Empirical Explanations of Carbon Mitigation during Periods of Economic Growth

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Abstract

Prior research on the empirical relationship between anthropogenic carbon dioxide (CO₂) emissions and economic growth, as measured by increases in gross domestic product (GDP), indicate that a 1% growth in GDP can lead to anything between an increase in emissions by 2.5% to a decline by 0.3%. Studies have paid little attention to independent mechanisms that reduce emissions. Statistical properties of the data undermine the estimation techniques used in many studies. To address these shortcomings, we used novel methods and panel data integrating emissions, economic, and energy-system characteristics across 70 economies over 1970-2013 to derive a universal GDP-emissions relationship and identify key emissions-reduction mechanisms. We found that, robust to a variety of estimation procedures, every 1% increase in GDP was associated with a 1% increase in CO₂ emissions when controlling for other mechanisms. Emissions reductions were mainly driven by four mechanisms: (i) energy system decarbonization, (ii) increased economic efficiency, (iii) electrification, and (iv) deindustrialization. A 1% increase in these factors was associated with 0.2-1.8% reductions in CO₂ emissions per year; together, these factors contributed to 18 petagrams of emissions reduction globally over 1970-2013. Decarbonization contributed most to emissions reductions in high-income economies, while economic efficiency and electrification contributed most to reductions in low-income economies.

Keywords: CO₂-GDP elasticity, carbon reduction mechanisms, environmental sustainability, economic growth

Significance Statement

National commitments to climate change mitigations are impeded by a widely perceived economy–environment tradeoff. Empirical literature has sought and failed to identify a consistent CO₂-GDP relationship and less is known about the effect of different emissions-reduction mechanisms. We quantify these mechanisms explaining recent observed CO₂ emissions reductions during periods of GDP growth, focusing on economic structural changes and energy system transformations. Remarkably, when these mechanisms are adequately considered, the influence of GDP growth is unequivocally proportional to emissions growth and a large fraction of the variation in emissions across >3,000 country-year observations is explained. Our study shows that moving to low-carbon energy sources and shifting economic activity from industry to services have indeed been effective mechanisms to reduce emissions.

1 Introduction

2 The empirical relationship between CO₂ emissions and economic development has attracted broad
3 interest from researchers and policy makers alike ([1](#)). Prior studies have focused on identifying this
4 relationship by estimating the elasticity of CO₂ with respect to the gross domestic product (GDP):
5 the percentage change in a country's CO₂ emissions for every 1% increase in GDP. Studies have
6 variously shown everything from a 0.3% *decrease* to a 2.5% *increase* in CO₂ emissions for every
7 percent growth in a country's GDP ([2-20](#)). As a result, they suggest fundamentally different
8 patterns between economic growth and CO₂ emissions ([Fig. 1 a-b](#)). Variation in these estimates has
9 been attributed to sample selection ([Fig. 1 b](#)) and to the failure to adequately address problematic
10 properties of the analyzed data, such as non-stationarity ([21](#)), endogeneity ([19, 22](#)), and cross-
11 sectional heterogeneity ([7, 23](#)), which are known to lead to spurious results.

12
13 More problematically, such GDP-focused statistical studies of past emission trends have provided
14 little insight into factors that shape a country's CO₂ emissions, such as particular kinds of policies
15 or changes in economic structure ([24](#)). The literature is especially inadequate at explaining why
16 some countries, including the United Kingdom, Germany, France, Denmark, Sweden, Romania,
17 Poland, and Hungary ([25-27](#)), have been able to reconcile GDP growth with emission reductions.
18 A popular explanation for emissions reductions is the Environmental Kuznets Curve (EKC)
19 hypothesis (e.g., ([6, 28, 29](#))), which posits that people have an increasing willingness-to-pay for
20 environmental quality once they become sufficiently affluent. Yet, recent studies have disputed the
21 methodological robustness of the EKC literature and largely undermined the EKC hypothesis for
22 CO₂ emissions ([7, 30](#)). Other explanations for declining CO₂ emissions have included the
23 offshoring of heavy industries and increased trade, but the evidence about these mechanisms
24 remains contradictory ([18-20, 22, 31](#)).

