CO_2 emissions and causal relationships in the six largest world emitters

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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 reducing 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 should still be actively 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 energy intensity Granger causes GDP in the developed countries, energy intensity also Granger cause CO_2 emissions in half of the countries and, GDP Granger causes CO_2 emissions only in one case, Japan.

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

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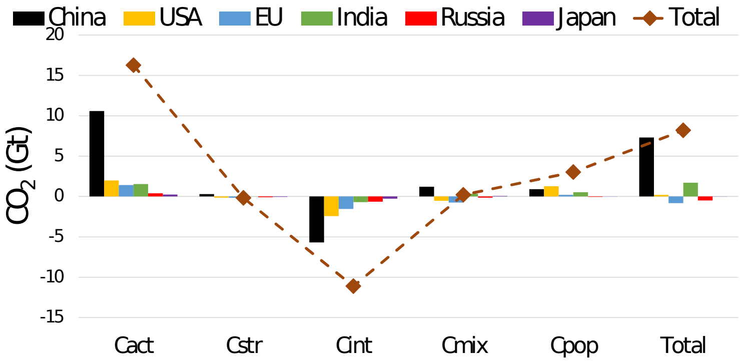
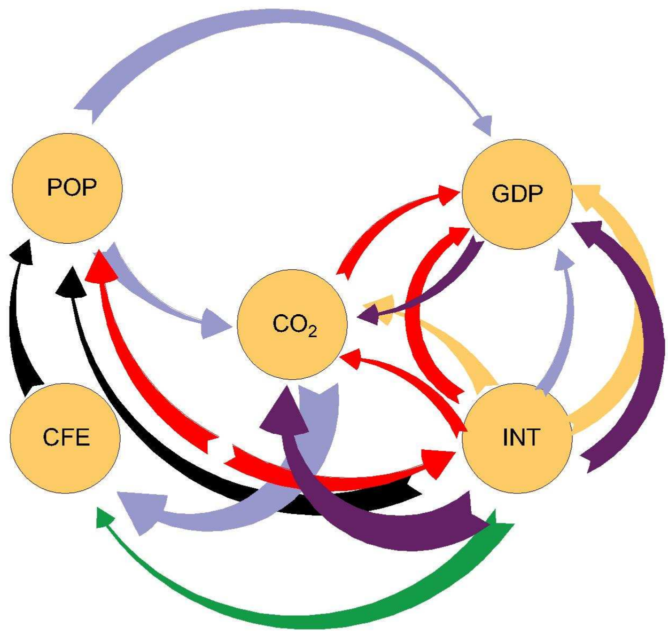
Graphical abstract





Highlights:

- China and India should greatly improve their energy intensity and energy mix contributions to reduce their CO_2 emissions.
- The USA and the EU shown promising trends concerning energy intensity and energy mix contributions capable of reducing their global CO_2 emissions.
- Granger causality analysis suggests that energy intensity Granger causes most of the rest of driving forces.

- Emission intensity of China, India and Russia is around four times greater than that 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.
- CFE: Carbon-free energy.
- CO_2: carbon dioxide.
- EU: European Union (twenty eight member state).
- ENE: energy.
- GDP: Gross Domestic Product.
- GHG: greenhouse gases.
- Gtoe: giga tonnes of oil equivalent.
- Gt: giga tonne.
- GW: giga watt.
- int (INT): energy 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 (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 showed 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, consequently, society now considers Climate Change a major threat to the present way of life and that it will negatively affect many ecosystems and living species around the world [1, 2]. This problem is strongly connected with the emission of 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 well established; in 2018, it was estimated that 81% of all GHGs were 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 sea levels, 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 life more in deprived or underdeveloped places, by negatively impacting on their livelihoods and traditional way of life. The worsening impacts of Climate Change in the three most densely populated regions of the world could force over 140 million people to move within their countries' borders by 2050, creating a looming humanitarian crisis and threatening the development process [4].

The main problem of reducing CO_2 emissions lies in the aforementioned connection between economy and emissions, and with energy used being the link between these two apparently disconnected elements. Therefore, the primary sources of CO_2 emissions should be studied 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 are, by far, the largest emitters. These countries are responsible for two-thirds of the energy-related emissions of the planet, notably China, which was responsible for around 28% of the global CO_2 emissions in 2018, followed by the USA with 14%. In Fig. 1, the total value of the CO_2 emissions of the six largest emitters in absolute terms is shown, corresponding to the year 2018 and, also, their aggregated share of the global emissions. This figure proves that the emissions under consideration reach approximately 67% of the world emissions. The considered set of countries is, moreover, of key importance because it represents a large fraction of the world's population (roughly 45%) and GDP (roughly 70%). On the other hand, it is worth noting that these countries fight, or plan to fight, against Climate Change in rather different ways, as shown in their Nationally Determined Contributions (NDC's) [5], as summarized in Table 1. Hence, it can be very enlightening to see how these different approaches have affected past emissions and most probably will affect future ones.

According to the data from World Bank [7], China population grew from 1135 million inhabitants in 1990 to 1393 million in 2018. China has promoted significant changes in its

[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

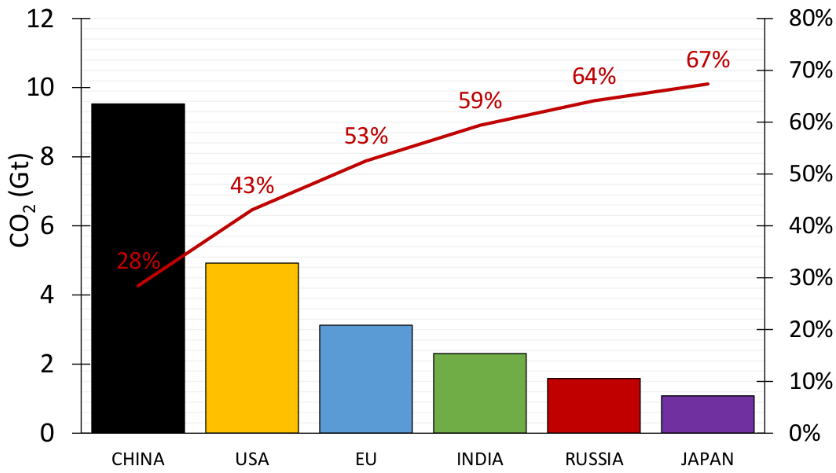


Figure 1: Emissions and share of the largest world CO_2 emitters in 2018. Data from IEA (International Energy Agency) [6].

economy since 1978 with the granting of licenses to private companies, which has 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 third-largest (considering the EU as a whole) world economy in 2018, with a GDP of 13895 billion dollars. The USA's population grew from 249 up to 326 million inhabitants during 1990-2018, maintaining an economic growth path except in the year of the global economic crisis in 2009, 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 grew to 447 million in 2018 and presented a relatively constant GDP growth, with an average value of 2% apart from the aforementioned economic crisis in 2009. 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 on average by 3% per year, reaching 2701 billion dollars in 2018. Russia's population decreased by around 3 million people during the studied period, having 144 million in 2018. Its GDP suffered a deep contraction due to the disintegration of the former Soviet Union, which resulted in the fall of its GDP until 1997, but since 1997, the country's GDP has risen markedly except in the years 2009 and 2015. In 2018 its GDP was 1657 billion dollars. The population of Japan experienced a small increase during the studied period, specifically 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 5.4%, and 2011 due to the Fukushima nuclear accident. Its GDP in 2018 was 4955 billion dollars. From 1991 to 2001, Japan suffered a period of economic stagnation and price deflation known as "Japan's Lost Decade" [8]. After this period the economic growth of Japan was much slower than in other high-income countries.

