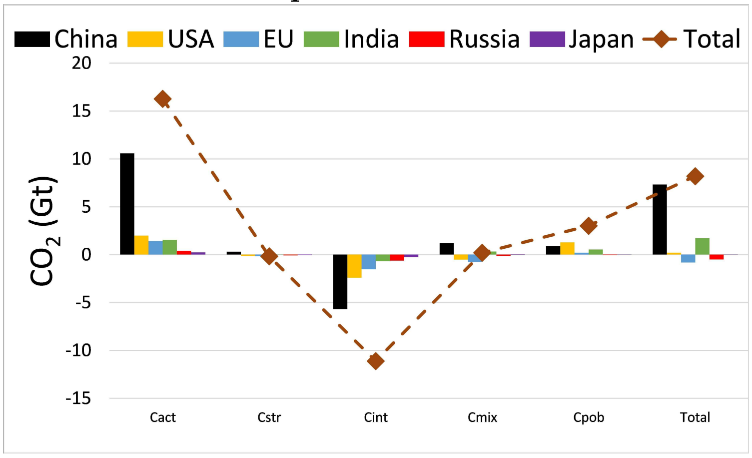
The Granger-causality analysis suggests that GDP Granger causes energy intensity in the developed countries; however, GDP and renewable energy consumption Granger cause

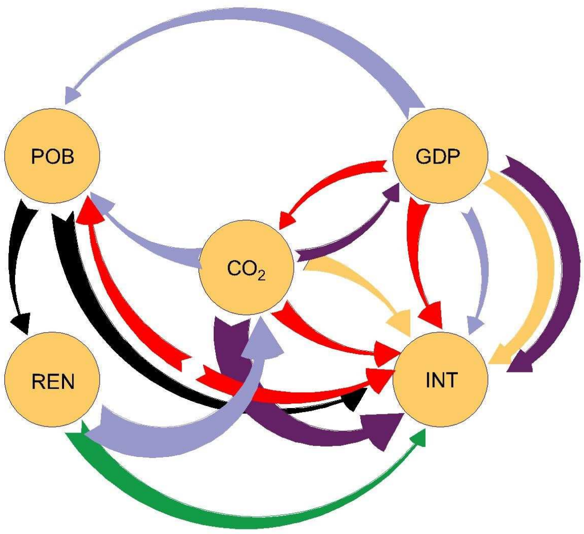
CO_2 emissions only in one case.

Keywords: CO_2 emissions, LDMI, Kaya identity, Granger causality, six largest world emitters

---

Graphical abstract





*Corresponding author: enrique.ramos@dfaie.uhu.es

Email addresses: gor5001@hotmail.com (Ortega-Ruiz G.), mena@uhu.es (Mena-Nieto, A.), antonio.golpe@dehie.uhu.es (Golpe, A.A.), enrique.ramos@dfaie.uhu.es (García-Ramos, J.E.)

Highlights:

- China and India should largely improve their energy intensity and energy mix contributions to reduce their CO_2 emissions.
- The USA and the EU own promising trends concerning energy intensity and energy mix contributions capable of reducing their global CO_2 emissions.
- Granger causality analysis suggests that CO_2 and GDP Granger cause most of the rest of driving forces.
- Emission intensity of China, India and Russia is around four times larger than the one of the USA, the EU and Japan.

Keywords: CO_2 emissions; LDMI analysis; Kaya identity; Granger causality; six largest world emitters.

Word count: 7900

List of abbreviations:

- act: economic activity.
- CO_2: carbon dioxide.
- EU: European Union (twenty eight state members).
- ENE: energy.
- GDP: Gross Domestic Product.
- GHG: greenhouse gases.
- Gtoe: giga tonnes of oil equivalent.
- Gt: giga tonne.
- GW: giga watt.

- int: intensity.
- IPCC: Intergovernmental Panel for Climate Change.
- $kgCO_2$: kg of CO_2.
- koe: kg of oil equivalent.
- LMDI: Logarithmic-mean Divisia index.
- LPG: liquefied petroleum gas.
- mix: energy mix.
- Mtoe: Mega tonnes of oil equivalent.
- NDC: Nationally Determined Contributions.
- pop: population.
- REN: renewable energy.
- str: economic structure.
- tCO_2: tonnes of CO_2.
- toe: tonnes of oil equivalent.
- UNFCCC: United Nations Framework Convention on Climate Change.
- USD: 2010 constant international dollar.
- WMO: World Meteorological Organization.

1. Introduction

Since the first studies that glimpsed the increase in the average temperature of our planet, global warming and its consequence, Climate Change, has become one of the main challenges for the world and, as a matter of fact, society considers Climate Change a major threat for the present way of living and that it will strongly affect many ecosystems and living species around the world [1, 2]. This problem is tightly connected with the emission of the so-called greenhouse gases (GHG), among which are methane (CH_4), nitrous oxides (NO_x), or hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and mainly carbon dioxide (CO_2), emitted in a natural or anthropogenic way. The importance of CO_2 is notorious; in 2018, it was estimated as 81% of all GHGs emitted anthropogenically in the USA [3]. The reduction of the anthropogenic component of the GHG emissions has thus become one of the significant challenges for world economies due to the connection between global warming, desertification, rising of the oceans, heat waves, extreme weather events or floods, according to recent International Panel for Climate Change (IPCC) [1] and World Meteorological Organization [4] reports. Furthermore, Climate Change affects people's way of living in most deprived places, reducing or ending their livelihoods and traditional way of life. The worsening impacts of Climate Change in the three most densely populated regions of the world could make over 140 million people moving within their countries' borders by 2050, creating a looming human crisis and threatening the development process [4].

The main problem of reducing CO_2 emissions lies in the tight connection between economy and emissions, being the used energy the link between these two apparently disconnected elements. Therefore, the primary sources of CO_2 emissions should be searched in the world's largest economies, namely, China, the United States of America, the European Union (considered as a whole, EU-28[1]), India, Russia and Japan, which by far are the largest emitters. These countries are responsible for two-thirds of the energy-related emissions of

[1]Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom

the planet, notably China, which is responsible for around 28% of the global CO_2 emissions in 2018, followed by the USA with 14%. In Fig. 1, it is shown the total value of the CO_2 emissions of the six largest emitters in absolute terms, corresponding to the year 2018 and, also, their aggregated share of the global emissions. This figure proves that the emissions of the considered countries reach approximately 67% of the world emissions.

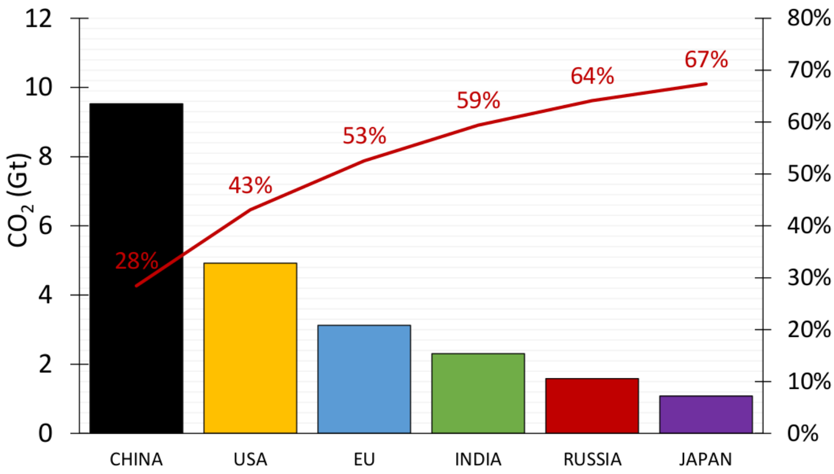


Figure 1: Emissions and share of the largest world CO_2 emitters in 2018. Data from IEA (International Energy Agency) [5].

According to the data from World Bank [6], China grew from 1135 million inhabitants in 1990 up to 1393 million in 2018. China promoted significant changes in its economy since 1978 with the granting of licenses to private companies, which made its GDP grow more than 10% per year since then and during the whole studied period of this work. As a matter of fact, China became the second-largest world economy in 2018, with a GDP of 13895 billion dollars. The USA grew from 249 up to 326 million inhabitants during 1990-2018, maintaining a economic growth path except in the 2009 year crisis, when its GDP fell by 2.5%. The GDP of the country in 2018 was 20612 billion dollars. With a population of 420 million in 1990, the European Union reached 447 million in 2018 and presented a relatively constant GDP growth, with an average value of 2% apart from the aforementioned economic 2009 crisis. Its GDP in 2018 was 15634 billion dollars. India registered a significant increase in population from 873 million inhabitants in 1990 to 1353 million in 2018. Its GDP grew in average a 3% per year, reaching 2701 billion dollars in 2018. Russia decreased its population by around 3 million people during the studied period, with 144 million in 2018. Its GDP suffered a deep contraction due to the former Soviet Union disintegration, which caused the fall of its GDP until 1997, but since then, the country's GDP has risen notably except the years 2009 and 2015. In 2018 its GDP was 1657 billion dollars. The population of Japan experienced a tiny increase during the studied period, namely, of 3 million inhabitants, reaching 126 million in 2018. Its GDP has slightly grown during the studied period, registering two significant drops, 2009, with a fall of a 5.4%, and 2011 due to Fukushima's nuclear accident. Its GDP in 2018 was 4955 billion dollars.

World economies have joined forces in different conventions to reduce GHG emissions in the near future. Since United Nations Framework Convention on Climate Change (UN-FCCC) was held in Brazil on March 21st, 1994, to UN Climate Change Conference COP-25 held in Madrid on December 2nd, 2019, different solutions have been proposed, highlighting the achievements reached in the Paris Agreement (COP-21) on Climate Change. This agreement, a legally binding international treaty, signed on December 12th, 2015 and entered into force on November 4th, 2016, obliges the countries studied in this work to comply with their contributions. However, the effect of this new legislation is still barely observed. These contributions have been established in the so-called Nationally Determined Contributions (NDC) [7]. Table 1 summarises the NDC contributions of the countries under study in this work, highlighting the target and the indicator used by each country.

Table 1: Contributions signed in the Paris agreements for the countries under study (NDC's).

Country	Date	Indicator	Commitment
China	2015-06-30	Emission intensity (CO_2/GDP)	To achieve the peaking of CO_2 emissions around 2030 or even earlier. To lower CO_2 emissions per unit of GDP by 60% to 65% from the 2005 level. To increase the share of non-fossil fuels in primary energy consumption to around 20%.
USA	2015-03-31	Emissions	To achieve an economy-wide target of reducing its GHG emissions by $26\% - 28\%$ below its 2005 level in 2025, trying to reach a 28% reduction.
	2021-04-22		To reach net-zero emissions economy-wide not later than 2050 and undertake rapid reductions thereafter, achieving a balance between anthropogenic emissions and removals.
EU	2015-03-06	Emissions	At least 40% domestic reduction in GHG emissions by 2030 compared to 1990.
	2020-12-18		Domestic reduction of at least 55% in GHG emissions by 2030 compared to 1990.
India	2015-10-01	Emission intensity (CO_2/GDP)	To reduce the emission intensity of its GDP by $33 - 35\%$ by 2030 from the 2005 level.
Russia	2015-04-01	Emissions	To reduce GHG emissions by $25 - 30\%$ from the 1990 levels by 2030.
Japan	2015-07-17	Emissions	Emission reductions of 26% in 2030 fiscal year compared to 2013 fiscal year (25.4% reduction compared to 2005 fiscal year).

