

Revisiting Copenhagen climate mitigation targets

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Many economies set climate mitigation targets for 2020 at the 2009 15th Conference of the Parties conference of the United Nations Framework Convention on Climate Change in Copenhagen. Yet no retrospective review of the implementation and actual mitigation associated with these targets has materialized. Here we track the national CO₂ emissions from both territory and consumption (trade adjusted) perspectives to assess socioeconomic factors affecting changes in emissions. Among the 34 countries analysed, 12 failed to meet their targets (among them Portugal, Spain and Japan) and 7 achieved the target for territorial emissions, albeit with carbon leakage through international trade to meet domestic demand while increasing emissions in other countries. Key factors in meeting targets were intensity reduction of energy and the improvement of the energy mix. However, many countries efforts fell short of their latest nationally determined contributions. Timely tracking and review of mitigation efforts are critical for meeting the Paris Agreement targets.

Climate change presents a fundamental challenge to lives, livelihoods and the sustainable development of society. Global net anthropogenic greenhouse gas emissions in 2019 were 1.54 times higher than those in 1990 (ref. 1). Climate-related extreme events such as floods, heat waves², droughts and compound events (extreme events emerging together or in succession) have continuously increased, resulting in greater public awareness of climate change as an urgent issue³. With the need for international action paramount, countries across the world are supposed to take action on the principle of ‘common but differentiated responsibilities’^{4,5}. It is thus critical to analyse countries’ specific climate change objectives, measure their implementation of commitments in a timely manner and work together to mitigate climate change.

The annual Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change is a vital platform for multi-lateral negotiations on the goal of tackling climate change and the contribution of countries towards that goal^{6,7}. The parties

submitted 2020 mitigation targets at the 15th Conference of the Parties (COP15) convened in Copenhagen in 2009 (ref. 8). COP15 made efforts to facilitate a comprehensive global agreement on climate change, with a particular focus on addressing the unique challenges faced by developing countries⁹. Developed countries primarily emphasized the establishment of emission reduction targets relative to a base year, while rapidly growing developing countries committed to adopting targets relative to the business as usual scenario or reducing carbon intensity (emissions per unit of gross domestic product (GDP))—for example, China, by 40–45% and India by 20–25% compared with the 2005 level by 2020. Recently, more than 100 countries committed to achieving their net zero during 2030–2070 to limit global warming¹⁰. The COP15 laid the necessary groundwork for subsequent COP meetings and climate accords (such as the Paris Agreement), while a review of the implementation and mitigation of Copenhagen mitigation targets can also provide insights into the practice and feasibility of moving forward to net-zero targets.

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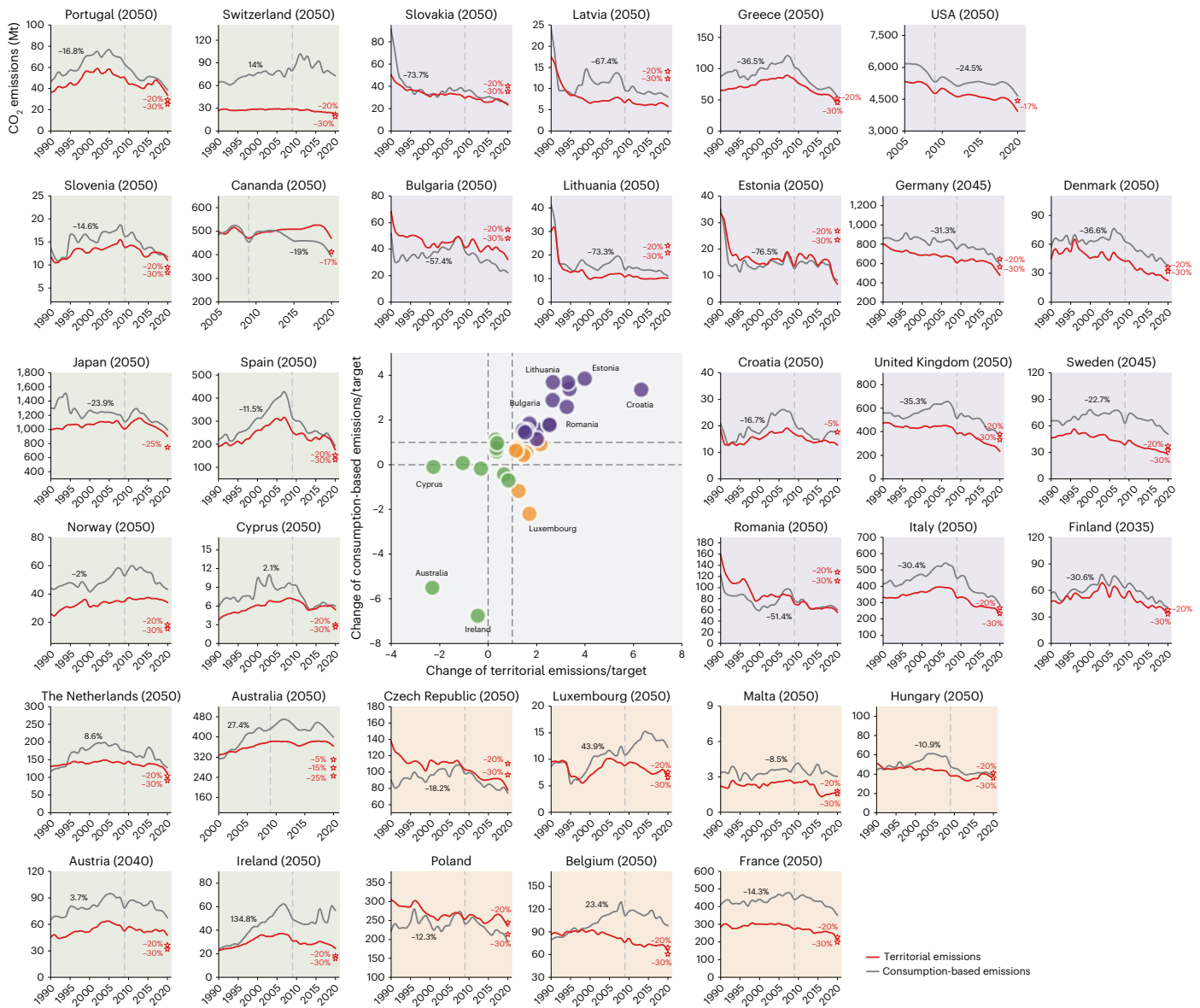