World economies have joined forces in different conventions to reduce GHG emissions in the near future. From the United Nations Framework Convention on Climate Change

(UNFCCC) which was held in Brazil on March 21st, 1994, to the UN Climate Change Conference COP-26 held in Glasgow, Scotland, United Kingdom in November, 2021, 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 noticeable. These contributions have been established in the so-called Nationally Determined Contributions (NDC) [5]. 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 a peak 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 just a slight reduction, for the USA, the EU, Russia and Japan. The rate of fossil fuel use in Japan had been steadily declining since 1960, but it has risen rapidly since 2011. The biggest reason for this is the Fukushima nuclear accident.

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

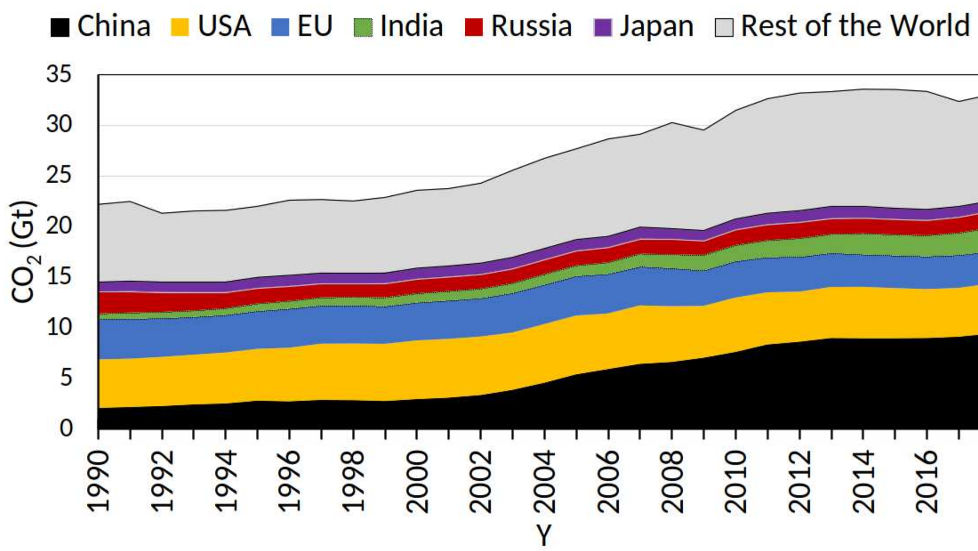


Figure 2: Evolution of the energy-related CO_2 emissions in the six largest world emitters during the period under study.

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 from the 1990s until the present day, serving as a tool for policymakers to determine future environmentally sustainable policies. The operational relationship between CO_2 emission and its driving forces was formulated in the seminal work [9], where the emissions are recorded as the product of population, GDP per capita, energy intensity, and emission factor. This identity clearly expresses that the emissions are strongly bound to GDP and modulated by the efficiency of energy use and by the type of energy fuels used.

Surprisingly enough, few previous studies shed light on the evolution over time of the emissions of these six largest emitters during the period 1990-2018. This time period is quite meaningful because, on one hand, it started at the reference date of the Kyoto Protocol and, on the other, it is possible to obtain from the databases uniform information for the different considered countries. The so-called logarithmic-mean Divisia index (LMDI) [10] 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 [11] analysis using the Toda-Yamamoto methodology [12] will be applied to explore the causal relationships between the driving forces that determine CO_2 emissions.

One of the main contributions of our work lies, on the one hand, in the combination of three different methodologies (the Kaya identity, the LMDI and the Granger causality) and, on the other hand, in the use of a heterogeneous group of countries. Thus, several previous studies have focused on a specific country. In contrast, others have relied on a homogeneous group, e.g., according to geographic patterns (ASEAN[2], European Union or MENA[3]), different stages of economic development (OECD, transition or emerging countries or BRIC countries) or motivated by other variables (G20 countries, tourism countries, Gulf Cooperation Council, etc). In our case, we have chosen to study the driving forces of the carbon dioxide emissions of the six largest world emitters, namely, China, the USA, the EU, India, Russia, and Japan, which represent two thirds of the total world emissions, but present different degrees of economic development, population or are at different environmental stages. We believe that this type of work can help to understand the main determinants of CO_2 emissions globally by using a group of countries with quite different structures. The design of future policies will be greatly benefited by the understanding of the relationships between the driving forces that modulate the CO_2 emissions and by the knowledge of the possible causal connections between them.

CO_2 emissions are influenced by economic activity, the way the energy is used and the kind of energy used and, finally, by the population. The design of future policies will be greatly benefited by the understanding of the relationships between the driving forces that modulate the CO_2 emissions and by the knowledge of the possible causal connections between them.

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 methodology used 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. [13] 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

[2] Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam

[3] Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates and Yemen

most significant reduction, while the increase in the GDP produces the most considerable rise of CO_2 emissions. In Ref. [14], the authors studied the influence of energy consumption, economic growth, and financial development on carbon emissions in a panel of 122 countries. The authors used cointegration and estimation procedures and found cointegration between the variables. An important conclusion is that in high-income countries, economic growth and financial development mitigate CO_2 emissions while in low- and medium-income countries the effect is the opposite. Ref. [15] is devoted to the analysis of the role of energy consumption in moderating the CO_2 emissions-income nexus in a panel of middle income countries and they analyze the cross-sectional dependence. The authors find no evidence of the influence of energy consumption in moderating the relationship between income and CO_2 emissions in the panel. In Ref. [16], 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 Ref. [17], the authors found the drivers for the long term 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 Ref. [18], 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 [19] proved that during the period 1990-2014 the slowdown of CO_2 emissions is strongly 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. [20], 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, with coal and oil being the main factors in the energy transition pathway of China and India. Marcucci and Fragkos [21] 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 [22], 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.

Ref. [23] 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 [24], 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 [25], the author conducted a Granger causal analysis for 91 less developed countries during the period 1970-2013, concluding that energy consumption Granger causes economic growth in twelve countries. Pata and Aydin [26] 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 to economic growth in Brazil and a bidirectional one between these two variables in China. In [27], 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. [28] uses the Toda-Yamamoto test to study causality between electricity consumption, per capita income, real exchange rate, import and export of manufacturing output, from 1980 till 2016, for ten recently industrialized nations, including India. Their results support the existence of growth, conservation, feedback and neutrality hypotheses for different nations. In [29], the authors conducted a study on the effects of foreign direct investment and 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 [30], 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.

After having 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 into the impact of the different CO_2 drivers over time in the group of most polluting 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. This global study scarcely appears in the literature and it would provide key indicators to design future mitigation policies.

