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Climate change in a changing world: Socio-economic and technological transitions, regulatory frameworks and trends on global greenhouse gas emissions from EDGAR v.5.0

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ABSTRACT

Over the last three decades, socio-economic, demographic and technological transitions have been witnessed throughout the world, modifying both sectorial and geographical distributions of greenhouse gas (GHG) emissions. Understanding these trends is central to the design of current and future climate change mitigation policies, requiring up-to-date methodologically robust emission inventories such as the Emissions Database for Global Atmospheric Research (EDGAR), the European Commission's in-house, independent global emission inventory. EDGAR is a key tool to track the evolution of GHG emissions and contributes to quantifying the global carbon budget, providing independent and systematically calculated emissions for all countries.

According to the results of the EDGAR v.5.0 release, total anthropogenic global greenhouse gas emissions (excluding land use, land use change and forestry) were estimated at 49.1 Gt CO_{2eq} in 2015, 50 % higher than in 1990, despite a monotonic decrease in GHG emissions per unit of economic output. Between 1990 and 2015, emissions from developed countries fell by 9%, while emissions from low to medium income countries increased by 130%, predominantly from 2000 onwards. The 27 Member States of the European Union and the United Kingdom led the pathway for emission reductions in industrialised economies whilst, in developing countries, the rise in emissions was driven by higher emissions in China, India, Brazil and nations in the South-East Asian region. This diversity of patterns shows how different patterns for GHG emissions are and the need for identifying regionally tailored emission reduction measures.

1. Introduction

Following the increasingly wide consensus in the scientific community that greenhouse gases (GHG) are a significant driver of climate change (IPCC, 2013) and pressed by a growing public awareness of the related impacts, different international negotiations have taken place over the last two and half decades to limit GHG emissions. The initial efforts in the fight against climate change have focused on reducing GHG emissions from industrialised nations – also named developed economies and high income countries along this manuscript – which eventually became the Annex 1 group of the Kyoto Protocol (UNFCCC, 1997). However, following the entry into force of the Paris Agreement (UNFCCC, 2015), over 180 countries have agreed to make nationally determined contributions to the goal of keeping global temperature increase well below 2 °C and pursuing actions to limit the increase to 1.5 °C. The 27 Member States of the European Union (EU27) and the United Kingdom of Great Britain and Northern Ireland (UK) have set legally binding commitments to become carbon neutral economies by 2050, with the European Commission proposing a reduction of 55% in GHG emissions, compared to 1990, to be reached by 2030 (EC

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(European Commission), 2019; EC (European Commission), 2020 and House of Commons, 2019).

Countries have followed a variety of development cycles since 1990. Simultaneously with the implementation of climate change mitigation policies, the EU27 + UK and the United States of America (USA) have seen an expansion in the service sectors of their economies, typically overtaking manufacturing and heavy industries as the main source of national Gross Domestic Product (GDP) (WB, 2020a). By contrast, some small to medium income and medium to high income countries – also referred as developing economies in this manuscript – have gone through unprecedented economic growth, as a consequence of industrialisation., In parallel, they have also experienced a significant population growth (UNDP, 2019). Examples of these countries are China, India, Brazil and other South East Asian nations, namely: Brunei, Indonesia, Cambodia, Laos, Myanmar, Malaysia, Philippines, Singapore, Thailand, Timor Leste and Vietnam.

These socio-economic and demographic transformations were also combined with global-scale technological changes, in part driven by policies designed to contain climate change and air pollution besides market conditions. An important uptake of renewables has taken place around the world. In Europe, this has been accompanied by a continuous fall in the use of coal, an initial expansion in consumption of natural gas (though this peaked in 2010 and is now falling) (Lapillonne and Sudries, 2020) and the deployment of more efficient energy production and consumption technologies. Examples of the latter include: natural gas fired combined cycles for power generation, fuel economy standards for vehicles and more efficient heating and cooling systems within buildings. Other high-income economies have followed a similar pattern, but continue to increase natural gas consumption (BP, 2019). By contrast, developing fast growing and industrialising economies have met their higher energy demand mostly through increased solid fuel usage, while also considerably increasing the use of renewables and natural gas (BP, 2019).

In this rapidly evolving and complex context, global emission inventories play an important role in understanding how economic and technological changes are translated into GHG emission patterns across the world. In the last decade, the European Commission's in-house Emissions Database for Global Atmospheric Research (EDGAR) has become a reference dataset supporting, both policy makers and the scientific community, providing a reliable and consistent benchmark. EDGAR covers systemically and consistently all the reporting categories in the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006), with the exception of Land Use, Land Use change and Forestry (LULUCF), (Janssens-Maenhout et al., 2019). Unlike other available tools, such as the emission inventory developed as part of the Global Carbon Project (GCP, 2019) or the annual release of fossil CO_2 emissions presented by the British Petroleum Statistical reviews (BP, 2019), EDGAR presents emissions for the three main GHG gases (fossil CO_2, CH_4 and N_2O) together with a selection of F-gases. Nevertheless, the EDGAR database does not substitute officially national inventories in terms of verification and compliance of GHG emission reductions: EDGAR assures a full cross-country comparability thanks to its consistent methodology. In addition, EDGAR contributes to the quantification of the global carbon budget by supplying up to date GHG emission data for all countries.

As mentioned, EDGAR time series are updated every year subject to the availability of their data sources. Fossil CO_2 emissions can reach up to calendar year −1 thanks to a Fast Track approach, based on the BP data for combustion based processes and proxy assumptions for by product emissions. Time coverage for other greenhouse gases, from all reporting categories, aim to be up to a couple of years before the calendar year using robust sectorial activity data. The extended time series are accompanied by a booklet summarising the main findings (Crippa et al., 2019) and presenting an overview of the more relevant trends. This paper integrates the cited publication, providing a more detailed analysis of EDGAR results and their implications for climate policy design. It consists of 5 sections, including this Introduction and the Conclusions. Section 2 describes methodological aspects for the estimation of EDGAR emissions whilst GHG emission trends at world scale and in large emitting regions (EU 27 + UK, USA, China, India, other South-East Asian countries and Brazil) are extensively analysed in Section 3. A comparison with other emission data sources is the main subject of Section 4. Moreover, given the peculiar current world situation, because of COVID-19, the paper also includes reflections on some of the sectors affected by the pandemic in Section 5. Furthermore, Section 6 summarises general features in regional and global emission trends, framing the discussion in terms of socio-economic, technological and regulatory transformations observed in the last four decades and in the context of the transition to net zero by mid-century. It is worth underlining that this study focuses on relevant differences, in emission totals and their origins, between countries in different geographical areas and in different developmental stages and not om demonstrating strong correlations between emissions and socio-economic indicators. The latter would imply a more detailed analysis (see e.g. Guan et al., 2008; Mardani et al., 2017; van Vuuren et al., 2007 and references therein). Nonetheless, it is expected that the results of this study may contribute to set the knowledge base for the design of regionally tailored climate change mitigation policies, identifying successful measures and spotting sectors requiring further attention.

2. Methodology

The EDGAR database compiles GHG and air pollutant emissions for all countries and all anthropogenic activities, apart from Land Use, Land Use Change and Forestry (LULUCF). GHG emissions in EDGAR are quantified by using a bottom-up approach, on the basis of independent global sets of activity data. IEA (International Energy Agency) fuel balances (IEA (International Energy Agency), 2017) are considered as data source for fuel consumption. Information for clinker, soda ash, lime, magnesium and aluminum production is obtained from the UNFCCC (United Nation's Framework on Climate Change Convention)'s online "Locator" tool (UNFCCC, 2019) for Former Annex I countries. This is supplemented by national production data for cement production presented in the USGS (United States Geological Survey) Statistical reviews (USGS, 2019). Yearly waste generation rates and data for the widespread of disposal methods are based on the UNFCCC Locator (UNFCCC, 2019), UN (United Nations) statistics (UN, 2019) and reports from the World Bank (Silpa et al., 2018). Figures for livestock populations and cultivated areas rely on the FAO (Food and Agriculture Organization) Statistical reviews (FAOSTAT, 2018) Where information is available and depending on the sector specificity, activity data are further disaggregated according to different technologies and processes. Where available, nationally, regionally or tailored technology based Tier 2 emission factors are implemented in EDGAR, and in their absence, default Tier 1 emission factors from IPCC guidelines (IPCC, 2006) are used. Global Warming Potential for a 100 year time horizon (IPCC, 2019) are considered for expressing emissions in terms of CO_2 equivalent units (See Fig. 1).