Fig. 1 CO₂ emission trends and emissions mitigation target range of COP15. The two lines represent territorial (red) and consumption-based (grey) emissions. The countries with green backgrounds (failing group) failed to meet their targets, countries with purple backgrounds (achieving group) achieved commitments through domestic efforts and countries with orange backgrounds (halfway

group) completed targets, with both domestic efforts and outsourcing in 2020. The vertical dashed grey line represents the year 2009, during which the COP15 conference took place. The stars represent national COP15 emission reduction targets compared with the base year (the first tick label on the x axis). The year in brackets in each subpicture is that country’s target year for carbon neutrality.

Some efforts have been made to construct the monitoring framework of the Paris Agreement^{11–14} adopted at COP21 in 2015 and signed the year after. However, the gap between mitigation targets and actual implementation has yet to be measured. Moreover, all of these frameworks about agreements of climate change mitigation focus solely on the emissions from a territory or production perspective without considering the emissions leakage in international trade, which has been a concern for many years¹⁵.

Territorial emissions are production based but exclude international aviation and shipping^{16,17}. By contrast, consumption-based emissions account for and adjust the emissions embodied in trade and attribute emissions in the supply chain to final consumers^{18,19}. A series of emission reduction targets, such as the Kyoto Protocol and the goals established at COP15, have focused primarily on territorial emissions and thus, to some extent, have ignored the global trading system and ‘carbon leakage’ among countries^{20,21}. Many analyses focusing on the impact of trade on national carbon emissions and mitigation raise

concerns about countries achieving mitigation targets by outsourcing production activities^{22–24}. Thus, it is critical to separate actual mitigation efforts from any outsourcing activities.

In this Article, we review the CO₂ emissions mitigation promised by countries in Appendix I and quantify the contribution from various mitigation actions. We select the emissions mitigation targets for 34 countries on the basis of data availability and assess both territorial and consumption-based emissions to investigate the extent to which countries rely on outsourcing emissions. Finally, we look forward to assessing challenges of economic growth and emission reduction targets based on the new nationally determined contributions (NDCs).

The gap between actual emissions patterns and COP15 targets

In terms of territorial emissions (red lines in Fig. 1 and Supplementary Table 1), 12 countries failed to meet their commitments, 16 achieved their commitments successfully and the remaining 6 achieved their