In Fig. 2, the energy-related CO_2 emissions are plotted, and one can highlights the almost constant level of emissions, with even a slight reduction, for the USA, the EU, Russia and

Japan. In a completely different situation are China and India, with a rapid increase in the emissions, while the rest of the world also grow, although not as fast as China or India.

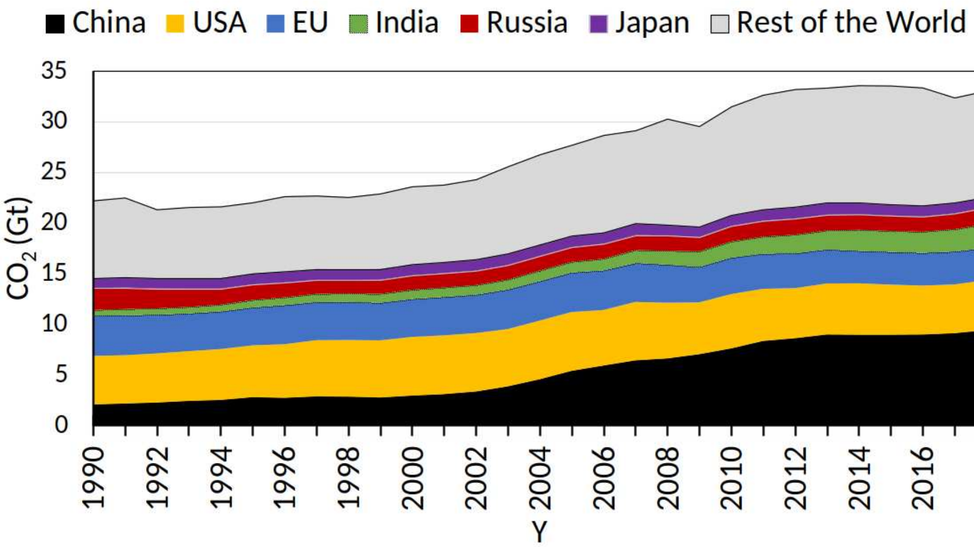


Figure 2: Evolution of the energy-related CO_2 emissions in the six largest world emitters during the period under study.

The main goal of this work is to analyse and compare the time evolution and causal relationships of the different driving forces that modulate the energy-related CO_2 emissions, namely, economic activity, economic structure, energy intensity, energy mix, and population, of the six largest CO_2 emitters since the 1990s until nowadays, serving as a tool to policymakers to determine future environmentally sustainable policies.

Surprisingly enough, few previous studies shed light on the evolution over time of the emissions in these six largest emitters during the period 1990-2018. The so-called logarithmic-mean Divisia index (LMDI) [8] will be used together with an extension of the Kaya identity [9] in which the energy is disaggregated in terms of its different types, and the different industrial sectors are separated. On the other hand, the Granger causality [10] analysis using the Toda-Yamamoto methodology [11] will be applied to explore the causal relationships between the driving forces that determine CO_2 emissions. This type of analysis will allow conclusions for future policies to fight against Climate Change in the six studied countries.

The rest of this paper is organized as follows. In Section 2, the relevant literature concerning the use of the LMDI and Toda-Yamamoto methods for the six considered countries is briefly reviewed; in Section 3, the used methodology is sketched; Section 4 serves to present the results and their discussion, and finally, Section 5 provides the conclusions and policy implications.

2. Literature review

The literature concerning the relationship between CO_2 emissions and economy for the countries considered in this work is extensive; therefore, we will focus only on those works which consider a set of countries like the one treated in this work, using moreover the Kaya identity and any kind of decomposition technique, mainly LMDI. Furthermore, in our review, we will also consider those works in which a Granger-causality analysis has been conducted among the different driving forces of CO_2 emissions or energy.

Dong et al. [12] conducted an LMDI decomposition for 133 countries with different levels of income (including those of this paper except Russia and five countries of the EU) for the period 1980-2015, with projections until 2030, concluding that energy intensity produces the most significant reduction, while the increase in the GDP the most considerable rise of the CO_2 emissions. In [13], the authors proposed a cross-country pyramidal approach for analysing and decomposing the energy intensity considering the LMDI decomposition method and focusing on China, the USA, the European Union, India, Russia, and Japan during the period 1995-2017. They concluded that the emerging economies had worsened their energy sector efficiency as they increased their income. In [14], the authors found the drivers for the long-run CO_2 emissions during the period 1980-2011 for nine countries of the EU-28, the USA, and Japan. Economic growth is the main driver, and technological change proves to be the main offsetting factor in the long term, particularly during the last decades. In [15], the CO_2 decoupling of 57 countries of the "Belt and Road Initiative", including China, India, Russia and 12 EU countries, are analysed from 1991 to 2016. Five driving forces of the CO_2 emissions are identified via the Kaya-LMDI model. Inglesi-Lotz [16] proved that during the period 1990-2014 the slowdown of CO_2 emissions is tightly connected with improvements in energy intensity and carbon intensity in all the BRICS countries, namely, Brazil, Russia, India, China, and South Africa, although for India and China a rebound effect was observed. In Shuping et al. [17], the authors analyse the connection between CO_2 emissions and economic development in different developing countries, including China and India, during the period 2001-2017. They concluded that economic development and population rapidly increase energy consumption, although energy intensity decreases, being coal and oil the main actors in the energy transition pathway of China and India. Marcucci and Fragkos [18] developed a multi-model decomposition analysis of the CO_2 emissions for China, India, the EU, and the USA under different scenarios during the period 2000-2100. The authors identify the assumptions and model characteristics that lead to different decomposition results in moderate and stringent climate policy scenarios. In [19], the authors analyse in-depth the coupling between economy and CO_2 emissions in BRIC countries during the period 1995-2014, finding that energy intensity can slow down the rise in CO_2 emissions. Energy mix and fossil energy effects also contribute to the reduction of the emissions, but neither during the whole period nor for all the countries.

[20] is devoted to the study of the causal relationships between CO_2 emissions, economic growth, energy generation, and value-added service for a panel of 65 countries. The study focused on the period 1980-2014 using the vector autoregressive model, Granger causality, and Toda–Yamamoto tests. Their most conclusive results point towards a strong bidirectional causality between CO_2 emissions and non-renewable energy, CO_2 emissions and value-added service, and between non-renewable energy and value-added service. In [21], the authors use the Toda-Yamamoto causality test, including a Fourier approximation, to investigate the Granger causes among financial development, energy consumption, and economic growth in 21 emerging markets. They found that the causality analysis with structural changes provides a causal linkage in half of the cases. These results support that economic activity mainly causes financial development and energy consumption in the fast-growing emerging economies of the sample. In [22], the author conducted a Granger causal analysis for the 91 less developed countries during the period 1970-2013, concluding that energy consumption Granger causes economic growth in twelve countries. Pata and Aydin [23] studied the

relationship between hydropower, energy consumption, ecological footprint and economic growth for the six largest hydropower-consuming countries, namely, Brazil, China, Canada, India, Norway, and the USA. They used the Fourier Toda-Yamamoto causality test, suggesting a unidirectional causality relationship pointing from hydropower energy consumption into economic growth in Brazil and a bidirectional one between these two variables in China. In [24], the authors conducted a Granger causality analysis in the G-8 and Southeast Asian countries from 1970 to 2010, concluding that energy consumption Granger causes industrial production. Sankaran et al. [25] use the Toda-Yamamoto test to study causality among electricity consumption, per capita income, real exchange rate, import and export of manufacturing output, from 1980 till 2016, for ten late industrialized nations, including India. Their results support the existence of growth, conservation, feedback and neutrality hypotheses for different nations. In [26], the authors conducted a study on the effects of foreign direct investment and the trade openness on clean energy consumption for BRICS countries during the period 1985-2017. The authors applied the Fourier Toda-Yamamoto approach to analyse the Granger causality. The authors found that foreign direct investment Granger causes clean energy consumption in China. In [27], the authors study the Granger causality using the Toda-Yamamoto test for energy consumption, economic growth, employment and gross fixed capital formation in several OECD highly developed countries. They found a bidirectional causal relationship between energy consumption and GDP in Italy, New Zealand, Norway and Spain.

Once we have gathered the most up-to-date literature on the analysis of CO_2 emissions concerning the six major emitters, we have identified the gaps in the existing literature, namely:

- To perform the analysis in a more extended and common period of time to gain insight on the impact of the different CO_2 drivers over time in the group of most relevant countries.
- To clarify the effect of the size of economic sectors on the amount of CO_2 emissions.
- To provide a clearer view of the evolution of CO_2 driving forces over time by referring

the LMDI values to a single reference year instead of presenting the relative change year by year.

- To study the Granger causal relationship between the driving forces of the CO_2 emissions.

Therefore, this work would contribute to the existing literature on the relationship among the driving forces of carbon emissions for the six largest world emitters, based on the Kaya-LMDI approach and the Granger causality study, using the Toda-Yamamoto test.

3. Materials and methods

3.1. LMDI analysis

The analysis of the driving forces of CO_2 emissions will be conducted using the Kaya identity [9, 28] combined with the LDMI method [29]. The Kaya identity has been widely used in the field of CO_2 inventories as well as in scenario analysis. Since its first proposal, it has been refined and written in a disaggregated way to consider the different economic sectors and types of energy fuels. Examples of the Kaya identity written in a disaggregated form can be found, for instance, in [30, 31, 32]. The Kaya identity in a disaggregated form is given in Eq. (1), where CO_2 emissions, C, of a given period are written as the sum of the contributions per industrial sector, i, and type of fuel, j (C_{ij}). Each contribution is then written down as the product of the population (P), the income per capita ($q = \frac{Q}{P}$), the share of sector i to the GDP ($S_i = \frac{Q_i}{Q}$), the energy intensity of the sector i ($EI_i = \frac{E_i}{Q_i}$), the energy matrix ($M_{ij} = \frac{E_{ij}}{E_i}$, the share of fuel j in sector i), and the emission factor ($U_{ij} = \frac{C_{ij}}{E_{ij}}$),

$$C = \sum_{ij} C_{ij} = \sum_{ij} P \frac{Q}{P} \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = P \cdot q \sum_{ij} S_i \cdot EI_i \cdot M_{ij} \cdot U_{ij}, \tag{1}$$

where Q is the GDP of the period under study at constant prices, Q_i the corresponding one for sector i, E_i is the total energy consumed in sector i, E_{ij} is the consumed energy of type j in the productive sector i. Note that in practice U_{ij} seldom depends on i, therefore, it is assumed to depend only on j, $U_{ij} = U_j$.