25
26 To address these gaps, we develop a novel empirical model using a rich panel data set from 70
27 countries between 1970-2013. Methodologically, we develop a two-equation simultaneous model,
28 with one equation describing the augmented Solow growth model and the other determining
29 changes in CO₂ emissions conditional on GDP growth. We model how changes in CO₂ emissions
30 were determined through GDP growth-related and non-growth-related mechanisms to understand
31 the empirical association with emissions reductions. Our model specification circumvents the
32 common challenges of endogeneity, non-stationarity, and cross-sectional heterogeneity and
33 ensures that the empirical relationships are consistently estimated. Based on the empirical
34 relationships and the observed year-to-year changes in the panel, we then identify key mechanisms
35 for emissions reduction and quantify their effects. Our analyses are enabled by recent developments
36 in data availability: our panel data set includes information about national CO₂ emissions,
37 economic growth, energy system transitions, and other emission-relevant mechanisms observed
38 over the past 44 years (1970-2013), covering 80-90% of the global CO₂ emissions, primary energy
39 use, population, and GDP. The data set and the model are explained in detail in [Data and Methods](#)
40 and [Supplementary Information B](#).

Fig. 1. Emissions-economy pathways: CO₂-GDP relationships and time-series observations. (a). A schematic illustration of characteristic CO₂-GDP relationship; (b). CO₂-GDP relationships suggested by the CO₂-GDP elasticity estimated by previous studies (ranging from -0.3 to 2.5), which are reviewed in detail in [Supplementary Information A](#); c-e, observed (165 countries, 1970-2015) CO₂ emissions related to fossil fuel combustion and industrial processes vs. real GDP in constant U.S. dollars (c), energy intensity of GDP (d), and CO₂ intensity of primary energy supply (e); (c) shows a fairly strong positive correlation between GDP and CO₂ emissions. A reduced-form analysis that controls for country- and year-fixed effects indicates a CO₂-GDP elasticity=0.77 ($p<0.001$), i.e., a 1% of GDP growth is associated with a 0.77% increase in CO₂ emissions on average. The less than unitary CO₂-GDP relationship, referred to as *relative decoupling*, is consistent with the findings of many recent empirical studies e.g., ([15-18](#), [20](#)). Despite a lack of empirical proof, the reduced emission rate is commonly attributed to the falling energy intensities of GDP illustrated in (d), given the energy supplies have been decarbonizing at very slow rates across the world (e).

Main emission reduction mechanisms during GDP growth

Using our benchmark model (containing one CO₂ equation and one GDP equation), we find that annual GDP growth had a 1:1 association with increases in carbon emissions ([Table 1](#) and [Table S4](#)). A 1% increase in GDP was associated with a 1% increase in CO₂ emissions on average, holding all other factors constant. Our estimates of this elasticity are robust to various model specifications, including for lagged economic growth, asymmetric effects of economic expansions

versus recessions, split sample specifications by economic development level, and expanding to a three-equation (CO₂, primary energy use, and GDP) simultaneous model (Table S5-6). Our estimates are also robust to models with five-year rolling windows, eliminating the influence of cyclical variations, and to alternative economic and emission data sources (Table S7).

Table 1. The empirical relationships between CO₂ emissions and driving forces based on the benchmark model.

Explanatory variables ^a	Coefficient	Notes ^b
(1) Growth rate <i>Real GDP annual growth</i>	1.0443*** ^c	Based on real GDP at constant 2011 U.S. dollars.
(2) Other growth-related factors <i>Economic efficiency growth</i> <i>De-industrialization</i>	-0.5967*** -0.4695**	Represented by annual growth rate of total factor productivity (TFP). Change ^d of the share ^d of value added by non-industrial sectors (defined in Supplementary Information).
(3) Energy transition <i>Decarbonization</i> <i>Fossil to non-fossil fuels</i> <i>Coal to natural gas</i> <i>Oil to natural gas</i>	-1.8412*** -0.5072*** -0.1617*	Changes of the share of non-fossil fuels in primary energy supply. Changes of the share of natural gas in fossil fuel supply, due to the share changes of coal and oil, respectively.
<i>Electrification</i>	-1.0367**	Changes of the share of electricity in final energy consumption.
(4) Other factors <i>Growth of trade deficit</i> <i>Winter warming</i>	-0.1770*** -0.0035***	Changes of the net import to GDP ratio Changes of the lowest monthly temperature in a year (in °C)
n (countries/regions) ^e	70	
N (observations) ^f	2955	
R-sq	0.53	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ (two-sided Z test, 1000 bootstrap runs); **a.** Dependent variable: annual growth rate of CO₂ emissions from fossil fuel combustion and industrial processes; **b.** more statistical results for all variables tested in the benchmark model and 95% bias-corrected and accelerated (BCa) confidence intervals are included in Table S4; **c.** the GDP coefficient, i.e. the CO₂-GDP elasticity, is not statistically different from 1 ($Prob > \chi^2_2 = 0.4843$); **d.** Throughout Table 1, “changes” refer to differences of the annual value in year t and year $t-1$ and “shares” are measured in decimals, not percentages. **e.** for each country in the sample, data for all variables are available for 42 years or longer; Zimbabwe is the only exception, where data are available for 33 years; **f.** globally, the observations cover 81% of CO₂ emissions by fossil fuel combustion and industrial processes, 87% of total primary energy supply, 80% of population, and 89% of GDP during 1970-2013 (Table S2).