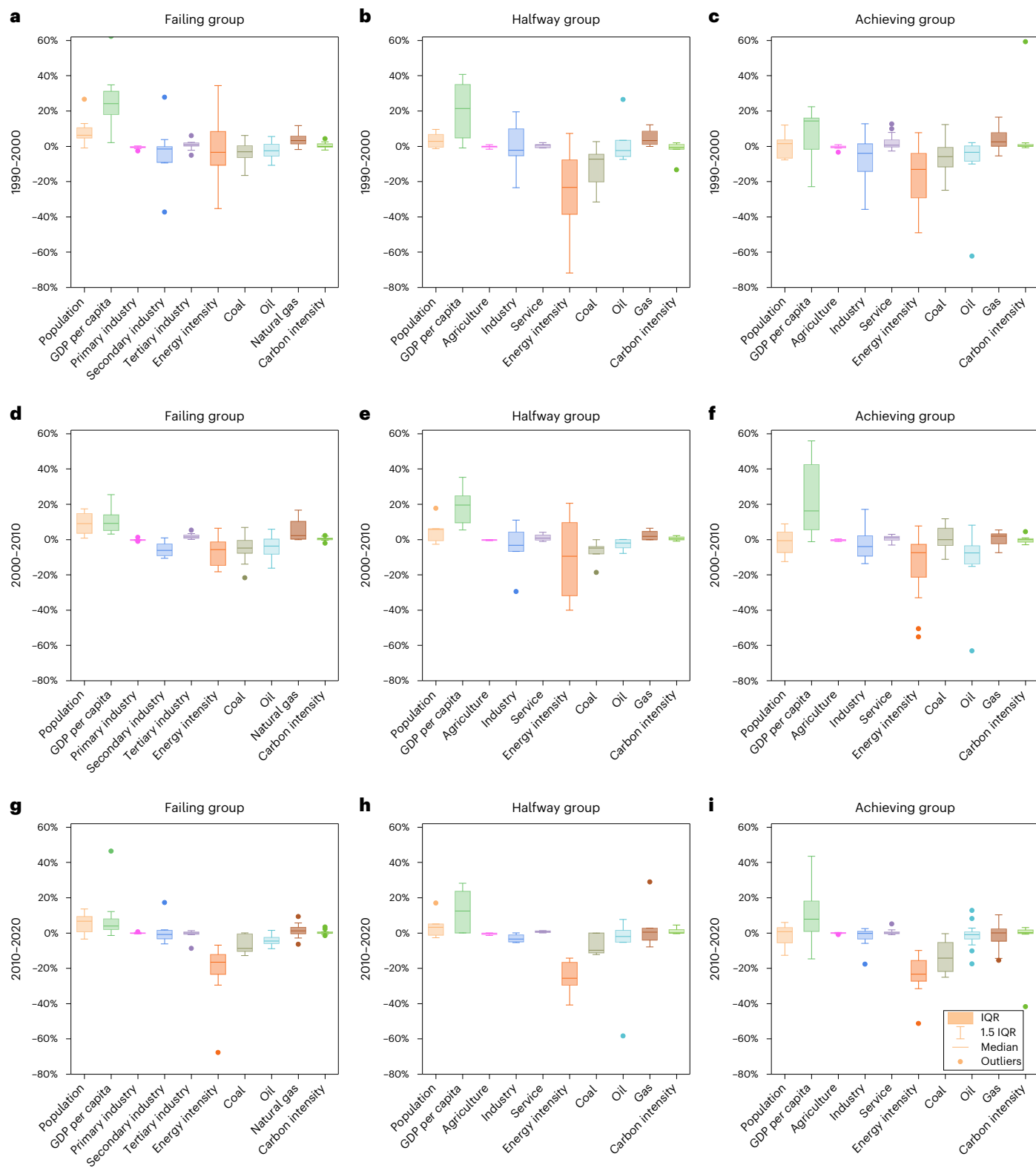


Fig. 2 | Contributions of different factors to changes in CO₂ emissions in various groups. **a–i.** The factors underlying changes in CO₂ emissions are shown in the periods 1990–2000 (**a–c**), 2000–2010 (**d–f**) and 2010–2020 (**g–i**). Left: the changes behind CO₂ emissions in the failing group (**a, d and g**). Middle: the changes behind CO₂ emissions in the halfway group (**b, e and h**). Right: the changes behind CO₂ emissions in the achieving group (**c, f and i**). The drivers are population; GDP per capita; the share of primary industry, secondary industry

and tertiary industry; energy intensity (energy use per unit GDP); the share of coal, oil and natural gas; and carbon intensity (CO₂ emissions per unit energy). The factors among groups are displayed in box plots that show the quartiles, medians, whiskers and outliers. The boxes span the IQR, with the upper and lower boundaries representing the 75th and 25th percentiles, respectively. The lines displayed inside boxes are median values across factors.

prescribed minimum emission-range commitments in 2020. As the targets set by countries at COP15 in Copenhagen are based on territorial accounting, countries can, as we have discussed, achieve their targets by outsourcing emissions to other countries—the so-called ‘carbon leakage’ or ‘carbon transfer’^{15,25}. Thus, we also track the trend of consumption-based emissions, which account for carbon emissions along the entire global supply chains (Fig. 1, grey lines).

When both consumption-based territorial emissions and carbon leakages are considered, the 34 countries can be divided into three groups. The first (failing group) consists of countries that failed to achieve their targets. The second (halfway group) consists of countries that achieved their targets with lower territorial emissions and increased net emissions embodied in trade, signifying that outsourcing contributed to their success. The third (achieving group) are countries that achieved their targets with lower territorial emissions and reduced net emissions embodied in trade, denoting that they achieved their targets through domestic efforts.

The failing group includes Australia, Austria, Canada, Cyprus, Ireland, Japan, the Netherlands, Norway, Portugal, Slovenia, Spain and Switzerland. Specifically, Australia has not yet completed its target of reducing carbon emissions by 5% up to 15% or 25% compared with 2000. Since 2000, emissions in Australia have generally shown an upwards trend, with a growth rate of 11.4% for territorial emissions. Similarly, emissions in Norway rose by 31%. Thus, Norway failed to achieve its goal of reducing carbon emissions by -30–40% compared with 1990. Furthermore, although the emissions of Portugal and Spain showed a downwards trend after 2005, they still failed to meet the targets of a decline of -20–30% compared with 1990, as promised at COP15. The majority of countries in this group have formulated net-zero targets and corresponding phased targets, geared to limiting global temperature rise to within 2 °C, and ideally within 1.5 °C (ref. 26). However, if short-term emission abatement targets are difficult to achieve, the achievement of long-term targets will become even more difficult. Notably, Austria has set relatively early carbon neutrality targets for 2040. Until now, Poland has yet to set corresponding targets.

The countries of Belgium, the Czech Republic, France, Hungary, Luxembourg, Malta and Poland belong to the halfway group. Hungary is typical of countries in the halfway group. It has achieved its target to reduce territorial emissions whereas consumption-based emissions, with 2009 as a turning point, have shown an initial increase followed by a decrease. Despite this trend, the targets set for consumption-based emissions have not been met. In contrast, Bulgaria, Croatia, Denmark, Estonia, Finland, Germany, Greece, Italy, Latvia, Lithuania, Romania, Slovakia, Sweden, the United Kingdom and the United States in the achieving group have all achieved their goals in terms of both territorial and consumption-based emissions.

Factors behind the changes in emissions

The most important factor influencing territorial emissions across groups was energy intensity, while the foremost driver of the emissions growth was GDP per capita (Fig. 2). Between 2010 and 2020, energy intensity contributed median values of 16.5%, 25.6% and 23.3% (with interquartile ranges (IQRs) of -12.2–23.2%, -16.7–29.6% and -15.6–27.2%, respectively) to emissions reduction in failing, halfway and achieving groups (Fig. 2g–i), respectively. Over the same period, the median share of coal led to a reduction of emissions by 8.6%, 9.7% and 14.2% in the failing, halfway and achieving groups, respectively. It was noted that the halfway group and achieving group demonstrated more substantial improvements in energy intensity and more substantial progress in reducing reliance on coal. Furthermore, the contribution of the share of coal to the reduction in emissions varied from 0.6% to 11.6% (IQR) in 1990–2000 and 5.3% to 21.7% in 2010–2020 (Fig. 2c,i), which also reflected the increasing effect of shifting away from coal on the decrease of emissions. By contrast, the share of oil and natural gas in

energy types did not have a substantial effect on reducing emissions. Additionally, the decrease in emissions of 0.7%, 3.4% and 0.1% from 2010 to 2020 are the result of the median share of secondary industry in failing, halfway and achieving groups, respectively.