In Eq. (1), one can easily identify six different terms; however, due to the mathematical form of the equation, it is not trivial to isolate the different contributions. To this end, Ang and Choi, in their seminal work [29], proposed the LMDI decomposition method that allows to identify and extract the contributions of the different driving forces of a given expression. We refer the reader to [33, 34] for a complete guide on the different types of LMDI decomposition methods. Using the LDMI method, the resulting changes in emissions for a given period, t, with reference to an initial time, 0, can be evaluated either in an additive or in a multiplicative way. In the case of the additive decomposition method, the variation of the emissions for a given period is written as:

$$\begin{aligned} \Delta C(t) &= C(t) - C(0) = \Delta C_{pop}(t) + \Delta C_{act}(t) + \Delta C_{str}(t) \\ &+ \Delta C_{int}(t) + \Delta C_{mix}(t) + \Delta C_{emission}(t), \end{aligned} \tag{2}$$

while in the multiplicative form as:

$$D(t) = C(t)/C(0) = D_{pop}(t) \cdot D_{act}(t) \cdot D_{str}(t) \cdot D_{int}(t) \cdot D_{mix}(t) \cdot D_{emission}(t), \tag{3}$$

where

$$\Delta C_{pop}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)} \ln \frac{P(t)}{P(0)}, \tag{4}$$

$$\Delta C_{act}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)} \ln \frac{q(t)}{q(0)}, \tag{5}$$

$$\Delta C_{str}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)} \ln \frac{S_i(t)}{S_i(0)}, \tag{6}$$

$$\Delta C_{int}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)} \ln \frac{EI_i(t)}{EI_i(0)}, \tag{7}$$

$$\Delta C_{mix}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)} \ln \frac{M_{ij}(t)}{M_{ij}(0)}, \tag{8}$$

$$\Delta C_{emission}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)} \ln \frac{U_{ij}(t)}{U_{ij}(0)} \tag{9}$$

and

$$
\begin{aligned}
D_{pop}(t) &= \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{P(t)}{P(0)}\right), && (10)\\
D_{act}(t) &= \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{q(t)}{q(0)}\right), && (11)\\
D_{str}(t) &= \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{S_i(t)}{S_i(0)}\right), && (12)\\
D_{int}(t) &= \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{EI_i(t)}{EI_i(0)}\right), && (13)\\
D_{mix}(t) &= \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{M_{ij}(t)}{M_{ij}(0)}\right), && (14)\\
D_{emission}(t) &= \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{U_{ij}(t)}{U_{ij}(0)}\right). && (15)
\end{aligned}
$$

Note that the expression $\frac{A-B}{\ln A-\ln B}$ is assumed to vanish for $A = B$ or $A = 0$ or $B = 0$. This method allows analysing the changes in the emissions generated by studying five factors: the changes in the economic activity (*act*), the changes in the structure of the economic sectors (*str*), the changes in the energy intensity (*int*), the changes in the energy mix (*mix*), and the changes in the population (*pop*). We assume there are no changes in the emission factors; therefore, no driving force is associated with this term.

3.2. The Granger causality analysis using the Toda-Yamamoto test

The analysis of the relationships among the different driving forces of CO_2 emissions should be carefully studied in order to disentangle the possible relationships among them and how they change in the different countries. To this end, we will conduct a Granger causality study [10] for all the involved variables in the Kaya identity. In the literature, one of the most common methods for testing the causality effects between different variables is by using the Granger causality method based on the estimation of vector autoregression (VAR) models. The Toda and Yamamoto's method [11] attempts to measure causality by solving problems derived from cointegrating relationships and non-stationary series. Delving into the suggested relationship, we follow the Toda-Yamamoto causality approach as an enlarged form of the Granger causality test based on augmented-VAR models in levels and extra lags, providing more efficient and robust results than the standard VAR model that may provide biased results with finite samples [35, 36, 37, 38, 39]. The core advantage of this test is the possibility of being applied regardless the series are cointegrated or not, and, in the case of cointegration, the order of integration is not crucial. In this work, a bivariate model including the variables CO_2, renewable energy consumption, GDP, population, and energy intensity is considered. Thus, in the case of CO_2 emissions and GDP, the Granger causality analysis involves the next couple of equations,

$$CO_{2\,t} = \alpha_1 + \sum_{i=1}^{l+d_{max}} \beta_{1i} CO_{2\,t-i} + \sum_{j=1}^{l+d_{max}} \gamma_{1j} GDP_{t-j} + \varepsilon_{1t} \tag{16}$$

$$GDP_t = \alpha_2 + \sum_{i=1}^{l+d_{max}} \beta_{2i} GDP_{t-i} + \sum_{j=1}^{l+d_{max}} \gamma_{2j} CO_{2\,t-j} + \varepsilon_{2t} \tag{17}$$

where l is the optimal lag structure for the VAR model according to the Akaike Information Criterion (AIC); d_{max}, extra lagged explanatory variables, corresponds to the maximum order of integration for the variables considered in the model; and the error terms ε_{1t} and ε_{2t} follow a Gaussian distribution and the are considered to be white noise processes. Therefore, this test estimates a VAR (l+d_{max}) model employing a Modified Wald test (MWALD), which is statistically asymptotically distributed as a χ^2 with p degrees of freedom.

To test the Granger causality between the two variables selected, attending to the Eq. (16), if $\sum_{j=1}^{l} \gamma_{1j} \neq 0$, this suggests that GDP Granger causes CO_2. Similarly, in Eq. (17), if $\sum_{j=1}^{l} \gamma_{2j} \neq 0$, CO_2 Granger causes GDP. Subsequently, if both hypotheses are rejected, this implies that there may exist a bi-directional causality in the examined relationship.

3.3. Sources of data

To carry out this work, we have used official data extracted from several official sources, namely, the World Bank [6], for economic data, the IEA (International Energy Agency) [5] for energy consumption, and the EPA (United States Environmental Protection Agency) [3] for the value of the emission factors.

Following the International Standard Industrial Classification of economic activities (ISIC version 3), the data have been grouped in the three traditional economic sectors: the Primary sector ($i = 1$), corresponding to the sections A and B of ISIC, which include agriculture, livestock, forestry and fishing, plus mining and quarrying. The Industrial sector ($i = 2$), corresponding to the sections C, D, E and F, including, among others, manufacturing, supply of electricity, gas, water, waste management and construction. Finally, the Service sector ($i = 3$) contains the rest of the sections, among which are trade, transport and storage, residential consumption, and public services. This classification promoted by the United Nations allows comparing the data corresponding to different countries, fuels and sectors uniformly.

In this work, a total of 21 fuels have been considered, which are enlisted in Table 2. Due to the significant influence of coal and petroleum in the amount of CO_2 emissions, we have considered as disaggregated in its distinct types the consumed coal and petroleum, instead of simply using the total amount and the average value of the emission factors. This disaggregation allows studying the evolution of CO_2 emissions as a function of the consumption of the diverse types of coal and petroleum over time. In Table 2, Coal* and Petroleum* correspond to the average values of their emission factor, and they will be used for those cases that are not disaggregated in their components. In most countries, these quantities represent a minor fraction of the total amount.

The used unit for energy has been the oil equivalent (koe, toe, Mtoe, or Gtoe), while for GDP the 2010 constant international dollar. The rest of used units are the ones of the International System of Units.

The carbon-free-emission energy sources correspond to solid biofuel, the solar, wind, nuclear and hydroelectric energy. In this work, when referring to *renewable energy*, we will follow this prescription.

Table 2: Emission factor per type of fuel, given in $kgCO_2$/koe. Source: EPA (United States Environmental Protection Agency) [3].

Fuel	Emission factor ($kgCO_2$/koe)
Coal*	4.511
Anthracite	4.116
Coking coal	3.742
Bituminous coal	3.702
Lignite coal	3.989
Coke oven gas	1.860
Blast Furnace gas	10.888
Petroleum*	2.978
Diesel	2.973
Gasoline	2.789
Naphtha	2.871
Kerosene	2.984
Jet kerosene	2.866
LPG	2.449
Natural gas	2.106
Biofuel (gas)	2.066
Biofuel (solid)	0
Biofuel (liquid)	2.930
Solar and wind	0
Nuclear	0
Hydroelectric	0

*Average value.

4. Empirical results and discussion

4.1. Energy and renewable energy consumption

Energy demand presents a different trend in the different countries, being possible to separate them into two groups, on the one hand, the USA, the EU, Russia, and Japan, which shows a flat evolution and China and India with a clear upsloping increase. As observed in Fig. 3A, in the first group of countries, there is a tiny increase of the energy consumption during the studied period or even a decrease, namely, the EU energy consumption changed a -1.5%, Russia a -13.2%, the USA a 16.4% and Japan a -2.4%. In the second group, there is a tremendous increase in energy consumption, with India increasing a 196.6% and China a 266.6%. Regarding the share of renewable energy, depicted in Fig. 3B, there is a group, made of the EU, the USA, and Russia, where this share steadily increases, though in a small fraction. The second group is formed by China and India, for which the share of renewables strongly decreases during the studied period. Finally, we separately consider Japan, where a sudden discontinuity in the share of renewable energy happened in 2011, corresponding to Fukushima's nuclear accident. Anyhow, without considering this discontinuity, the behaviour of Japan coincides with that of the first group of countries.

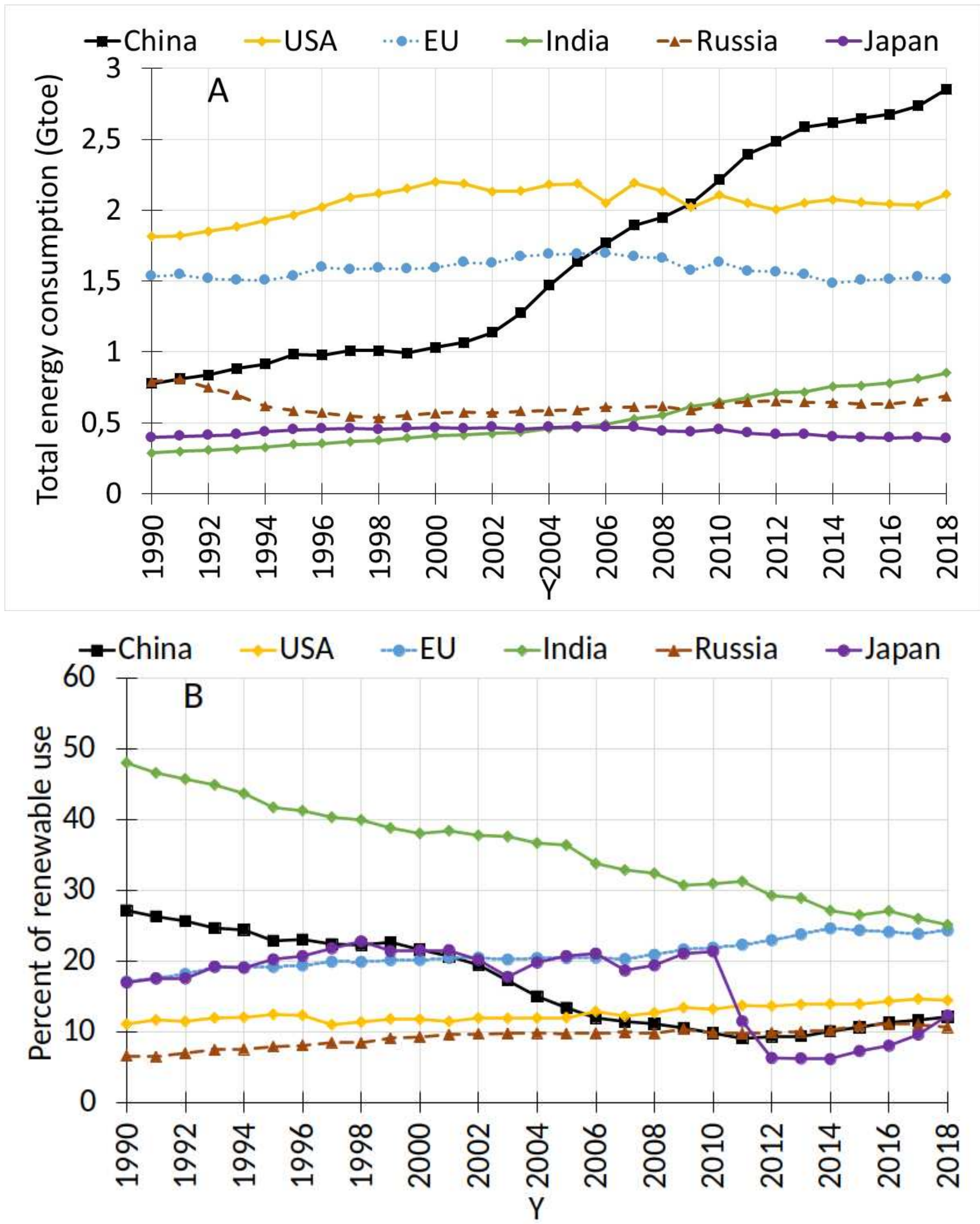


Figure 3: Evolution of annual total energy consumption (panel A) and share of used renewable energy (Panel B) during the period 1990-2018.

