Science of the Total Environment 737 (2020) 139638

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Is India on the right pathway to reduce CO_2 emissions? Decomposing an enlarged Kaya identity using the LMDI method for the period 1990–2016

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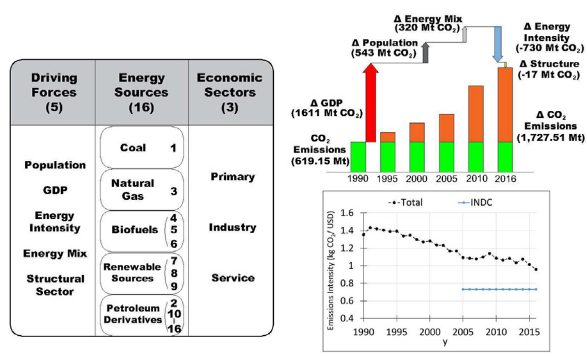
HIGHLIGHTS

- The per-capita income is the main contributor to CO2 emissions increase in India.
- The energy intensity is the main contributor to CO2 emissions decrease in India.
- The share of renewable energy in India has continuously dropped from 1990 to 2016.
- India will reach its government target for 2020 regarding emission intensity.
- India can fulfil its NDC without reducing its net CO2 emissions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 February 2020
Received in revised form 30 April 2020
Accepted 21 May 2020
Available online 29 May 2020

Editor: Pavlos Kassomenos

Keywords:
CO_2 emission
Energy consumption
Driving forces
Kaya-LMDI
India

ABSTRACT

Nowadays, India is the third-largest CO_2 emitter and energy consumer in the world, and, it is soon expected to surpass China as the most populated country. Therefore, it is of great interest to analyse how India is developing its energy transition to a lower-carbon economy. This work analyses the evolution of the main driving forces of CO_2 emissions in India during the period 1990–2016 through the use of an enlarged version of the Kaya identity, which establishes a link between CO_2 emissions, types of energy sources (16), size of the economic sectors (3) and value of the Gross Domestic Product. India's CO_2 emissions increased by 276% in the period under study, due to the rapid economic growth of India, which has been the dominating driving force contributing to the increase in CO_2 emissions by 241%, while the energy intensity has been the main one reducing them by approximately −47%. So far, the use of coal has supported the rapid economic growth and the contribution of renewable energy, although significant, is still short compared to the total amount of energy employed. Remarkably, the estimated value of the emission intensity for 2020 supposes a 26% reduction concerning the value in 2005. According to this result, India is on the right pathway to fulfil its Nationally Determined Contribution but not to reduce its net CO_2 emissions.

Abbreviations: act, economic activity; BRIC, Brazil, Russia, India, and China; CO_2, carbon dioxide; GDP, Gross Domestic Product; GHG, greenhouse gases; HDI, Human Development Index; IDA, index decomposition analysis; int, intensity; IPAT, Impact, population, affluence, and Technology; IPCC, Intergovernmental Panel for Climate Change; kCO_2, kg of CO_2; koe, kg of oil equivalent; LMDI, logarithmic-mean Divisia index; LPG, liquefied petroleum gas; mix, energy mix; $MtCO_2$, million tonnes of CO_2; NDC, Nationally Determined Contributions; OECD, Organisation for Economic Co-operation and Development; pop, population; ppm, parts per million; 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 dollars.

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https://doi.org/10.1016/j.scitotenv.2020.139638
0048-9697/

1. Introduction

Climate has become, in this century, a major concern for population who perceive global warming as a threat for the future of our society. Global warming and its outcome, namely, the Climate Change, is largely connected with anthropogenic CO_2 emissions. The Intergovernmental Panel for Climate Change (IPCC), in its latest assessment report (Stocker et al., 2013) and in its special report on a 1.5°C increase in global temperature (Masson-Delmotte et al., 2018), points towards the direct connection between human activity and the observed rising value of the Earth's average temperature during the last centuries. The temperature has increased by around 1°C over the last 100 years. The link between global warming and human activity is CO_2 emission, although other gases are also noteworthy, such as methane (CH_4), nitrous oxides (NO_x), or hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). All these are known as greenhouse gases (GHGs) because they contribute in a strong manner to the so called greenhouse effect which is, as a matter of fact, responsible for the relatively warm and *pleasant* temperature of the Earth. However, nowadays, it has been exacerbated and is leading us into a global climate emergency (Ripple et al., 2020) because GHG levels, far from being stabilised, show a clear tendency to increase according to the IPCC report (Masson-Delmotte et al., 2018).

The connection between CO_2 or other GHG emissions and human activity is found in the economic activity mediated by the use of energy of fossil origin. In a more detailed way, the emissions are connected to economic development, which can be roughly described through the value of the Gross Domestic Product (GDP) and the structure of the production system. Furthermore, the emissions are connected with the size of the population, the types of energy used, the available technology or the magnitude of international trade (Alcántara and Padilla, 2005). According to IPCC reports, economic development and global warming are likely to be connected in a straightforward one-way manner, i.e. from economic growth into CO_2. However, Stern (2007) points towards a two-way connection, from CO_2 emissions into economic growth as well. It is noteworthy that the use of energy is not the only source of CO_2 emissions, although it is by far the largest, representing 76% of the world GHG emissions (approximately 65% is from fossil fuels, 11% from deforestation and land use) (US EPA, 2019), the rest of GHG emissions corresponding mainly to methane and nitrous oxides.

The causal relationship between CO_2 emissions and economic development was first suggested in the 1990's by Kaya (Kaya and Yokobori, 1993) and the term *Kaya identity* was coined soon after. The Kaya identity is a kind of tautology in which CO_2 emissions are written down in terms of population, GDP per-capita, energy intensity, i.e., energy use over GDP, and emission factors, i.e., CO_2 emission over energy. It has been extensively used to calculate CO_2 inventories, to estimate CO_2 emissions or in the framework of scenarios theory in the medium and short term (IPCC, 2006).

In view of the size of the problem that represents global warming and Climate Change, most of developed nations have designed policies oriented to the reduction of CO_2 emissions, in spite of affecting its economic development (see Nationally Determined Contributions (NDCs) (UNFCCC, 2019a)). Very good examples of this tendency are the European Union and California (Meckling et al., 2017), where the investments in energy efficiency and renewable energies has been strongly promoted, while the use of fossil fuels has been discouraged through the rising of taxes. In the short term, these measures could affect GDP growth, but in the long term, EU decarbonisation strategy is expected to have a positive effect (Antimiani et al., 2016).

In general, in most of the developed countries, the reduction of CO_2 emissions is a major goal regardless of the possible effect on economic growth. However, in developing countries, such as India, the position is rather the opposite, with economic development as the cornerstone to design medium and long term policies. As a matter of fact, according to the World Bank (WB, 2019a), the GDP per capita of the European Union was 37,417 USD[1] in 2018, which corresponds to 344% of the world's average (10,882 USD), while the case of India corresponds to 2104 USD, representing only 19% of the world's average and 5.6% of the European Union's value. Therefore, this strong difference between a well-developed area, such as the European Union, and India should determine clear differences between the policies in both regions concerning mitigation measures affecting CO_2 emissions. In India a rapid increase of its GDP is expected and desirable, which, in principle, will suppose a notable increase of the country's emissions, unless, mitigation measures are implemented. Considering the size of the country, its rapid economic development will, without doubt, imply an increase of the world's emissions, in spite of the efforts of developed countries (Shuang et al., 2016).