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, 31] combined with the LDMI method [32]. 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 [33, 34, 35]. 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 ($U_{ij} = \frac{C_{ij}}{E_{ij}}$),

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

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) (see also Eqs. (2) and (3)), one can easily identify six different terms related with its six factor terms. The first term, which we will refer to as "pop" provides the amount of CO_2 emissions due to the change in population, the term "act" provides the contribution to CO_2 emissions due to the change in the GDP per capita, the term "str" refers to the contribution to the CO_2 emissions due to changes in the structure of economic sectors, the term "int" provides the contribution due to the intensity term, which is the ratio of energy and GDP, the term "mix" refers to the contribution due to changes in the energy matrix, and finally, the term "emission" corresponds to the contribution to the CO_2 emissions due to changes in the emission factor (ratio between CO_2 emissions and energy). This last contribution will be zero in our case because Eq. (1) is fully disaggregated and the emission factors of the different energy sources do not change over time. However, due to the mathematical form of Eq. (1), it is not trivial to isolate the different contributions. To this end, Ang and Choi, in their seminal work [32], proposed the LMDI decomposition method that allows one to identify and extract the contributions of the different driving forces of a given expression. We refer the reader to [36, 37] 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

$$D_{pop}(t) = \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{P(t)}{P(0)}\right), \quad (10)$$

$$D_{act}(t) = \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{q(t)}{q(0)}\right), \quad (11)$$

$$D_{str}(t) = \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{S_i(t)}{S_i(0)}\right), \quad (12)$$

$$D_{int}(t) = \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{EI_i(t)}{EI_i(0)}\right), \quad (13)$$

$$D_{mix}(t) = \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{M_{ij}(t)}{M_{ij}(0)}\right), \quad (14)$$

$$D_{emission}(t) = \exp\left(\sum_{ij} \frac{\frac{C_{ij}(t)-C_{ij}(0)}{\ln C_{ij}(t)-\ln C_{ij}(0)}}{\frac{C(t)-C(0)}{\ln C(t)-\ln C(0)}} \ln \frac{U_{ij}(t)}{U_{ij}(0)}\right). \quad (15)$$

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 one to analyse 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.

It is worthy of understanding under which circumstances the contribution of the different driving forces will become "positive", which supposes an increase of the emissions, or "negative" which supposes a decrease. In some cases, it is self-evident, as for the "act" and the "pop" terms, which become positive (negative) under an increase (decrease) of the GDP per capita or the population, respectively. The use of the energy in a more efficient way leads to a negative contribution of the "int" term, while the opposite leads to a positive one. Concerning the "mix" term, the relative increase (decrease) of the use of carbon-free-emission energy sources generates a negative (positive) "mix" contribution. Finally, the shift into industrial sectors less intensive in emissions leads to a negative contribution of the "str" term, while the opposite leads to a positive one.

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 and how they change in different countries. To this end, we will conduct a Granger causality study [11] 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. Toda and Yamamoto's method [12] 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 [38, 39, 40, 41, 42]. The core advantage of this test is the possibility of being applied regardless of whether 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. Note that previous variables do not correspond to the LMDI contributions written in Eqs. (2) and (3), but they directly correspond to the data taken from the sources specified in Section 3.3.

Thus, in the case of CO_2 emissions and GDP, the Granger causality analysis involves the next couple of equations,

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

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

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 an 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 a bi-directional causality in the examined relationship may exist.

3.3. Sources of data

To carry out this work, we have used data extracted from several official sources, namely, the World Bank [7] for economic data, the IEA (International Energy Agency) [6] 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 sections A and B of ISIC, which include agriculture, livestock, forestry and fishing, plus mining and quarrying. The Industrial sector ($i = 2$), corresponding to 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, which include trade, transport and storage, residential consumption, and public services. This classification promoted by the United Nations allows us to uniformly compare the data corresponding to different countries, fuels and sectors.

In this work, a total of 21 fuels have been considered, which are listed in Table 2. Due to the significant influence of coal and petroleum in the amount of CO_2 emissions, we have considered coal and petroleum consumption, in its distinct types, as disaggregated, instead of simply using the total amount and the average value of the emission factors. This disaggregation allows one to study 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 is the US dollar. The rest of the units used are the ones from the International System of Units.

The carbon-free-emission energy sources correspond to solid biofuel, solar, wind, nuclear and hydroelectric energy.

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 different countries, making it possible to separate it into two groups. On the one hand, the USA, the EU, Russia, and Japan show, a flat evolution and China and India show a clear incremental increase. As observed in Fig. 3A, in the first group of countries, there is a small increase in energy consumption during the studied period or even a decrease, namely, the EU energy consumption changed −1.5%, Russia −13.2%, the USA 16.4% and Japan −2.4%. In the second group, there is a tremendous increase in energy consumption, with India increasing by 196.6% and China by 266.6%. Regarding the share of carbon-free energy, depicted in Fig. 3B, there is a group, made up of the EU, the USA, and Russia, where this share steadily increases, albeit only fractionally. The second group is formed by China and India, for which the share of renewables greatly decreases during the studied period. Finally, we separately considered Japan, where a sudden discontinuity in the share of carbon-free energy happened in 2011, corresponding to the

Fukushima nuclear accident. However, without considering this discontinuity, the behaviour of Japan coincides with that of the first group of countries.

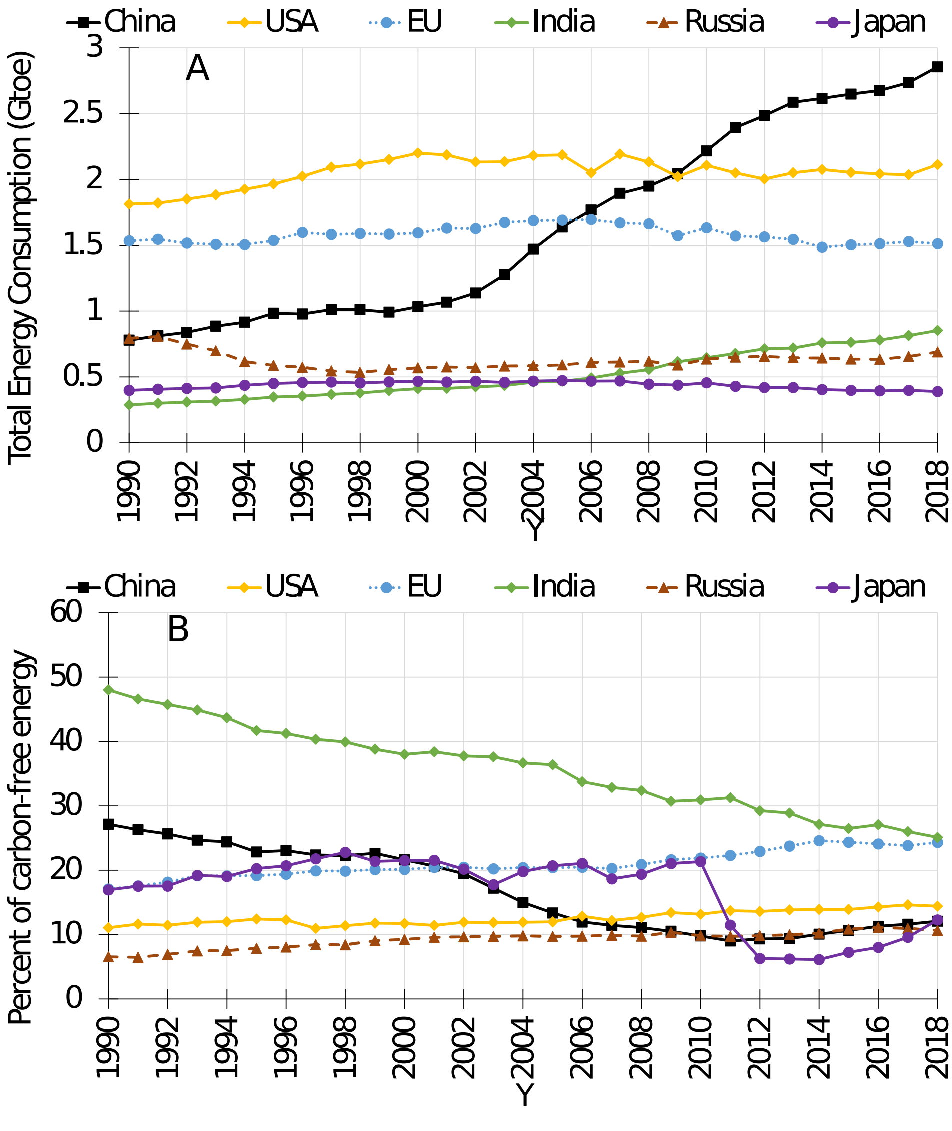


Figure 3: Evolution of annual total energy consumption (panel A) and share of used carbon-free energy (panel B) during the period 1990-2018.