Fig. 3B highlights the decreasing renewable energy share in China, which passes from 27% to 12%, and India, which drops from 48% to 25% during the studied period. As will be explained below, that happens despite the enormous new renewable capacity that has been incorporated into the energy system of both countries.

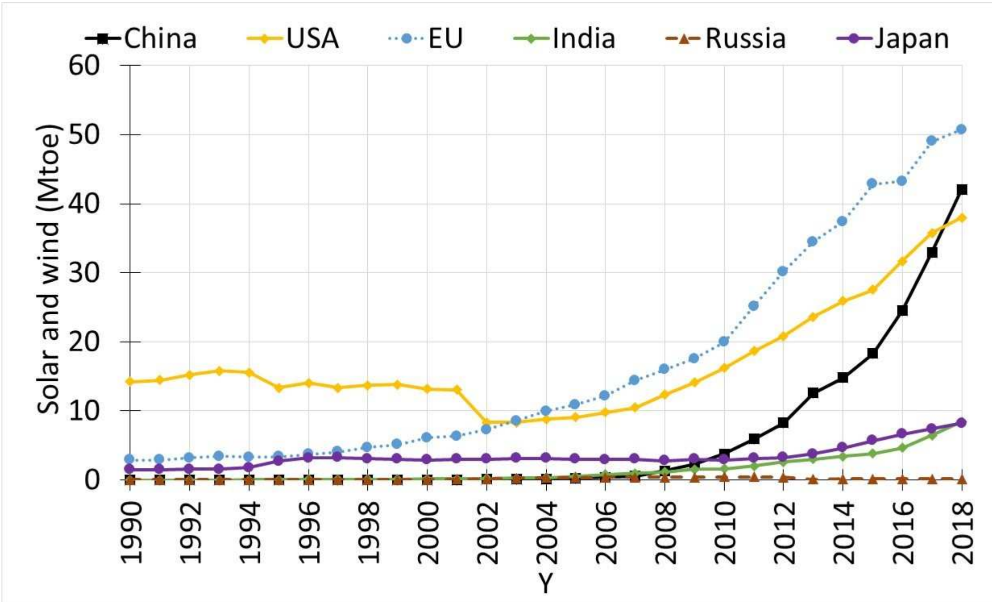


Figure 4: Evolution of solar and wind renewable energy used during the period 1990-2018.

In Fig. 3, the evolution of solar photovoltaic (PV) and wind power is depicted, where it is worth mentioning the remarkable increase in five of the six considered countries. The policies regarding CO_2 emission reductions, together with the commitment to wind and solar technologies, have made these two technologies almost as economically competitive as the traditional ones based on the burning of fossil fuels. Taking the EU as a reference, with a cost bracket in the traditional energies that range from 60 to 200 USD/MW, the final price in solar photovoltaic has been reduced from 360 USD/MW in 2010 to 100 USD/MW in 2017, also been reduced the cost of onshore and offshore wind farms down to 60 and 140 USD/MW, respectively, for 2017. Continuing with the case of the EU, its production of solar and wind energy has passed from 2.9 Mtoe in 1990 to 50.7 Mtoe in 2018, turning the solar and wind sources into the most significant renewable sources in the EU. In 2018, the EU share of renewables reached 32% of electricity production. The case of the USA is noticeable, with a rapid increase in the production of solar and wind energy, mainly from the year 2002, growing from 14.2 Mtoe in the base year up to 38 Mtoe in 2018. One of the main contributors to this trend has been the solar PV owing to federal tax incentives and state-level policies, as well as the new onshore power plants, which added new 6.9 GW in 2018, reaching 9.1 GW in 2019, once more, pushed by the existence of tax credits with a deadline in 2020. China, where numerous new projects have promoted the contribution of these sources, has grown at a remarkable rate since 2006. China's onshore wind capacity expansion has steadily increased, reaching 19.0 GW in 2018 and growing to 23.8 GW in 2019, which helped by lifting development bans in certain regions. Although more moderately, Japan and India also show an increase in the use of renewable energies based on wind and solar sources. Finally, in Russia, the use of renewable energy was almost zero during the whole considered period.

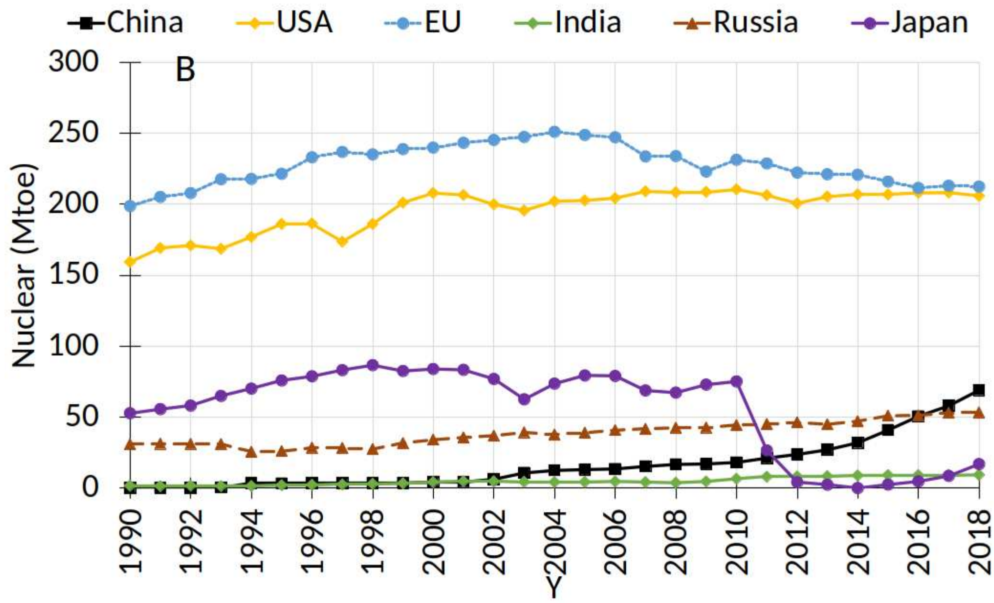


Figure 5: Evolution of nuclear energy used during the period 1990-2018.

The production of nuclear energy is depicted in Fig.5, where a different behaviour is observed between developed and developing countries. The first group shows a relatively constant production with a decrease in the last fifteen years, while the second group started with an almost negligible contribution but rapidly grew during the analysed period [5].

Let us start with the group of developed countries. The EU generation, traditionally led by France, Germany and the UK, passed from 198.7 Mtoe in 1990 to its maximum recorded in 2004 with 251.0 Mtoe, though from this year and onwards, the production decreased to 212.48 Mtoe in 2018. The USA kept its nuclear power capacity almost constant during the studied period, reaching a share of electricity production of 29.3%. In 2018, the energy generated in nuclear plants in the USA was similar to the one of the EU. Russia also presented a large nuclear energy production during the considered period, with 35 reactors in service. The evolution of nuclear energy production in Japan was strongly influenced by Fukushima nuclear power plant accident on March 11th 2011. Nuclear energy in the country grew from 52.7 Mtoe in 1990 to 75.1 in 2010, triggered by the opening of new reactors. After Fukushima's accident, all 39 reactors in the country were shut down. Since then, the nuclear energy production in Japan has partially rebounded but still is very far from its maximum and most probably will never be fully recovered [5].

Concerning the group of developing countries, the number of commissioned new reactors has been notable, reaching in the case of India the number of 22 reactors in operation in 2018, passing the annual production from 1.5 Mtoe in 1990 to 9.3 Mtoe in 2018. On the other hand, China installed 35 new reactors in the period studied, reaching an annual production of 69.0 Mtoe, surpassing the Russian nuclear energy production.

4.2. CO_2 emissions by type of fuel and sector

In this section, we deeply analyse the evolution of the CO_2 emissions in the different countries, disaggregating in types of fuel and sector, paying particular attention to the different types of used coal and petroleum. All this information is summarised in Fig. 6.

In Fig. 6A, the evolution of emissions in China is depicted. The most obvious fact from this figure is the rapid increase of the emissions over time. The main source of emissions corresponds to the different forms of coal. In 1990, it was responsible for 85% of the emissions, corresponding mainly to the bituminous kind (69% of emissions). Even in 2018, coal is still the main source of emissions, 78%, although the use of bituminous coal has been reduced to a 37%, introducing new types of coal such as coke, oven coke or blast furnace, which present a very high emission factor. Diesel and gasoline utilisation have also increased, passing the diesel from 3.9% in 1990 to 5.4% in 2018. It is worth mentioning the reduction of fuel oil use, which falls from 1.9% in 1990 to 0.4% in 2018, moreover, natural gas entered the scene in 2005, with a share in the emissions of 1.4%, until 4.6% in 2018. Concerning the economic sectors, their shares of emissions are relatively constant over the whole period, with approximated values of 67%, 26% and 7% for industrial, service and primary sectors, respectively. However, a specific reduction of the primary sector share favouring industrial and service ones is observed at the end of the period.

In Fig. 6D, the evolution of India is presented, also owning a rapid increase of emissions like in China. Its emissions are strongly determined by the contribution of the different types of coal, being responsible for 59% of total emissions in 1990, reaching 65% in 2018, also with significant use of bituminous type, responsible for 44% of total emissions in 2018. Concerning the share of economic sectors, the primary sector presents a quite stable trend during the whole period with roughly 10%. However, the service sector passed from 30% in 1990 to 36% in 2018, while the industrial sector dropped from 60% in 1990 to 54% in 2018. Note that the increase in diesel and gasoline use has been masked by the rapid increase of the emissions coming from coal.