The main goal of this work will be to analyse how, in India, the different driving forces that modulate the CO_2 emissions, namely, population, economic activity, economic structure, energy intensity and energy mix, have evolved since the 1990's until nowadays to serve as a reference to policymakers to determine possible environmentally sustainable policies. Surprisingly enough, there are not too many previous studies (see Section 3 for the literature review) that shed light on the evolution over time of emissions in India during the period between 1990 and 2016. To this end, the so-called logarithmic-mean Divisia index (LMDI) will be used in conjunction with an extension of the Kaya identity in which the energy is disaggregated in terms of the type of fossil fuel or its renewable origin, considering, in total, sixteen types of energy sources. Moreover, we will consider the economic system as divided in three sectors, such disaggregation is a key point of this work, allowing a fine-grained analysis. The scarcity of Kaya-LMDI studies concerning CO_2 emissions for India is one of the main reasons for conducting this work. Additionally, as far as we know, such a detailed breakdown by fuel type and energy source has not been performed before, using the Kaya identity.

The rest of this paper will be organized as follows. In Section 2, the main figures of India are depicted, to define the size of the problem of CO_2 emissions for this country. In Section 3, the relevant literature concerning the use of the LMDI method in India is reviewed. In Section 4 the used methodology is sketched. Section 5 serves to present the results and their discussion, and finally, Section 6 provides the conclusions and policy implications.

2. Overview of the study area

India is a federal republic based on a parliamentary democracy, whose population in 2018 was 1353 million inhabitants, being the second most populated country in the world (population of 7594 millions in 2018) (WB, 2019b). That is, almost 18% of the planet's population is living in India. On the other hand, India is the seventh largest country in terms of GDP (2.846 trillions USD), having an area of 3.287 million km^2 (WB, 2019b). India is expected to surpass China as the most populated country in the world in 2027 (UN, 2019).

Unfortunately, according to the Organisation for Economic Co-operation and Development (OECD), almost 25% of its population still lives below the poverty line. Indeed, about one third of the world's population living with less than 1.9 USD a day lives in India (OECD, 2019). Moreover, social inequalities in India are very large. As a matter of fact, the richest 1% of the population owns 53% of the country's wealth (WEF, 2019).

In spite of the problems mentioned above, the economic growth of India remained stable during the last few decades. Surprisingly enough, even during the *Great Recession*, India's GDP grew at rates always above 5%. According to the International Monetary Fund (IMF) (IMF, 2019), the Indian economy recorded the third highest growth in the world,

[1] Throughout this work we will consider as currency, by default, 2010 constant international dollars which we will refer to as USD, for brevity, unless otherwise is specified.

Table 1
Economic indicators for India. (e) Stands for estimated data.
Data taken from the IMF (2019).

	2016	2017	2018	2019(e)	2020(e)
GDP (current prices, billions USD)	2289.75	2652.24	2718.73	2935.57	3202.18
Real GDP growth (annual percent change) %)	8.17%	7.17%	6.81%	6.12%	7.03%
GDP per capita (current prices USD)	1761.63	2014.01	2037.69	2171.64	2388.11
Inflation rate, average consumer prices (annual percent change (%)	4.5	3.6	3.4	3.4	4.0

driven by the recovery of industrial activity, especially in manufacturing and construction, and an expansion of agriculture. The sectors that most promoted that growth were manufacturing, electricity, gas and water supply, construction, public administration and defence industry (IMF, 2019). That growth is expected to continue rising in the next years, with, for example, an expected increase of 6.12% in 2019 and of 7.03% in 2020. In Table 1, the main economic indicators for India are depicted. Moreover, in Fig. 1, the evolution of the GDP and the relative size of the three economic sectors in India are shown from 1990 until 2016. All these indicators show the great potential of India, where, in coming years, a steady economic growth is expected, which could lead the country to be one of the main actors in the global economy. In Fig. 2, the evolution of the world's GDP per capita compared with India's can be seen. Both have strongly increased in the period under study, but the distance between India and the average world GDP is even larger than at the beginning of the studied period.

According to the British Petroleum Statistical Review of World Energy 2018 (BP, 2018), India, in 2017, was ranked as the third largest energy consumer and CO_2 emitter in the world, with 2344.2 $MtCO_2$, which represents 7% of global CO_2 emissions. By far, the largest emitter is China

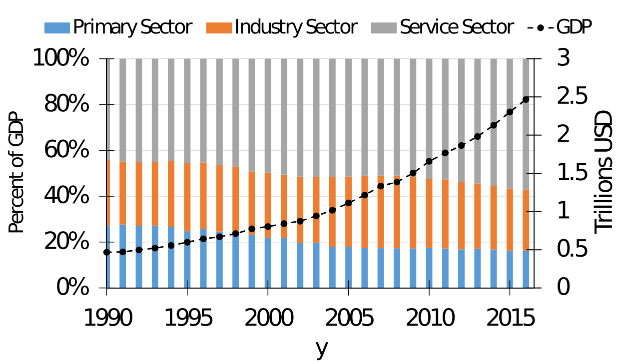

Fig. 1. GDP value and share of economic sectors of India during the period 1990–2016. Data taken from WB (2019b).

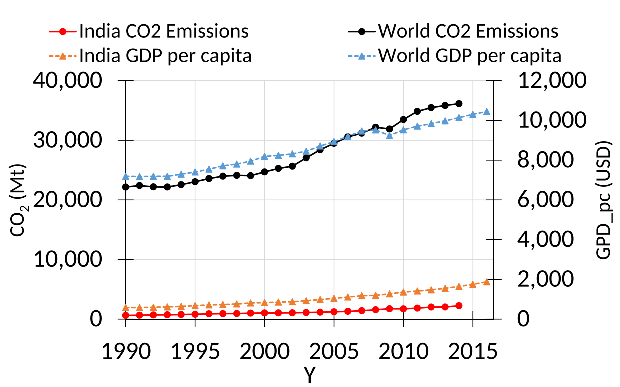

Fig. 2. Comparison of CO_2 emission and GDP per capita for India and the world for the period 1990–2016.
Data taken from WB (2019b).

with 9232.6 $MtCO_2$ (27.6%), followed by United States with 5087.7 $MtCO_2$ (15.2%). Hence, these three countries account for almost half (49.8%) of the global CO_2 emissions. However, the observed trends of these countries are very different. On one hand, United States reduced its emissions in the 2006–2016 decade (−1.2%), while China and India increased them by a 3.2% and 6%, respectively. Most probably, this rapid increase could be the reason for the growth (1.6%) of global emissions in 2017, after several years of almost constant emissions. In Fig. 2, the CO_2 emissions of India and the world are compared during the period 1990–2016, showing that India already represents a sizeable fraction of the total global emissions. Moreover, the trend clearly shows how, in the future, India could become one of the main contributors. In terms of carbon emissions per capita, India emits 1.9 tCO_2 per inhabitant and year, which is four times lower than the emissions of China per capita and the European Union or eight times lower than that of United States. As a matter of fact, emission per capita in India are even lower than in many developing countries (UN, 2017).

Under the point of view of energy consumption, the average annual energy consumption of India in 2014 was only 0.637 tonnes of oil equivalent (toe) per capita as compared to the global average of 1.920 toe per capita (WB, 2019b). That is, less than a third of the global average consumption. Finally, it is worth to mention what is claimed in page 5 of the India's NDC submitted to the United Nations Framework Convention on Climate Change (UNFCCC) for the period 2021–2030: "It may also be noted that no country in the world has been able to achieve a Human Development Index of 0.9 or more without an annual energy availability of at least 4 toe per capita" (UNFCCC, 2019b). Considering that India's Human Development Index (HDI) in 2017 was 0.640 (UNDP, 2019), being in the position 130 of the global rank, there is still a long road for India's authorities to provide a more dignified life to its population. This improvement in the standard of living of Indian population will suppose a very large increase of India's emissions if no mitigation measures are undertaken. As a matter of fact, the elements of the India's roadmap defined in its NDC are adaptation and mitigation strategies, financial aspects, technological shift, building capacity and, last but not least, transparency of action and support (UNFCCC, 2019b, page 4). Regarding the mitigation strategy, the unconditional goal of India's NDC for the period from 2020 to 2030 (UNFCCC, 2019b, page 29) consists in reducing the emissions intensity of its GDP by 33 − 35% by 2030 below levels of 2005. However, by 2030, two other conditional goals should be accomplished: the increase in the share of non-fossil energy over the total power generation capacity up to 40% and the creation of an additional cumulative carbon sink of 2.5 − 3 $GtCO_2$ equivalent through additional forest and tree cover. The adaptation strategy is developed by enhancing investments in development programs in sectors which are vulnerable to climate change, particularly agriculture, water resources, Himalayan and coastal regions, health and disaster management.