Further, economic and energy-related factors in our statistical model explain observed carbon emissions reductions. We find that a 1% increase in total factor productivity (TFP), describing a country’s overall economic efficiency, was associated in our panel with a 1% annual increase in GDP and a 0.6% annual reduction in the carbon intensity of GDP, thereby limiting the net increase in emissions to 0.4% per year, on average (Table 1). Consistent with conventional wisdom that the growth of services dampens CO₂ emissions, our results also show that as the share of non-industrial output grew by 1%, CO₂ emissions were reduced on average by about 0.5% per year. The majority (>80%) of the emissions-reducing effect of service growth was attributable to a reduction in primary energy use (Table S6). We also find that increases in intangible assets dampened the effect of GDP growth on carbon emissions (Table S4). In other words, we find that economic growth was

associated with lower carbon emissions in countries that increasingly invested in intangible assets such as software and patents. The accounting rules for intangible assets, however, are relatively new and the heterogeneity within the four aggregated asset classes (Structural, Machinery, Transport Equipment, and Intangibles (27)) may obscure the underlying relationship.

We also estimate that decarbonization and electrification contributed to reduced carbon emissions during our observation period ($p < 0.05$, Table 1 and Table S6). Specifically, a 1% annual growth in the share of non-fossil energy was associated with a 1.8% annual decrease in CO₂ emissions on average. Two-thirds of this reduction was attributable to lower carbon intensity, and the rest to lower overall energy use. The latter estimate could indicate that non-fossil fuels were more efficient overall than fossil fuels during our observation period, but this result could also be attributable to different accounting approaches used for calculating the primary energy content of fossil and non-fossil fuels (32). Among fossil fuels, we find that decarbonization associated with natural gas displacing coal and oil (also known as fuel switching), also accounted for large reductions in emissions. We estimate that annual CO₂ emissions decreased by between 0.2% and 0.5% with every 1% increase in the share of natural gas substituted for oil and coal, respectively. The decarbonization effect of natural gas being substituted for oil arose mainly from energy efficiency gains. The effect of natural gas substituted for coal, meanwhile, arose from both reduced carbon intensity (60%) and improved energy efficiency (40%). We also find that, with the same fuel mix, electrification contributed to reduced carbon emissions by improving energy efficiency: on average, every 1% increase in the share of electricity in the final energy supply was associated with a 1% decrease in annual CO₂ emissions.

Our benchmark model shows that national CO₂ emissions could also be reduced through other mechanisms (Table 1) but with minimal implications for global climate change. Annual CO₂ emissions decreased by 0.2% annually with a 1% annual increase in a country's trade deficit. These reductions were realized through energy outsourcing, which decreased emissions in some regions while increasing emissions in other regions (Table S6). The corresponding emissions outcomes were likely cancelled out on the global level (this is affirmed in later analyses, see Fig. 2a). Our results also showed that increases in the average temperature of the coldest month in a year by 1°C was associated with a 0.4% annual reduction in carbon emissions over the observation period. We find little evidence that changes in CO₂ emissions were driven by time-invariant country characteristics, contemporaneous shocks, or trends. The goodness-of-fit of our model as measured by *R-squared* is 0.53, as compared to *R-squared* statistics of between 0.05-0.27 for prior models (13, 15). Statistical tests indicate our model circumvents or greatly alleviates several critical estimation problems related to the properties of our analyzed data: non-stationarity, endogeneity, and cross-sectional correlation (Supplementary Information C5). Our estimates are robust to alternative model specifications and data sources (Table S5-7).