A detailed description of the methodology for the quantification of GHG emissions for all IPCC reporting categories in EDGAR was presented in previous works (Janssens-Maenhout et al., 2019) and a brief summary is also available in Supplementary Information (SI), focusing on the categories that were considered key sectors for fossil CO_2, CH_4 and N_2O in the results. It must be noted that the latest EDGAR data included in the last year EDGAR booklet (Crippa et al., 2020) presents fossil CO_2 emissions up to 2019, while emissions for other GHG, mainly CH_4 and N_2O, are quantified up to 2015 in the previous booklet release (Crippa et al., 2019). Reaching such a recent time coverage for fossil CO_2 emissions is possible due to EDGAR "fast-tracked" emission data, obtained by applying incremental/decremental coefficients to the 2015 fossil fuel and sectorial based CO_2 emissions. This approach, is also further explained in SI 1.

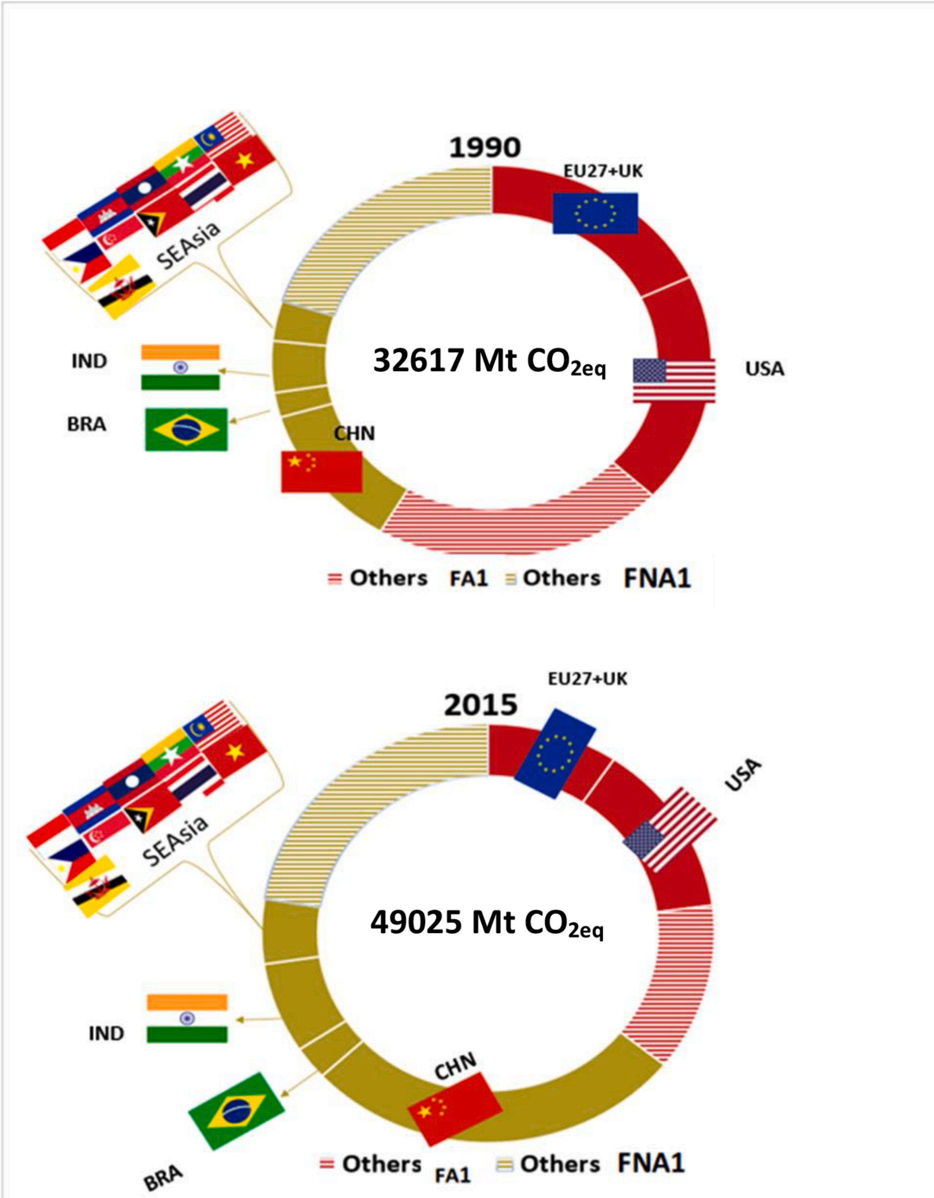

Fig. 1. Total world GHG emissions and contributions for different regions and economic blocs.

Although fossil CO_2 emissions have been computed up to 2019 in Crippa et al. (2020), the present paper mostly discusses the CO_2 data up to 2018 and GHG data up to 2015, both presented in Crippa et al. (2019). This approach assures a full consistency among data sources, mainly activity data, used to estimate both CO_2 and total GHG emissions. Furthermore, the results from a special update for methane emissions from landfills – conducted during 2020 – were included as a way to incorporate the latest recommendations from the IPCC refinements to national GHG emission reporting (IPCC, 2019) for these sectorial emissions. More recent CO_2 emissions will be properly discussed in an upcoming EDGAR release in which emissions of all GHGs will also be updated and aligned with the latest data sources.

3. Results

3.1. World GHG emission trends and patterns

Global GHG emissions, excepting LULUCF but including international aviation and bunkers, reached 49,025 Mt CO_{2eq} in 2015. This constitutes a 50% increase compared with 1990′s values (Table 1), exhibiting a monotonic upward evolution during this period. Such a trend was interrupted in 2008 and 2009, when emissions remained constant and decreased by 1% respectively. This was caused by reduced activity in all economic sectors, following the 2008 financial crisis, as manifested by the data input employed for the emission quantification.

Table 1
Total GHG emissions, in different world regions, in 1990 and 2015.

GHG emissions (Mt CO_{2eq})	1990	2015
World	32,617	49,025
European Union's 27 Member States and the United Kingdom of Great Britain and Northern Ireland (EU27 + UK)	5653	4423
United States of America (USA)	6118	6444
China's People Republic (CHN)	3855	12,842
Brazil (BRA)	684	1265
India (IND)	1335	3292
South East Asia region (SEAsia)	1055	2389

Global GHG emissions also remained constant in 2015, due to a slowdown in China's GHG emissions. However, after 2016, fossil CO_2 global emissions returned to grow in the range of 1–2% per year, indicating that GHG emissions may not have reached their peak yet.

Fossil CO_2 emissions represented 74% of total global GHG emissions in 2015, having increased by 60% between 1990 and 2015. Such an increase is primarily a consequence of a 43% rise in world fuel consumption since 1990 (IEA (International Energy Agency), 2017). This trend was most notable in developing economies undergoing an industrialisation process – such as China, India, other South-East Asian countries and Brazil. This also translated into changes in global GHG emission distributions, as displayed in Fig. 2. In addition to the countries mentioned in Table 1, other key contributor to world GHG emissions in 2015 were: Russia, Japan, Iran, Canada, Mexico, Saudi Arabia, South Korea, Australia, South Africa and Turkey, all of them individually accounting for more than 1% of global totals.

Methane emissions represented 19% of GHG emissions in 2015 at world scale, when considering central values presented in Table 3, having grown by 21% over the same period. N_2O and F-gas emissions accounted by 5% and 2%, respectively. It must be noted though that EDGAR's global CH_4 and N_2O emissions exhibit uncertainties reaching up to 40% and 191%, respectively (Solazzo et al., 2021). These figures

Table 2
Total fossil CO_2 emissions, in different world regions, in 1990, 2015 and 2018.

