Energy system decarbonization and productivity gains reduced the coupling of CO2 emissions and economic growth in 73 countries between 1970 and 2016

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One Earth

Article

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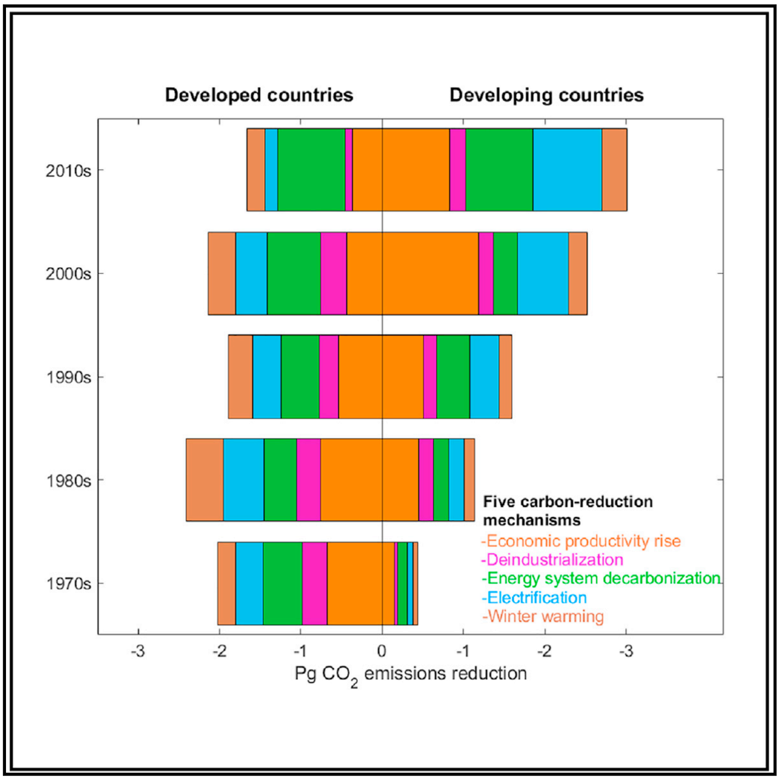
Graphical abstract



Highlights

- We estimate impacts of five mechanisms on nations' CO_2 emissions over 1970–2016
- Without these mechanisms, emissions grow as fast as the economy
- Energy system decarbonization was the primary mechanism for high-income countries
- Productivity gains were the primary mechanism for low-income countries

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In brief

To successfully combat climate change we must understand what mechanisms are most effective in reducing CO_2 emissions while maintaining economic growth. Existing literature proposes divergent estimates on this relationship. Here, we study emission trends for 73 countries between 1970 and 2016 and identify five mechanisms that reduced CO_2 emissions. We show that energy system decarbonization and economic productivity gains were the most effective mitigation mechanisms during times of growth. However, emission-reduction trends in all observed countries fall short of meeting net-zero targets by 2050.

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Energy system decarbonization and productivity gains reduced the coupling of CO_2 emissions and economic growth in 73 countries between 1970 and 2016

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SCIENCE FOR SOCIETY Fearing negative repercussions for economic growth, climate policy is not on track to meet the Paris Agreement temperature target. However, the academic literature disagrees on both the impact of economic growth on climate mitigation and the effectiveness of various mitigation mechanisms on CO_2 emissions reduction. Here, we investigate the relationship between CO_2 emissions and economic growth in 73 countries during the period 1970–2016. We find that in the absence of mitigation mechanisms, emissions would have indeed grown at the same rate as the economy. However, these five mechanisms—energy system decarbonization, electrification, increased economic productivity, deindustrialization, and winter warming—are identified as successfully reducing emissions by 19 gigatonnes, mostly during periods of economic growth. Yet, observations indicate that emissions reduction rates consistent with the Paris Agreement could be achieved while maintaining economic growth only if energy systems are more rapidly decarbonized.

SUMMARY

Nations must curtail carbon dioxide (CO_2) emissions by 7% per annum to meet the Paris Agreement temperature targets. A perceived economic growth-climate mitigation trade-off has diminished political will to act. However, there is no scholarly consensus regarding the magnitude of the trade-off between economic growth and CO_2 mitigation and a lack of *ex post* evidence regarding the extent to which mitigation measures can effectively lower CO_2 emissions. Here, we present a structural equation model integrating emissions and economic and energy system characteristics over the period 1970–2016 to empirically assess mechanisms that influence the GDP-CO_2 relationship for 73 countries. Robust to various model specifications and statistical tests, we found a simple unitary scale effect between per capita GDP and per capita CO_2 emissions, while five emission-reduction mechanisms, principally energy system decarbonization and productivity gains, collectively contributed to global emission reductions by 19 petagrams. Within the observed year-to-year emissions development, reductions at a rate consistent with the Paris Agreement can be achieved in about 10% of instances while maintaining economic growth.

INTRODUCTION

The world achieved explosive growth of the human population and unprecedented levels of economic welfare in the past two centuries through increased and improved utilization of fossil fuels.[1] In the 2015 Paris Agreement, 192 countries agreed to halt the global temperature rise at well below 2°, preferably 1.5°.[2] Achieving a 1.5°C warming goal requires cutting global greenhouse gas (GHG) emissions by more than 7% per year on average from 2020 on.[3] However, the latest UN synthesis of the nationally determined contributions (NDCs) under the Paris Agreement warns that current climate commitments, even if fully

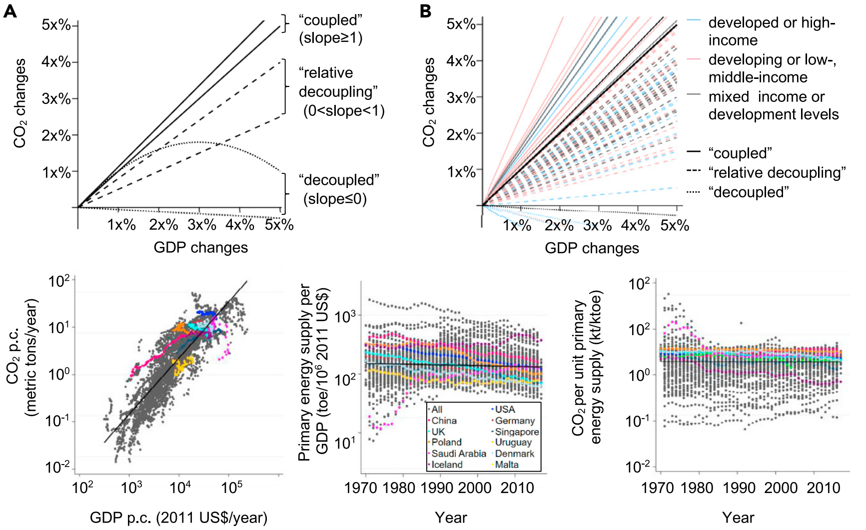

Figure 1. Emissions-economy pathways: CO$_2$-GDP relationships and time series observations