3. Literature review

The literature concerning the analysis of the driving forces of CO_2 emissions and its connection with economic development and energy consumption is vast. In this section, we will concentrate on those papers that apply a similar methodology to the one used in this paper, in particular, the Kaya identity and the LMDI methods applied to India or a group of countries of which India is part.

The LMDI method which appeared in the late 1970s, it is framed in the index decomposition analysis (IDA), and it is an analytical tool tailored originally for energy studies. However, since then, it has been extended to many other areas, including CO_2 emission studies, environmental management, and sustainable use of natural resources. The LMDI is based on a sum of relative changes that is weighted in an appropriate way and that uses the concept of Divisia index introduced in the 1920's by F. Divisia. On the other hand, the logarithmic mean weight function was first introduced by Ang (Ang and Choi, 1997), generating the first family of LMDI decomposition methods. In that paper, the authors focused on the decomposition of the aggregate energy and gas emission intensities for the industry. Since then, the use of LMDI had a rapid growth, in particular thanks to the works (Ang and Liu, 2001) where LMDI-I and LMDI-II were set up and to (Ang, 2005) which provides a practical guide of LMDI for non-practitioners. A few years ago, an updated review on the use of LMDI was published by Ang (2015) where the author reported 554 journal articles using LMDI as an analytical tool published until 2014.

The relationship between economic growth, energy use and CO_2 emissions in India has not been studied extensively in the literature and the publications are mostly concentrated in the last ten years. In particular, the connection between economy and CO_2 emissions has been studied in a set of publications for panels of countries, with India among them. In Andreoni and Galmarini (2016) 33 countries were studied during the period between 1995 and 2007, concluding that the main impact on the growth of CO_2 emissions came from economic growth, while improvements on energy efficiency generate the largest reductions. However, the analysis for India was restricted to the period 2004–2008. In Shuang et al. (2016), the authors analyse in depth the coupling between economy and CO_2 emissions in BRIC countries, namely, Brazil, Russia, India, and China, during the period between 1995 and 2014. Once more, it was observed how energy intensity played a major role in moderating the rise in CO_2 emissions. In the case of India, that happens in 13 out of the 20 studied years. Energy mix and fossil energy effects also contribute to the reduction of emissions, but neither during the whole period nor for all the countries. In Kangyin et al. (2019), the authors carried out a LMDI decomposition for countries with different levels of income, during the period between 1980 and 2030, considering different levels of income and defining several scenarios, concluding that, once more, energy intensity produces the biggest reduction while the increase in the GDP the largest rise of CO_2 emissions. It is worth to mention that upper-middle-income countries present, by far, the largest potential to reduce CO_2 emissions in the near future. In Henriques and Kander (2010), an LMDI decomposition of 10 developed and 3 emerging economies, India among them, was conducted for the period between 1971 and 2005. An interesting conclusion is that the major driver in mitigating the rise in CO_2 emissions is the evolution of energy intensity in the manufacturing sector. On the other hand, the transition to a service sector had a small impact in the decline in value of the energy intensity in 7 of the developed countries analysed. In the case of India the technological effect in the manufacturing sector and the use of more efficient fuels are responsible for the reduction of energy intensity. In Inglesi-Lotz (2018) the BRIC countries, together with South Africa, are studied for the period between 1990 and 2014. In the five countries analysed, it was observed that the slowdown of CO_2 emissions is tightly connected with improvements in energy intensity and carbon intensity, although for India and China the rebound effect was observed.

In Kanitkar et al. (2015), different developing countries and scenarios during the period between 1971 and 2008 were studied concluding that the efforts in mitigation should be larger than expected to fulfil the required reductions. In Lima et al. (2017), three emerging economies, Brazil, China and India, and three well developed ones, Portugal, Spain and United Kingdom, were studied during the period between 1971 and 2008. It was observed how in developing countries the increase of energy consumption is a common factor, while in the developed ones the trend is just the opposite. Only the improvement in energy efficiency can compensate the rise in energy consumption in developing countries, induced by a rapid economic growth. Marcucci and Fragkos (2015) study CO_2 emissions in China, India, the European Union, and United States, using scenarios that allow extrapolations until 2100, starting the analysis in 1990. As stated in other references, energy intensity is shown to be a key factor to moderate the rise in CO_2 emissions. However, in the long term, the use of carbon capture and storage methods to achieve a reasonable level of CO_2 in the atmosphere has been proved compulsory. In Solaymani (2019), the author studied CO_2 emissions coming from the transport sector in Brazil, Canada, China, India, Japan, Russia, and United States during the period between 1990 and 2015. Among other conclusions, they observed that in the case of India the emissions increased rapidly, being India the third largest contributor mainly due to diesel vehicles. In Voigt et al. (2014), 40 different countries, developed and developing ones are analysed during the period between 1995 and 2007. It is observed in the case of India how the improvement in energy intensity is mostly obtained through the technological change.

There are very few publications in which India alone has been studied using the LMDI decomposition technique. In Das and Paul (2014), CO_2 emissions from the household sector in India have been studied during the period between 1993 and 2007, obtaining that activity, structure and population factors are the main contributors to the rise in emissions. In Kanitkar et al. (2019), the impact of the deployment of renewable energies on economic growth, incomes, and income distribution in India is studied for the period between 2003 and 2030. It is shown that, under certain scenarios, these policies affect negatively on household incomes. Paul and Nath Bhattacharya (2004) is devoted to the study of a CO_2 decomposition for India in the period between 1980 and 1996, concluding that economic activity has the most significant effect in the rise of CO_2 emissions, while energy intensity contributes the most to their reduction. Industry and transport sectors present a decreasing trend owing to the improvement of energy intensity and to the shift to less carbon-intensive fuels. In Tiwari and Gulati (2013), the authors carried out a study of the transport sector in India during the period between 2001 and 2007, reaching the reasonable conclusion that changes in the amount of consumed energy are modulated by the growth of transport volume. In Wang and Li (2016), the drivers of energy consumption in China and India are studied using the IPAT (Commoner et al., 1972) and the LMDI methods in the period 1970–2012. In the case of India, it is observed that a 7.39-folds growth of energy use between 1970 and 2012 is the result of the increase in population and the slow increase in income, without a clear improvement in the technology used, which suggests that new policies should be implemented to promote energy-efficient technologies. In Yeo et al. (2015), the authors studied the driving forces of CO_2 emissions in the residential sector of China and India during the period between 1990 and 2011, using a Kaya identity decomposed by type of fuel and an additive LMDI, concluding that the changes of population and energy consumption were the major driving forces that impinge CO_2 emissions. It is worth mentioning a set of very recent works that use the LMDI and decoupling analysis which, despite being focused on China, shows a very relevant analysis to comprehend the connection between CO_2 intensity and economic growth. This analysis can also be of interest for the case of India. In particular, in Ma et al. (2019a), carbon mitigation is studied in the residential building sector. In Ma et al. (2019b), the decoupling between carbon intensity and economic growth in the service industry is analysed. Finally, in Liang et al. (2019), the connection between carbon intensity and the level of income in the residential building sector was explored.