For the achieving group, 8 of 15 countries reduced emissions primarily through changes in energy intensity (orange bars in Fig. 3 and Supplementary Fig. 1) from 1990 to 2000, which have decreased emissions by -12.9–41.1%. While GDP per capita drove emissions growth in ten countries, contributing to 5–22.5%. Between 2000 and 2010, energy intensities continued to wield notable influence, particularly in Croatia, Finland and Slovakia. Nevertheless, enhancements of industrial structure, notably in the United Kingdom, led to a substantial 50 Mt decrease during this period.

Countries in the achieving group underwent continuous or more rapid decline in 2010–2020, after COP15 in Copenhagen. Emissions continued to rise by 0.3% to 43.6%, driven by GDP per capita growth, excluding Italy and Greece. In contrast, energy intensity strengthened to emerge as a paramount factor in reducing emissions compared with the period of 2000–2010, notably in Germany, the United Kingdom and the United States, offsetting population and GDP per capita contributions. Furthermore, another key driver behind the reduction in emissions was the energy structure. Among the achieving group, 11 out of 15 countries primarily emphasized energy intensity as the pivotal factor in mitigating emissions, with reductions ranging from 13.5% to 51.2%. The remaining four countries achieved declines through energy structure modifications, resulting in reductions ranging from 12.2% to 32.8%.

In the halfway group, the rise of GDP per capita was the topmost factor driving the growth of emissions from -15.7% to -40.8% in five out of seven countries for 1990–2000. Conversely, energy intensity played a pivotal role in curbing emissions growth by 7.7–71.7% in six countries. From 2000 to 2010, energy intensity—the predominant factor—made emissions drop from 9% to 40.1% in four countries. During this duration, Malta primarily adjusted industrial structure, resulting in a decrease of 0.6 Mt (27%), despite the growth of emissions mainly driven by population and GDP per capita. Emissions decreased by 15.6% and 4.2%, induced by energy structure in Belgium and Luxembourg, respectively.

From 2010 to 2020, the halfway group experienced notable emission reductions, with a slowed impact of population growth. Six of the seven countries in the halfway group primarily relied on lowering energy intensity, resulting in reductions of 16.6–40.8%. In France (halfway group), energy structure was the most key driver of a decrease in emissions (39.8 Mt or 14.3%).

In the failing group, GDP per capita led to an increase in emissions across 11 countries from 1990 to 2000. Notably, Australia and Canada, both part of the failing group, saw increases (28.5% and 18.1%, respectively) primarily driven by rising GDP per capita. Conversely, energy intensity emerged as the leading factor in reducing emissions by -3–35.3% in 5 out of 12 countries during this period. During 2000–2010, six failing group countries continued prioritizing energy intensity, resulting in reductions from 7% to 18.3%. Particularly, Australia's focus on energy intensity led to a notable 15.6% reduction, remaining a primary driver in subsequent years.

From 2010 to 2020, energy intensity still dominated the emission reduction in 10 out of 12 failing group countries, achieving reductions from 10.2% to 67.7%. In Canada, population growth contributed to a 9.8% growth (47.4 Mt), while energy intensity played a critical role in reducing emissions (49.5 Mt or 10.2%). Additionally, Spain and Norway experienced notable emission reductions of 10.9% (26.3 Mt) and 12.5% (4.6 Mt), respectively, driven by adjustments in energy structure. Moreover, changes in industrial structure in eight failing group countries resulted in varying degrees of emission declines, with Spain and Cyprus achieving over a 3.5% reduction. Conversely, the emissions of four countries increased to varying degrees due to changes in industrial structure, such as an 8.4% increase (2.6 Mt) in Ireland.