Fossil CO_2 emissions (Mt CO_{2eq})			
	1990	2015	2018
World	22,637	36,312 [34555–38057]	37,887
European Union's 27 Member States and the United Kingdom of Great Britain and Northern Ireland (EU27 + UK)	4481	3492 [3378–3616-]	3457
United States of America	5064	5225 [5108–5353]	5275
China's People Republic	2398	10,821 [10231–11393]	11,256
Brazil	229	530 [498–561]	500
India	595	2287 [2166–2408]	2621
SEAsia	414	1418 [1343–1492]	1616

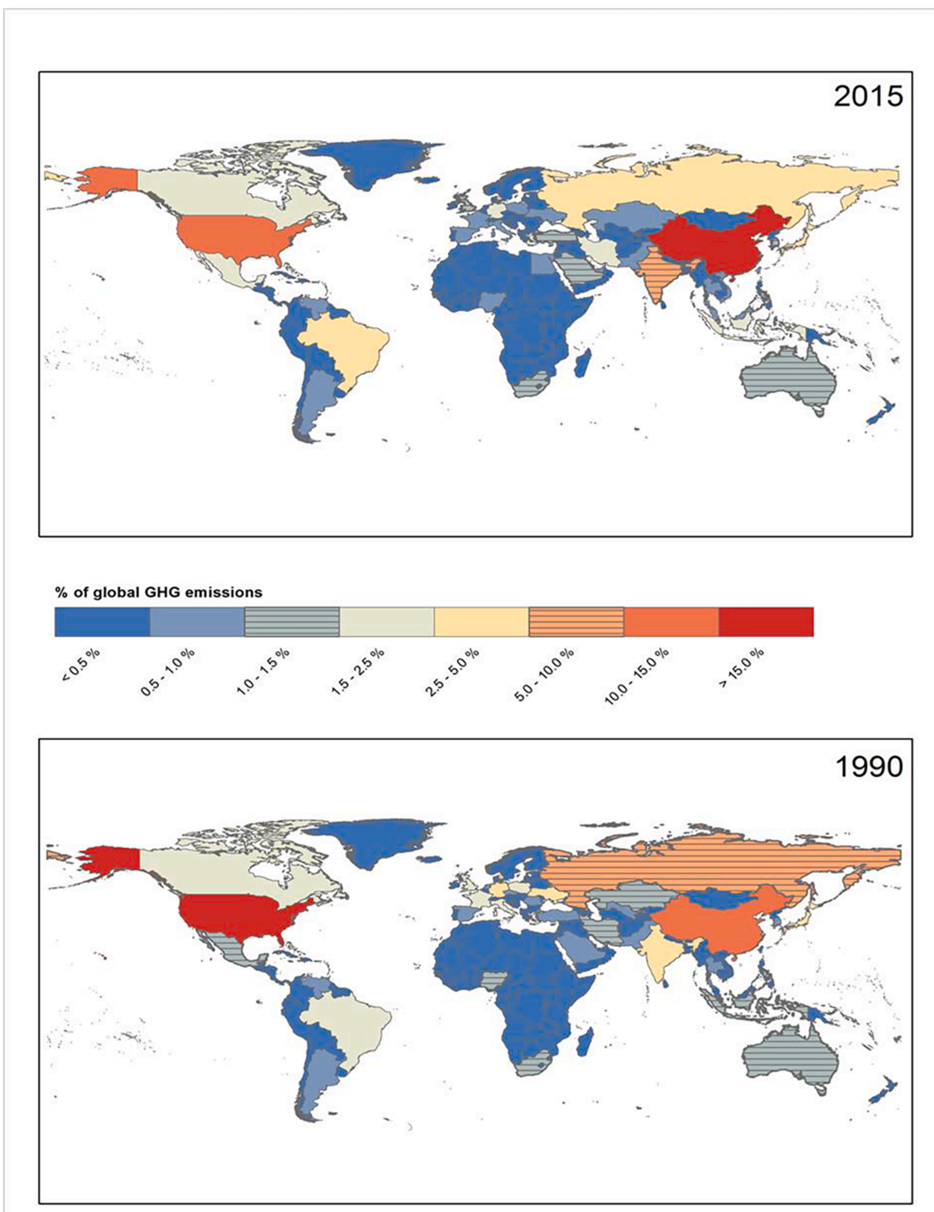

Fig. 2. National contribution to global GHG emissions in 1990 and in 2015.

Table 3
Total CH_4 emissions, in different world regions, in 1990 and 2015.

Total CH_4 emissions (Mt CO_{2eq})		
	1990	2015
World	7561	9145 [6599–12810]
European Union's 27 Member States and the United Kingdom of Great Britain and Northern Ireland (EU27 + UK)	791	533 [442–633]
United States of America	661	632 [513–966]
China's People Republic	1168	1609 [1417–1820]
Brazil	350	553 [421–709]
India	606	779 [583–986]
SEAsia	534	808 [566–1163]

are significantly higher than the uncertainty modelled for fossil CO_2 emissions (5%); thus, larger shares for non-fossil CO_2 in total GHG emissions could be expected if the upper bounds for the intervals in Tables 3 and 4 were considered.

Fig. 3 shows the GHG emissions per capita in 1990 and 2015 for the different regional blocs under study in this work. Different patterns, according to the economic development cycles and the implementation of climate change mitigation and efficiency improvement policies, were observed. The EU27 + UK has seen the largest reductions in emissions per capita since 1990, but still 36 % higher than the global average in 2015. This decrease in emissions per capita has occurred whilst there has been an increase of the average GDP per capita in the bloc (WB, 2020a), evidencing a decoupling of emissions and economic growth. GHG emissions per capita in the USA were 17% lower in 2015, when comparing with 1990 values, however, they are the highest of all the regions considered in this article, being three times higher than the global average and more than twice as large than in the EU27 + UK. Consistently with the evolution of absolute emissions, fossil CO_2 emissions per capita were the largest contributor to GHG emissions per capita. As discussed, fossil CO_2 emissions are largely influenced by fuel consumption trends. Energy consumption per capita tends to increase with GDP per capita, however, the fossil fuel intensity of energy supply has shown to be lower in countries with higher GDP per capita (BP, 2019). This can help for understanding the trends at the global level and in developing economies, where higher emissions per capita have occurred in parallel with higher GDP per capita.

GHG emissions per unit of GDP have seen reductions in all the regions and at the world level (Fig. 4), with the largest decreases taking place in the EU27 + UK bloc. These trends obey a lower energy intensity of the economy and a decrease in fossil fuel intensity of the energy matrix, the latter mostly observed in developed economies which also witnessed a concentration of the service sector replacing industrial activities. Energy intensity, in this work, is defined as the ratio between the total fuel reported – for each country in the IEA Balances – and the GDP at 2010 constant purchasing power (WB, 2020a). It is also worth mentioning that methane emissions per unit of GDP went down in all the regions considered here. This can be explained due to a reduction of the influence of the primary sectors in total GDP (WB, 2020b). Agriculture sources remain the largest contributors to methane emissions, as discussed in Section 3.3.

Table 4
Total N2O emissions in different world regions in 1990 and 2015.

Total N_2O emissions (Mt CO_{2eq})		
	1990	2015
World	2068	2597 [786–9113]
European Union's 27 Member States and the United Kingdom of Great Britain and Northern Ireland (EU27 + UK)	385	278 [177–730]
United States of America	277	294 [183–873]
China's People Republic	283	406 [245–1134]
Brazil	98	176 [18–705]
India	126	201 [27–729]
SEAsia	102	156 [25–539]

3.2. Fossil CO_2 emissions

3.2.1. General overview

Fossil CO_2 emissions reached 37,887 Mt CO_{2eq} in 2018, when estimated using the Fast Track routine in EDGAR v.5.0, and 35,000 Mt CO_{2eq} in 2015 based on the emissions quantified using officially released statistics from different organisations as activity data. This represents increases of 60% and 67% when comparing 2015 and 2018 with 1990 (Table 2).

The main process, by far, that produces CO_2 emissions is combustion which accounted for 84–87% of global fossil CO_2 emissions during the period under analysis (Fig. 5 and Table 2). Besides energy, the main non-combustion sectors with significant shares of global fossil CO_2 emissions in 2018 were: cement industry (5% of world fossil CO_2 emissions), the fuel production and transformation sector (5%) the chemical industry (3%) and steel production (1%).