Fig. 3B highlights the decrease of carbon-free energy in China, which is reduced from 27% to 12%, and India, which likewise decreases from 48% to 25% during the studied period. As will be explained below, this has happened despite the enormous new carbon-free energy capacity that has been incorporated into the energy system of both countries.

In Fig. 3, the evolution of solar photovoltaic and wind power is depicted, where it is worth mentioning the remarkable increase in five of the six considered countries. The poli-

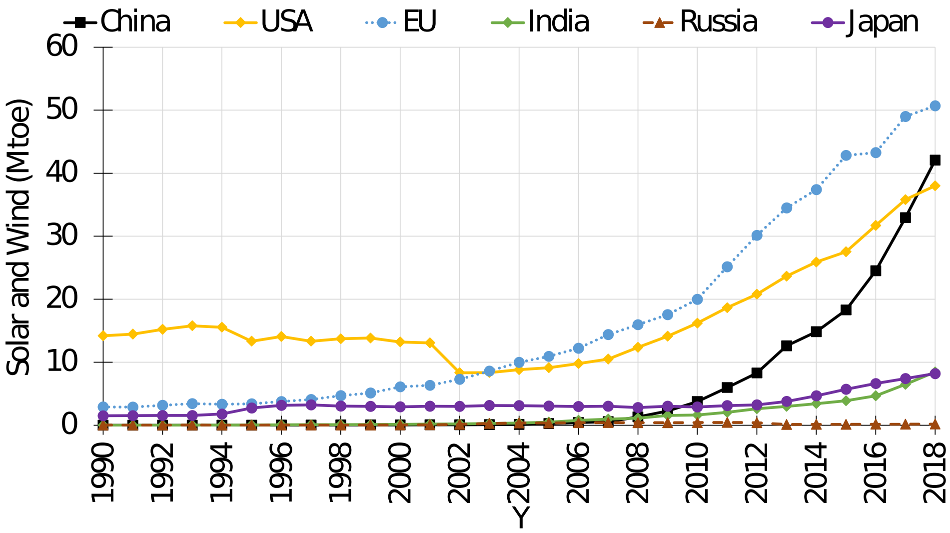


Figure 4: Evolution of solar and wind renewable energy used during the period 1990-2018.

cies 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, while the cost of onshore and offshore wind farms has also been reduced to 60 and 140 USD/MW, respectively, for 2017. Continuing with the case of the EU, its production of solar and wind energy has increased 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 expansion of solar photovoltaic owing to federal tax incentives and state-level policies, as well as the new onshore power plants, which added an extra 6.9 GW in 2018, reaching 9.1 GW in 2019, once again, 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 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 variable renewable energy was almost zero during the whole considered period.

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

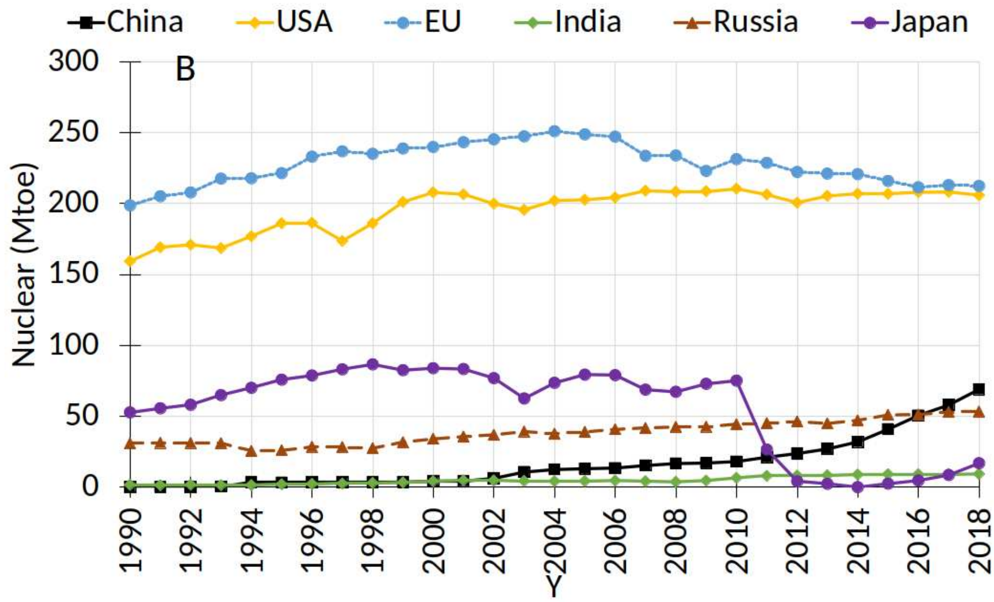


Figure 5: Evolution of nuclear energy used during the period 1990-2018.

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 [6].

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 of 251.0 Mtoe recorded in 2004, though from this year 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 that of the EU. Russia also presented 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 the 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 the Fukushima accident, all 39 reactors in the country were shut down. Since then however, nuclear energy production in Japan has partially rebounded but still is very far from its maximum and most probably will never fully recover [6].

Concerning the group of developing countries, the number of commissioned new reactors has been notable, reaching in the case of India 22 reactors in operation in 2018, increasing 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 Russian nuclear energy production.

4.2. CO_2 emissions by type of fuel and sector

In this section, we analyse in depth the evolution of CO_2 emissions in the different countries, disaggregating in types of fuel and sector, paying particular attention to the different types of coal and petroleum used. 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 in emissions over the time period. 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 was still the main source of emissions, 78%, although the use of bituminous coal has been reduced to 37%, mainly by introducing new types of coal such as coke oven coke or blast furnace, which all present a very high emission factor. The abrupt increase in the emissions in 2005 comes from the change in the policy of China concerning exports and imports of coal. This policy gives priority to energy conservation. From 2004 and onwards, the exports were considerably reduced, while the imports greatly increase [43]. This change also affected to the share of the different types of used coal [44].

Diesel and gasoline use have also increased, with diesel increasing 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. Furthermore, natural gas entered the equation in 2005, with a share in the emissions of 1.4%, and reaching 4.6% in 2018. Concerning the economic sectors, their shares of emissions are relatively constant over the whole period, with approximate values of 67%, 26% and 7% for industrial, service and primary sectors, respectively. However, a specific reduction in the primary sector share compared to the industrial and service sectors is observed at the end of the period.