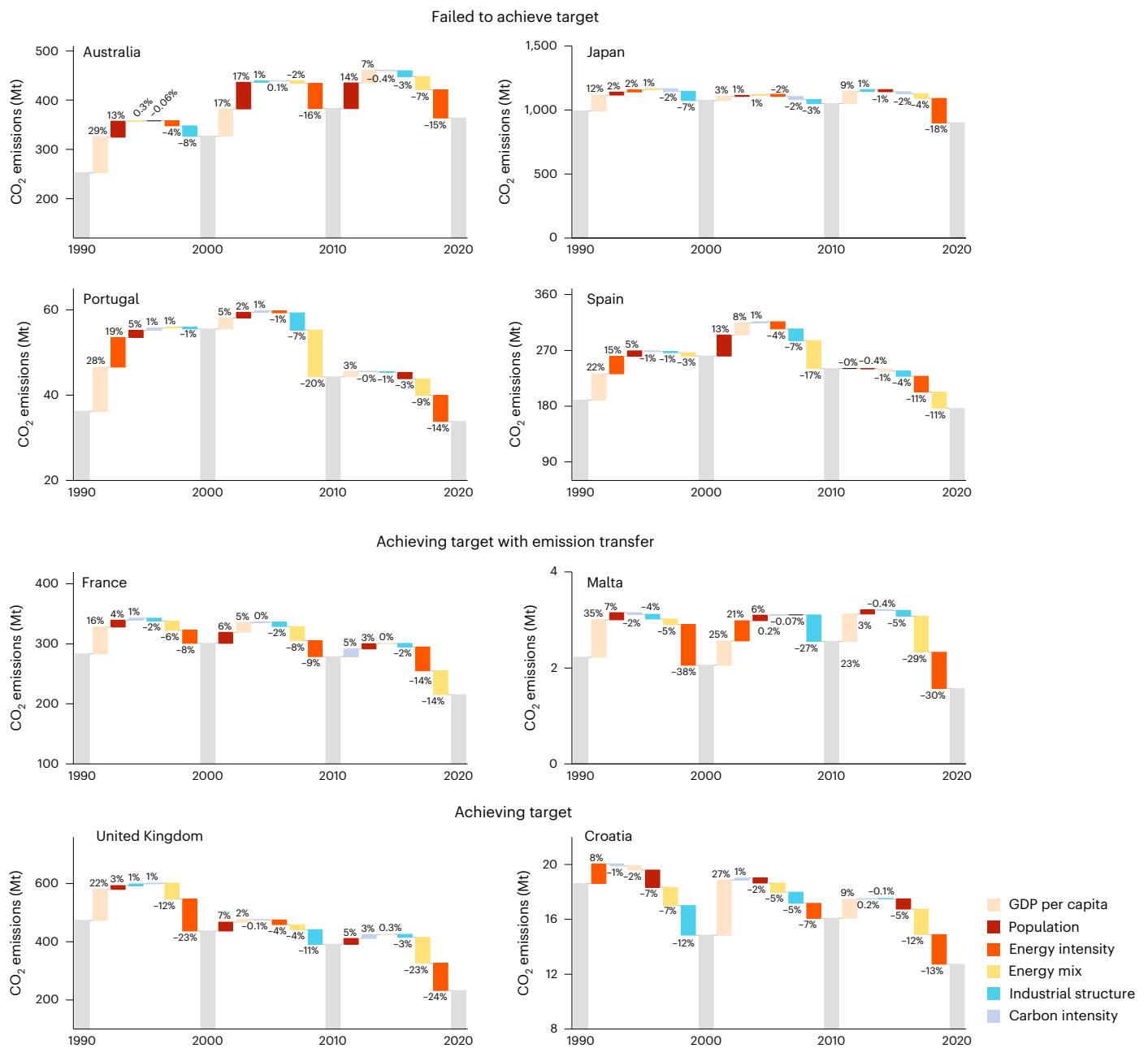


Fig. 3 | Contributions of different factors to changes in CO₂ emissions in various countries in the periods 1990–2000, 2000–2010 and 2010–2020. Mt CO₂ refers to a million tonnes of CO₂ emissions. Different factors include

population, GDP per capita, industrial structure, energy intensity, energy mix and carbon intensity. The numbers represent the percentage change in emissions for different factors.

More efforts are needed for NDCs and economic growth

To achieve NDCs in 2030, 19 countries out of the 34 will have to cut more emissions in the next 10 years than they did from 2010 through 2020 (Fig. 4a). Thus, the shift in emissions levels in 2020–2030 must be greater than that in 2010–2020. Conversely, countries such as Estonia, Lithuania, Latvia and Romania (achieving group) have achieved the 2030 target set by the European Union (that is, a level of emissions 50% lower than that in 1990) over the period 2010–2020. This achievement, however, is mainly because these countries had highly inefficient technologies and energy-intensive development in the early 1990s²⁷.

Intuitively, countries that have struggled to meet their goals in COP15 will probably encounter even more substantial challenges in the future. These challenges extend beyond emission reduction and encompass the intricate interplay between reducing emissions and

stimulating economic growth. Notably, Croatia stands out in this context. While it successfully achieved the emission reduction target set in COP15, it is essential to acknowledge that this target was comparatively modest—a 5% decrease from 1990 levels. To determine how much more it needs to reduce emissions to meet its NDC target, we would need specific information about NDC, current emissions and details of the target. The economic growth rates of Norway, Croatia and Japan in 2010–2020 were 14.8%, 19.5% and 3.6% (Fig. 4b), and emissions in these countries dropped by 9.1%, 20.9% and 14.2%, respectively. Their economies will grow largely by 25.2%, 31.4% and 12.4%, respectively, under Shared Socioeconomic Pathway 2 (SSP2, middle of the road), whereas their emissions will need to fall by a further 61.8%, 34.2% and 30.7% to meet their NDCs for the next stage (2020–2030). Therefore, these countries must urgently improve energy intensity and adjust their energy mix to meet the dual pressure of emission reduction and