The EU27 + UK has seen the largest reductions in fossil CO_2 emission, among the countries and blocs considered. This is due to a 43% decrease in its energy intensity, a reduction in fossil CO_2 intensity of the energy supply, close to 16%, which offset the impact of total GDP growth on emissions. It must be noted though that the increase in total GDP (53%, between 2015 and 1990) within the EU27 + UK was the lowest of all the economies analysed in this article. The USA's emissions have kept relatively constant despite a GDP rise close to 98% due to a decrease in energy intensity of its economy (by 40%) and a reduction in the fossil intensity of the energy matrix (close to 7%). China has experimented a significant decrease (61%) of the energy intensity of its economy, while the fossil CO_2 intensity of its energy matrix has seen a rise of 6%. This trend has also been observed, to a lesser extent, in India and other South-East Asian countries and Brazil. Nonetheless, these economies have experienced significantly higher GDP increases, which led to the trends for GHG emissions.

Uncertainty for EDGAR's fossil CO_2 emissions have been modelled in Solazzo et al. (2021). The results of this analysis show that the uncertainty for EDGAR's global fossil CO_2 emissions is close to 4.8%. In the case of the EU27 + UK, figures for the uncertainty associated with EDGAR emissions ranged between 3.3% and 3.6%, based on a 95% confidence interval for a log-normal distribution, whilst the uncertainty for the officially submitted total fossil CO_2 emissions for 2015 was close to 3.6% (EEA (European Environmental Agency), 2017). Modelled uncertainty for EDGAR's total fossil CO_2 emissions, occurred during 2015 in the USA, ranging between 2.2% and 2.4%, while the estimates for officially reported emissions were between 2 and 4% (EPA (United States Environmental Protection Agency), 2017). For non UNFCCC submitting parties considered in this article, the modelled uncertainty for total fossil CO_2 emissions was higher than 5% – with lower and upper bounds laying between 5.2% and 8.8%, depending on the country being analysed. These figures are aligned with the uncertainty quantification presented in some of the consulted National Communications (UNFCCC, 2019).

3.2.2. Analysis of key sectors for fossil CO_2 emissions

3.2.2.1. Energy industries. As seen in Fig. 6, the regions under study exhibit key differences in terms of the fuel basket for power generations and significant changes have taken place in the last three decades.

Electricity production in the EU27 + UK is nowadays highly reliant on renewable sources, nuclear energy and fossil thermal units, for which natural gas is the most used fuel. Coal and liquid fuels have partially

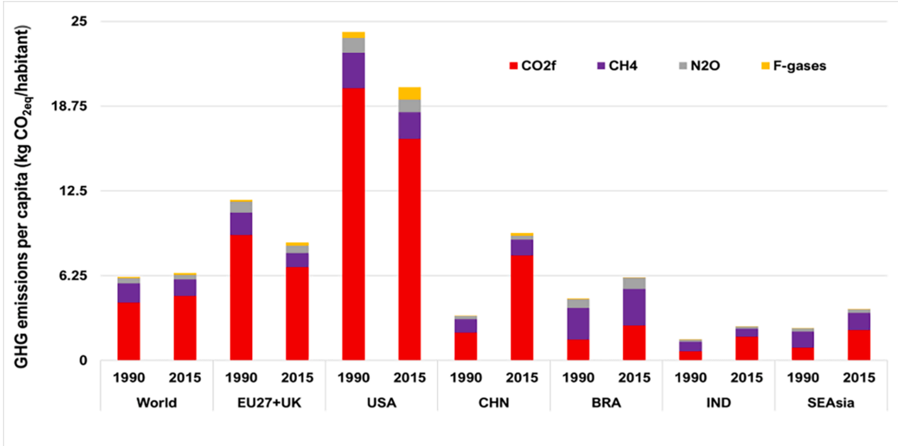

Fig. 3. GHG emissions per capita for the selected countries, economic blocs and at world scale.

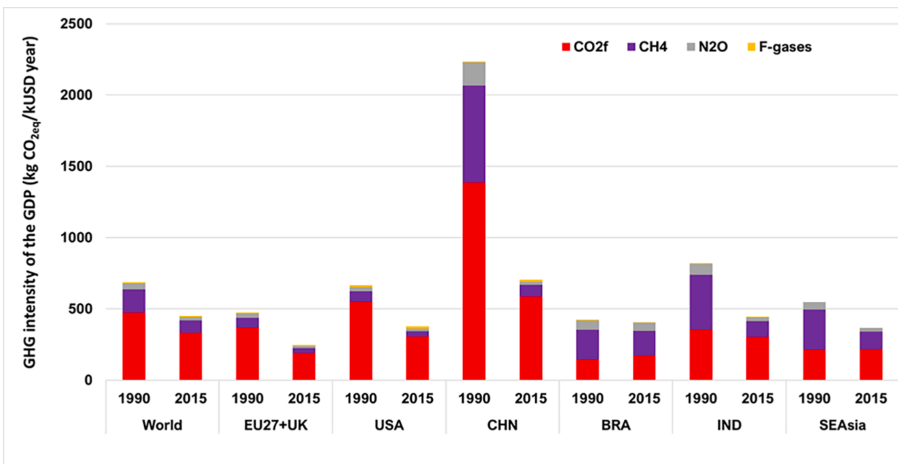

Fig. 4. GHG intensity per unit of GDP for the selected countries, economies blocs and at world scale.

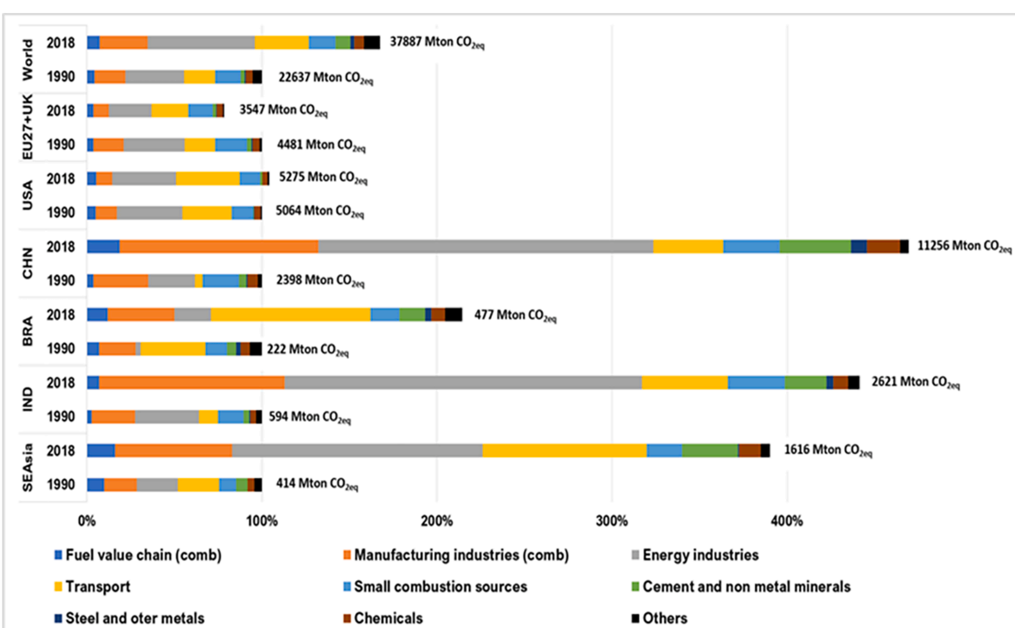

Fig. 5. Sectorial contributions, increases (2018 vs. 1990) and total fossil CO_2 emissions from different countries, economic blocs and at world scale. (1990 = 100%)