In Fig. 6D, the evolution of India is presented, which also shows a rapid increase of emissions as 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, and 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 increased 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.

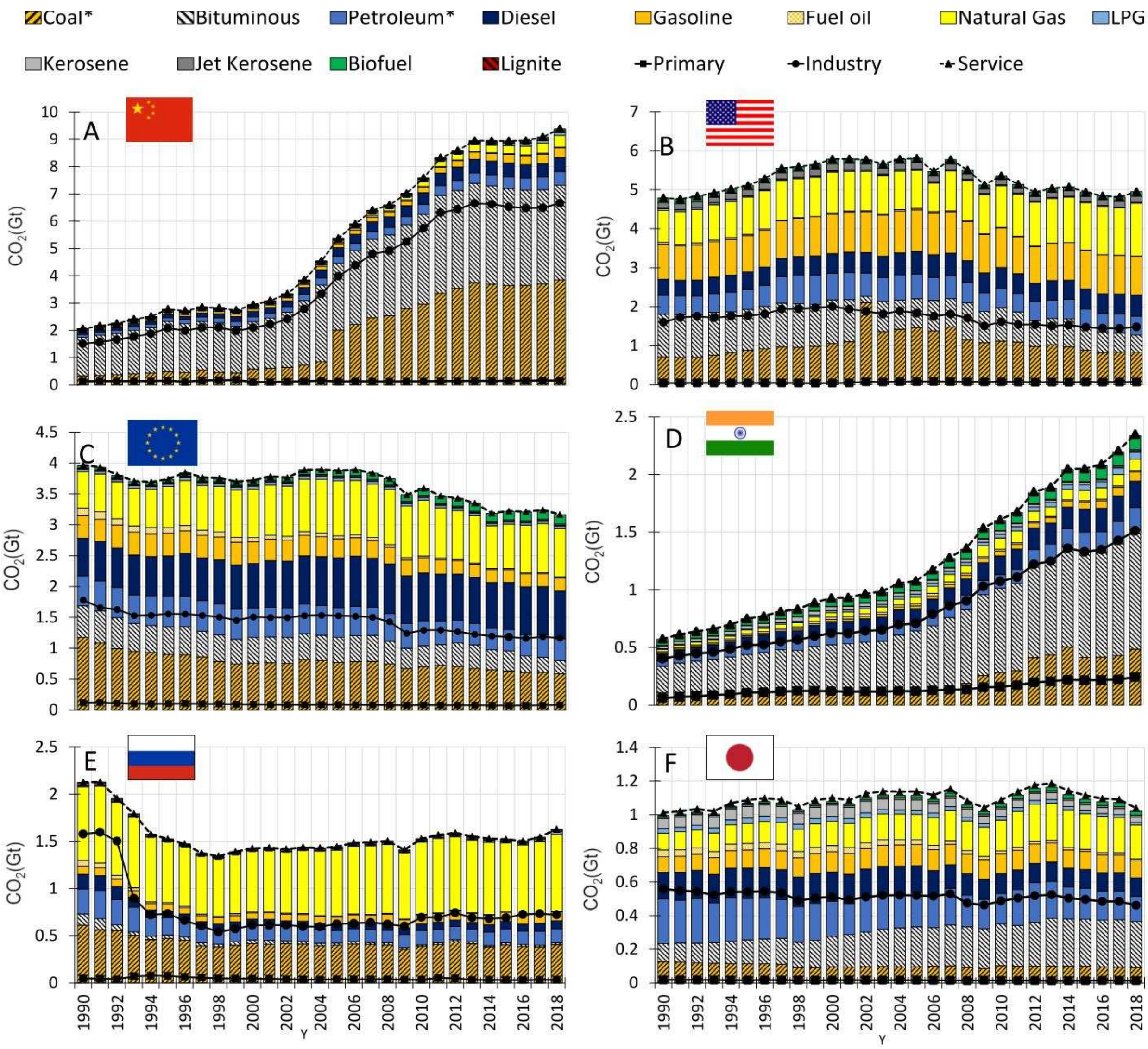


Figure 6: CO_2 emissions separated by energy sources (colour bars) and sectors (lines) and countries.

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 fact, more than 27% of the emissions in the USA can be credited to this source (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, increased 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) 27% in 1990 and 31% in 2018, while the EU went from 25% in 1990 to 31% in 2018. On the other hand, in 2018 Russia replicated 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, decreasing from 25% in 1990 to 20% in 2018.

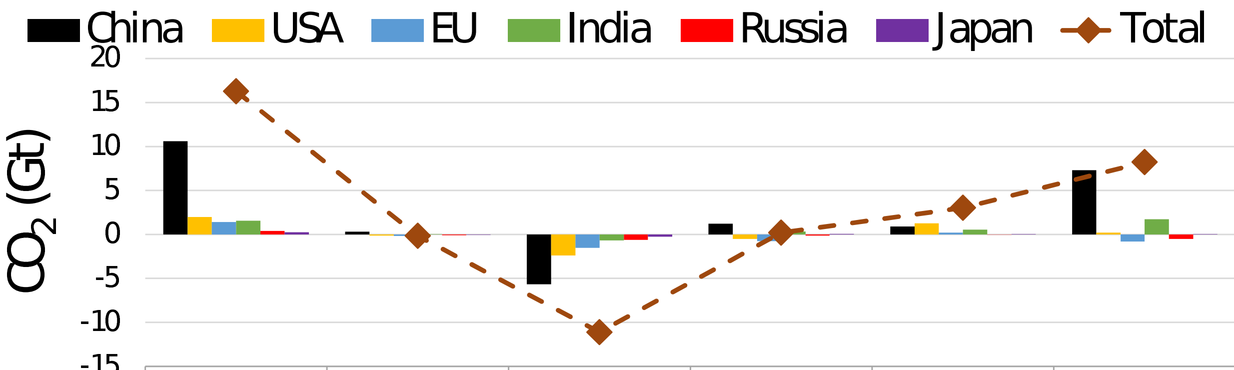
Finally, concerning the evolution of emissions by sectors, all the developed economies have kept a relatively constant share, while the share of the industrial sector has decreased and the share of the service sector has increased. In the USA, the industrial sector share decreased from 33% in 1990 to 29% in 2018, with the service sector increasing from 67% to 70%. 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 noticeable aspect is that apparently, all the countries have a common behaviour, although with a clearly different scale, especially in the case of China, but when analysed in detail, notable differences are observed. In the case of the activity term (act), all the countries present positive contributions, with China having the largest one, which is as large as double the sum of the contributions of the rest of the countries. The second contributor is the USA, with a contribution of around 20% of that of China. The important positive contribution of the activity term has been already observed in other works such as [17]. The contribution of the structure term (str) is almost negligible in all countries. The intensity term (int) is negative in all countries, with China having the most negative contribution, corresponding to the sum of the contributions of the rest of countries combined, which implies that China is not capable of compensating the activity term described above. In [19], the authors concluded that in Russia, China and India energy intensity plays a major role in mitigating CO_2 increase, although in [20] a rebound effect is observed. Ref. [17, 45] also support the existence of a negative contribution of the energy intensity term. In the case of the mixing term, China and India present positive contributions, Japan a negligible contribution, while the USA, the EU and Russia present a negative one which implies that so far China and India are unable to reduce their emissions with clean energy. The observed results for the USA, the EU and Russia are expected according to IEA data [6], the rather flat behaviour of Japan is a consequence of the past policies [46]. China and India are not yet able to achieve a negative mixing term in spite of the large increase in the use of carbon-free energy [6] due to the increase of the use of fossil energy. Finally, the population term is positive in all countries, except in Russia, with the

USA having the largest and then followed by China. It is worth to mentioning the small size of the population contribution in India in spite of the large increase of its population in the considered period, increasing by 40% [7]. This is related to the still too low GDP per capita of the country, which produces a small increase in the emissions for every extra inhabitant. 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 8.2 Gt, corresponding to 7.3 Gt for China, 1.7 for India, and 0.2 for 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.