(A) A schematic illustration of the characteristic CO$_2$-GDP relationship; (B) CO$_2$-GDP relationships suggested by the CO$_2$-GDP elasticity estimated by previous studies (ranging from −0.3 to 2.5), which are reviewed in detail in Note S1 and Table S1, supplemental information; (C–E) observed (165 countries, 1970–2020) CO$_2$ emissions per capita related to fossil fuel combustion and industrial processes versus real GDP per capita in constant US dollars (C), the energy intensity of GDP (D), and CO$_2$ intensity of primary energy supply (E); (C) shows a relatively strong positive correlation between GDP and CO$_2$ emissions. A reduced-form analysis that controls for the country- and year-fixed effects indicates a CO$_2$-GDP elasticity = 0.53 ($p < 0.001$), i.e., a 1% of GDP growth is associated with a 0.53% increase in CO$_2$ emissions on average. The less than unitary CO$_2$-GDP relationship referred to as *relative decoupling* is consistent with the findings of many recent empirical studies, e.g., Burke and coworkers.[22–25,27,31,32] Despite a lack of empirical proof, the reduced emission rate is commonly attributed to the falling energy intensities of GDP illustrated in (D), given that energy supplies have been decarbonizing at slow rates across the world (E).

realized, are far from adequate to meet the target of the Paris Agreement.[4] Worse, countries have not been on track to achieving their past NDC pledges, and global GHG emissions continued to grow in 2019 and fell by only 6.4% in 2020 owing to the COVID-19 pandemic.[3,5] A first step in ratcheting up the NDCs will occur at the upcoming 26th conference of the parties (COP26) of the UNFCCC in Glasgow in November 2021.

The political commitments and negotiations about emission reductions are invariably tied up with the question of economic growth, both through the fundamental question of how to reconcile emission reductions with the economic development required to attain most other sustainable development goals and through the tricky issues of how to share the cost of emission reductions as well as the remaining emissions budget.[6,7] Studies of the empirical relationship of CO$_2$ emissions and economic development[8] have focused on estimating the CO$_2$-GDP elasticity, i.e., the percentage change of a country's CO$_2$ emissions per capita for every 1% increase in the GDP per capita (Figures 1A and 1B). They have variously shown everything from a 0.3% *decrease* to a 2.5% *increase* in CO$_2$ emissions for every percent growth in a country's GDP[9–27] (for details, see Note S1 and Table S1 in supplemental information). As a result of these disparate findings, policymakers have not been able to rely on empirical analysis in weighing the trade-offs of potentially conflicting social goals. Variation in these estimates has been attributed to sample-selection issues (see Figure 1B) and the potential for spurious results given insufficient consideration of statistically problematic properties of the investigated data (i.e., non-stationarity,[28] endogeneity,[26,29] and cross-sectional heterogeneity[14,30]). We hypothesize, meanwhile, that the failure of the empirical studies to identify a simple monocausal relationship between GDP and CO$_2$ emissions lies in the separate influence of independent causal mechanisms on historical CO$_2$ emission pathways.

The recent success of selected countries to reduce their CO$_2$ emissions even during periods of economic growth has been noted prominently in the literature.[33–35] However, we do not have an adequate understanding of the mechanisms that have enabled such a hopeful development. Existing knowledge about how to reduce anthropogenic CO$_2$ emissions while not impeding economic development was predominantly derived using *ex ante* analyses.[36–38] *Ex ante* analyses predict emissions based on the modeling of presumed causal relationships of, e.g., electrification, solar power deployment, and other energy system transformations, on CO$_2$ emissions. Empirical studies have shown, *ex post*, that historical developments can differ qualitatively and quantitatively from *ex ante* engineering estimates, confirming or disproving the hypothesized relationships adopted by *ex ante* studies.[39,40] Moreover, emission reductions in highly developed countries have been posited by the environmental Kuznets curve (EKC) hypothesis.[13,41–43] It suggests that people have an increased willingness to pay for environmental quality once they become sufficiently affluent. Recent studies, however, have disputed the methodological robustness of the EKC literature and essentially undermined the validity of the EKC hypothesis as an explanation for emission reduction during periods of economic growth.[14,44] Another explanation for declining emissions accompanying economic growth is the offshoring of heavy industries with increased trade, but the evidence about these mechanisms remains contradictory.[25–27,29,45]

Here, we propose a structural equation model of the relationship between GDP and CO$_2$ emissions, which can investigate the role of additional factors mediating the GDP-CO$_2$ relationship and apply it to an extensive dataset covering 73 economies over the period 1970–2016 (detailed in Note S2 and Table S2, supplemental information). The results show that, keeping other factors constant, per capita CO$_2$ emissions change in lockstep with per capita GDP. We test various mechanisms suggested in the literature to reduce CO$_2$ emissions and our model identifies the following emission-reduction mechanisms as influential: (1) increases in economic productivity, (2) energy system decarbonization (including both increasing renewable shares and the

Table 1. The empirical relationships between CO_2 emissions per capita and economic, energy system, and temperature-related factors based on the benchmark model

Factors affecting per capita CO_2 emissions[a]	Explanatory variables	Coefficients	Bootstrap SE	95% Bca CI	
Economic development					
Economic growth	Δ[b] *GDP/p*	1.0194***[c]	0.1082	0.8150	1.2406
(1)[d] Increases in productivity	Δ *A·L/p*	−0.4824***	0.0923	−0.6764	−0.3184
(2) Deindustrialization	- Δ *Vsh_Ind*	−0.7724***	0.2890	−0.3107	−1.4585
Energy system transition					
(3) Decarbonization					
Fossil fuel to renewables	Δ *TPESsh_renw*	−1.4942***	0.1333	−1.7125	−1.1761
Coal to natural gas	- Δ *TPES_FFsh_coal*	−0.5883***	0.1063	−0.3568	−0.7541
(4) Electrification	Δ *Electrification*	−1.2589***	0.6091	−2.4193	−0.4669
Other					
(5) Winter warming	Δ *Tmin*	−0.0050***	0.0007	−0.0065	−0.0037
n (countries/regions)	73				
N (observations)	3,283				
R^2	0.45				

*p < 0.05, **p < 0.01, ***p < 0.001 (two-sided *Z* test, 1,000 bootstrap runs).