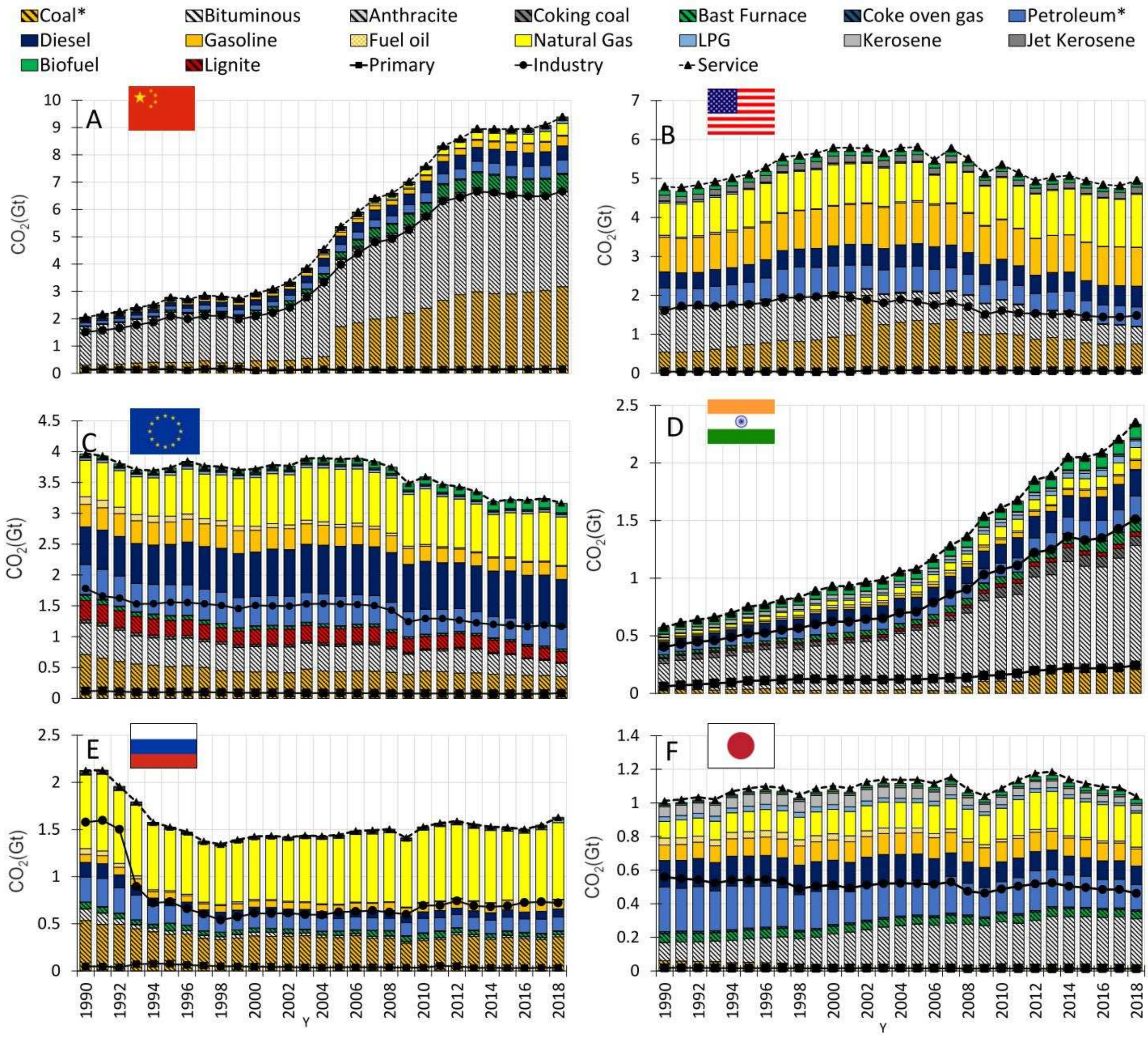


Figure 6: CO_2 emissions separated by energy sources (colour bars) and sectors (lines) and countries.

The observed trend in the emissions of the developed countries (panels B, C, E, and F of Fig. 6) presents either a certain stabilization or even a decrease, despite the rapid economic growth of this group of countries during the last thirty years. A common aspect in these four countries is the steady withdrawal of coal-derived fuel emissions in favour of natural gas, which has grown in this set of developed economies, becoming one of the main sources of energy. As a matter of example, more than 27% of the emissions in the USA (Fig. 6B).

In the EU (Fig. 6C) emissions from natural gas grew from 15% to 25%, while in Japan (Fig. 6F) from 10% to 20%. Finally, Russia (Fig. 6E), a traditional producer and exporter of natural gas, passed from 42% in 1993 to 50% in 2018.

A common problem in developed economies is their high percentage of emissions related to petroleum-derived fuels such as gasoline and diesel, mainly used in the transportation sector. These emissions represent in the USA (Fig 6A) a 27% in 1990 and 31% in 2018, while the EU went from 25% in 1990 to 31% in 2018. On the other hand, Russia recovered in 2018 the share of emissions from diesel and gasoline it had in 1990, approximately an 11%. The only developed country where the share of emissions related to diesel and gasoline has decreased is in Japan, passing from 25% in 1990 to 20% in 2018.

Finally, concerning the evolution of emissions by sectors, all the developed economies have kept a relatively constant share, while the share of the industrial sector decrease and the one of the service sector increases. In the USA, the industrial sector share passed from 33% in 1990 to 29% in 2018, being these numbers 67% and 70% for the service sector. In the EU, emissions from the industrial sector decreased from 42% in 1990 to 34% in 2018; in Japan, from 53% to 43%; and in Russia, from 46% in 1993 to 42% in 2018.

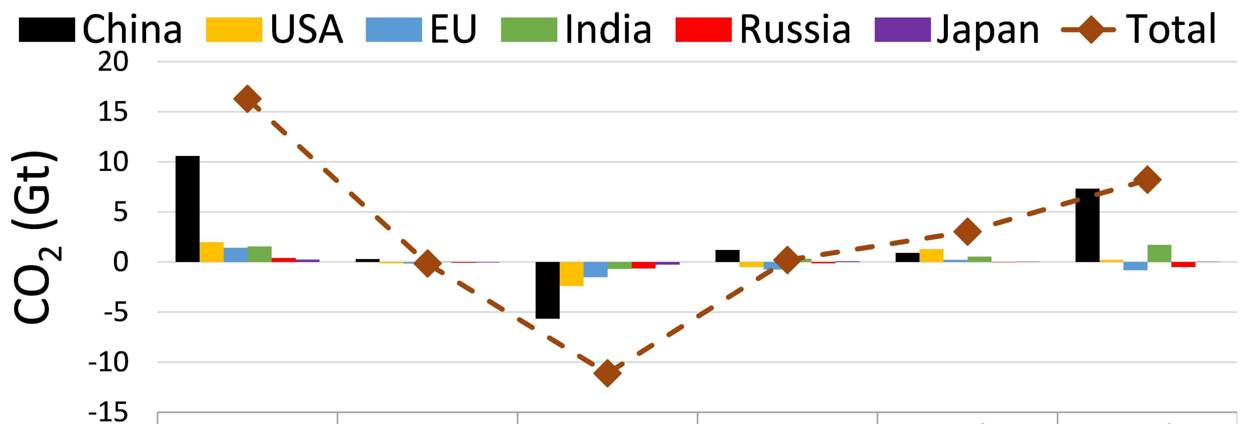
4.3. CO_2 LMDI decomposition

The main goal of this work is to determine the contribution of the different driving forces of the CO_2 emissions calculated through the Kaya identity and for each of the studied countries. According to the shape of the Kaya identity, Eq. (1), the driving forces are population (pop), economic activity (act), economic structure (str), energy intensity (int), and energy mix (mix). The emission term is assumed to vanish because the emission factors have been taken as constant for the whole period, and the disaggregation is detailed enough.

In Fig. 7, the LMDI contribution in the additive form of the five driving forces separated by the country for the whole period is depicted. The first noticing aspect is that apparently, all the countries have a common behaviour, although with a clear different scale, especially in the case of China, but when analysed in detail, notable differences are in order. In the case of the activity term (act), all the countries present positive contributions, having China the largest one, which is as large as the double the the sum of the contributions of the rest of the countries. The second contributor is the USA, with a contribution of around 20% of the one of China. The contribution of the structure term (str) is almost negligible in all countries. The intensity term (int) is negative in all countries, owing China the most negative contribution, corresponding it to the sum of the contributions of the rest of countries, which implies that China is not capable of compensating the activity term described above. In the case of the mixing term, China and India present positive contributions, Japan a negligible contribution, while the USA, the EU and Russia a negative one which implies that so far China and India are unable of reducing their emissions with clean energy. Finally, the population term is positive in all countries, except in Russia, corresponding the largest one to the USA and then to China. All in all, China and India are the main positive contributors, with the USA and Japan also having positive contributions, although almost negligible, and Russia and the EU being the only countries with a negative-sum. In other words, the increase of yearly CO_2 emissions (relative to 1990) of the six countries was of 8.2 Gt, corresponding 7.3 Gt to China, 1.7 to India, and 0.2 to the USA, moreover, the EU and Russia generated a reduction of 0.8 Gt and 0.5 Gt, respectively, with Japan having a null contribution.

As a matter of conclusion from this figure, the main element behind the rise of CO_2 emissions is the activity term (act), while so far, the energy intensity one (int) is the only one with a clear capacity of reducing them, and the mixing term (mix) is only effectively acting in the USA, the EU, and Russia. A different way of presenting the same results is provided in Fig. 8, where the multiplicative LMDI decomposition is depicted. It is noteworthy how clearly separated are the developed and developing countries, according to the scale of change of their driving forces. As a matter of fact, to really appreciated this fact, in Fig. 8A all the countries are depicted, while in Fig. 8B, only the developed ones.

In Fig. 9, the evolution of the five LMDI components of the Kaya identity in its additive form, together with the aggregated value, separated by country, are plotted. The first common feature is that China presents a distinct trend compared with the rest of the countries in all the driving forces, except in the case of the population (panel E). In fact, all countries except China cover a relatively narrow range, while China is far from this region.



	Cact	Cstr	Cint	Cmix	Cpob	Total
China	10.577	0.302	-5.682	1.213	0.912	7.323
USA	1.984	-0.133	-2.410	-0.518	1.276	0.199
EU	1.418	-0.163	-1.531	-0.752	0.209	-0.819
India	1.549	0.001	-0.687	0.329	0.530	1.723
Russia	0.390	-0.077	-0.632	-0.137	-0.041	-0.497
Japan	0.243	-0.045	-0.261	0.066	0.024	0.027
Total	16.268	-0.175	-11.110	0.199	3.020	8.202

Figure 7: Additive CO_2 LMDI decomposition for the whole period 1990-2018 and the six analysed countries.

Concerning the activity driving force (panel A), all countries present an upsloping trend, with China increasing considerably, showing a clear acceleration from 2002 and onwards. The intensity term is the most significant contributor to the emissions, and China is the main actor. The structure contribution (panel B) is negative in all countries except in India and mainly in China, with a clear maximum around the 2010 year. Note that in absolute values, the contribution of this driving force is the smallest one. The intensity term (panel C) is, in most cases, the main contributor to the reduction of CO_2 emissions; this is especially noticeable in the cases of the EU, the USA and China, while in Japan, India, and Russia, the behaviour is rather flat. Panel C clearly shows how energy is used increasingly in a more efficient way in all the analysed countries. The mixing term (panel D) is the second contributor to the reduction of the CO_2 emissions, but indeed, that only happens during the whole period for the EU, which presents a clear downsloping trend. It is a prove of the promotion of renewable in the EU since the '90s. The USA had a flat or even a positive

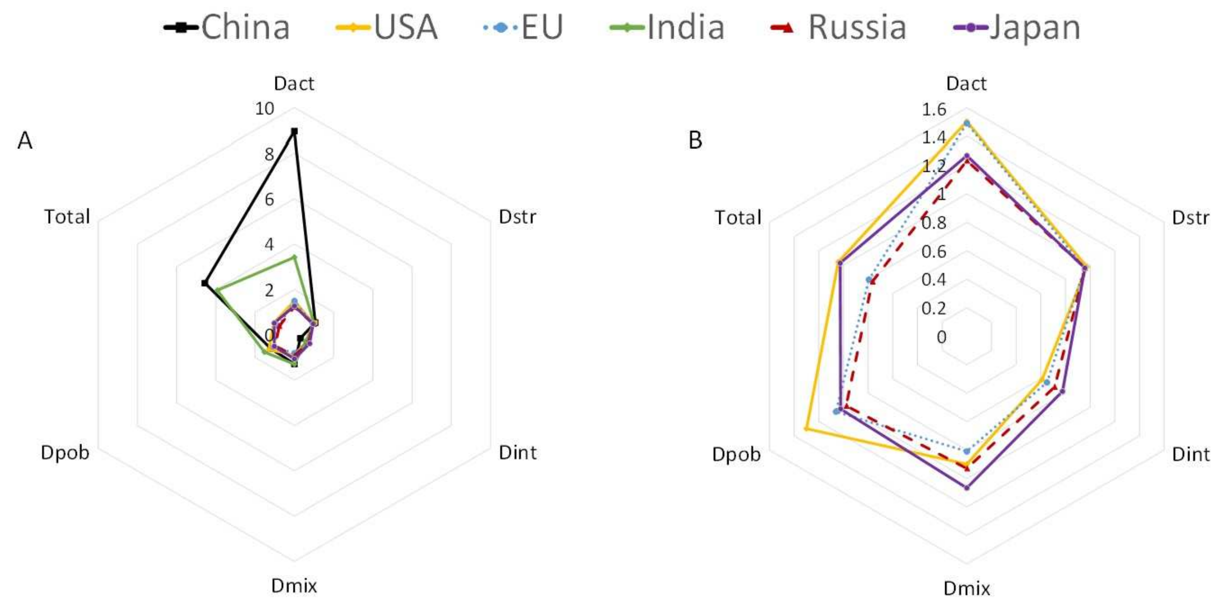


Figure 8: CO_2 LMDI multiplicative decomposition for the whole period 1990-2018. In panel A) all the countries are depicted, while in panel B) only the developed ones.