	Cact	Cstr	Cint	Cmix	Cpop	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.

Drawing a 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 the developed and developing countries are, according to the scale of change of their driving forces. As a matter of fact, to really appreciate this, in Fig. 8A all the countries are depicted, while in Fig. 8B, only the developed ones are.

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

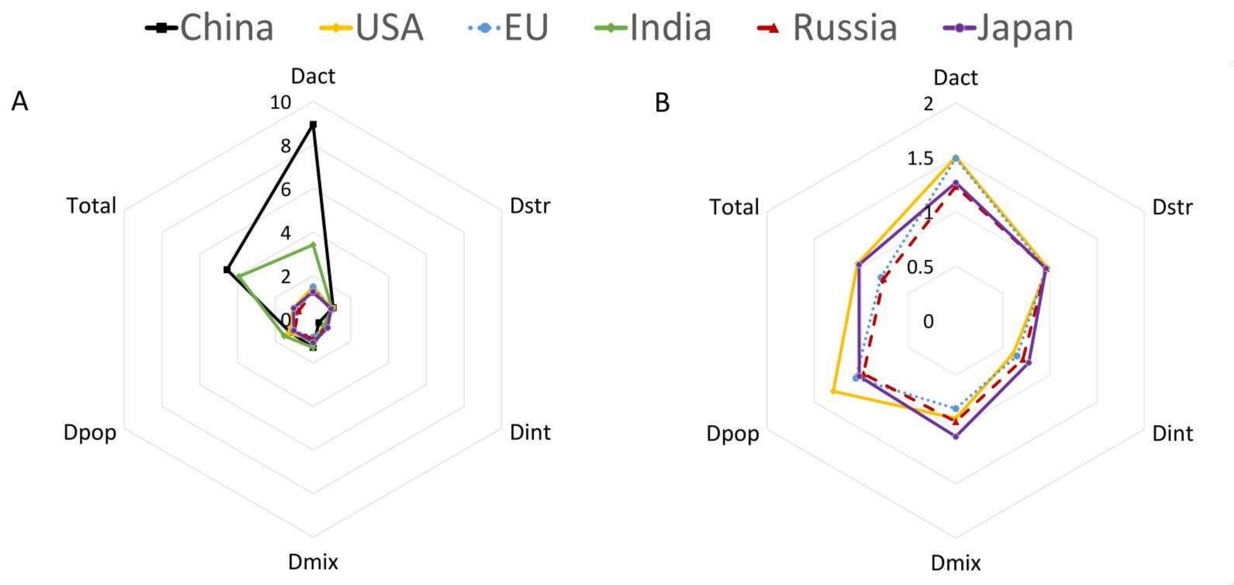


Figure 8: CO_2 LMDI multiplicative decomposition for the whole period 1990-2018. In panel A) all the countries are depicted, while in panel B) only the developed ones.

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.

Concerning the activity driving force, i.e., the contribution due to the change in the GDP per capita (panel A), all countries present an upwards trend, with China increasing considerably, showing a clear acceleration from 2002 and onwards. Most probably, the reason is the changes carried out in 2004 in the state constitution of the country which includes the protection of private property rights and a new overall government economic policy. This trend has continued to today, proving the maturation of the Chinese economy. The decrease of the activity term in Russia is also remarkable, which is a consequence of the crisis that the country suffered after the disintegration of the former Soviet Union. In this figure it is also possible to detect the impact of the Great Recession of 2008 which is mainly visible in the USA and the EU. These results are consistent with the ones obtained in [17]. The activity term is the most significant contributor to the emissions, and China is the main actor. The structure contribution, i.e., the contribution due to the changes in the structure of the economic sectors (panel B) is negative in all countries except in India and mainly in China, with a clear maximum around the year 2010. Note that in absolute values, the contribution of this driving force is the smallest one. The intensity term, i.e., the contribution due to the changes in the ratio of energy and GDP (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. These results are in line with those obtained in [19, 20, 45]. Panel C clearly shows how energy is used increasingly in a more efficient way in all the analysed countries. The mixing term, i.e., the contribution due to the changes energy matrix (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 downwards trend. It is evidence of the promotion of variable renewable energy in the EU since the 1990s. The USA had a flat or even a positive 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 carbon-free energy. The NDC's of both regions [5] show that present environmental policies will reinforce this trend in the near future. Russia and Japan present a quite flat trend, although there is a sudden increase in 2011 because of the Fukushima accident in the case of Japan [46]. However, it is expected that future policies, as settled in their NDC's [5] will produce a net reduction from the mixing term. In the case of India, there is an increasing trend with no signs of reduction, while in China, it is possible to distinguish two periods, one up to the year 2004, representing a moderate increase, and from then until 2018, when the mixing contribution started to increase. It clearly indicates that 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 fossil fuel in China and India is the main energy source and its use is increasing [6]. 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 that of the EU has increased steadily, reaching saturation in recent years.

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, from 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, and Russia a constant but negative value and, finally, the EU presents an almost zero contribution until 2008, but since then there has been a clear down sloping contribution. The case of Japan is worth analysing separately because it shows a fully flat trend almost in all panels of Fig. 9. This is a clear consequence of the