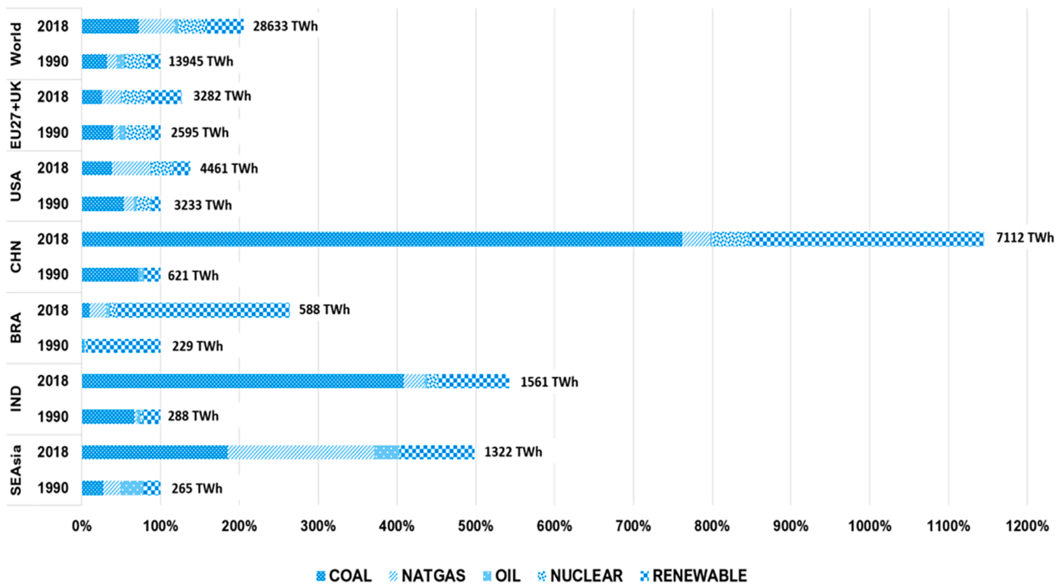

Fig. 6. Shares of power generation by fuel type in 1990 and 2018 for different countries, economic blocs and the world (BP, 2019).

been replaced by lower carbon intense vectors such as solar PV, wind and tide energy as well as natural gas (though EU natural gas consumption has fallen compared to 2010). Despite these transitions, which enabled sectorial reductions of up to 30% between 1990 and 2018, energy industries are still the largest contributors (31%) to fossil CO_2 emissions in the bloc. Fossil CO_2 emissions from energy industries in the USA have, to a lesser extent, seen reductions in the period under analysis (2%) in parallel with a growth of 26 % in power generation. This can also be explained due to coal being substituted primarily by natural gas.

Higher coal consumption for supplying an exponentially rising power demand – especially in China, India and countries in the South-East Asian regions – has caused a significant growth of coal based power production at the global level. Nevertheless, the fraction of electricity generated in China using coal has decreased between 1990 and 2018 despite the massive increase in absolute terms. Coal is still the most employed fuel for power production in China and emissions derived from its combustion accounted for 37% of total national fossil CO_2 emissions. Renewable energy sources are rapidly expanding as high efficiency and low air pollutant emission (HELE) coal based power generation plants with installed CO_2 capture units (IEACCC (IEA – Clean Coal Centre), 2015; S&P, 2018). In the case of Brazil, hydro-power is the main source of electricity; however, in recent years, a rise in natural gas consumption, in the context of the energy industries, has been observed.

3.2.2.2. Industrial sources (combustion and by-product fossil CO_2 emissions). Direct fossil CO_2 emissions from industries in EDGAR include emissions from combustion processes and fossil CO_2 emissions obtained as a by-product of oxidation–reduction reactions for the manufacturing of certain goods (such as cement, iron and chemicals). Both type of emissions have respectively increased by 56% and 141% at the global level between 1990 and 2018. This increase was mainly driven by the rises in direct industrial emissions having taken place in countries like China (337%), India (249%) and other South East Asian countries (287%) and Brazil (89%). Simultaneously, direct emissions from the industrial sector in the EU27 + UK and the USA went down by 28% and 19%, respectively.

While the increase for developing economies can be explained just as a direct consequence of a larger industrial production, the trends for the EU27 + UK and USA are more complex. This is due to changes in the industrial matrix in addition to efficiency improvement, process optimisation and modifications to the fuel basket. In the case of the EU27 + UK, the value added, measured at constant monetary basis, of the industrial sector has gone up by 34% during the last 30 years. However, the contribution of the so-called heavy industries and construction to the total sectorial value added has decreased from 42% in 1990 to 31% in 2018 (WB, 2020a). This mostly obeys reductions in production rates for steel (24%) and cement (31%). Moreover, Energy intensity, especially for steel production, decreased by 55%, while in the case of cement industries kept constant. Carbon intensity of the energy supply, when considering emissions from combustion processes within the facilities, decreased by 9% for steel and 2 % for cement. Specific process CO_2 emissions saw a reduction close to 18 % for the steel industry. This can be attributed to a progressive replacement of blast furnaces by electric arc based steel manufacturing technologies, relying on electricity to melt scrap steel, and allowing a consequent reduction in direct fossil CO_2 emissions.

To a lesser extent, the contribution of the value added from heavy industries and construction in the total industrial income has seen a reduction in the USA – from 46% in the early 90 s to 41% in 2018. Focusing on carbon and energy intense industries, steel production rates went down by 30% between 1990 and 2018 while the amount of cement produced increased by 20% during the same period, despite being still lower than the pre 2008 crisis level. Emission trends for these two key sectors were also influenced by the aforementioned changes in the technology and fuel matrix, particularly for steel manufacturing which fossil CO_2 emissions have seen a larger reduction (46%) than the production rates.

3.2.2.3. Transport. Fossil CO_2 emissions from the domestic transport sector increased by 73% at the world level, with road transport being the main contributor to this category (88%). The increase in emissions is proportional to a larger transport demand (Emisia, 2019; IRF (International Road Federation), 2018; IRF (International Road Federation), 2009) which is related to higher GDP per capita. Focussing on road transport, its demand rise can be explained due to a higher number of circulating vehicles and larger yearly travelled distances. This growth has occurred at a different pace in the blocs considered here. Data from different releases of the yearly IRF (International Road Transport Federation) statistics, show good correlation for sigmoid functions relating to the country GDP per capita and the number of vehicles per 1000 habitants. As a general pattern, data from low-income countries lay on the lower plateau of the curve whilst the values for developed economies are already approaching the upper plateau during mid-90 s. China, India, other countries in the Southern East Asian region and Brazil have moved along the exponential part of the sigmoid curve over the years. This explains the increases in emissions from this category in the aforementioned countries, accounting for respective rises of 779%, 347%, 298% and 146% between 1990 and 2018.

Fossil CO_2 emissions from road transport in the EU27 + UK increased by 24% between 1990 and 2018 and 4% between 2000 and 2018. It must be recalled that this is the only final energy use for which emissions have gone up in the bloc. During the period 2000–2018, transport activity (including passenger and freight travel distance) grew by 27%. However, efficiency also went up by 16%. This is due to the implementation of regulations, focussing on fuel economy; setting procedures to the measure, quantification and labelling of newly produced units on the basis of fuel consumption per travelled distance (EU, 1998; EC (European Commission), 1993; EC (European Commission), 1999a). Carbon intensity of the fuel supply for road transport has also decreased in this period, as a consequence of the incorporation of natural gas, electricity and biogenic originated fuels. In fact, biofuels represented 5% of the road transport energy input by 2015 (IEA (International Energy Agency), 2017). Road transport emissions also saw an ascending trend in the USA despite a slight (2%) increase in the overall efficiency during the last decade.

Significant market penetration by diesel fuelled vehicles has also taken place in the last 28 years in different world regions so that it is now the main fuel, at the world level, for heavy duty and long-distance transport and it is a key energy vector for passenger cars. Globally, emissions from diesel fuelled vehicles accounted for 30% of CO_2 emissions from the road transport in 1990 and 43% in 2018.

In terms of non-road transport, fossil CO_2 emissions from domestic and international aviation accounted for 2% of global CO_2 emissions in 2018. Similarly, fossil CO_2 emissions from maritime transport, including domestic navigation and international shipping also contributed 2% in 2018, having grown by 86% since 1990.

3.2.2.4. Small combustion sources. Global fossil CO_2 emissions from small combustion sources – including the residential, commercial buildings and fuel burning in the agriculture and fisheries sector – grew by 6% between 1990 and 2018, whilst global fuel consumption increased by 10%. This growth in fossil fuel consumption was driven by developing countries –experiencing a concentration of the industrial and service sector –such as China, India and the rest of the industrialising countries in the South East region and Brazil. In these countries, higher income per capita and an increase in the urban population have contributed to larger fossil fuel consumption despite the continuing widespread use of woody biomass and agriculture waste as fuels in rural communities. This has led to significant rises in fossil CO_2 emissions, when comparing 2018′s values with 1990, 127% in India, 115% in Brazil, 105% in South-East Asian countries and 56% in China.