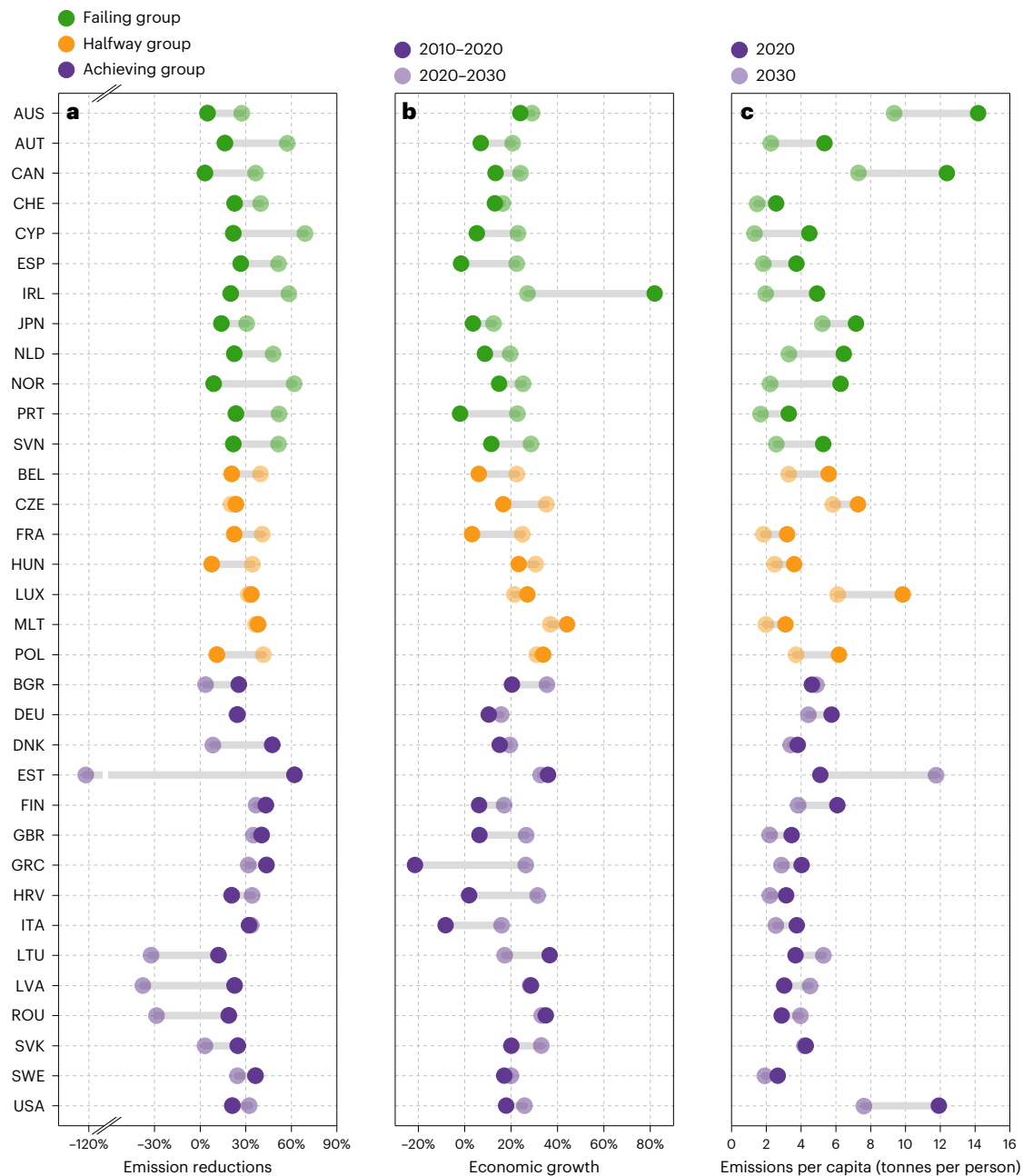


Fig. 4 | Progress and challenges in meeting emission targets of NDCs alongside economic development. a–c. Changes in CO₂ emissions (a) and economic growth (b) from 2010 to 2020 and 2020 to 2030, and emissions per capita in 2020 and 2030 (c). The projection of CO₂ emissions is consistent with the reduction targets set in the NDCs. The projection of GDP and population is from the SSP2 (middle of the road) scenario set by the Potsdam Institute for Climate Impact Research³⁷. AUS, Australia; AUT, Austria; CAN, Canada;

CHE, Switzerland; CYP, Cyprus; ESP, Spain; IRL, Iceland; JPN, Japan; NLD, the Netherlands; NOR, Norway; PRT, Portugal; SVN, Slovenia; BEL, Belgium; CZE, Czech Republic; FRA, France; HUN, Hungary; LUX, Luxembourg; MLT, Malta; POL, Poland; BGR, Bulgaria; DEU, Germany; DNK, Denmark; EST, Estonia; FIN, Finland; GBR, United Kingdom; GRC, Greece; HRV, Croatia; ITA, Italy; LTU, Lithuania; LVA, Latvia; ROU, Romania; SVK, Slovakia; SWE, Sweden; USA, United States.

economic development. The emissions per capita of these developed countries have decreased compared with 2020 levels; Switzerland achieved the lowest in 2020, at 2.6 t. If Cyprus reaches its NDC target in 2030 with a growing population, its emissions per capita will need to decrease by 70.7% in 2030 (that is, 1.3 t per person in Fig. 4c). The emissions per capita of Australia also need to be reduced from 14.2 t per person in 2020 to 9.3 t per person.

Discussion

The actual mitigation of emissions and the achievement of mitigation targets varied, especially for Australia, Japan and Norway, which missed

the targets by the widest margin. To address potential emission leakage, we analyse both territorial and consumption-based emissions. For example, in Luxembourg, territorial emissions decreased by 34.1% while consumption-based emissions increased by 43.9% compared with 1990, which highlights the discrepancy between the two kinds of emission. Energy intensity was among the main factors affecting the decline of emissions. However, countries where both territorial and consumption-based emissions goals have not been achieved will face increasing challenges in their future emission reduction efforts or might even miss certain pathways altogether. In addition, the reduction of emissions primarily depends on the change in the energy structure

and the industrial structure in some countries, such as Spain and Poland. Therefore, it is necessary to strengthen the policy support to adjust the energy structure as well as industrial structure to promote the further reduction of emission intensity^{28,29}. Concerningly, many countries are still grappling with economic recovery as the coronavirus disease 2019 pandemic recedes. It remains uncertain whether energy intensity will continue to decrease. Notably, emission intensity and production structure played pivotal roles in reducing consumption-based emissions (Supplementary Fig. 4). Assuming that countries can meet their latest NDCs by 2030, it is expected that these 19 countries will face even more pressure to reduce emissions than they did during the 2010–2020 period. In fact, 17 of these countries will face the dual challenges of stimulating economic growth and reducing emissions, being more pronounced than they were in the previous decade.