Once we gathered the most up-to-date literature on the analysis of CO_2 emissions for India which use one of the many versions of IDA methods, we noticed that it is still necessary to fill certain gaps in the existing literature. Namely:

1. To extend the analysis to a longer period of time in order to gain insight on the impact of the different drivers over time.
2. To perform a more detailed disaggregation in types of sectors and fuels.
3. To clarify the effect of the size of economic sectors in the amount of CO_2 emissions.
4. To provide a clearer view of the evolution over time of the CO2 driving forces by referring the LMDI values to a single reference year instead of presenting the relative change year by year.

All in all, this study can be of use for shedding light on certain questions:

1. Is energy intensity the key factor in the reduction of CO_2 emissions in India?
2. How can the high energy demand in a developing country like India be modulated in order to moderate the rise in CO2 emissions?
3. Is the increase in CO2 emissions in a steady-growing GDP scenario unavoidable?
4. Are the Indian Government's efforts in incentivising renewable energies enough?
5. How is the CO2 intensity in India evolving?

All these questions will be answered throughout this work.

4. Model and methodology

4.1. Formulation of the model: the enlarged Kaya identity

The model to calculate CO_2 emissions from fossil energy corresponds to a nexus relationship, which is an extension of the original Kaya identity where we disaggregate by type of fuel and economic sector and it is quite similar to the formalism used in Refs. Robalino-López et al. (2014a), (2014b), (2015). According to the Kaya identity, the amount of CO_2 emissions from industry and other energy uses may be studied by quantifying the contributions of six different factors: population, value added per capita, economic structure, energy intensity, energy mix, and CO_2 emission factors. The CO_2 emissions can be written down as,

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

where C is the total CO_2 emission of India in a given year; C_{ij} is the CO_2 emission arising from fuel of type j in the economic sector i (note that the index i runs over 3 sectors, namely, primary, industry and service sector, and the index j over sixteen types of energy sources, namely, coal, petroleum, gas, biofuel-solid, liquid and gas, solar and wind, nuclear, hydroelectric, diesel, gasoline, fuel oil, LPG, naphtha, kerosene and kerosene for aviation; P is the population of India; Q is the total GDP of the country; Q_i is the GDP of sector i; q is the GDP per capita in India; S_i is the share of sector i to the GDP of the country; E_i is the energy consumption in the sector i; E_{ij} is the consumption of fuel j in the sector i; the energy intensity in sector i is given by EI_i ($\frac{E_i}{Q_i}$); the energy matrix is given by M_{ij} ($\frac{E_{ij}}{E_i}$) representing the share of energy use of type j in the sector i; finally, the CO_2 emission factor is given by U_{ij}($\frac{C_{ij}}{E_{ij}}$).[2] The driving forces appearing in Eq. (1) are imposed ad hoc but are well supported in the literature (Yeo et al., 2015; Yang et al., 2020; Wang and Li, 2016).

[2] Throughout this paper, as a convention, we will always refer to the sector with the i index and to the type of energy source with the j index.

4.2. The Logarithmic mean Divisia Index (LMDI)

There is a broad set of decomposition methods based on LMDI (see Section 3), but among them, we will use the LMDI-I because several of its characteristics, namely, it satisfies the factor-reversal test, i.e., there is no residual term in the results, the decomposition formula has a relatively simple form, being the same regardless the number of factors involved in the decomposition, and both versions of the model, the multiplicative and the additive are connected in a straightforward way. The goal of this method is to write down the value of the aggregated quantity in a given year, t, with respect to a reference one as the sum or product of the contributions of the driving forces, which corresponds, in the case of the additive decomposition to,

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

where $\Delta C_{pop}(t)$, $\Delta C_{act}(t)$, $\Delta C_{str}(t)$, $\Delta C_{int}(t)$, $\Delta C_{mix}(t)$, $\Delta C_{emission}(t)$, should be understood as the CO_2 variations due to the change in population, the change in GDP per capita, the change in the economic structure, the change in energy intensity, the change in the energy mix, and the change in the emission factor, respectively. The value of these contributions provided by the LMDI (Ang and Choi, 1997) can be written down as

$$\Delta C_{pop}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)}\ \ln\frac{P(t)}{P(0)}, \tag{3}$$

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

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

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

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

$$\Delta C_{emission}(t) = \sum_{ij} \frac{C_{ij}(t) - C_{ij}(0)}{\ln C_{ij}(t) - \ln C_{ij}(0)}\ \ln\frac{U_{ij}(t)}{U_{ij}(0)}. \tag{8}$$

It is also possible to perform the decomposition in a multiplicative way such that,

$$D(t) = C(t)/C(0) = D_{pop}(t) \cdot D_{act}(t) \cdot D_{str}(t) \cdot D_{int}(t) \cdot D_{mix}(t) \cdot D_{emission}(t), \tag{9}$$

where $D_{pop}(t)$, $D_{act}(t)$, $D_{str}(t)$, $D_{int}(t)$, $D_{mix}(t)$, $D_{emission}(t)$, should be understood as the CO_2 relative variations due to the change in population, the change in GDP per capita, the change in the economic structure, the change in the energy intensity, the change in the energy mix, and the change in the emission factor, respectively. The value of these contributions provided by the LMDI (Ang and Choi, 1997) are:

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

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

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

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

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

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

Note that all the quantities correspond to an aggregated magnitude over all sectors and types of energy, but they can also be defined for a given sector or a given type of energy. To do so, it is only needed to limit the sum inside previous equations to the appropriated range. Moreover, latter expressions present an explicit dependence on time, which will allow studying the time evolution of all driving forces.

4.3. Sources of data

The data considered along this work has been obtained from the official databases of the World Bank (WB, 2019b), the IPCC (IPCC, 2006), the International Energy Agency (IEA, 2019), the United States Environmental Protection Agency (US EPA, 2019), and the International Agency for Atomic Energy (IAAE, 2019). CO_2 emissions are given in $kgCO_2$, tCO_2 or $MtCO_2$, GDP is given in 2010 constant international dollars and we will refer to as USD, energy in kg of oil equivalent (koe) or tonne of oil equivalent (toe). The emission factors are provided in $kgCO_2$/koe as shown in Table 2. These factors are calculated by dividing the amount of CO_2 emitted by the amount fuel used and they are assumed to be representative values of long-term averages. Note that the carbon-free-emission energy sources are the solid biofuel, solar and wind, the nuclear and the hydroelectric energy. Throughout this work, when referring to *renewable energy*, we will group under the same name all energy sources with a null emission factor, namely, to the latter four energy sources.

Table 2
Emission factor per type of fuel, given in $kgCO_2$/koe.
Source: US EPA (2019).

Fuel	Emission factor ($kgCO_2$/koe)
Coal	4.511
Petroleum	2.978
Natural gas	2.106
Biofuel (gas)	2.066
Biofuel (solid)	0
Biofuel (liquid)	2.930
Solar and wind	0
Nuclear	0
Hydroelectric	0
Diesel	2.973
Gasoline	2.789
Fuel oil	2.935
LPG	2.449
Naphtha	2.871
Kerosene	2.984
Jet kerosene	2.866

5. Empirical results and discussion

5.1. Energy and renewable energy consumption

The demand of energy in India has rapidly increased during the studied period, as can be seen in the right scale of Fig. 3. Due to its large impact on the reduction of CO_2 emissions, it is worthy to study in detail the contribution of renewable energies to the energy mix. Note that along this section when referring to renewable energies, we mean CO_2 free emissions energy sources, namely, solid biofuel, nuclear energy, hydroelectric energy, solar and wind energy.

There is a paradoxical effect regarding the participation of renewable energy in India's energy mix, namely, its participation has been steadily dropping during the whole studied period in all the different economic sectors (see left scale of Fig. 3), especially in the service sector, in spite, of the global increase of its use. The reason is the large increase of the energy used during the period under study that has been multiplied by a factor 2.5 (see the right scale of Fig. 3) and that, therefore, it has been reached thanks to the use of fossil energy sources.