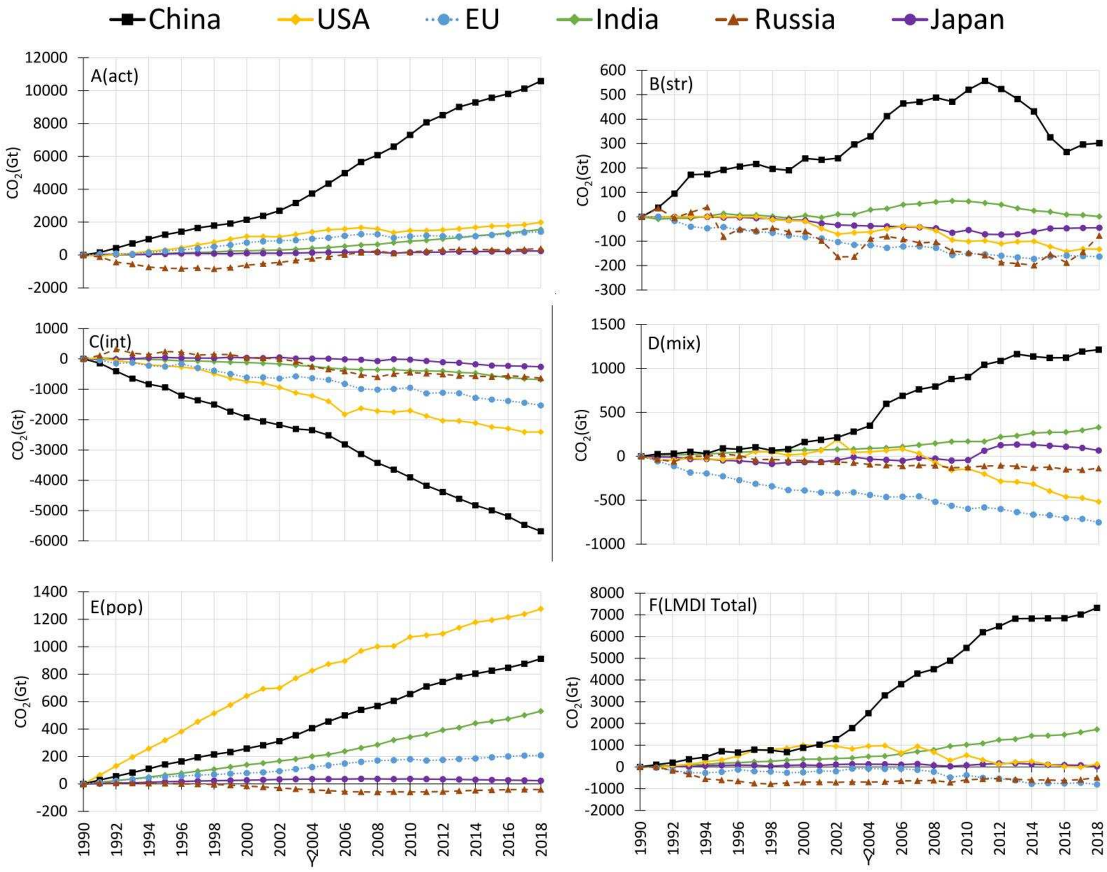


Figure 9: Evolution of the different components of the additive LMDI during the period 1990-2018. Panel A) for the activity term, B) for the structure one, C) for the energy intensity one, D) for the energy mix term, E) for the population term, and F) for the total sum.

evolution of Japan economy since the 1990's, when a deep economic crisis lead to the so called "lost twenty years" [8] that clearly still has effect today and has produced almost no changes in the CO_2 emissions, with the exception of the influence of the Fukushima nuclear accident.

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 of 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 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,steadily decreasing value, 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 later years, India, Russia, Japan, and the EU have shown a certain stabilization of their levels, while the USA and especially China have a clear downwards trend. Today, China, India, and Russia present a level of CO_2 intensity that is more than four times that of the EU, Japan, and the USA.

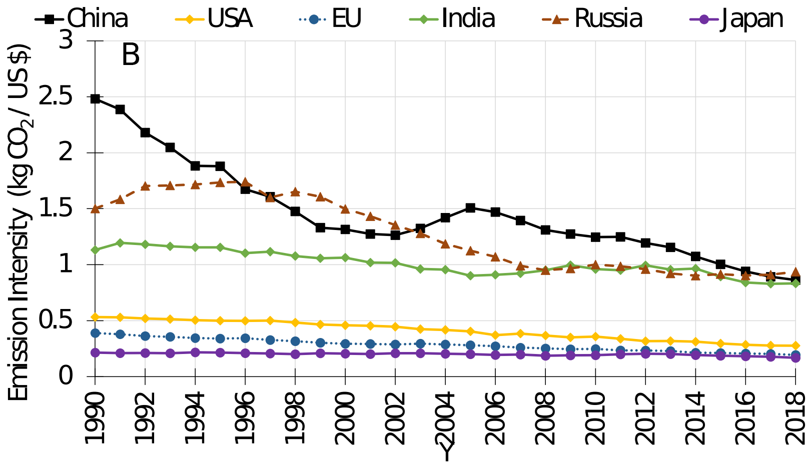


Figure 10: Evolution of the emission intensity for the six studied countries.

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), carbon-free energy (CFE), and population (POP), which suppose ten pairs of variables, whose relationships are studied in both directions. Before performing the Granger-causality analysis, the order of integration of the different involved variables needs to be determined, for example by, using the tests of Ng and Perron [47]. 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.

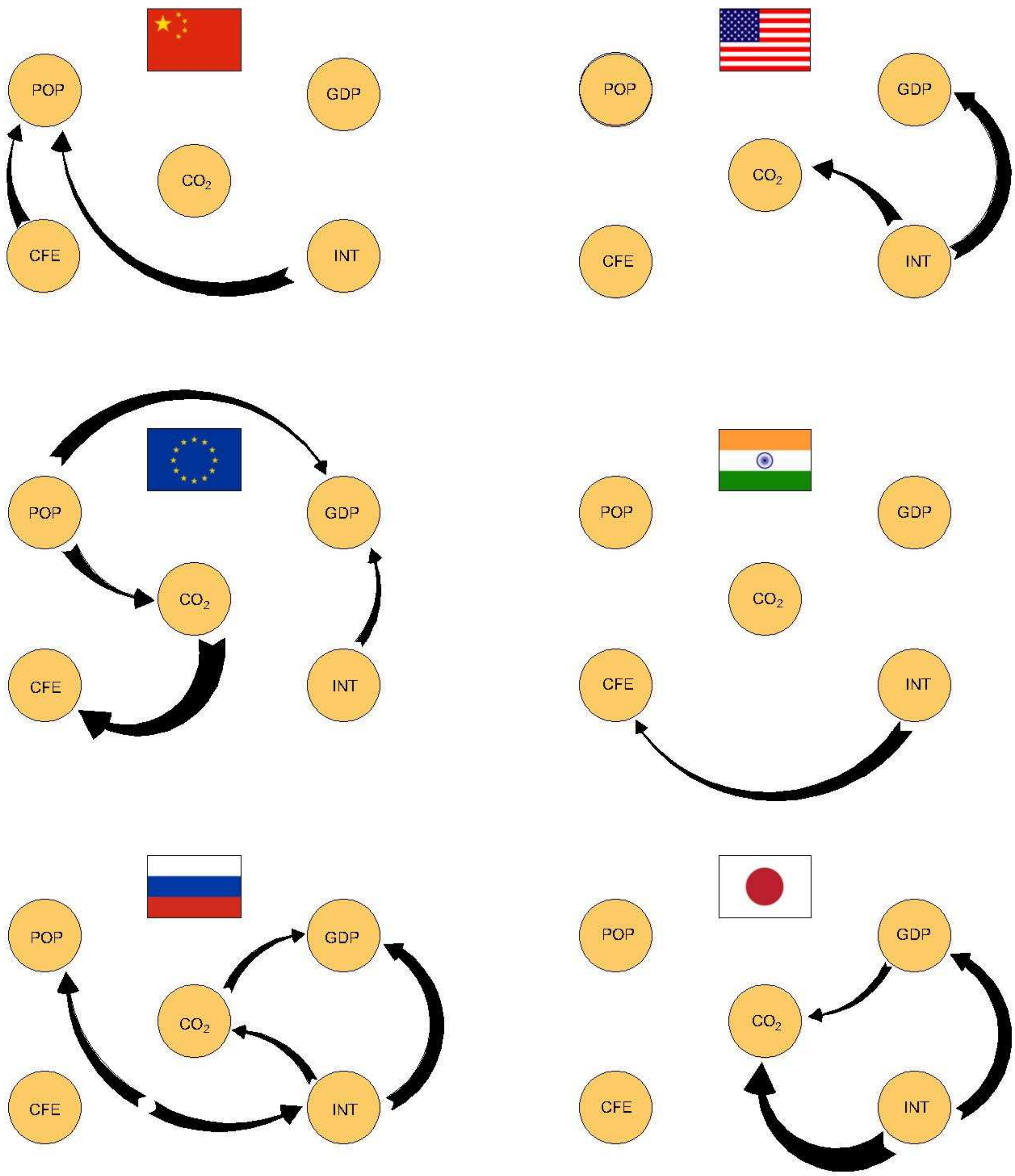


Figure 11: Pictorial representation of the statistically meaningful Granger-causes separated by countries.