Considering the remarkable decline in CO₂ emissions during the pandemic, we also choose 2019 as the target year for a more reasonable analysis. Thirteen countries achieved their targets by reducing net emissions embodied in trade. Additionally, there were four countries classified into the halfway group (Fig. 1 and Supplementary Table 2). However, the failing group, composed of 17 countries, has failed to effectively achieve their emissions domestically. Combining the two target years of 2019 and 2020, France, Belgium and Luxembourg have been relocated from the failing group to the halfway group. France's emissions decreased by 23.9% from 1990 to 2020, surpassing the minimum of its stated aim of ranging between a 20% and 30% reduction. France has established a goal of achieving carbon neutrality by 2050, but it must take measures to prevent outsourcing emissions to reach the target.

Some countries, such as Malta, achieved their carbon emissions targets by offshoring emissions to other countries—'carbon leakage'—which affects the success of their climate mitigation. As action on climate change is a global imperative, it is questionable to effectively shift emissions to less-developed countries along global supply chains. In other words, countries need to avoid 'free-riding' on their own carbon emissions targets³⁰. The road towards more equitable and transparent distribution of national responsibilities is provided by the view of consumption-based emissions. Specifically, the trends of global consumption-based emissions have been thoroughly analysed in the Intergovernmental Panel on Climate Change Sixth Assessment Report Working Group III chapter 2, which reflects the discussions of inequalities in consumption associated emissions and determination for the just transition¹. However, it is crucial to realize the fact that most countries have now set carbon neutrality targets is thus both an opportunity and a challenge. On the one hand, there is a need to continue to promote the achievement of national carbon neutrality targets, on the other, there is a need to match measures such as border taxes to prevent carbon leakage to countries that have not yet set carbon neutrality targets^{31,32}. In brief, consumption-based emissions represent a promising way for advancing the effectiveness and fairness of climate action in the international climate negotiations or commitments.

The 2009 Copenhagen conference shaped the progress of global climate change negotiations, setting the stage for subsequent COP meetings, particularly the attainment of the Paris Agreement. Despite the absence of a comprehensive global agreement, countries established emission reduction targets during COP15, leading to diverse processes and ongoing challenges. Croatia, with a modest 5% reduction goal, faces the task of reducing 34.2% emissions while ensuring a 31.4% economic growth to meet its NDC under SSP2. In contrast, we also need to admit that Switzerland, despite falling short of its ambitious COP15 target, has still been noteworthy in mitigating emissions. The Paris Agreement, established during COP21, marks a pivotal shift, aiming to limit global temperature increases³³. Subsequent COP meetings focus on addressing critical themes such as climate adaptation, loss and damage and financial support mechanisms³⁴. The retrospective analysis of COP15 and the prospective analysis of NDCs as well as ongoing COP

meetings create a continuous global framework for climate actions. It is crucial to track and evaluate factors such as energy intensity and mix timely. Meanwhile, the effectiveness and feasibility of targets in every country, compatible with their development stage, are vital. These insights reveal emission trends, highlight policy issues in developed countries and guide future reduction strategies.

Currently, there are also circumstances in developing countries making policies or commitments difficult to achieve. Especially in recent years, the emissions of these countries have continued to grow, forming the key driver of future emissions^{35,36}. Quantifiable climate targets for developing countries need to prioritize future achievability, drawing insights from the emission targets and accomplishments of developed countries. Meanwhile, timely reviews of national climate commitments are crucial, fostering collaborative global efforts to combat climate change.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41558-024-01977-5>.

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Methods

IO analysis

The input–output (IO) is an economic analysis tool that estimates the relationships among different sectors around the economy by quantifying the inputs required by one sector and the outputs generated by another³⁸. Specifically, each column in the IO table represents the required inputs and each row indicates the production activities³⁹. IO analysis offers a synthetical framework for understanding how changes in a sector can have ripple effects throughout the entire economy. The core concept underpinning this model is that the output is driven by the final demand. Hence, its fundamental equation is

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{F} \quad (1)$$

where \mathbf{X} denotes the total output. $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, which demonstrates the direct and indirect requirements of all sectors in all countries. In addition, \mathbf{I} is the identity matrix, \mathbf{A} is the direct requirement matrix and \mathbf{F} is the final consumption.

Emissions embodied in trade

Generally, territorial emissions account for the emissions produced by national production by compiling an emissions inventory that covers both emissions from domestic production to serve domestic consumption and those associated with export^{40,41}. By comparison, consumption-based emissions generally account for the emissions generated by that country's consumption of all products across global supply chains^{42,43}, including domestic and imported products to meet domestic demand⁴⁴. The linkage and allocation between territorial and consumption-based emissions are usually shown through IO tables⁴⁵. The accounting of consumption-based emissions of country r is as follows:

$$C_r^c = \mathbf{E}\mathbf{L}\mathbf{F}^r \quad (2)$$

where \mathbf{E} is a vector that reflects the CO₂ produced by the unit output of subsectors and subregions and \mathbf{F}^r represents the final demand in the r region.

International trade activities can cause the transfer of emissions, leading to the issue of carbon leakage⁴⁶. Thus, carbon leakage of country r can be specified as

$$\text{Carbon leakage}^r = C_r^t - C_r^c \quad (3)$$

where C_r^t indicates territorial emissions.

Decomposition analysis

A decomposition analysis is frequently employed to identify the underlying factors responsible for shifts in a specific environmental indicator^{47,48}. Decomposition analysis encompasses two primary methods: index decomposition analysis (IDA) and structural decomposition analysis (SDA)^{49,50}. The IDA method primarily focuses on the decomposition of environmental indicators from territorial perspective and can be used to estimate direct impact⁵¹. The SDA method needs to be combined with IO tables, focusing on the decomposition environmental indicators from consumption-based emissions⁵². In the past, the SDA method was constrained by time lag and the lack of time series IO tables⁵³, making it difficult to track the causes of changes in environmental indicators in a timely and effective manner. Now however, the endeavour of numerous researchers and the construction of databases make it feasible for us to timely and effectively track changes in environmental indicators over a time series⁵⁴.