Indeed, in Fig. 4 the evolution of the total amount of renewable energy is depicted. In panel A, all the energies are included, while, in panel B, the much larger component, namely biofuel, has been removed to enhance the contribution of the rest of sources. One can notice how the use of renewable energy has largely increased during the whole period. The use of biofuel, especially wood, for cooking and heating has increased by 25% (see panel A of Fig. 4). The use of nuclear energy has also increased by a factor five due to the construction of new nuclear power plants, although its contribution is still below 1.5% of the total energy consumption of the country. As a matter of fact, the production of electricity from nuclear plants increased from 26.4 GW·h in 2011 to 31.5 GW·h in 2012 (IAAE, 2019) with a total number of 21 operating reactors and an installed capacity of 6680 MW. Note the sudden increase of the amount of nuclear energy in 2007 due to the operation of two new reactors in the Tarapur plant with a total power of 1.08 GW. It is worth mentioning that 11 additional reactors are under construction in order to generate an extra 8100 MW of power. The use of hydroelectric energy has been more than doubled in the period under study, with a continuous rate of construction of new infrastructures during the studied period. The use of solar and wind energy was essentially negligible at the beginning of the period, but it has largely increased in the last years at a yearly rate of 15%. In summary, the use of renewable energies has been largely promoted in India in the last 25 years, but still its contribution is not enough to compensate the large increase of energy consumption that has been covered so far mainly with fossil sources.

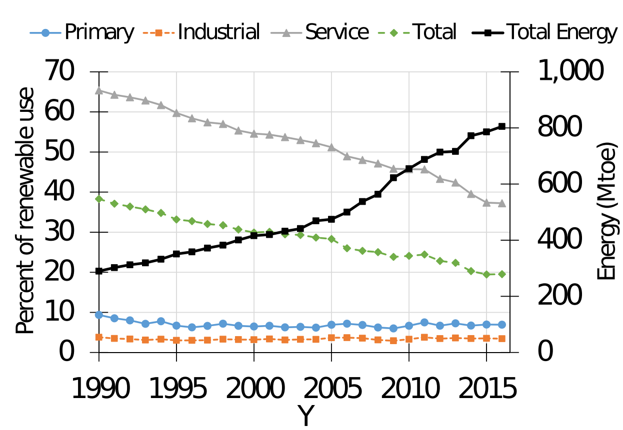

Fig. 3. Fraction of renewable energy use per sector (left scale) and total energy and renewable energy consumption (right scale).

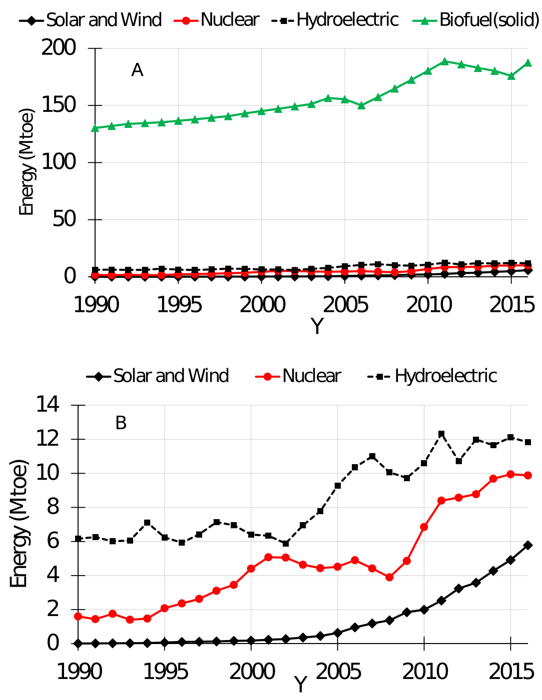

Fig. 4. Evolution of the amount of renewable energy used during the period under study. Top panel includes all energies while bottom one does not include biofuels.

5.2. CO_2 emissions by type of fuel and sector

One of the novelties of this work is that it deals with sixteen different energy sources that present very different emission factors, and three different economic sectors. In Fig. 5, the CO_2 emissions separated by sector in the period under study are depicted. Note that the value of the emissions has been calculated using Eq. (1) adding up over the sixteen different types of fuels for every given sector. The increase of the emissions during the studied period is a common factor regardless the sector. However, the major increase happens in the industry sector, followed by the service sector. The primary sector shows a much more constant tendency over the whole period, although its emissions at the end of the period are roughly double than at the beginning. According to the Kaya equation, this behaviour can be partially understood by considering GDP growth, by a factor of 5, and the evolution of the relative size of the three economic sectors, as shown in Fig. 1. On the other hand, the size of the primary sector has been reduced, going from 28% to 15%. The industry sector has remained stable during the whole period with a share of roughly 28%, and the service sector has passed from 44% to 55%. In spite of the general growing tendency, the emissions in the primary and the industry sectors have shown a clear stabilization during the last three years.

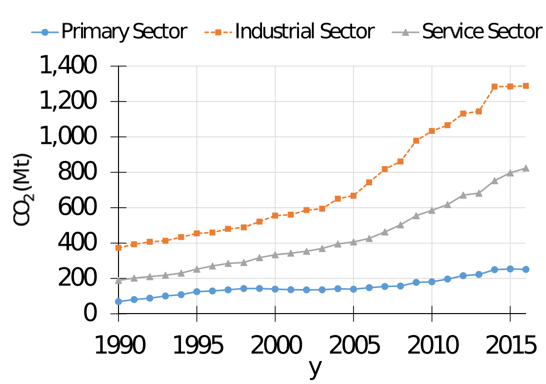

Fig. 5. India's CO_2 emissions separated by economic sector during the period 1990–2016.

To understand in depth the evolution of CO_2 emission it is worthy to study the contribution of the different fuels per economic sector. Hence, in Fig. 6, we present, in a disaggregated way, the CO_2 emissions per type of fuel and sector. In the upper panels (A and D), the results for the primary sector are depicted, panel A including all type of fuels and panel D taking out the coal, to appreciate better the evolution of the rest of fuels whose contributions are much smaller. One can see how coal and diesel, and, to a lesser extent, oil and natural gas are the main contributors to the emission of this sector, with an increasing contribution of biogas during the last decade. Coal is used for the production of electricity, while diesel to power vehicles in agricultural tasks. Note the clear reduction of emissions coming from coal in the last three years, which is most probably the reason for the stabilization of emissions of the sector during the same period (see Fig. 5).

In panels B and E of Fig. 6, the emissions for the industry sector are depicted. This sector presents by far the largest emissions, as shown in Fig. 5, which is a consequence of its large size and also of its large emission intensity. In Fig. 6 one can appreciate how coal is also by far the main contributor to CO_2 emissions from industry, followed by oil, biogas and natural gas, but in a rather minor proportion. Note that the rest of fuels present a much smaller and almost constant contribution. Note that the use of coal is mainly indirect, through the production of electricity. The trend of CO_2 emissions coming from coal remained rather stable until the mid 2010's, with a modest steady increase, but since then, the emissions increased at a large rate, until 2015, where a certain decrease and later stabilization was observed. This is also clearly reflected in the total emissions of the sector in Fig. 5. One can conclude that the emissions in this sector are largely driven by the use of coal and, as a consequence, it represents a key target for future CO_2 reduction policies.

Finally, in panels C and F of Fig. 6, the emissions coming from the different fuels used in the service sector are presented. Here, to a large extent, coal, diesel, gasoline, and LPG are the four main contributors to the emissions of the sector. The rest of fuels contribute much less to its CO_2 emissions, with a noticeable decreasing contribution from kerosene. Here, coal in mainly used for production of electricity, while diesel, LPG, gasoline and kerosene for transportation. Note that in this sector the emissions from coal did not drop in the last years of the studied period, although they show a certain deceleration.