Analyzing the results by countries reveals that in China, carbon-free energy consumption and energy intensity is statistically linked to population, however, in [29] it is found that foreign direct investment Granger causes clean energy consumption in China. On the other hand, in Ref. [26] a bidirectional causal relationship between hydropower energy consumption to economic growth is observed for China. USA shows a causal relationship from energy intensity to CO_2 emissions and GDP. In [30], the authors analyze several developed countries belonging to the OECD without founding for the case of the USA any connection between the explored variables in this work. In the EU, the results of Granger causality tests indicate one causal relationship running from CO_2 emissions to carbon-free energy, other from population to CO_2 emissions and two relationships from energy intensity and population to GDP. In Ref. [30], several countries of the EU are studied and a bidirectional connection between energy consumption and GDP is obtained. In relation to India, the results of Granger causality tests indicate only one way causality running from energy intensity to carbon-free energy consumption. The finding relative to Russia reveals that there is a causal link from energy intensity to GDP and CO_2 emissions while this last one is statistically linked to GDP. Finally, in Japan, results show causal relationships from energy intensity to GDP and CO_2 emissions (as in Russia), and from GDP to CO_2 emissions. These results can seem a little paradoxical because they are not the obvious outcome that one might 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, Japan, GDP Granger causes CO_2 emissions, in three cases, the USA, Russia, and Japan, energy intensity Granger causes CO_2 emissions, and only in one case, the EU, population Granger causes CO_2 emissions. However, CO_2 emissions Granger causes carbon-free energy consumption in the EU. It is worth mentioning that in four countries, namely, the USA, the EU, Russia, and Japan, energy intensity Granger causes GDP. These conclusions are drawn in Fig. 11, where only statistically meaningful Granger causes are plotted, with the arrow's thickness being 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 with more Granger causes (six arrows are pointing to the GDP), while energy intensity is the one that generates more Granger causes (ten arrows pointing to outside INT). Particularly interesting is the Granger causality between energy intensity and GDP (four of the six countries), which shows the importance of the energy intensity, not only to moderate CO_2 emissions as shown in previous sections, but also to determine the GDP value. In general, the results are only partially in agreement with [23], where a strong bidirectional causality relationship between CO_2 emissions and non-renewable energy is obtained. Moreover, another bidirectional causality exist between the service sector toward CO_2 emissions and between value-added service and non-renewable energy. It is also of interest to compare our findings with the ones obtained for a panel of 25 African countries [48] where a long-run and short-run causality from GDP to carbon emissions is obtained. Moreover, a long-run and short-run causality from carbon emissions to GDP is also found and, finally, a short-run causality from GDP and renewable electricity to carbon emissions is obtained. In the ASEAN group of countries plus China it is obtained a bidirectional causality relationship between industrialization and environmental degradation [49], which is related with our causal connection between GDP and CO_2 emissions, although in our case, this connection is only observed for Russia and Japan, but not in a bidirectional way.

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
CFE	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
POP	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
CFE	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
POP	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
POP	CFE	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	CFE	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	POP	20.086**	0.118	6.479	0.400	1.036	5.300	1.379	0.000	9.080**	9.308*	3.479	5.32

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 period 1990-2018. To this end, we have used the Kaya identity [9], the LMDI decomposition technique [10] and the Granger causality analysis [11] with a Toda-Yamamoto test [12]. 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 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. Strongly related to the latter point is that the share of carbon-free energy (including nuclear energy) has decreased in China and India, while it has steadily increased in the rest of the countries, except for Japan after the Fukushima nuclear accident. The behaviour of China and India with respect to the use of carbon-free energy is somehow paradoxical because a reduction of the share to the energy mix exists despite the large increase in the use of variable renewable and nuclear 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 comes from 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 in reducing emissions is the energy intensity term, with China having 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, which is far from compensating the activity contribution. Concerning the mixing term, China and India present a large and increasing contribution, Russia and Japan almost a null contribution, while the USA and especially the EU present decreasing contributions. It proves that the USA (in the last decade) and the EU promote an effective policy of carbon-free energy, while China and India should still pursue the promotion of these energy sources. All in all, India and China continue to increase their emissions without evidence of a change of trend. However, the rest of the countries, especially the USA and the EU, are clearly on the path to 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 Russia, the USA and Japan, for which energy intensity Granger causes the CO_2 emissions and in the case of Japan for which GDP Granger causes 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 energy intensity is the factor that most Granger causes other variables. In other words, energy intensity is the variable that will better serve to predict the evolution of the rest of the driving forces. Finally, energy intensity Granger causes GDP in the four developed countries. According to the empirical evidence obtained in the literature and presented in Sections 2 and 4.5, no clear conclusions can be reached on the Granger causal relationship among the CO_2 driving forces considered in this work.

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, a tight bond still exists 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 implemented to promote the reduction of the intensity term and, mainly, the contribution of the carbon-free 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 that a profound improvement still needs to be made 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 this latter term is expected to increase in the future. However, most probably, both countries will fulfil their

NDC's (see Table 1) because they are based on the value of 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 signs 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 recent decades a consistent improvement of the energy intensity and the energy mix term has been observed (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.

All in all, there is a clear difference between high-income and middle-income countries, especially between, on the one hand, the USA and the EU and, on the other, China and India. Clearly in the first two areas, the environmental legislation concerning CO_2 emissions is much more strict than in the last two, as prove by their NDC's (see Table 1). According to the results presented in Section 4.3, it seems clear that the future of CO_2 emissions will be mainly determined by the behaviour of China, which is the current largest emitter, and India, which is expected to greatly increase its emissions in the near future [50]. Therefore, it is of prime importance to improve the contribution of the mixing term, mainly substituting the use of coal with other carbon-free energies in China and India. So far, in both countries, the increase in energy consumption in recent decades has been generated by the extra use of coal, and this situation should change in the future. Both countries are investing significantly in new carbon-free facilities, but this is still not enough and the share of carbon-free energy in the energy mix has reduced in the last decades. Assuming that in both countries the GDP per capita will continue increasing, the energy intensity, through the efficient use of the energy, should be largely reduced, otherwise the exponential increase of the CO_2 emissions will become unavoidable. High-income countries, mainly the USA and the EU, should act as "test-beds" for new technologies to reduce CO_2 emissions that could be exported to middle-income countries. Moreover, citizens of developed countries, most probably will force their governments to implement more ambitious environmental regulations which in turn will affect the emissions in developing countries through global trade. It is worth considering that the present more stringent environmental legislation most probably will hinder the future economic growth in middle- and low-income countries, something that did not happen to the present high-income countries in the past. This fact should be remembered in designing future global policies to fight against Climate Change.

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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
CFE	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 [51]. The critical values are taken from Table 1 of [47].