[a] Full results are provided in Table S3, Note S3, including the non-statistically significant emission effects ($p \geq 0.05$), estimates of the GDP equation, and SEs and CIs estimated without bootstrapping.

[b] Δ is the first difference operator.

[c] The CO_2 elasticity of GDP is not statistically different from 1 (prob > χ^2 = 0.81).

[d] Changes of the factors in desirable directions, as indicated by the negative coefficients, correspond to the emission-reduction mechanisms (1)–(5) we referred to throughout the manuscript.

fuel switching from coal to gas), (3) electrification, (4) winter warming, and (5) deindustrialization (see explanation of the selection and test of these five and other suggested mechanisms in the experimental procedures). Over the past 47 years, energy system decarbonization contributed the most (i.e., 28%) to emission reductions at high economic development levels when electrification was saturated, while at low development levels, increases in economic productivity contributed the most (i.e., 36%) to emission reductions in addition to being a driver of economic growth. Therefore, our study resurrects the debate about the role that economic growth plays in anthropogenic CO_2 emissions and identifies vital energy systems and economic development characteristics that contribute to emission reductions. Our findings also inform the policy debate around these issues by showing that, without unprecedented transformations, no country is likely to achieve economic growth annually while gradually cutting CO_2 emissions, i.e., by the 2% (Tanzania) to 17% (Qatar) annual average reduction rate required to reach net-zero by 2050. The *ex post* empirical evidence we present can be valuable for informing emission-reduction policies, given that there can be only a few years left at our current rate of emissions before we exceed the 1.5°C carbon budget.[46]

RESULTS

Emission-reduction mechanisms during economic growth

Using our benchmark model, we find that a 1% increase in GDP per capita was associated with a 1% increase in CO_2 per capita on average, holding all other factors constant (Table 1; full results of the benchmark model are available in Note S3 and Table S3, supplemental information). Our estimates of this elasticity are robust to various model specifications. The specifications account for the emission effect of economic growth in previous years, the asymmetric emission effects of economic expansions versus recessions, emission effects related to countries' development levels, and using a three-equation (CO_2, primary energy use, and GDP) simultaneous model. In addition, our estimates are robust to models estimated with 5-year rolling windows to eliminate the influence of cyclical variations and using alternative data sources. Results of the various tests are available in Note S4 and Tables S4–S6, supplemental information.

In addition to changes in GDP per capita, five factors describing changes in the economy, energy system, and temperature were identified to significantly affect observed carbon emission reductions in our sample (Table 1). We find that while economic productivity drives economic growth, at the same time a 1% increase in a country's overall economic productivity was associated with roughly a 0.5% annual reduction in its CO_2 emissions per capita (Table 1). Combining the growth-inducing and direct effects of productivity on CO_2 emissions, a 1% rise in productivity causes a net increase in emissions of 0.5%. Such mediating effect was not found for other growth-driving factors (Table S3), indicating that the type of economic growth plays a role in a nation's emission pathway. Consistent with the conventional wisdom that deindustrialization—for example, through a move to services—reduces CO_2 emissions, our results also show that CO_2 emissions per capita were reduced by about 0.8% as the share of non-industrial output in GDP grew by 1%. Our results further reveal that the majority (>80%) of the emission-reduction effect of deindustrialization was attributable to a reduction in primary energy use (Table S5).

Energy system decarbonization and electrification also contributed to reduced carbon emissions. A 1% annual increase in the share of renewable energy used in energy supply (referred to as "renewables share" thereafter) was associated with a 1.5% yearly decrease in CO_2 emissions per capita on average (Table 1). The three-equation (CO_2, primary energy use, and GDP) simultaneous model further reveals that two-thirds of the renewable shares' emission-reduction effect was attributable to lowering carbon intensity, and the rest to improving energy efficiency (Table S5). Specifically, a 1% annual increase in renewables share is associated with a 1% yearly decrease in CO_2 emissions per capita (see "CO_2 equation") and a 0.5% decrease in primary energy use per capita (see "energy equation"); the relationship between primary energy use and CO_2 emissions per capita is unitary (CO_2 equation). Our result could indicate that renewable energy was more efficient than fossil fuels in serving energy demand during the observation period. However, this result could also be attributable to different accounting approaches used for calculating the primary energy content of fossil and non-fossil fuels.[47]

Among fossil fuels, we find that decarbonization owing to natural gas displacing coal (i.e., fuel switching) also contributed to significant CO_2 emission reductions. We estimate that annual CO_2 emissions per capita decreased by 0.6% for every 1% increase in the share of natural gas substituted for coal (Table 1). As further revealed by results from the three-equation simultaneous model (Table S5), much of the decarbonization effect of fuel switching was attributable to reducing carbon intensity, and the rest was attributable to improving energy efficiency. Specifically, for every 1% increase in the share of natural gas substituted for coal, the direct reduction of CO_2 emissions per capita was 0.4% (CO_2 equation), and the impact via primary energy use was 0.2% (energy equation). With the same fuel mix, electrification contributed to reduced carbon emissions by improving energy efficiency. Every 1% increase in the share of electricity in the final energy supply was associated with a 1.3% decrease in annual per capita CO_2 emissions.

Winter warming also reduced national CO_2 emissions per capita (Table 1). Our results showed that an increase in the average temperature of the coldest month by 1°C was associated with a 0.5% annual reduction in carbon emissions during the observation period. Finally, only 0.02%–0.04% of the annual emission reduction ($p < 0.05$) was attributable to the time-invariant characteristics of a few developed and emerging European economies (Bulgaria, France, Ireland, Poland, Romania, Sweden, and the UK) and Mozambique. The time-invariant characteristics can be, for instance, countries' political institutions[48] geography, culture, and renewable energy potentials.[49]

All factors included in Table 1 had significant effects on changing annual CO_2 emissions per capita over the 47 years of data in our sample. The effects of the five emission-reduction mechanisms were estimated precisely ($p < 0.001$) despite variation across time and countries' development levels. For deindustrialization and electrification, the magnitudes of their emission-reduction effects depended on further characteristics of the two processes, as illustrated by the relatively greater confidence intervals (CIs) shown in Figure 2A. The goodness-of-fit of our model, as measured by R^2, was 0.45, as compared with R^2 statistics of between 0.05 and 0.27 from prior models examining the empirical relationship between changes in GDP and CO_2 emissions per capita.[20,22,50,51] Statistical tests show that our results are robust to alternative model specifications and data sources (Note S4 and Tables S4–S6 in supplemental information) and are verified by statistical tests for multicollinearity, non-stationarity, and cross-sectional correlation (Note S5 and Tables S7–S11, supplemental information).