Within the EU 27 + UK, total fuel consumption went down by 9% during this period while fossil fuel consumption decreased by 18%, in particular, coal consumption was reduced by 73% and liquid fuel use was 41% lower. Different policies aimed to lower heat waste in buildings were implemented in this bloc (EC (European Commission), 2002; EU (European Union), 2010; EU (European Union), 2018a). In the USA, residential fuel consumption remained constant in the period under analysis; however, a shift from liquid fuels to natural gas was observed, enabling a slight reduction (2%) in fossil CO_2 emissions for this sector.

3.3. Methane emissions

3.3.1. General overview and regional features

An increase of 21% was reported in global CH_4 emissions between 1990 and 2015 (Table 3), reaching 9145 Mt $CO_{2eq.}$ China was the main CH_4 emitter in 2015, followed by India, USA, the EU27 + UK, the South East Asian countries considered, and Brazil. The world's largest contributing sectors (Fig. 7) to methane emissions were: agriculture– as a consequence of the CH_4 emissions from enteric fermentation, manure management and rice cultivation – followed by the emissions from coal and natural gas supply and by methane emissions originating in the waste sector– including landfills and waste water treatment.

Modelling non-fossil CO_2 GHG gas emissions involves a more challenging activity data collection besides more complex practices for technology disaggregation and quantification of emission factors. This translates into larger uncertainties, as evidenced by the results in Table 3 based on Solazzo et al. (2021). In the case of the EU27 + UK, lower and upper bounds for total EDGAR's methane emissions were close to 18%, whilst the modelled uncertainty for officially reported emissions were around 25% (EEA (European Environmental Agency), 2017). Bounds for uncertainties associated with EDGAR's total methane emissions, during 2015 in the USA, were close to 12%, whilst the range for official data comprised between 9% and 19%. For the developing economies considered here, estimated uncertainty for EDGAR's total methane emissions ranged between 23% and 42%. Such a variance adheres mostly to the difference in sectorial uncertainties and shares in total national or regional emissions. Nonetheless, these values agree with the uncertainties in the consulted National Communications submitted to UNFCCC (UNFCCC, 2021). Sectorial modelled uncertainties for EDGAR's methane emissions are presented in SI.

3.3.2. Emission trends in key sectors

3.3.2.1. Enteric fermentation. Emissions from enteric fermentation contributed to 32% of global CH_4 emissions in 2015 (Fig. 7). For the major beef and milk producing countries, emissions from this sector were the largest or the second largest source of methane and a very influential sector for overall GHG emissions. For example, CH_4 emissions from enteric fermentation accounted for 73% of total CH_4 emissions in Brazil and 32% of national GHG emissions during 2015. Countries exhibiting the largest methane emissions, as a consequence of enteric fermentation and manure management, in 2015 were: Brazil, India, China, USA, Pakistan, Argentina, Australia, Mexico and Ethiopia. Focussing on the EU27 + UK, methane emission from enteric fermentation went down by 20% between 1990 and 2015 – aligned with a decrease in the cattle population– both for milk and beef production, as reported by the statistics for livestock compiled by FAO (FAOSTAT, 2018).

3.3.2.2. Natural gas and coal supply chain. Globally, CH_4 emissions from natural gas value chain increased by 15% between 1990 and 2015, resulting in this sector becoming the second largest source of CH_4 emissions. A notable increase of 69% in CH_4 emissions, from the gas value chain, occurred in the USA with the development of natural gas as an energy vector (BP, 2019; IEA (International Energy Agency), 2017). These emissions also saw an ascending trend in the EU27 + UK but in a lower proportion (22%).

Global CH_4 emissions from coal mining related activities during 2015 were 58 % higher than in 1990. This growth in emissions is the natural consequence of a larger coal consumption in fast growing developing economies in Asia. In particular, methane emissions from coal production in China, during 2015, were 177% higher than in 1990. Following the trends described for the fuel basket in the power and heat production sector, CH_4 emissions from solid fossil fuel supply chain decreased by 81% in the EU27 + UK and by 48% in the USA.

3.3.2.3. Rice cultivation. CH_4 emissions from rice cultivation accounted for 13% of global CH_4 emissions in 2015, a reduction of 6% since 1990. These emissions were, in 2015, mostly located in: China (38% of global CH_4 emissions), India (11%), Indonesia (8%), Bangladesh (7%), Thailand (8%), Vietnam (5%), Myanmar (4%), Philippines (3%),

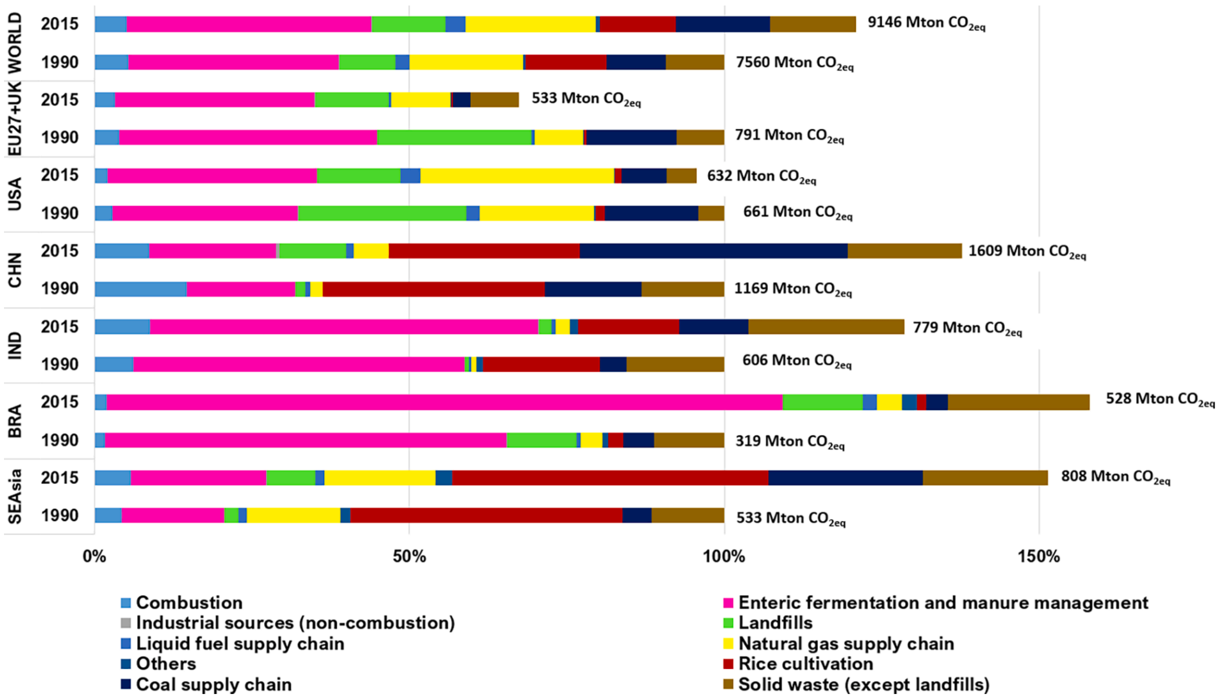

Fig. 7. Sectorial contribution, increases between 1990 and 2018 and total CH_4 emissions from different countries, economic blocs and at world scale.(1990 = 100%)

Pakistan (2 %), Japan (2%), Cambodia (1%) and Nigeria (1%). Overall in these countries, emissions from rice cultivation represented 30% of 1990 total CH_4 emissions, on average, whilst this contribution went down to 22% in 2015.

3.3.2.4. Waste. Emissions from waste treatment plants accounted for 21% of global CH_4 emissions in 2015. These emissions include CH_4 emissions from landfills, waste water treatment processes and waste incineration ("Other waste not landfills" in the plots). Landfills are the largest contributor, within these three subsectors, in the USA and the EU27 + UK, despite that decreases larger than 45% have been observed between 1990 and 2015 in both geographical domains. These reductions are aligned with a lower amount of waste being landfilled (Silpa et al., 2018) – as a consequence of waste reduction and recycling programs and the deployment of waste to energy plants – in combination with the implementation of CH_4 recovery energy units and flaring on site practices. These mitigation actions, at the European scale, were proposed in the different "Landfill and waste management" EC/EU directives (EC (European Commission), 1999b, EU (European Union), 2006; EU (European Union), 2008; EU (European Union), 2018b).