contribution up to 2006, but since then, the reduction has been very intense, almost reaching the EU level, which shows a change in policy concerning the use of green energy. Russia and Japan present a quite flat trend, although there is a sudden increase in 2011 because of Fukushima's accident in the case of Japan. In India, there is an increasing trend with no symptoms of reduction, while in China, it is possible to distinguish two periods, one up to the year 2004, presenting a moderate increase, and since then until 2018, when the mixing contribution started to increase. It clearly indicates that the fossil fuel in China and India is the main energy source, and its use is increasing. In the case of India, there is an increasing trend with no symptoms of reduction, while in China, it is possible to distinguish two periods, one up to the year 2004, presenting a moderate increase, and since then till 2018, when the mixing contribution started to increase. It clearly indicates that the fossil fuel in China and India is the main energy source and its use is increasing. In panel E, the population contribution is plotted, and surprisingly enough, the most significant contribution corresponds to the USA, well above the contributions of China and India. The contributions of Japan and Russia are very flat and almost zero, while the one of the EU increases smoothly, reaching during the latest years certain saturation.

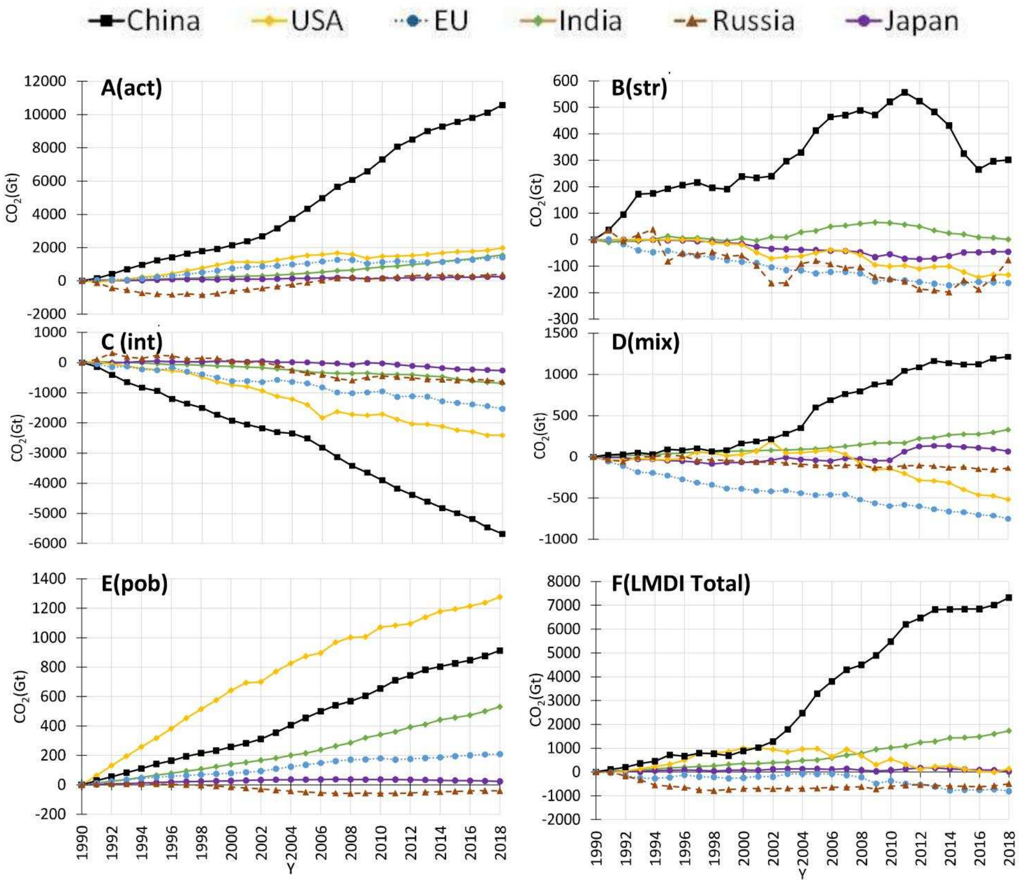


Figure 9: Evolution of the different components of the additive LMDI during the period 1990-2018. Panel A) for the activity term, B) for the structure one, C) for the energy intensity one, D) for the energy mix term, E) for the population term, and F) for the total sum.

Finally, in panel F the aggregated contribution is provided. China presents a similar behaviour to that of the USA until 2002, with an impressive increase in emissions, since then up to 2012, followed by a certain stabilization at the end of the period. The USA has shown a positive contribution during the major part of the period, but since 2012 it has managed to reach a null contribution. India shows a continuous increase in emissions during the whole period with a certain acceleration during the last twelve years. Japan presents a null contribution during the whole period, Russia a quite constant but negative value and, finally, the EU presents an almost zero contribution until 2008, but since then there has been a clear downsloping contribution.

4.4. Emission intensity

Emission intensity is a key observable to quantify the performance of a given economy concerning the reduction of CO_2 emissions regardless the economic growth. As a matter of fact, this is the indicator used in the NDC of China and India (see Table 1). There is no doubt that an NDC based on emission intensity is, by far, much easier to be fulfilled than a one based on emission levels. According to Fig. 10, there are two separate sets of countries. On the one hand, the USA, the EU and Japan, which present a relatively small value all the way with a steady decrease, and, on the other hand, China, India, and Russia, which present a much more significant value but with a more abrupt global decrease, although they also have specific periods of increase. During the last years, India, Russia, Japan, and the EU have shown a certain stabilization of their levels, while the USA and especially China have a clear downsloping trend. Nowadays, China, India, and Russia present a level of CO_2 intensity that is more than four times the one of the EU, Japan, and Russia.

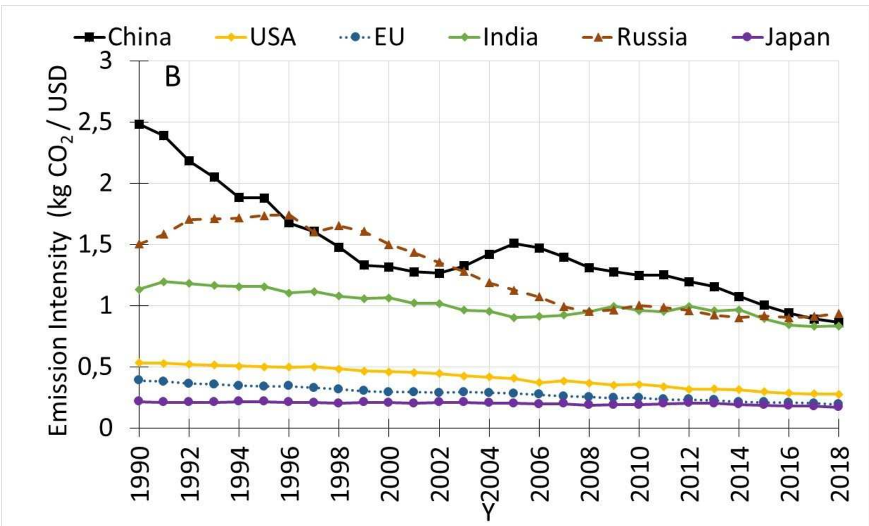


Figure 10: Evolution of the emission intensity for the six studied countries.

4.5. Granger causality analysis

In this section, the Granger causality analysis between pairs of variables appearing in the Kaya identity is analysed using the Toda-Yamamoto test. In particular, the variables considered are CO_2 emissions, GDP, energy intensity (INT), energy (ENE), renewable energies (REN), and population (POP), which suppose ten pairs of variables, which relationships are studied in both directions. Before performing the Granger-causality analysis, it is needed to determine the order of integration of the different involved variables, for instance, using the tests of Ng and Perron [40]. The analysis results are given in Table A.1 in Appendix A and one can conclude that the null hypothesis of no stationarity cannot be rejected in most cases, independently of the used statistic, except in the case of population. Therefore, all the time series are of $I(1)$ type except CO_2 emissions in the USA, GDP in China and population in China, India, Japan, and the USA, which are $I(0)$.

The Granger causality analysis is conducted separately for each of the six considered countries, and the results are presented in Table 3 and Fig. 11, where only the statistically significant connections are plotted.

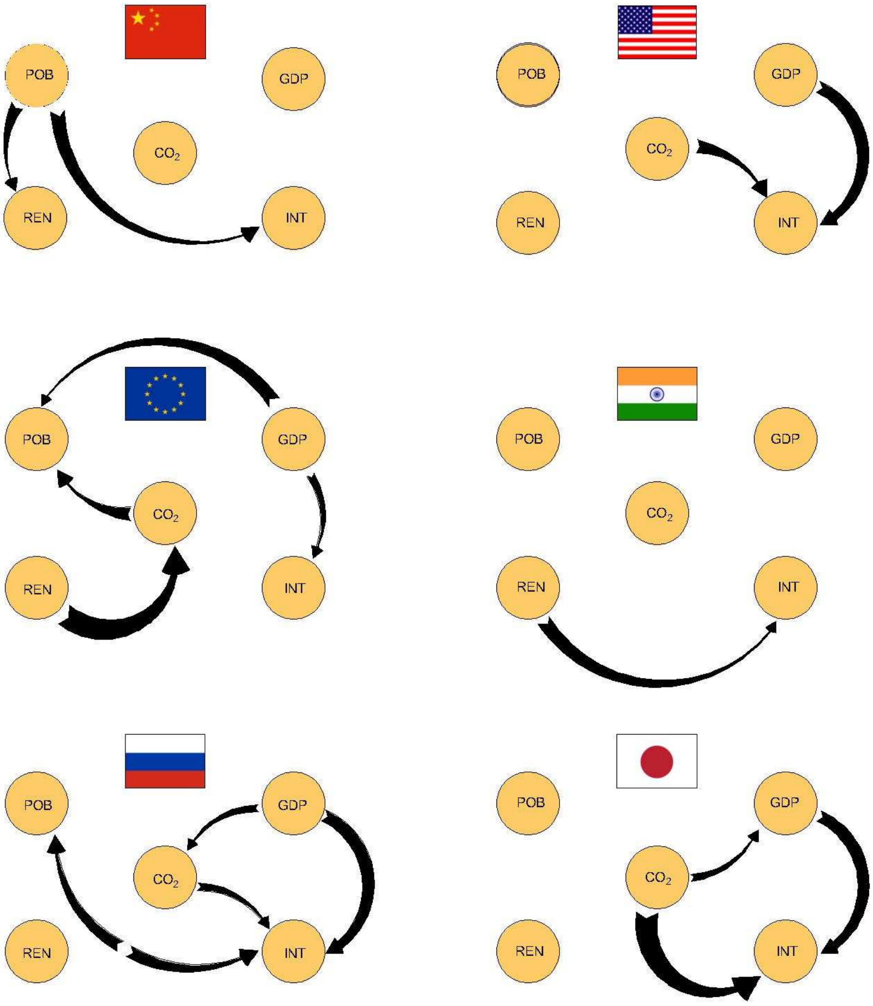


Figure 11: Pictorial representation of the statistically meaningful Granger-causes separated by countries.