Emissions cuts contributed by the reduction mechanisms

To quantify the total CO_2 emissions contributions of the main mechanisms over 1970–2016, we combined the estimates from the benchmark model with data from the observed year-by-year changes in economic output in our data (3,283 country-year observations, Equation 7 in experimental procedures). The results from these analyses showed that changes in GDP per capita lead to an increase in CO_2 emissions per capita adding up to a total of 16–29 petagrams (Pg) (95% CI) of global CO_2 emissions during 1970–2016 (Figure 2B). Please note that changes in per capita GDP comprised both periods of growth (76% of instances) and periods of decline. A decline of GDP per capita commonly contributed to a decline in per capita CO_2 emissions. This finding is consistent with prior findings that increases in GDP per capita are a primary driver of increases in CO_2 emissions per capita.[53–55] Our results are based on empirically estimated relationships. By contrast, prior assessments have relied mostly on index-decomposition analysis and have assumed that changes in each mechanism contribute to proportional and independent changes in carbon emissions; for instance, a doubling of energy intensity leads to a doubling of emissions. Contrary to these assumptions, our empirically estimated relationships reveal that most of the main mechanisms have had non-proportional effects on carbon emissions (Table 1) arising from stochastic influences and interdependencies.

Aside from the emission effects associated with changes of GDP per capita, the five emission-reduction mechanisms contributed to global CO_2 emission reduction over 1970–2016. Specifically, increases in economic productivity, energy system decarbonization, electrification, deindustrialization, and winter warming resulted in emission reductions of about 6, 5, 4, 2, and 2 Pg, respectively (Figure 2C). The emission reductions were contributed by the desirable changes of the economic, energy, and temperature factors, which were present in 42%–69% of the country-year sample, depending on the factors of interest. In the rest of the samples, changes of these factors contributed to increasing emissions, e.g., by shifting from gas to coal or increasing the share of industry in the GDP. Considering all country-year samples, only economic productivity and electrification changes contributed to net CO_2 emission reductions globally, as shown in Figure 2B. The mix of upward and downward trends of other factors resulted in minimal or upward effects (only in the case of the share of renewables) on CO_2 emissions globally over the past 47 years.

Understanding what mechanisms contributed to past CO_2 emission reductions for countries of varying levels of economic development is informative for both the design and the evaluation of emission-abatement policies (Figure 2D). We find that emission reductions in developed economies were always and increasingly dominated by energy system transition, especially

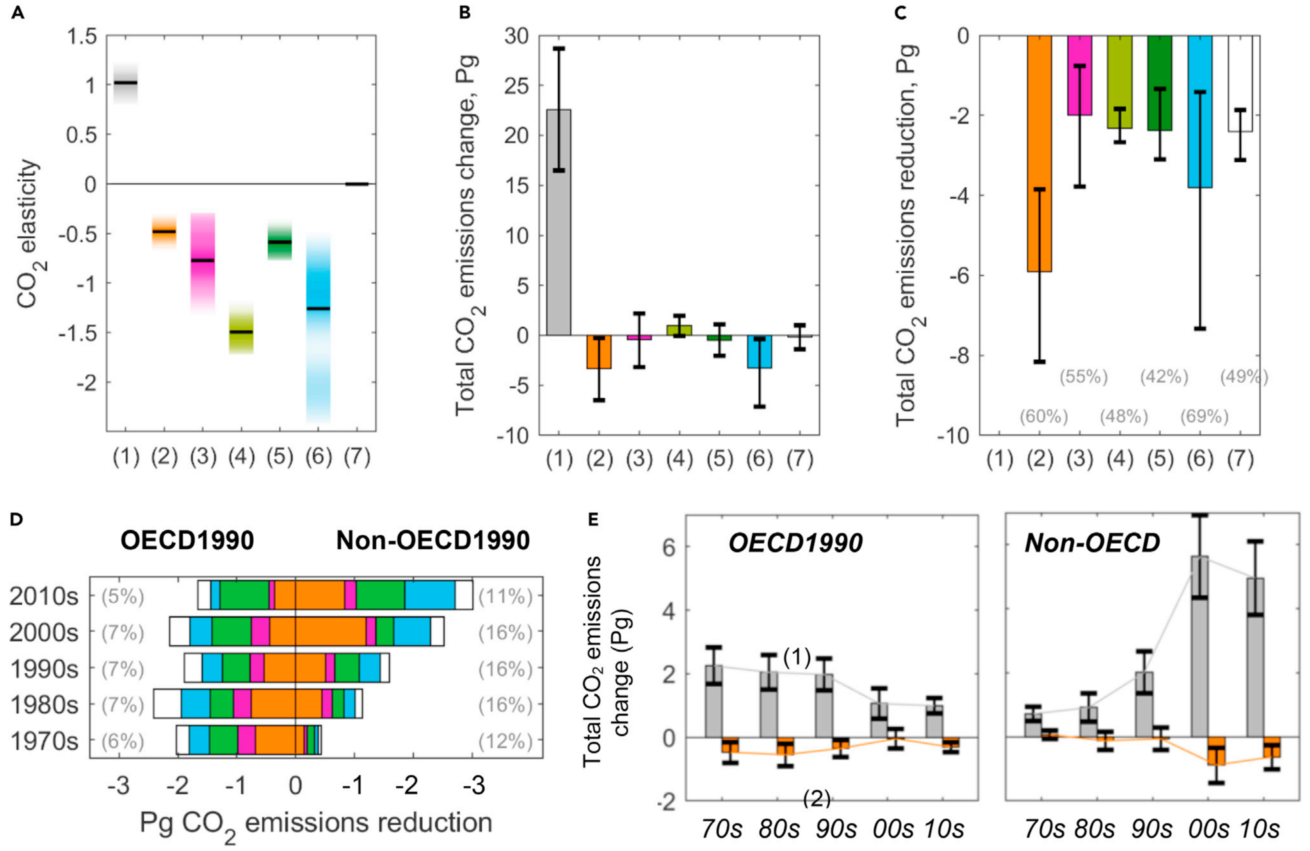

Figure 2. Effects of the economic, energy, and temperature factors on CO$_2$ emissions derived from the benchmark model

The same labeling as in Table 1: economic growth rate (1), economic productivity (2), deindustrialization (3), decarbonization by shifting to renewables (4) or from coal to natural gas (5), electrification (6), and winter warming (7). They are consistently color coded in the subplots. Error bars show the ranges calculated from the 95% bias-corrected and accelerated (BCa) confidence intervals (Table 1).