5.3. CO_2 LMDI decomposition

The main goal of this work is to calculate how the different components of the Kaya identity contribute to the CO_2 emissions of India. According to the Kaya identity (1), there are 5 drivers, namely, population (pop), economic activity (act), economic structure (str), energy intensity (int), and energy mix (mix). Note that the emission factor has not been taken into account because it has been assumed as constant for the whole period. This decomposition analysis will allow determining how big the impact of the different driving forces of the CO_2 emissions is.

First, in Fig. 7, the performance of the different driving forces for the whole period is presented, in its additive form (chart A) and in its multiplicative one (chart B). The main conclusion is that economic activity, i.e., the increase of GDP per capita, generated the largest surplus of CO_2 emissions, accounting for 1611 $MtCO_2$ (241%), followed by population with 543 $MtCO_2$ (51%), and energy mix with 320 $MtCO_2$ (28%). The only drivers that mitigate CO_2 emissions are the energy intensity term with −730 $MtCO_2$ (−47%), and in an almost negligible extent, the economic structure term with −17 $MtCO_2$ (−1.3%). All in all leads to an increase in emissions during the whole period of 1727 $MtCO_2$ (276%). In short, at least globally, it is fair to say that the energy intensity term manages to compensate the effect of population and energy-mix contributions, while the increase in CO_2 emissions comes from the activity

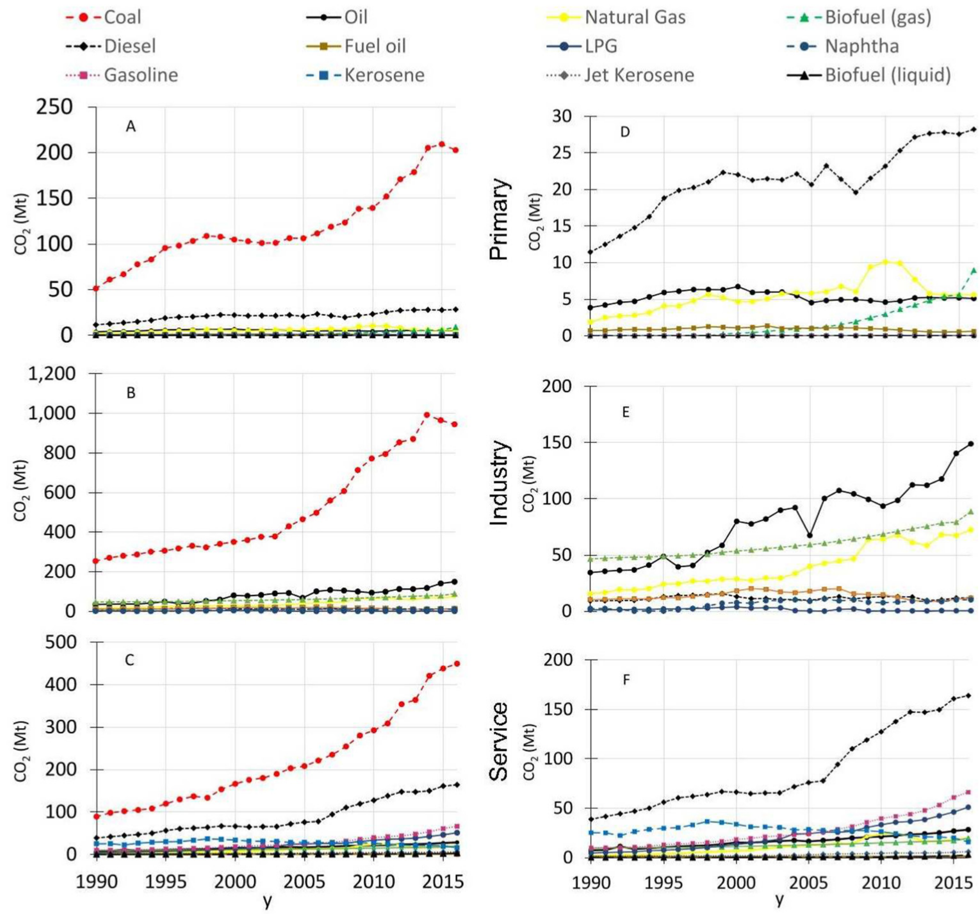

Fig. 6. India's CO_2 emissions in the primary (panels A and D), industry (panels D and E) and service (panels C and F) sectors separated by type of fuel during the period 1990–2016. Panels A, B and C include all energy sources, while in panels D, E and F, coal is excluded.

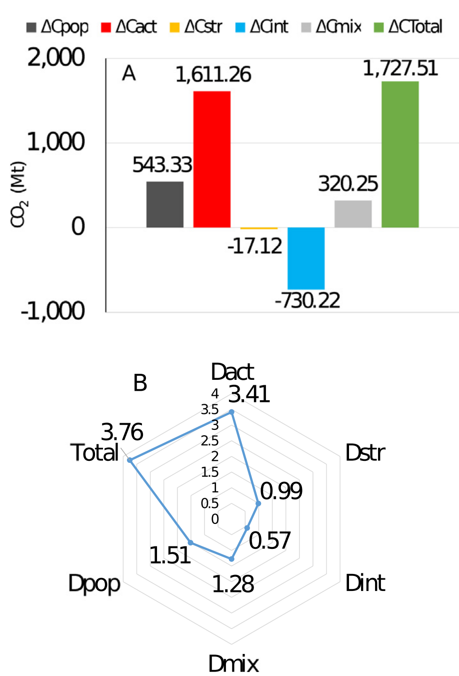

Fig. 7. India's LMDI decomposition for the whole period, 1990–2016, additive in panel A and multiplicative in panel B.

term, being the effect of economic structure term negligible. In particular, in Refs. Paul and Nath Bhattacharya (2004) and Yeo et al. (2015) the authors also concluded that the main contributors to CO_2 emissions for India were the activity and the population term and the increase in the consumption of energy, while in Ref. Kangyin et al. (2019) it was proven that the reduction of energy intensity is the most effective factor to mitigate the increase of CO_2 emissions.

To obtain a more accurate view of the CO_2 emission problem, it is worth to show the evolution of the LMDI decomposition as a function of time. This is presented in Fig. 8, where in panel A it is depicted the additive, while in panel B, the multiplicative LMDI decomposition. The results of both charts are connected but the information they provide is complementary. The first fact one can easily appreciate in both charts is that all the drivers, except the activity term, present quite a homogeneous tendency during the whole period, with a steady increase in population and energy-mix terms, an almost constant value of the structure term and a continuous drop in the energy intensity term with a certain acceleration at the middle of the 2000's and a deceleration at the beginning of the 2010's. However, the activity term presents two clear periods. The first one, until the mid 2000's, which presents a moderate rise in emissions, and the second one, from the mid 2000's onwards, which has a much larger increase in emissions. As already mentioned for the global analysis, the activity term closely follows the total emissions, which implies that at any moment the rest of components are almost compensated among themselves. It is worth to mention the increasing contribution of the energy-mix term, which suggests that the energy mix in India has diminished the contribution of carbon-free energy sources during the studied period, as was already shown in the previous section. However, one can notice a deceleration of the

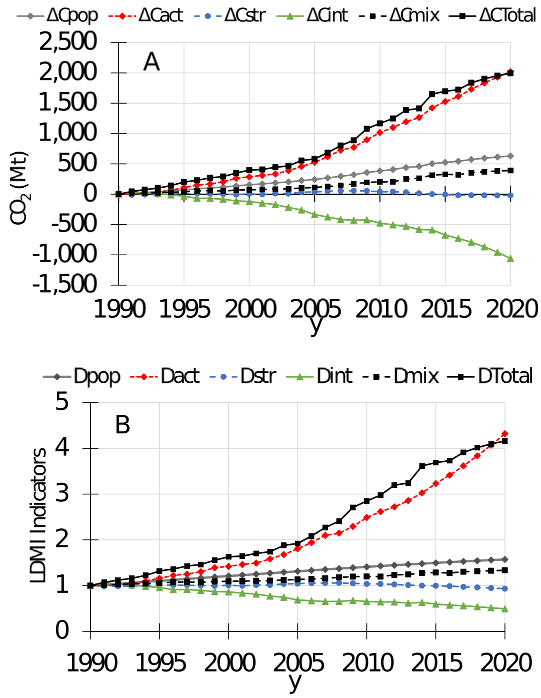

Fig. 8. Evolution of the additive (panel A) and multiplicative (panel B) LMDI for India during the period 1990–2016 and 2017–2020 (extrapolated values).

energy-mix contribution in the last two years which is motivated by the large increase in renewable energy use.