IDA is extensively used to analyse the contributions of economic and social factors to changes in greenhouse gases, such as CO₂ and air pollutants, such as SO₂ (refs. 55–57). Among IDA methods, the Laspeyres and Divisia decomposition analyses are two of the most commonly used.

Further, Divisia decomposition analysis includes the arithmetic mean division index and the logarithmic mean division index (LMDI)⁵⁸. The LMDI method has been applied to varied sectors such as manufacture, transportation and electricity^{59,60}, covering analysis at different scales such as countries^{47,61}, regions⁶² and subregions⁶³. In this study, the LMDI is taken to decompose the change in carbon emissions of every country into carbon intensity (**CI**), energy structure (**ES**), energy intensity (**EI**), industrial structure (**IS**), GDP per capita (**GP**) and population (**P**) factors, as follows:

$$C_T = \sum_{i=1}^3 \sum_{j=1}^4 \frac{C_{ij}}{E_{ij}} \times \frac{E_{ij}}{E_i} \times \frac{E_i}{G_i} \times \frac{G_i}{G} \times \frac{G}{P} \times P \quad (4)$$

$$= \sum_{i=1}^3 \sum_{j=1}^4 C_{ij} \times ES_{ij} \times EI_{ij} \times IS_i \times GP \times P$$

$$\Delta C_T = C_T^2 - C_T^1 \quad (5)$$

$$= \Delta C_T^{CI} + \Delta C_T^{ES} + \Delta C_T^{EI} + \Delta C_T^{IS} + \Delta C_T^{GP} + \Delta C_T^P$$

where i denotes various industrial sectors, which are categorized into primary, secondary and tertiary industries; j represents distinct types of energy, namely coal, oil, gas and others. Specifically, given that other factors remain constant, ΔC_T^{CI} represents the change in emissions caused by the change in carbon intensity during a specific period. Similarly, ΔC_T^{ES} , ΔC_T^{EI} , ΔC_T^{IS} , ΔC_T^{GP} and ΔC_T^P manifest the changes in energy structure, energy intensity, industrial structure, GDP per capita and population, respectively, resulting in changes in emissions.

In this regard, each of the items in equation (6) is as follows:

$$\Delta C_T^Y = \sum_{i=1}^3 \sum_{j=1}^4 \frac{C_{ij}^2 - C_{ij}^1}{\ln C_{ij}^2 - \ln C_{ij}^1} \times \ln \left(\frac{Y_{ij}^{t2}}{Y_{ij}^{t1}} \right) \quad (6)$$

SDA requires the usage of IO tables that cover information on trade flow, production structure, final demand and so on. If there are n factors, there are $n!$ decomposition methods. Thus, there are five elements in this study, that is, 120 decomposition methods. In this study, the two polar method⁶⁴ is taken to decompose into emission intensity (**E**), production structure (**L**), consumption structure (**F_S**), consumption per capita (**F_C**) and population (**P**) factors, as follows:

$$C_C = \mathbf{E}\mathbf{L}\mathbf{F}_S\mathbf{F}_C\mathbf{P} \quad (7)$$

$$\Delta C_C = C_C^2 - C_C^1$$

$$= \Delta \mathbf{E}\mathbf{L}\mathbf{F}_S\mathbf{F}_C\mathbf{P} + \mathbf{E}\Delta \mathbf{L}\mathbf{F}_S\mathbf{F}_C\mathbf{P} + \mathbf{E}\mathbf{L}\Delta \mathbf{F}_S\mathbf{F}_C\mathbf{P} + \mathbf{E}\mathbf{L}\mathbf{F}_S\Delta \mathbf{F}_C\mathbf{P} + \mathbf{E}\mathbf{L}\mathbf{F}_S\mathbf{F}_C\Delta \mathbf{P} \quad (8)$$

$$= \Delta C_C^E + \Delta C_C^L + \Delta C_C^{F_S} + \Delta C_C^{F_C} + \Delta C_C^P$$

Specifically, given that other factors remaining constant, ΔC_C^E represents the change of emissions caused by the change of emission intensity during a specific time period. Similarly, ΔC_C^L , $\Delta C_C^{F_S}$, $\Delta C_C^{F_C}$ and ΔC_C^P respectively manifest the changes of production structure, consumption structure, consumption per capita and population in emissions.

Data availability

The emission and energy data from 1990 to 2019 used in this study are from the International Energy Agency⁶⁵. CO₂ emissions only include those associated with fossil fuel consumption and do not encompass emissions from industrial processes and international aviation or shipping⁶⁶. Meanwhile, we have chosen to use the IO table from EXIOBASE database⁵⁴. EXIOBASE has covered 44 countries and 5 regions, 163 sectors from 1995 to 2022 (ref. 67). While the starting year of this table is 1995, we supplemented it with the IO table from the Eora database⁶⁸

from 1990 to 1994. The Eora database spans 189 countries, encompasses 26 aggregated sectors and includes a time series from 1990 to 2015 (ref. 69). Moreover, we use data of gross value added by kind of economic activity from the United Nations⁷⁰ to reflect GDP and aggregate economic activity into primary, secondary and tertiary industries. Similarly, the population data used in the analysis of driving factors also originates from the United Nations.

Code availability

The code in MATLAB analysing the results of this study is available from Zenodo (<https://doi.org/10.5281/zenodo.10780940>) (ref. 71).

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Author contributions

J.M. designed and supervised the project. S.L. undertook the data analysis with support from P.C. The manuscript was primarily finished by S.L. and J.M. and enriched by important suggestions and contributions from K.H., S.M.S.U.E., Y.L. and D.G.

Competing interests

The authors declare no competing interests.

Additional information

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