(A) Estimated CO$_2$ elasticities (coefficients in Table 1, black bars) and distributions of the 1,000 bootstrapped estimates (shaded areas). The color saturation indicates the probability that the CO$_2$ elasticity is at a given value plotted in a "visually weighted" fashion based on Burke et al.[52]

(B and C) Total contributions to emissions changes (*TEC*) (all 3,283 observations) and emissions reductions (*TEC_R*) (based on observations where the mechanisms resulted in emissions reduction effects; sample coverage in the parenthesis), respectively (in petagrams [Pg]). Error bars show the ranges calculated from the 95% BCa confidence intervals (Table 1). See Figure S1 for a breakdown by decade and developed/developing countries.

(D and E) (D) *TEC_R* by decade and development level. Sample coverage by development level and decade are provided in the parentheses. The green bars represent emission-reduction effects of energy decarbonization, i.e., (4) and (5). (E) The emission implication of economic development: economic growth rate (1) and productivity (2).

decarbonization. At high levels of economic development, decarbonization became ever more critical for CO$_2$ emission reductions. The importance of energy transitions (i.e., decarbonization and electrification) for CO$_2$ reductions has grown steadily since the 1980s (from 36% to 57%) in developed countries. By contrast, across developing countries increased economic productivity and electrification were the primary mechanisms, accounting for 60% of their CO$_2$ emission reductions. Moreover, our results show that CO$_2$ emission reductions in developing economies have grown since the 1990s and dominated global mitigation over the last decade (comprising 64% of global emission reductions in the 2010s). However, more rapid CO$_2$ emission increases due to rapid economic growth over the same period outpaced these reductions.

On a global level, increasing economic productivity was a universal mechanism of both reducing per capita CO$_2$ emissions and driving up economic growth in our sample (Figure 2E). This explains much of the emission reductions achieved in developing economies during the 2000s (47% of total reductions) and over the past 47 years (36% of total reductions). The emission-reducing effect of productivity growth declined in importance in developed countries, while it rose from zero to quite crucial for developing economies. The small relative importance of productivity growth as a CO$_2$-reduction mechanism in developed countries as a whole is due mainly to the steady and notable emission-reduction effects contributed by energy system decarbonization in developed countries since the 1970s (see Note S6 and Figure S1, supplemental information). As such, our results show that the emission-increasing effects of economic growth can be reduced when countries increase economic productivity. Thus, increases in economic productivity—and not merely in output—may be needed to help developing economies balance the dual objectives of economic growth and environmental sustainability.

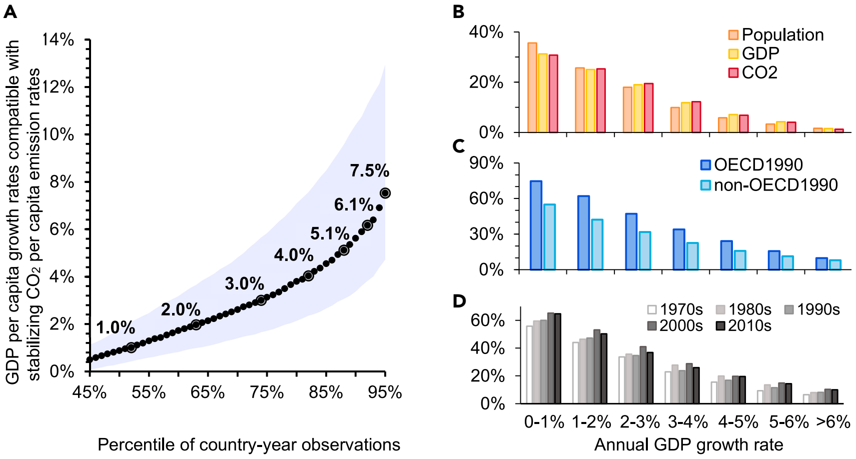

Figure 3. GDP per capita growth rates compatible with stabilizing or declining CO_2 per capita emission rates under future "business-as-usual" development

(A–D)The percentile distribution of the maximum annual GDP growth rates compatible with a zero-emissions growth rate in the same year (A). The maximum compatible GDP growth rates are equivalent to the sum of the emission reduction outcomes of the same-year changes in economic productivity, deindustrialization, energy system decarbonization, and electrification over 1970–2016. The shading represents the range based on the 95% confidence interval for the estimated effects. The remaining panels show the corresponding distribution of global population, GDP, and CO_2 emissions of fossil fuel combustions and industrial processes (B), country-year observations for developed (OECD) and developing (non-OECD) countries, respectively (C), and country-year observations over different decades since the 1970s (D). Emission reductions associated with economic recessions (periods of negative per capita GDP growth) are not the focus of this analysis and thus are not shown here.

Our model accurately predicts net emission reductions for 83% of the observed occurrences of declines in carbon emissions during periods of economic growth over 1970–2016. Such consistency is most notable for 15 developed and developing economies where our estimated reductions match 95% of observed, repeated occurrences (≥15 years) of emission decline coupled with GDP growth (see Figure S2, supplemental information). Energy system decarbonization dominated the recent CO_2 emission reductions achieved during periods of economic growth in the UK, Denmark, New Zealand, Uruguay, and the US. In France, Ireland, Sweden, and Poland, the most recent CO_2 emission reductions during periods of economic growth were driven primarily by time-invariant country characteristics. These characteristics and their emission-reduction effects need to be explored further in future research.

GDP growth compatible with declining emissions

Suppose the observed trends of the main emission-affecting mechanisms held steady over the near term. In that case, we could identify economic growth rates compatible with stabilizing or declining carbon emission rates (see experimental procedures). This assumption appears plausible considering that we found no trends in our sample over the 47 years: national spending on emission-abatement programs remains low and stagnant,[8] and abatement technologies, such as carbon capture and sequestrations, are commercializing and deploying at a very slow rate.[56,57]

Based on these assumptions, we estimate that, under varying rates of positive economic growth, stabilizing CO_2 emissions per capita can be achieved in roughly 55% of country-year observations in our data sample (Figure 3A). These country-year pairs account for 36% of the global population and 31% of global economic output and CO_2 emissions (Figure 3B). The viability of achieving economic growth while stabilizing CO_2 emissions drops dramatically for higher economic growth targets. If GDP per capita grows by >1%, >2%, >3%, and >5%, stabilized same-year per capita CO_2 emissions can be expected in roughly 50%, 40%, 25%, and 10% of the country-year pairs in our sample, respectively (Figure 3C). The percentages are higher among developed economies than among developing economies. We do not find sufficient evidence that the prospect of sustainable economic growth has increased over time (Figure 3D).