Urban population increase and economic growth has also impacted on methane emissions from the waste sector in Asian fast-growing developing economies. Despite the widespread of landfilling practices, and associated emissions, the emissions from waste water treatment and solid waste incineration are still dominant within the waste sector. Overall, an increase of 95% in methane emissions from waste was registered in China, 655% in India, 200% in other South East Asian counties and 59% in Brazil.

3.4. N_2O emissions

3.4.1. General overview and regional features

World N_2O emissions in 2015 were 26% higher than in 1990; reaching 2600Mt CO_{2eq} (Table 4). N_2O emission in EU 27 + UK decreased by 28% and increased by 6% in the USA while N_2O emissions from China in 2015 resulted in being 44% larger than in 1990. Increases of 80%, 60% and 52% were observed respectively in Brazil, India and the South-East Asian countries. Lower and upper bounds for uncertainty associated with EDGAR's global overall N_2O emissions were estimated to be −70% and + 350%, respectively (Solazzo et al., 2021). In the case of EU27 + UK, uncertainty bounds were modelled to be −30% and + 265%, whilst the figures estimated for the USA were −30% and + 297%. Uncertainty for N_2O emissions also resulted in being the highest in the case of the officially submitted emissions, ranging close to 100% for the EU27 + UK (EEA (European Environmental Agency), 2017) and −10% and + 27% (EPA (United States Environmental Protection Agency), 2017). For the developing countries considered in this article, modelled uncertainties were even larger in alignment with uncertainty reported in the National Communications submitted to UNFCCC (UNFCCC, 2019) covering years between 2010 and 2015. Modelled bounds for uncertainties for key categories are also presented in the SI.

3.4.2. Emission trends in key sectors

The contribution of the different type of N_2O emission sources is shown in Fig. 8. A further detailed description of the influences of these sectors and the emission trends are discussed as follows.

3.4.2.1. Agriculture sector. N_2O emissions from the agriculture sector, including: direct soil emissions, NH_3 based fertiliser and manure management, were the main sources of N_2O emissions; being emissions from agriculture soils by far the largest subsector contributor (Fig. 8). These emissions showed a slight decrease in the EU27 + UK whilst larger emissions were registered for the USA (17%), China (29%), other South-East Asian countries (38%), India (47%) and Brazil (78%). These trends obey the evolution in terms of fertiliser usage, crop and livestock population.

3.4.2.2. Combustion sources. N_2O emissions from the combustion sector accounted for 11% at the global level in 2015, having increased by 40% between 1990 and 2015. Trends in emissions for this category depend on the fuel consumption evolution, the swift in fuel types with different nitrogen contents and on the implementation of mitigation policies aimed to reduce NO_x. This is because NO_x reduction end of pipe technologies lead to N_2O as a co-product. For example, fossil CO_2 combustion emissions in the EU27 + UK went down by 21 % between 1990 and 2015 whilst N_2O emissions remained relatively constant. This difference

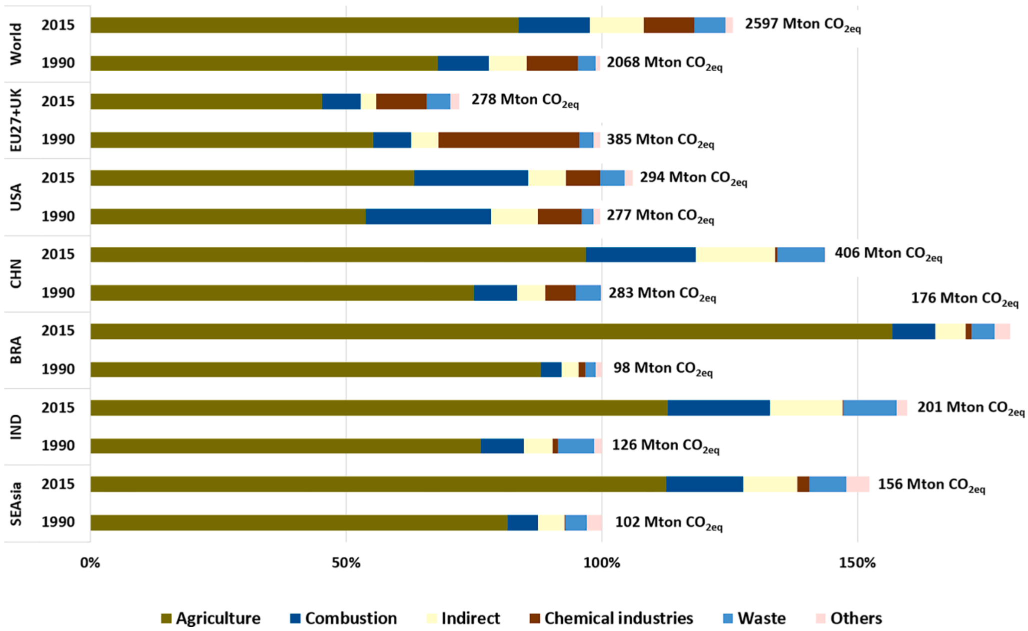

Fig. 8. Sectorial contribution, increases (2018 vs. 1990) and total N_2Oemissions from different countries, economic blocs and at world scale. (1990 = 100%)

in trends can be mainly explained due to the implementation of NO_x control units both in the road transport sector, derived from the EURO standard limits (EU, 1994; EU, 1998; EU, 2007) and in the energy industries, derived from the different updates of the "Large Combustion Plant" directives (EC (European Commission), 1988; EU, 2001). These legislations were aimed to reduce CO, NOx, NMVOC and PM emissions from stationary and mobile combustion sources within the countries that were part of the European Single Market. Particularly, for NO_x, these controls were also based on the incorporation of end of pipe catalysed chemical reduction units.

3.4.2.3. Chemical industries and indirect emissions. N_2O emissions from chemical industries accounted for 8 % of global N_2O emissions, primarily due to N_2O emissions from adipic acid and nitric acid production, while N_2O emissions, arising from the atmospheric deposition of nitrogen in nitrogen oxides and ammonia are responsible for 8% of global N_2O emissions.

4. Comparison with other emission inventories

As a result validation exercise, EDGAR v.5.0 estimates were compared against available data covering different regions and economic blocs. Fossil CO_2 emissions and total aggregated GHG emissions from EDGAR were confronted against: i) data for fossil CO_2 and total GHG emissions submitted by parties to UNFCCC (UNFCCC, 2019) ii) fossil CO_2 emissions estimated in the context of the Global Carbon Project (GCP, 2019), iii) fossil CO_2 emissions released by British Petroleum (BP, 2019) and iv) fossil CO_2 emissions published by IEA (IEA (International Energy Agency), 2019). Further details for these comparisons are presented in SI 2. The main outcomes are summarised as follows:

- For the UNFCCC submitting parties, EDGARv5.0 fossil CO_2 emissions fall between the higher emissions reported by UNFCCC and the lower emissions reported by GCP (GCP, 2019). The relative differences are smaller than the lower or upper uncertainty percentages for 2015′s EDGAR emissions, presented by Solazzo et al. (2021) and the ranges proposed by the official inventories.
- For the rest of the world, larger relative differences for CO_2 emissions could be explained due to i) sectors covered in the emission inventories, particularly, industrial by-product emissions and ii) the uncertainty for activity data and iii) for emission factors.
- Fast tracked fossil CO_2 combustion emissions were compared against the IEA's fossil CO_2 emissions (IEA (International Energy Agency), 2019), estimated on the basis of actual fossil fuel consumption for 2016 and 2017. The observed relative difference, at the global level, was around 0.27% on average for the non FT period whilst the relative global difference for 2016 and 2017, on average, was close to 0.29%.
- EDGARv5.0′s GHG emissions for EU27 + UK, USA and UNFCCC submitting parties were compared with the officially reported emissions. Larger absolute and relative differences – in comparison with fossil CO_2 emissions – were estimated. This is a consequence of higher variance in the results for CH_4 and N_2O. Nonetheless, these differences fall within the uncertainties estimated for EDGAR's v.5.0 emissions (Solazzo et al., 2021) and the values reported in the official submissions (EEA (European Environmental Agency), 2017; EPA (United States Environmental Protection Agency), 2017; UNFCCC, 2019).