In China, population Granger causes renewable energy consumption as well as energy intensity. In the USA, CO_2 emissions Granger cause energy intensity, and GDP Granger causes energy intensity. In the EU, renewable energy consumption Granger causes CO_2 emissions; CO_2 emissions and GDP Granger cause population, and GDP Granger causes energy intensity. In India, renewable energy consumption Granger causes energy intensity, but no other relationship exists. In Russia, GDP Granger causes CO_2 emissions, CO_2 emissions and GDP Granger cause energy intensity, and finally, population and energy intensity are mutual Granger causes. In the last case, Japan, CO_2 emissions Granger cause GDP and energy intensity, while GDP Granger causes energy intensity. These results can become a little paradoxical because they are not the obvious outcome that one can trivially conclude from the Kaya identity. One should, however, take into account that the Granger causality does not mean a correlation between the analysed variables, but rather that the first variable can be used as a meaningful indicator to forecast the second. It is worth mentioning that only in one case, Russia, GDP Granger causes CO_2 emissions, and in only one case, the EU, renewable energy consumption Granger causes CO_2 emissions while no other Granger causes exist into CO_2 emissions. However, CO_2 emissions Granger cause GDP, population, and energy intensity in several countries. It is worth mentioning that in four countries, namely, the USA, the EU, Russia, and Japan, GDP Granger causes energy intensity. These conclusions are drawn in Fig. 11, where only statistically meaningful Granger causes are plotted, being the arrow's thickness proportional to the statistical significance of the connection. If all the Granger causes are considered simultaneously for the six countries, as plotted in the graphical abstract, one can easily note that GDP is the variable that generates more Granger causes (six arrows are pointing outside the GDP), while energy intensity is the one with more Granger causes (ten arrows pointing to int). It is worth to mention that CO_2 is Granger caused by other variables only in the case of the EU where renewable energy consumption Granger causes CO_2.

5. Summary, conclusions and policy implications

In this work, we have analysed the driving forces that modulate the CO_2 emissions of the six major world emitters, namely, China, the USA, the EU, India, Russia, and Japan, during the time span 1990-2018. To this end, we have used the Kaya identity [9], the LMDI decomposition technique [8] and the Granger causality analysis [10] with a Toda-Yamamoto test [11]. The study has been conducted considering 3 economic sectors and 21 types of fuels. Coal and petroleum energy consumption have been disaggregated in their different types taking into account their very different emission factors. During the

Table 3: Coefficients from Toda-Yamamoto Granger causality analysis. *Significance at 10% level, **Significance at 5% level, and ***Significance at 1% level.

		China		USA		EU		India		Russia		Japan	
α	β	$\alpha \to \beta$	$\alpha \leftarrow \beta$	$\alpha \to \beta$	$\alpha \leftarrow \beta$	$\alpha \to \beta$	$\alpha \leftarrow \beta$	$\alpha \to \beta$	$\alpha \leftarrow \beta$	$\alpha \to \beta$	$\alpha \leftarrow \beta$	$\alpha \to \beta$	$\alpha \leftarrow \beta$
GDP	CO_2	2.773	6.007	4.468	2.080	0.187	0.000	0.000	0.001	1.841	4.969*	5.190*	2.77
REN	CO_2	0.779	1.279	4.372	0.721	0.124	6.470**	0.089	1.756	0.193	0.020	1.286	3.04
POB	CO_2	0.136	1.777	0.778	2.388	11.799*	1.090	0.000	3.177	1.234	1.926	0.297	0.76
INT	CO_2	2.981	3.253	16.294*	3.455	1.456	0.323	0.633	0.043	6.223*	4.759	58.450**	0.85
REN	GDP	0.297	4.740	0.279	1.423	0.004	2.066	0.070	0.485	0.012	0.098	6.688	2.99
POB	GDP	0.036	1.119	2.167	3.809	10.739*	0.658	0.000	0.067	0.770	4.709	6.162	2.49
INT	GDP	1.805	3.528	11.785*	5.874	3.267*	0.095	0.128	0.025	12.439*	6.034	9.296**	1.71
POB	REN	0.097	12.527**	0.369	1.295	0.917	3.310	0.000	11.638	0.472	0.943	0.672	2.14
INT	REN	0.920	0.917	2.854	0.252	0.351	0.025	5.331*	0.445	0.012	0.004	2.286	1.77
INT	POB	20.086**	0.118	6.479	0.400	1.036	5.300	1.379	0.000	9.080**	9.308*	3.479	5.32

considered period, the six analysed economies share certain aspects; namely, the fuel with the most significant contribution to the emissions is coal. In China and India, the coal's share of the energy mix has increased during the considered period, while it has diminished in the rest of the countries. Tightly connected with the latter point is that the share of renewable energy (including nuclear energy) has decreased in China and India, while it has steadily increased in the rest of the countries, except for Japan during Fukushima's nuclear accident. The behaviour of China and India with respect to the use of renewable energy is somehow paradoxical because a reduction of the share to the energy mix exists despite the large increase in the use of renewable energy in both countries. The explanation is the huge increase in energy consumption that has been mainly supported by the use of coal.

The driving forces that have been identified in the Kaya identity are the population (pop), the activity term (act) connected with the GDP *per capita*, the structure term (str) connected with the relative size of the economic sectors, the energy intensity term (int), related to the ratio of the consumption of energy and the GDP, and, finally, the mixing term (mix) which is connected to the energy mix of the country. Once more, there are strong similarities between the different countries, and it is possible to separate them into two groups. On the one hand, China and India and, on the other, the USA, the EU, Russia, and Japan. The activity term is the main contributor to the CO_2 emissions, but this term is much larger in

China and India than in the rest of the countries (see Fig. 8). The population term is another driving force that contributes to the increase of the emissions, and surprisingly enough, the largest contribution stands for the USA, followed by China and India. The structure term supposes a small influence, being negative in all the countries except for China. The main factor reducing the emissions is the energy intensity term, presenting China the largest value followed by the USA and the EU (in absolute terms). However, in China, this contribution is unable to compensate for the increase due to the intensity term. The same happens for the case of India, which presents a quite modest energy intensity contribution, and that is far from compensating the activity contribution. Concerning the mixing term, China and India present a large and upsloping contribution, Russia and Japan almost a null contribution, while the USA and especially the EU present downsloping contributions. It proves that the USA (in the last decade) and the EU own an effective policy promoting green energies, while China and India still should pursuit the promotion of carbon-free energy sources. All in all, India and, mainly, China continue increasing their emission without a evident change of trend. However, the rest of the countries, especially the USA and the EU, are clearly in the way of reducing their emissions.

The Granger causality analysis does not generally show a causal relationship between the drivers and the CO_2 emissions, except in the case of the EU, for which the renewable energy Granger causes the CO_2 emissions. This result could be considered paradoxical, but it is worth noting that a Granger causality relationship only supposes that the first variable can be used to forecast the second one reliably. If we consider the Granger causality for the complete set of countries as a whole, as shown in the graphical abstract, we can draw the interesting conclusion that GDP and CO_2 emissions are the factors that most Granger cause other variables. In other words, GDP and CO_2 emissions are the variables that will better serve to predict the evolution of the rest of the driving forces. Finally, GDP Granger causes energy intensity in the four developed countries.

The fight against Climate Change is clearly in a critical moment when the different countries and regions are defining much more stringent targets for CO_2 emissions (see NDC's summarized in Table 1), especially the USA and the EU, which clearly are leading the structural changes to move into a world with low CO_2 emissions. However, still there exists a tight bond between CO_2 and income, therefore in China and India, where the rapid increase of the GDP is granted, the CO_2 emission undoubtedly will rapidly increase unless structural changes are carried out to promote the reduction of the intensity term and, mainly, the contribution of the renewable energies to the mixing term. A way of measuring the performance of a given economy with respect to CO_2 emissions is through its emission intensity (see Fig.9), which accounts for the emissions without taking into account the size of the economy. According to this indicator, China, India and even Russia present a much larger value (four times) than the USA, the EU and Japan, which proves the profound improvement that still should be conducted in the first group of countries in order to reduce their emissions.

In summary, China and India should primarily improve their energy intensity and energy mix terms to compensate for their significant activity contribution because it is expected to increase this latter term in the future. However, most probably, both countries will fulfil their NDC's (see Table 1) because they are based on the value on the emission intensity, which is an indicator decoupled from the economic growth and, moreover, the target is not too ambitious. Russia and Japan present rather flat trends in all the driving forces, including the global value (see Fig. 9). No symptoms are observed of improvements in the value of the energy intensity and the energy mix term, therefore, new policies should be implemented in order to change the past trend. Finally, the USA and the EU are the regions where in the last decades it has been observed a consistent improvement of the energy intensity and the energy mix term (see Fig. 9). New legislation in both regions could accelerate the observed trend and, as a matter of fact, the USA and the EU most probably will become the paradigm of regions with CO_2 free emission economies.

6. Acknowledgment

This work has been partially supported by the Consejería de Economía, Conocimiento, Empresas y Universidad de la Junta de Andalucía (Spain), under Group FQM-370 and by European Regional Development Fund (ERDF), ref. SOMM17/6105/UGR. Resources supporting this work were provided by the CEAFMC and Universidad de Huelva High-Performance Computer (HPC@UHU) funded by ERDF/MINECO project UNHU-15CE-2848.

References

[1] T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,, 2013.

[2] V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, Tignor M. Maycock, and T. (eds.) Waterfield. *Summary for Policymakers. In: Global Warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* World Meteorological Organization, Geneva, Switzerland, 2018.

[3] EPA (United States Environmental Protection Agency). Global Greenhouse Gas Emissions Data. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data, 2019. Accessed date: 1 September 2021.

[4] World Meteorological Organization. WMO Statement on the State of the Global Climate in 2019. `https://library.wmo.int/doc_num.php?explnum_id=10211`, 2019. Accessed date: 1 September 2021.

[5] IEA (International Energy Agency). Data Services homepage. http://www.iea.org/, 2019. Accessed date: 1 September 2021.

[6] World Bank. Data and statistics. http://data.worldbank.org/, July 2021. Accessed date: 1 September 2021.

[7] United Nations Framework Convention on Climate Change (UNFCCC). Intended Nationally Determined Contributions. https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx, 2021. Accessed date: 1 September 2021.

[8] B.W. Ang. Decomposition of industrial energy consumption. The energy intensity approach. *Energy Economics 16, 163-174*, 1994.

[9] Y. Kaya. Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios. *Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, (mimeo)*, 1990.

[10] C. Granger. Investigating Causal Relations by Econometric Models and Cross-spectral Methods. *Econometrica, 37(3), 424-438*, 1968. doi: https://doi.org/10.2307/1912791.