Moreover, our results indicate that the viability of achieving economic growth drops dramatically if more CO_2 emissions were to be reduced to attain key climate targets. Given past patterns of productivity gains, electrification, deindustrialization, and shifts in energy supply, only about 10% of country-year instances in the sample can achieve the 7% global average annual emission-reduction rate for the 1.5°C warming goal while maintaining positive economic growth. Furthermore, given the current national emission level and without population growth, the country-specific annual average reduction rate of CO_2 emissions from now on ranges between 2% (Tanzania) and 17% (Qatar) to achieve zero CO_2 emissions by 2050 (see Note S7). Based on the observed trends of the main emission-reduction mechanisms and the estimated emission effects, no country can achieve the net-zero-emissions goal while maintaining economic growth without drastically strengthening the mitigating forces (see Note S7 and Figure S3, supplemental information). In light of this target, our results suggest that even the most recent trends of energy system transitions in developed economies are insufficient for reaching the 1.5°C global warming goal.

Our estimates of future emission outcomes are based on historical patterns, assuming similar future trends. Countries may reduce their future emissions by shifting more aggressively toward low-carbon energy sources or deploying emerging CO_2-abatement strategies, such as bioenergy with carbon capture and sequestration. According to recent analyses by Integrated Assessment Models (IAMs), these technologies are essential for meeting the 1.5°C target.[58,59] Emission outcomes from economic development can also be altered if more mechanisms are included, such as climate change legislations[49] in response to global warming,[52] and if population size diminished.[51] Nonetheless, the findings suggest that, without unprecedented transformations, few countries can sustain economic growth while stabilizing or reducing their carbon emissions.

DISCUSSION

The emission-reduction mechanisms we tested and estimated are constrained by the plausible and theoretical ranges of the economic and non-economic factors. Such factors include but are not limited to the mix of low-carbon energy sources in the electrical grid, the electrification rate, and the extent of deindustrialization. Economic productivity reduces but does not entirely offset the positive unitary effect GDP growth rate has on the CO_2 emission rate. The explanatory variables we tested explained less than 50% of the variance observed among countries and across time, indicating that a considerable fraction of the emission variations either remains unexplained or may be related to noise in the data. It is subject to further research. All of the variables used in this study are subject to some level of noise resulting from changes in data collection practices, reporting standards, and definitions. Such noise invariably influences the explanatory power of a model. Some of the unexplained variances may be attributable to factors not included in the model, such as various influences of the weather, regional differences in the strength of various mechanisms, structural changes not captured by the simple indicator of industry's share of GDP, or changes in emissions not related to energy consumption, such as from cement production. Moreover, to reduce problems introduced by country heterogeneity and poor data quality, we omitted countries with short time series (<40 years) and small populations (<1 million in the year 2010) in our analysis.

Using a structural equation model in a first-difference form and a large number of observations, we showed a clear and unitary relationship between GDP and CO_2 emissions. At the same time, we identified five mechanisms that explain deviations from this unitary relationship and can hence serve as potential reasons why previous empirical studies focusing on GDP as the only driver of CO_2 emissions have yielded such divergent results. More importantly, the estimated emission-reduction effects of the mechanisms offer crucial empirical evidence for pursuing mitigation strategies during economic growth. The observed strong coupling between economic growth and growing CO_2 emissions can be weakened by increased economic productivity and mediated by energy system decarbonization, electrification, increasing winter temperatures, and a shift from industry to services. Based on an extensive global dataset and verified by various statistical tests, our *ex post* analysis confirms the emission reductions from energy system decarbonization and electrification suggested by *ex ante* studies. Previous *ex post* research suggested that renewables, in particular, did not contribute to reduced use of fossil fuels and would instead increase energy consumption[40] was based on smaller datasets. Our results further highlighted that shifting to renewables is about 2.5 times as effective as the coal-to-gas switching for reducing CO_2 emissions. This is good news for climate change mitigation, as a shift toward low-carbon energy sources is the only one of the investigated mechanisms not limited by an upper (electrification) or lower (shift to gas, deindustrialization) bound.

Our empirical findings are broadly supportive of recent critiques of the economic growth model,[51] but they also allow for a compromise position. Our results indicate that countries, such as Germany, Denmark, Finland, New Zealand, and Uruguay, have managed to achieve decoupling, i.e., reducing CO_2 emissions during periods of economic growth, primarily through decarbonization of the energy system. Our model, however, suggests that a continued and timely decoupling will require further decarbonization and structural change and that, as soon as the shift toward lower-carbon energy sources stops, emissions will increase as the economy grows. While some, mostly European, countries serve as a model for how to achieve a temporary decoupling of emissions from economic growth, their rates of emission reduction have not been rapid enough to halt global warming at 1.5°C. Thus, one can understand the full significance of the empirical analysis provided with reference to humanity's fixed emission budget to stay within the 1.5°C of the Paris Agreement on climate change. Reducing economic growth, increasing the share of services in the GDP, and electrifying the energy system are all mechanisms that can reduce the emissions while the energy system is decarbonized and hence limit the rate at which this transition needs to happen. The reverse is also true: economic growth per se and investments in construction and manufacturing, in particular, make the Paris target harder to achieve, requiring even faster decarbonization of the energy system.

The policy implications of the above results are as follows. First, continued economic growth leads to a growth in emissions from the present level; the higher the carbon intensity and the lower the productivity of an economy, the higher the emission increase resulting from an input-driven economic growth. It is hence crucial that decarbonization and productivity improvements happen first. Second, some European countries offer a successful model for decarbonizing the economy in which emissions decline while the economy still grows (such as Denmark, Finland, France, Germany, and Sweden, see Note S6)[60]; however, rates of decarbonization even in these leading economies need to be accelerated substantially to reach the Paris climate target. Third, while developing countries have received the economic and emission mitigation benefits from increased productivity, the historical development of their energy mixes has mostly contributed to increasing emissions. Recent trends of electrification and energy system decarbonization resulted in considerable emission reductions in the developing countries, but a dramatic upgrade in their energy system is still needed to mitigate climate change and meet the global temperature goals.