In Fig. 8, the projection of the LMDI results until 2020 has also been performed. To such an end, a baseline scenario has been assumed for the five components of the LMDI analysis, assuming that the rate of variation for the forthcoming years corresponds to a kind of average of the last few years. Hence, the partial values for the five components are combined to obtain the full variation, either in both the additive and the multiplicative forms. The projection has been carried out as described in Robalino-López et al. (2015),

$$y_t = y_{t-1}(1+r), \tag{16}$$

where y_t and y_{t-1} stand for the studied quantity in time t and $t-1$, respectively, and r for the rate of change. According to the extrapolated values, the activity component continues being the largest contribution, even surpassing the value of the total emissions in 2020, which supposes that the effect of the rapid economic growth cannot be compensated by the effect of the rest of the components. The effect of the increase in population is still moderated, the contribution of the economic structure term is almost negligible, the energy-mix effect continues being positive with an upward sloping trend and the energy intensity term continues with a clear downward sloping trend.

The results presented in Fig. 8 are based on a very well established procedure (Ang, 2005). However, it is important to evaluate how reliable these results are. Therefore, a comparison with a different method of decomposition is in order. Hence, we will conduct an alternative LMDI calculation, using the LMDI-II (see (Ang, 2015) for further details), that will be compared with the LMDI-I results, obtained through the calculation of its mean absolute percentage error (MAPE):

$$MAPE_{\Delta C_m} = \frac{1}{n}\sum_{t_i}\left|\frac{\Delta C_m(LMDI_I, t_i) - \Delta C_m(LMDI_{II}, t_i)}{\Delta C_m(LMDI_I, t_i)}\right| \times 100, \tag{17}$$

where m stands for “pop”, “act”, “str”, “int”, and “mix” (see Eqs. (3)–(7), n is the number of years and t_i runs over the analysed years. The obtained values for the MAPE are $MAPE_{\Delta C_m} = 0.61\%$. Due to the small magnitude of these values, it is safe to say that the presented results are reliable enough.

In view of the importance of the activity and the intensity components it is worth to disaggregate them in sectors. In panels A and B of Fig. 9, the additive LMDI for the activity and the energy intensity components, respectively, for the three sectors are depicted. One can notice how the primary sector has an increase in contribution, though small, during the whole studied period for both components. Its energy intensity contribution is also slightly positive, but when comparing with the other two sectors, one notices that there is a lot of room for improvement in the primary sector. Concerning the industry sector, its activity contribution raises rapidly during the whole period, presenting a noticeable acceleration from 2005 onwards. However, its energy intensity term started increasing, then dropping and stabilizing and finally, dropping smoothly. Regarding the service sector, once more, its activity contribution also steadily increases, although slower than that of the industry sector. Its energy intensity contribution shows a steady decrease at the beginning, similarly to the industry sector, but from the year 2000 onwards, the drop becomes much more rapid.

As a conclusion of this subsection, one can say that the major contributor to the raising of the emissions is the activity term of the industry sector, while the main reduction of CO_2 emissions comes from the energy-intensity term of the industry and, especially, of the service sector, which is similar to the conclusion reached in Henriques and Kander (2010). It is also noticeable that the contribution of the energy-mix term is positive, i.e., it contributes to the increase in emissions, while it would be expected to have a negative contribution as it happens in developed countries. In other words, the effect of the use of renewable energies is still small. To the best of our knowledge these conclusions have been never reached in the available literature. The vast increase in total power generation capacity from renewable sources has not been sufficient to offset emissions from non-renewable energy for two reasons:

- The total energy consumption has grown much faster than the use of renewable energy. This huge growth in energy consumption is a consequence of the economic and demographic growth of India, added to the growing urbanization and industrialization of the country, which has exponentially increased the demand for municipal services, such as energy, housing, transportation, water and waste treatment.
- The newly installed renewable power does not guarantee the

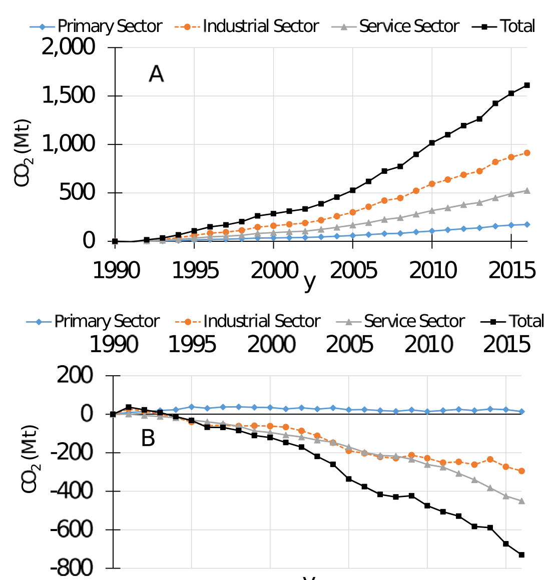

Fig. 9. Activity (panel A) and energy intensity (panel B) components of the additive LMDI for India during the period 1990–2016.

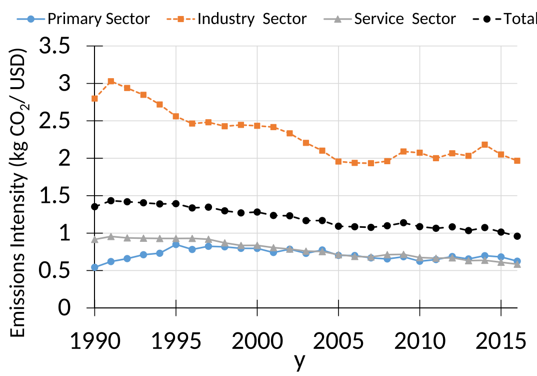

Fig. 10. Emission intensity for India, disaggregated in sectors, during the period 1990–2016.

continuous operation of these facilities. The critical issue is not the power generation capacity, but the real generation, that is, the hours of operation of renewable generation facilities, which are few compared to the hours of fossil fuel power plants (Andrew, 2018). For instance, in 2017, the load factor of renewable energy-based power plants in India was, on average, about 30%, compared with the one coal-based power plants, 60%.

As a consequence, it would have been more efficient to formulate Indian's NDC energy goal in terms of "final energy consumption" and not in terms of "installed electric power capacity".

5.4. Emission intensity

Emission intensity is a very useful concept in order to characterise the relative performance of an economy with respect to CO_2 emissions, regardless of the size of the economy and the growth rate. As a matter of fact, India has set up a voluntary goal reduction of its emission intensity of 20 − 25% in 2020 with respect to the value in 2005 (UNFCCC, 2019b). In Fig. 10, the evolution of emission intensity and, moreover, the separate value for the three economic sectors are depicted. First thing that is clearly shown is the continuous reduction in emission intensity over the whole period, which is compatible with the goal in reduction of 20 − 25% in 2020 with respect to the value in 2005. Indeed, according to the figure, the goal will be most probably surpassed. According to the extrapolation presented in the previous section, emission intensity in 2020 will be roughly 0.81 $kgCO_2$/USD, while in 2005, it had a value of 1.09 $kgCO_2$/USD, which supposes a reduction of 26%, in agreement with the voluntary target fixed by the government.