[11] Hiro Y. Toda and Taku Yamamoto. Statistical inference in vector autoregressions with possibly integrated processes. *Journal of Econometrics*, 66(1):225–250, 1995. ISSN 0304-4076. doi: https://doi.org/10.1016/0304-4076(94)01616-8. URL `https://www.sciencedirect.com/science/article/pii/0304407694016168`.

[12] Kangyin Dong, Hongdian Jiang, Renjin Sun, and Xiucheng Dong. Driving forces and mitigation potential of global CO_2 emissions from 1980 through 2030: Evidence from countries with different income levels. *Science of The Total Environment*, 649:335–343, 2019. ISSN 0048-9697. doi: https://doi.org/10.1016/j.scitotenv.2018.08.326. URL `https://www.sciencedirect.com/science/article/pii/S0048969718332972`.

[13] M. González-Torres, L. Pérez-Lombard, J.F. Coronel, and I.R. Maestre. A cross-country review on energy efficiency drivers. *Applied Energy*, 289:116681, 2021. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2021.116681. URL `https://www.sciencedirect.com/science/article/pii/S0306261921002105`.

[14] Sofia Teives Henriques and Karol J. Borowiecki. The drivers of long-run CO_2 emissions in Europe, North America and Japan since 1800. *Energy Policy*, 101:537–549, 2017. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2016.11.005. URL `https://www.sciencedirect.com/science/article/pii/S0301421516305985`.

[15] Hu Minjie, Li Ruzi, You Wanhai, Liu Yaobin, and Lee Chien-Chiang. Spatiotemporal evolution of decoupling and driving forces of CO_2 emissions on economic growth along the Belt and Road. *Journal of Cleaner Production*, 277:123272, 2020. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2020.123272. URL `https://www.sciencedirect.com/science/article/pii/S0959652620333175`.

[16] Roula Inglesi-Lotz. Decomposing the South African CO_2 emissions within a BRICS countries context: Signalling potential energy rebound effects. *Energy*, 147:648–654, mar 2018. ISSN 03605442. doi: 10.1016/j.energy.2017.12.150. URL `https://www.sciencedirect.com/science/article/pii/S036054421732193X?via%3Dihub`.

[17] Li Shuping, Meng Jing, Zheng Heran, Zhang Ning, Huo Jingwen, Li Yuan, and Guan Dabo. The driving forces behind the change in energy consumption in developing countries. *Environmental Research Letters*, 16(5):054002, apr 2021. doi: 10.1088/1748-9326/abde05. URL `https://doi.org/10.1088/1748-9326/abde05`.

[18] Adriana Marcucci and Panagiotis Fragkos. Drivers of regional decarbonization through 2100: A multi-model decomposition analysis. *Energy Economics*, 2015. ISSN 01409883. doi:

10.1016/j.eneco.2015.06.009.

[19] Dai Shuang, Zhang Ming, and Huang Wei. Decomposing the decoupling of CO_2 emission from economic growth in BRICS countries. *Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards*, 84(2):1055–1073, November 2016. doi: 10.1007/s11069-016-2472-0.

[20] Mehdi Ben Jebli and Montassar Kahia. The interdependence between CO_2 emissions, economic growth, renewable and non-renewable energies, and service development: evidence from 65 countries. *Climatic Change*, 162(2):193–212, 2020. doi: https://doi.org/10.1007/s10584-020-02773-8.

[21] Dilek Durusu-Ciftci, Ugur Soytas, and Saban Nazlioglu. Financial development and energy consumption in emerging markets: Smooth structural shifts and causal linkages. *Energy Economics*, 87:104729, 2020. ISSN 0140-9883. doi: https://doi.org/10.1016/j.eneco.2020.104729. URL `https://www.sciencedirect.com/science/article/pii/S0140988320300682`.

[22] Kablamaci Baris. A re-examination of causal relation between economic growth and energy consumption: Evidence from 91 countries. *Economics Bulletin*, 37(2):790–805, 2017. URL `https://ideas.repec.org/a/ebl/ecbull/eb-16-00740.html`.

[23] Ugur Korkut Pata and Mucahit Aydin. Testing the EKC hypothesis for the top six hydropower energy-consuming countries: Evidence from Fourier Bootstrap ARDL procedure. *Journal of Cleaner Production*, 264:121699, 2020. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2020.121699. URL `https://www.sciencedirect.com/science/article/pii/S0959652620317467`.

[24] Md. Saifur Rahman, Abu Hanifa Md. Noman, Farihana Shaharim, Mohamed Aslam, Chan Sok Gee, Che Ruhana Isa, and Sajeda Pervin. Efficient energy consumption in industrial sectors and its effect on environment: A comparative analysis between G8 and Southeast Asian emerging economies. *Energy*, 97:82–89, 2016. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2015.12.109. URL `https://www.sciencedirect.com/science/article/pii/S0360544215017545`.

[25] A. Sankaran, Sanjay Kumar, K. Arjun, and Mousumi Das. Estimating the causal relationship between electricity consumption and industrial output: ARDL bounds and Toda-Yamamoto approaches for ten late industrialized countries. *Heliyon*, 5(6):e01904, 2019. ISSN 2405-8440. doi: https://doi.org/10.1016/j.heliyon.2019.e01904. URL `https://www.sciencedirect.com/science/article/pii/S2405844019325642`.

[26] Veli Yilanci, Onder Ozgur, and Muhammed Sehid Gorus. The asymmetric effects of foreign direct investment on clean energy consumption in BRICS countries: A recently introduced hidden cointegration test. *Journal of Cleaner Production*, 237:117786, 2019. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2019.117786. URL `https://www.sciencedirect.com/science/article/pii/S0959652619326460`.

[27] Ertugrul Yildirim and Alper Aslan. Energy consumption and economic growth nexus for 17 highly

developed oecd countries: Further evidence based on bootstrap-corrected causality tests. *Energy Policy*, 51:985–993, 2012. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2012.09.018. URL https://www.sciencedirect.com/science/article/pii/S0301421512007768. Renewable Energy in China.

[28] Y. Kaya and K. Yokobori. *Environment, Energy, and Economy: strategies for sustainability.* Conference on Global Environment, Energy, and Economic Development (1993 : Tokyo, Japan), 1993.

[29] B.W. Ang and K.-H. Choi. Decomposition of Aggregate energy and gas emission intensities for industry: A refined divisia index method. *Energy Journal 18, 59-73*, 1997.

[30] A. Robalino-López, J.E. García-Ramos, A. Mena-Nieto, and A. Golpe. System dynamic modelling and the environmental Kuznets curve in Ecuador (1980-2025). *Energy Policy 67, 923-931*, 2014.

[31] A. Robalino-López, A. Mena-Nieto, and J. E. García-Ramos. System dynamics modeling for renewable energy and CO_2 emissions: A case study of Ecuador. *Energy for Sustainable Development 20, 11-20*, 2014.

[32] A. Robalino-López, A. Mena-Nieto, J.E. García-Ramos, and A. Golpe. Studying the relationship between economic growth, CO_2 emissions,and the environmental Kuznets curve in Venezuela (1980-2025). *Renewable and Sustainable Energy Reviews 41, 602-614*, 2015.

[33] B.W. Ang. The LMDI approach to decomposition analysis: a practical guide. *Energy Policy 33, 867-871*, 2005.

[34] B.W. Ang. LMDI decomposition approach: A guide for implementation. *Energy Policy*, 86: 233 – 238, 2015. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2015.07.007. URL http://www.sciencedirect.com/science/article/pii/S0301421515300173.

[35] S. Johansen and K Juselius. Maximum likelihood estimation and inference on cointegration - with applications to the demand for money. *Oxford Bulletin of Economics and Statistics*, 52(2):169–210, 1990. doi: https://doi.org/10.1111/j.1468-0084.1990.mp52002003.x. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1468-0084.1990.mp52002003.x.

[36] Hector O. Zapata and Alicia Rambaldi. Monte Carlo Evidence on Cointegration and Causation. *Oxford Bulletin of Economics and Statistics*, 59(2):285–98, 1997. URL https://EconPapers.repec.org/RePEc:bla:obuest:v:59:y:1997:i:2:p:285-98.

[37] G.S. Maddala and In-Moo Kim. *Unit Roots, Cointegration, and Structural Change*. Cambridge University Press, 1998. doi: https://doi.org/10.1017/CBO9780511751974.

[38] M. Hashem Pesaran, Yongcheol Shin, and Richard J. Smith. Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics*, 16(3):289–326, 2001. doi: https://doi.org/10.1002/jae.616. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/jae.616.

[39] Judith A. Clarke and Sadaf Mirza. A comparison of some common methods for detecting Granger noncausality. *Journal of Statistical Computation and Simulation*, 76(3):207–231, 2006. doi: 10.1080/10629360500107741. URL `https://doi.org/10.1080/10629360500107741`.

[40] S. Ng and P. Perron. Lag Length Selection and the Construction of Unit Root Tests with Good Size and Power. *Econometrica 69, 1519-1554*, 2001.

[41] Pierre Perron and Serena Ng. Useful Modifications to some Unit Root Tests with Dependent Errors and their Local Asymptotic Properties. *The Review of Economic Studies*, 63(3):435–463, 07 1996. ISSN 0034-6527. doi: 10.2307/2297890. URL `https://doi.org/10.2307/2297890`.

Appendix A. Test for unit root

Table A.1: Ng and Perron[1,2] tests for a unit root.

	Country	$\overline{M}Z_{\alpha}^{GLS}$	$\overline{M}Z_{t}^{GLS}$	$\overline{M}SB_{\alpha}^{GLS}$	ADF_{MAIC}^{GLS}
CO_2	China	-12.201	-2.404	0.197	7.811
	USA	-27.058^{***}	-3.657^{***}	0.135^{***}	3.491^{***}
	EU	-3.637	-1.275	0.351	23.886
	India	-4.395	-1.480	0.336	20.710
	Russia	-1.393	-0.674	0.485	47.345
	Japan	-6.460	-1.508	0.230	13.934
GDP	China	-60.947^{***}	-5.412^{***}	0.089^{***}	1.983^{***}
	USA	-4.483	-1.451	0.324	19.944
	EU	-3.142	-1.231	0.392	28.460
	India	-4.882	-1.433	0.294	17.928
	Russia	-6.747	-1.832	0.271	13.508
	Japan	-9.069	-2.125	0.234	10.063
REN	China	-2.561	-1.039	0.406	9.127
	USA	-4.947	-1.561	0.316	18.355
	EU	-4.519	-1.500	0.332	20.147
	India	-9.811	-2.173	0.222	9.463
	Russia	-2.691	-1.017	0.378	29.245
	Japan	-3.896	-1.373	0.353	23.091
POP	China	-30.474^{***}	-3.846^{***}	0.127^{***}	3.314^{***}
	USA	-113.808^{***}	-7.478^{***}	0.066^{***}	1.030^{***}
	EU	-3.368	-1.209	0.359	25.319
	India	-49.686^{***}	-4.881^{***}	0.098^{***}	2.333^{***}
	Russia	-0.016	-0.010	0.638	87.909
	Japan	-63.514^{***}	-5.553^{***}	0.087^{***}	1.797^{***}
INT	China	7.016	-1.862	0.265	13.001
	USA	4.281	-1.447	0.334	21.125
	EU	.184	0.157	0.855	151.11
	India	6.073	-1.696	0.280	14.951
	Russia	2.268	-0.998	0.440	36.979
	Japan	1.404	-0.621	0.442	41.907

[1] *Significance at 10% level, **Significance at 5% level, and *** Significance at 1% level.

[2] The MAIC information criteria is used to select the autoregressive truncation lag and k, as proposes in Perron and Ng [41].

The critical values are taken from Table 1 of [40]