The findings have clear policy implications. As examples, in the US, the infrastructure bill likely to be approved by Congress will result in an increase in industry's share of the GDP and help to grow the GDP while contributing little to decarbonization. To offset the emission increases resulting from the expansion of infrastructure and economic growth, additional investments in clean energy need to be implemented. In China, the continued construction boom with flats being used as a vehicle for savings leads to high emissions and makes it harder to achieve the desired peak in emissions. For developing countries, our findings highlighted the economic and climate benefits of pursuing productivity gains and suggest ending fossil fuel subsidies and increasing climate-related funding targeting clean energy investment and electrification.

While politicians tout the "green recovery" and "building back better," a recent tally of energy-oriented expenditure in recovery packages indicates higher subsidies for fossil fuels than for clean energy.[61] Support for fossil fuel production and emission-intensive industries, such as aviation and construction, will make it more challenging to reconcile future economic growth with the need to stabilize the climate. It will inadvertently strengthen the argument for a different economic model.[62] Furthermore, the effect of public policy on the economic structure is often not recognized as climate relevant. However, our research clearly underlines the climate benefit of both a shift from industry toward services and an increase in productivity. The recovery is being led by growth in manufacturing and construction, while service industries are still suffering. A stimulus directed at construction and manufacturing cannot help in the required transition unless the expenditure is explicitly directed at mitigating steps, such as building refurbishment and transmission grid upgrades, needed to absorb higher shares of renewables.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Edgar Hertwich (edgar.hertwich@ntnu.no).

Material availability

This study did not generate new unique materials.

Data and code availability

The datasets/code generated during this study are available at https://doi.org/10.17632/spmbbrb3y6.1.

Data sources and dataset description

We develop a novel empirical model using a rich panel dataset from 73 countries over 47 years, from 1970 to 2016 (Note S2; Table S2). Our empirical analyses estimate the relationship between anthropogenic CO_2 emissions per capita and GDP per capita based on a strongly balanced panel dataset that contains annual CO_2 emissions and a variety of economic, energy system, temperature, and policy variables. Anthropogenic CO_2 emissions related to fossil fuel combustion and industrial processes and energy use data were obtained from the International Energy Agency.[47] These emissions have been the main contributor to the rising CO_2 levels in the atmosphere, and CO_2 emissions are the most significant component of anthropogenic GHG emissions.[63] Our data on GDP, capital stocks, population, total factor productivity, labor, and human capital index come from the Penn World Table version 9.1.[35,64] The value-added economic data by sectors is collected from the United Nations National Accounts Main Aggregates Database.[65] Climate data for monthly average temperatures are collected from the Climatic Research Unit Time Series (CRU TS version 4.03).[66]

After omitting countries with short time series (<40 years) and small populations (<1 million in the year 2010), each of the 73 countries kept in our sample has 43–47 years of data for all variables used in our model. The dataset covers 88% of the CO_2 emissions by fossil fuel combustion and industrial processes, 87% of total primary supply, 81% of the population, and 89% of GDP in the world over 1970–2016. It offers a good representation of countries from different geographic regions and of different development levels. Detailed descriptions of the dataset and country sample are available in Note S2, supplemental information.

Empirical framework and benchmark model

Equation 1 provides the overarching structure of the benchmark model. CO_2 per capita represents annual per capita carbon dioxide emissions related to fossil fuel combustion and industrial processes in a country. Economic output per capita is measured by GDP per capita. For every unit of economic activity, Ω units of CO_2 are generated.

$$CO_2\ per\ capita. = GDP\ per\ capita \bullet \Omega. \qquad \text{(Equation 1)}$$

We develop a benchmark two-equation simultaneous structural equation model (SEM), with one equation (Equation 5) describing the economic production function that includes the accumulation of human as well as physical capital and the other (Equation 6) determining changes in CO_2 emissions per capita conditional on growth in GDP per capita.

GDP per capita based on the Cobb-Douglas aggregate production function, economic output for country i at time t ($Y_i(t)$) is produced through a combination of capital stock $K_i(t)^\alpha$, human capital stock $H_i(t)^\beta$, and labor $L_i\ (t)$ multiplied by total factor productivity $A_i(t)$, where α and β represent the model parameters to be estimated empirically[67]:

$$Y_i(t) = K_i(t)^\alpha H_i(t)^\beta (A_i(t)L_i\ (t))^{1-\alpha-\beta}. \qquad \text{(Equation 2)}$$

Dividing both sides by population (p), we obtain *GDP per capita* (Equation 3). Furthermore, we substitute the human capital index (*hc*) as the measure of human capital per person and specify the share of intangible assets in capital *(Ksh_Intang)* in Equation 3, considering that intangible capital assets may have different growth implications than tangible assets as captured by the parameter δ. Other determinants of GDP are captured by the multiplier ε_1, including country characteristics (e.g., political institutions, geography, and culture) and contemporaneous shocks (e.g., global financial crisis). These factors are not specified separately in Equation 3 either because of the lack of data or because they change very slowly and are considered time invariant. Furthermore, substituting $\gamma = 1 - \alpha - \beta - \delta$ for the parameter on the product of labor and total factor productivity, we obtain the following model:

$$GDP\ per\ capita = (K_i(t)/p_i(t))^\alpha \bullet hc^\beta\ Ksh\_Intang^\delta \bullet \varepsilon_1 \bullet (A_i(t)L_i(t)/p_i(t))^\gamma. \qquad \text{(Equation 3)}$$

The anthropogenic carbon dioxide emission intensity of an economy, Ω, depends on multiple growth-related and non-growth-related factors that are observable and unobservable, $\boldsymbol{x}$ and ε_2, respectively, as follows:

$$\Omega = f(x, \varepsilon_2) = f(Ysh, Ksh, A, hc, O, EST, T, \varepsilon_2). \qquad \text{(Equation 4)}$$

Growth-related factors

Firstly, the composition of the economic output (*Ysh*) matters for the emission intensity of the economy. The process of industrialization, which historically has been energy intensive, is regarded as an essential driver for the increase of fossil fuel combustion anthropogenic CO_2 emissions.[13] In comparison, the energy or CO_2 implications of a growing service sector have been speculated, but evidence about the role of this sector has been limited.[68] Industrialization is commonly represented by the fraction of total value added by industrial activities, *Vsh_ind*. To explore the emission implications of the capital asset mix, we also included the fraction of intangible assets *Ksh_Intang* in the emission intensity equation, as we did in the GDP equation, Equation 3. Besides economic "composition," Ω can also be affected by the productivity of economic production (*A*) and the level of human capital *hc*. Furthermore, trade-emission linkages also have received considerable attention in recent research, e.g., Franzen and coworkers.[25,27] We, therefore, also test the emission effects of international trade openness (*O*), commonly calculated as the total trade (imports plus exports) as a fraction of total GDP.