The three economic sectors present a common steady decrease, although the primary sector showed a certain increase at the beginning of the period. The industry sector is characterised by a value that is roughly 2.5 that of the primary and service sectors. Therefore, once more, it is proved that the industry sector is the major contributor to the value of emission intensity, owing to its relative size and large use of coal as an energy source.

The evolution of emission intensity in India shows that the country is doing intense efforts to reduce CO_2 emissions through the implementation of new technologies which use energy more efficiently and through the use of more renewable energy sources. However, there is still a lot of room for improvement and, as matter of fact, the emission intensity of India is still four times that of Europe.

6. Summary, conclusions and policy implications

In this work, the time evolution of CO_2 emissions separated by economic sector (3 sectors) and type of fuel (16 types of fuel) have been calculated through the use of the Kaya identity. The emissions in the industry sector are the largest ones, followed by the service and, in a rather minor proportion, by the primary sector. Concerning fuels, coal is by far the major contributor to CO_2 emission in the three sectors, presenting a steady increase during the whole period, with the exception of the last three years, for which a modest reduction was observed (except in the service sector).

Moreover, the analysis of the impact of renewable energies on the energy mix of India leads to a striking result, namely, the share of renewable in the energy mix of the three sectors has constantly decreased, passing from a 40% at the beginning of the 1990's to a 20% in 2016. However, great efforts have been taken to promote the use of renewable energies, greatly increasing the amount of renewable energy used. The obvious reason is the large increase in total energy consumption, which has grown much faster than the use of renewable energy.

The key results of this work come from the LMDI analysis (Section 5.3). The first outcome is that CO_2 emission grew tremendously during the studied period, 1727 $MtCO_2$ (276%). The main reason of this large growth was the rapid economic development, which reflects the increase of the GDP per capita and that supposes an increase of 1611 $MtCO_2$ (241%). As a matter of fact, the time evolution of the CO_2 emissions always presents an upward sloping trend with an acceleration of growth since the mid 2000's onwards. The second driver with a positive contribution is the population term, which accounts for 543 $MtCO_2$ (51%) but is much smaller than the activity term contribution. Therefore, population is not the main source of increase of CO_2 emissions as one might naively think. The third driver with positive contribution is the energy-mix term, which accounts for 320 $MtCO_2$ (28%). Although this contribution seems to be small, in the majority of the developed countries it is negative, and therefore helps for the reduction of CO_2 emissions as a consequence of the impact of renewable energies in the energy mix. In the case of India, this impact is still small and, indeed, the share of renewables in the energy mix has continuously dropped during the studied period. Finally, the two drivers with a negative contribution are the energy intensity term, which has been rapidly dropping during the whole period, even with a certain acceleration during the last decade, and the economic structure term, although with an almost negligible contribution.

In summary, the main factor contributing to the growth in emissions is the activity term, in particular, in the industry sector. The main factor contributing to the reduction in emissions is the energy intensity term, in particular, in the service sector and to a lesser extend in the industry sector.

India is now the third largest CO_2 emitter in the world, and could become in the future the largest one, even surpassing China and USA. This situation will happen in spite of the big efforts of the country to mitigate the emissions because it is one of the economies that is growing faster in the world and needs a large supply of energy to maintain its annual economic growth rates above 7%. Taking into account that the increase in GDP per capita seems to be a positive aspect in itself in spite of the increase of CO_2 emissions, it is needed to promote those factors that can compensate the natural increase in emissions due to the increase in wealth. To such an end, the first recommendation is to implement policies that discourage the use of coal, e.g., through an appropriate tax policy to induce a negative contribution from the energy-mix term. So far, the large increase in the use of renewable energy was unable to compensate the growth in total energy consumption. Therefore, it is compulsory to cover the new energy needs with renewable energy (including nuclear power) or, at least, natural gas (which has a much smaller emission factor than coal) to get a real reduction in CO_2 emissions. A second recommendation concerns energy intensity, which is tightly linked to the technology used to transform the primary energy in the different sectors. According to our findings, energy intensity has had a very appropriated behaviour during the studied period contributing negatively to the CO_2 emissions. It seems that this trend is quite natural in the Indian economic system, especially in the industry and service sectors but not in the primary one (see Fig. 9). Therefore, it is worthy to promote a technological transformation in the primary sector that could effectively contribute to a faster reduction of the energy intensity contribution. In summary, as suggested in Wang and Li (2016), the promotion of energy-efficient technologies is highly desirable. The last recommendation, but not least, is to moderate the growth of the population because although its effect is not as big as the activity term, its contribution accounts for more than 30% of the total increase during the period 1990–2016.

India is in a privileged position to fulfil its NDC regardless of its economic growth because some of its goals are defined relative to the value of the GDP. A good example is the target value of the emission intensity for 2020 which was established as a reduction of 20 − 25% with respect to the value of 2005. The estimated reduction for 2020, calculated in this work, is roughly 26%, in line with the goal of the government. Moreover, the Indian NDC establishes for 2030 a reduction in emission intensity of 30 − 35% with respect to 2005, which most likely could be fulfilled. However, none of the NDC's goals are connected neither with the evolution of the GDP nor they do refer to any specific reduction in emissions. This decoupling of the climatic goals from the GDP makes almost unfeasible to get a real reduction of CO_2 emissions neither at least a moderation of the growth.

It is time to answer the questions posed in Section 3, namely:

1. Is energy intensity the key factor in the reduction of CO_2 emissions in India? The answer is obviously yes because, during the whole studied period, the energy intensity factor has caused a sharp decrease in emissions, especially in the industrial and service sectors, but not in the primary sector, which could be the target for future mitigation policies.
2. How can the energy demand in a developing country like India be modulated in order to moderate the rise in CO_2 emissions? The answer to this question is noteworthy. In order to continue promoting the use of renewable energy and to avoid the use of high-carbon fuels, the latter should be gradually replaced by natural gas, which contains a much lower emission factor.
3. Is the increase in CO_2 emissions in a steady-growing GDP scenario unavoidable? Yes, unless there are drastic changes in the mitigation policies.
4. Are the Indian Government's efforts in incentivising renewable energies enough? As it was shown in Section 5.2, the critical point is the replacement of coal as the main source of primary energy by gas, combined with the strong current incentive of renewable energies.
5. How is the CO_2 intensity in India evolving? It is evolving very well, meeting the goals established in its NDC UNFCCC (2019b). However, for faster progress in the right direction, it would have been more efficient to formulate the commitments in its NDC in terms of net emissions reduction, as it has been done by, for example, the European Union. Nevertheless, India has formulated its goals in terms of emissions intensity (emissions/GDP) and total power generation capacity, but as has been explained previously, this does not guarantee a decrease in emissions because renewable energy power plants may be not functioning most of the time (for example, due to a lack of wind), as is occurring.

It is of major importance that the international community supports India's efforts to combat Climate Change in two major aspects. On the one hand, financing projects to mitigate CO_2 emissions that in most of the cases will provide more significant revenues than if invested in developed countries and, on the other, transferring the state-of-the-art technology concerning the production of carbon-free energy. If the group of developed countries does not seriously consider these two aspects, the NDCs of developing ones, such as India, will become a wet paper and the goal of keeping global temperature below 2°C will become just a dream, if not a nightmare.

CRediT authorship contribution statement

G. Ortega-Ruiz: Investigation, Data curation, Formal analysis, Visualization, Software, Writing - review & editing. **A. Mena-Nieto:** Conceptualization, Methodology, Formal analysis, Resources, Supervision, Validation, Writing - review & editing, Writing - original draft. **J.E. García-Ramos:** Conceptualization, Methodology, Supervision, Validation, Formal analysis, Writing - original draft, Resources, Writing - review & editing, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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.

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