The overall positive outcome of the inter-comparison and the uncertainty estimates confirms how EDGAR is a robust source for national emissions data, rooted in a transparent and consistent methodology. A deeper discussion on sectorial comparisons for EDGAR emissions with other sources and with top-down inventories can also be found in a recently published article (Petrescu et al., 2021), covering the European domain. As reminded, EDGAR does not replace official inventories but it has shown to be an extremely valuable resource, especially whenever national accounts are not available or are incomplete.

5. GHG emissions in times of crisis

At the time of the final revision of this paper (June 2021), the world is undergoing a new stage in the COVID-19 pandemic. Such an unexpected global-scale event has had a relevant impact on human activities and, consequently, it has influenced anthropogenic GHG emission trends. Emissions changes in 2020 have been approximately modelled, due to the absence of consolidated data. Tollefson (2021) forecasted a world decrease of 6.4% in CO_2 emissions, while Larsen et al. (2021)

preliminary foresaw a decrease of US emissions, equal to 10.3%. As for Europe, the European Commission has announced that GHG emissions from operators, covered by the EU Emissions Trading System (EU ETS), fell by 13.3% in 2020 compared to 2019 levels (European Commission, 2021). Climate Action Tracker (2021) also estimates that GHG emissions in EU27 may have decreased by 10–11%.

As discussed, power and heat production is the major source of CO_2 emissions, on the world scale, accounting for more than one third. According to International Energy Agency (2020) most developed countries have shown a decrease in electricity demand, in comparison with 2019, ranging from 5% to 25% during spring 2020. For China, International Energy Agency (2021) reports a reduction between January and March, with rebounds occurring thereafter, leading to an overall yearly increase of around 2–3%.

Nevertheless, the variation in electricity demand gives only part of the picture, as the energy mix has also been modified by unusual demand patterns and by the fact that in several countries, renewable energies are supported by dispatching priority policies Colelli et al. (2021) have indeed shown that renewable have provided 60% of power generation in Germany (15% more than a non-COVID counter factual scenario), and 50% in Italy and Spain (i.e., 5 to 10 percentage points more than a non-COVID scenario).

Transport, the emissions from which represented one fifth of the world CO_2 emissions in 2018, is the sector most impacted by the crisis. According to (IEA (International Energy Agency), 2020) oil global demand fell by 9% on average in 2020, but it is expected to regain 6% in 2021. The overall impact of the pandemic on industrial production, contributing to a quarter of CO_2 emissions in 2018, is probably the most complex to be addressed because of the initial lockdown measures and the later on partial recovery of missed production.

Discussions are being held, by the scientific community and policymakers, in terms of post COVID recovery and how this can be an opportunity for easing the transition to net zero, continuing those environmentally friendly demand patterns observed during the pandemic (Pradhan et al., 2021). Given its very detailed granularity in terms of sectors, fuels and geographical entities, EDGAR will be useful for following the development of the late pandemic and the coming years, once reliable data will become available.

6. Discussion

Data and trends in this study show the overall picture of GHG emissions – at the world level detailed per gas and per main sectors – taking into consideration blocs at different stages of development and with different societal and economic structures. GHG are caused by a wide range of human activities and the full picture of the phenomenon is extremely complex and multifaceted. However, some facts seem to emerge from such a diversity:

- An upward trend in global GHG emissions has been observed in the last three decades, despite a decrease in 2009 and periods of slow growth – namely between 2013 and 2015. EDGAR v.5.0′s GHG emissions cover up to 2015; however, Fast Track methodology shows that CO_2 emissions have increased between 2015 and 2018 at the rate of about 0.5 Gt/year.
- The overall increasing trend is common to all GHGs, but fossil CO_2 accounts for the largest growth, both in absolute and relative terms.
- With a few exceptions, such as China, the patterns for the shares of individual species in total GHG emissions reflect the national or regional economic structures. Larger contribution for CH_4 and N_2O are observed in developing economies due to the relevance of agriculture related activities within the latter. This also influences the overall uncertainty of the calculations. Nevertheless, it has to be again reminded that this analysis does not account for emissions related to LULUCF, including deforestation.
- Examining emissions by region indicates that different areas of the world have followed different paths over recent decades. Industrialised countries have shown both increasing trends (Australia and Canada, for instance), upward and downward evolution along the years (USA and Japan) and decreases (European Union). Developing countries, driven by the important industrialisation taking place in some of them, are generally increasing their emissions and combined now have the largest share of world greenhouse gas emissions.
- In general, per capita emissions remain on average higher in industrialised countries than in developing economies, although there are some key differences among countries worth highlighting. Per capita emissions from China (the single largest emitter) have overtaken those of the EU27 + UK, but remain well below the levels of the USA.
- GDP has grown faster than GHG emissions although with different paces: GHG per unit of GDP has decreased by 48.9% in EU-27 + UK, between 1990 and 2015, while in the same period this indicator in developing countries decreased by 35.7%. It has nevertheless to be noted that GHG emissions per unit of GDP in developing countries remain 33.4% higher than in developed ones.

EDGARv.5.0 data confirms that fighting climate change at the global level remains a demanding task. The COVID-19 global crisis is clearly expected to impact deeply on this picture, but, considering the time scale of EDGAR data production, such an effect will be visible only in the next data releases. Climate change mitigation actions should not ignore shorter lifetime species, such as methane, especially in the short to medium term. Methane emissions are the second largest contributor to global GHG emissions, accounting for a considerable fraction of total GHG emissions in some developing economies. Furthermore, methane share in total GHG emissions is expected to increase, particularly in developed economies, a consequence of the reduction of fossil CO_2 emissions derived from the transition to low carbon energy systems. Efforts must be then put into improving methods and reducing uncertainty for the quantification of methane emissions from key categories.

Taking the mid-term perspective, EDGAR data witnesses success stories in mitigation efforts, especially in the European Union, particularly for fossil CO_2 emissions from energy industries and small combustion. For instance, an interesting feature emerging from EDGAR data is the decreasing trend of global GHGs emissions per unit of GDP. Such a trend evidences the likelihood of decoupling emissions with economic growth. This pattern needs to be strengthened in the future so that emission caps associated with international climate goals can be met.

7. Conclusions

EDGARv.5.0 provides a complete view of the GHGs emissions from human activities from the entire world, detailed per regions, gas and sector for at least 25 years. Socio-economic, technological and demographic changes have led to variations in the global distribution for GHG emissions, which are on an ascending trend despite having slowed down in the latest years.

Within such a complex picture, some patterns can be observed in key world regions. The Member States of the EU27 and the United Kingdom have seen a significant reduction of their GHG emissions, driven by efficiency increases and the reduction of the carbon intensity of the energy supply; partially due to the implementation of climate change policies and to the deindustrialisation of the economic matrix. By contrast, in countries undergoing a concentration of the secondary sector such as China, India, other South-East Asian countries and Brazil, upwards trends for GHG emissions were registered. This is mainly a consequence of higher demand for the different sectors, despite higher overall efficiency, and due to a larger amount of fossil fuel being consumed. These changes have swapped contributions in terms of total global greenhouse gases, with fast-growing developing economies mostly contributing to higher emissions.

This work, presenting changes and diversity in emission trends in several world regions, evidences the need of constant updates to global emission inventories so that they can be an effective tool for the assessment of global emission trends and the monitoring of climate change mitigation policies, especially in times of crises.

8. Disclaimer

The views expressed in this article are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

CRediT authorship contribution statement

Gabriel David Oreggioni: Conceptualization, Methodology, Data curation, Writing – original draft, Writing - review & editing, Visualization. **Fabio Monforti Ferraio:** Data curation, Writing – original draft, Writing - review & editing, Validation, Supervision. **Monica Crippa:** Methodology, Data curation, Writing – original draft, Writing - review & editing, Resources, Validation. **Marilena Muntean:** Data curation, Writing – original draft, Writing - review & editing, Validation. **Edwin Schaaf:** Data curation, Writing – original draft, Writing - review & editing, Resources, Validation. **Diego Guizzardi:** Data curation, Writing – original draft, Writing - review & editing, Resources, Validation. **Efisio Solazzo:** Data curation, Writing – original draft, Writing - review & editing, Resources, Validation. **Marlene Duerr:** Data curation, Writing – original draft, Writing - review & editing. **Miles Perry:** Writing – original draft, Writing - review & editing, Resources. **Elisabetta Vignati:** Writing – original draft, Writing - review & editing, Resources, Supervision.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2021.102350.

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