Energy system transformation

Electrification[8,57] and less carbon-intensive fuels[33,57,68,69] have been identified as the leading causes of falling energy intensity observed in many countries. Here, we specify and estimate the effects of decarbonizing energy supplies by Equation 1 displacing fossil fuels with non-fossil fuels, Equation 2 displacing coal and coal products with natural gas and natural gas products, and Equation 3 displacing oil and oil products with natural gas and natural gas products. The three decarbonizing processes are measured by three variables, respectively: *TPESsh_renw* (share of renewable energy in total primary energy supply), *TPES_FFsh_coal* (share of coal and coal products in total fossil primary energy supply), and *TPES_FFsh_oil* (share of oil and oil products in total fossil primary energy supply). We define *electrification* as the fraction of electricity in total final energy consumption. Increases in energy prices may reduce emission intensity Ω by affecting energy demand.[68,70,71] However, energy price signals are more heterogeneous across times and countries. Unfortunately, such detailed information is unavailable for the temporal and spatial coverage of our analysis.

Other factors

Temperature (*T*) may affect energy demand and thus emission intensity Ω. We use the lowest and the highest monthly average temperatures in a year (*Tmin* and *Tmax*) to estimate the emission effects of winter warming and summer warming, respectively. Other determinants of emission intensity Ω are captured by ε_2, including country characteristics (e.g., political institutions, geography, and culture) and contemporaneous shocks (e.g., global financial crisis).

Using the 47-year longitudinal sample covering 73 countries around the world, we derive the functional form of the primary model as follows. First, to estimate changes over time, we took the first differences of Equation 3 for country *i* and year *t*. The upper dot () is the first difference operator (instead of using Δ, the dot is used for a more concise representation). Second, to obtain a linear functional form of the model specified in Equation 3, we took the natural logarithms of both sides of this equation to obtain Equation 5. To obtain Equation 6, we again took the first differences of the variables expressing "shares" or "ratios" (e.g., *TPESsh_renw*, and *electrification*) and temperature extremes (*Tmin*, *Tmax*). In both equation specifications, the country-fixed effects (*u*) capture the aggregated effects of the time-invariant variables, and the year-fixed effects (*t*) capture the aggregated effects of global time trends. They are not specified further due to the lack of data or the fact that they change very slowly and are considered time invariant. $\varepsilon_{*i,t}$ is the error term in each equation.

Our two-equation SEM then took the following functional form:

$$(G\dot{D}P/p)_{i,t} = \alpha \cdot (K/p)^{\dot{}}_{i,t} + \beta \cdot h\dot{c}_{i,t} + \delta \cdot Ksh\_In\dot{t}ang_{i,t} \dot{+}$$

$$\gamma \cdot (AL/p)_{i,t} + u_{1i} + t_{1t} + \varepsilon_{1\,i,t} \qquad \text{(Equation 5)}$$

$$(C\dot{O}_2/p)_{i,t} = \omega \cdot (G\dot{D}P/p)_{i,t} + \theta \cdot Vs\dot{h}\_Ind_{i,t} + \delta_2 \cdot Ksh\_I\dot{n}tang_{i,t} + ^{\cdot}$$

$$\alpha_2 \cdot (AL/p)_{i,t} + \gamma_2 \cdot \dot{h}c_{i,t} + \varepsilon \cdot \dot{O}_{i,t} + \rho \cdot TPESs\dot{h}\_renw_{i,t} +$$

$$\varphi \cdot TPES\_FFsh\_coa\dot{l}_{i,t} + \vartheta \cdot TPES\_FFsh\_oi\dot{l}_{i,t} +$$

$$\sigma \cdot Electrificatio\dot{n}_{i,t} + \tau \cdot T\dot{m}in_{i,t} + \psi \cdot Tma\dot{x}_{i,t} + u_{2i} + t_{2t} + \varepsilon_{2\,i,t} \qquad \text{(Equation 6)}$$

We estimated the coefficients of this model using the three-stage least-squares estimator (3SLS) and obtained robust standard errors by 1,000 bootstrapping runs in Stata/MP.[72]

By estimating the GDP-CO$_2$ relationship using the two-equation simultaneous model, we ensured the consistency of the estimates under endogeneity. Endogeneity can arise from common factors that affect both GDP and CO$_2$ emissions and which can, therefore, induce a spurious relationship, such as capital formation and technological changes. By specifying how CO$_2$ emissions are affected by growth-related and non-growth-related mechanisms, while also controlling for GDP changes, we allowed for heterogeneous responses to changes in CO$_2$ emissions to the same rate of economic growth across countries. Results from a wide range of statistical tests showed that our model was robust to non-stationarity and cross-sectional dependence that have undermined estimate consistency in prior studies (see Note S4 and Tables S4–S8). Our estimates were also robust to alternative model specifications and data sources, as shown in Tables S9–S11.

Computing total emission change and reduction

For each emission-driving factor *j*, Equations 7 and 8 calculate its total contribution to CO$_2$ emission change ($TEC^{(j)}$) and to CO$_2$ emission reduction ($TEC\_R^{(j)}$), respectively, over 1970–2016. $\beta^{(j)}$ is factor *j*'s CO$_2$ elasticity (i.e., the regression coefficient in Equation 6), $\dot{x}^{(j)}_{i,t}$ is the rate of change from year *t*–1 to year *t* in the level of factor *j* in country *i*, and $CO_{2\,i,t-1}$ is the total national emissions in year *t*–1. Ranges of *TEC* and *TEC_R* are calculated using the 95% accelerated bootstrap CI (bias-corrected and accelerated) estimated for each $\beta^{(j)}$.

$$TEC^{(j)} = \beta^{(j)} \cdot \sum_t \sum_i \dot{x}^{(j)}_{i,t} \cdot CO_{2\,i,t-1} \qquad \text{(Equation 7)}$$

$$TEC\_R^{(j)} = \beta^{(j)} \cdot \sum_t \sum_i \dot{x}^{(j)}_{i,t} \cdot CO_{2\,i,t-1}\ \forall\ \beta^{j} \cdot \dot{x}^{j}_{i,t} < 0 \qquad \text{(Equation 8)}$$

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.10.010.

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AUTHOR CONTRIBUTIONS

Conceptualization, E.G.H. and R.W.; methodology, R.W. and V.A.A.; investigation, R.W. and E.G.H.; writing – original draft, R.W.; writing – review & editing, R.W., E.G.H., and V.A.A.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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