Emission reductions contributed by the main reduction mechanisms over 1970-2013

To quantify the total CO₂ emissions contributions of the main mechanisms over 1970-2013, we combined bootstrapped empirical relationships uncovered from our benchmark model with observed year-to-year changes in our panel (2,955 observations, see Table 1 and Supplementary Information D). Emission rates changes from year-to-year ranged from -7% to +12% in response to observed changes in the GDP (95% confidence interval (CI)) across the sample (Fig. 2a left). The changes of GDP, with GDP growth observed in 86% of the country-year pairs, increased the

emissions rate by 25 to 37 petagrams (Pg) (95% CI) between 1970 and 2013 ([Fig. 2a right](#)). Changes in productivity and electrification offset this rise by 3-9 Pg. The mix of upward and downward trends in the other mechanisms does not allow us to discern a statistically significant effect of these on the global total. Our results are consistent with prior findings that per capita GDP growth and population increases are the main drivers of CO₂ emissions ([33-35](#)). Yet, our results differ from prior findings in one important respect: Prior assessments assume that changes in each mechanism contribute to proportional and independent changes in carbon emissions; for instance, that a doubling of energy intensity will lead to a doubling of emissions. By contrast, our results are based on empirically estimated relationships ([Table 1](#)). Most of our estimates demonstrate non-proportional changes in carbon emissions, arising from stochastic influences and interdependencies.

- GDP growth and related forces: (1) GDP growth rate; (2) Overall economic efficiency; (3) De-industrialization;
- Energy system transformation: Decarbonization: (4) fossil to non-fossil fuels, (5) coal to natural gas, (6) oil to natural gas; (7) Electrification;
- Other factors: (8) Trade deficit; (9) Winter warming

Fig. 2 CO₂ emissions contributions of the main mechanisms computed from the empirical relationships estimated from the benchmark model. **a. (left)** percentage contribution to annual CO₂ emissions of a country or region. Based on empirical estimates of 1000 bootstrap runs of the benchmark model, the shaded area represents the 95% confidence interval of the percentage contribution values, color saturation indicates the probability that the CO₂ impact is at a given value, and yellow lines indicate the median percentage contribution values. **(right)** net contributions to CO₂ emissions during 1970-2013 (in petagrams, Pg). Error bars show the net CO₂ contributions calculated from the 95% bias-corrected and accelerated confidence interval. **b.** is the same as **a.** except only emission reductions contributed by forces (2)-(9) are accounted for in **b.** Sample coverage is shown in parentheses. Based on **b.**, **c.** shows the relative contributions of forces (2)-(9) by development level and period. **d.** when CO₂ reduction accompanied by GDP growth was observed (“circle”), computed results show CO₂ emissions reduction in the same year (“colored circles”). Color of the circle indicates the dominant emission reduction force: deindustrialization and economic efficiency (red), decarbonization and electrification (blue), and trade deficit and winter warming (grey). Quantities of CO₂ and GDP in **d.** are normalized to 1 in 1971.

Understanding past CO₂ emissions reductions is important to the design and evaluation of emissions abatement policies and mechanisms. By limiting the analysis to country-year pairs with CO₂ reductions, we find that (i) *energy system decarbonization* contributed up to 12% national CO₂ emissions reduction per year (Fig. 2b left, (4)+(5)+(6)) and a total of 8 Pg in global CO₂ emission abatements over 1970-2013 (Fig. 2b right, (4)+(5)+(6)), (ii) *economic efficiency* contributed up to 5% national emissions reduction and 6 Pg in global emission abatements, (iii) *electrification* contributed 3% national emissions reduction and 3 Pg in global emission abatements, and (iv) *deindustrialization* contributed up to 2% national emissions reduction and 1 Pg in global emission abatements. These desirable mechanisms were present in 43%-70% of our sample (Fig. 2b left).

Further, we find that the importance of these mechanisms differed across countries, depending on their level of development (Fig. 2c). Emissions reductions in developed economies over the 44-year period were dominated by energy system transitions (53%), the majority of which were associated with decarbonization policies (37%). These patterns were similar in our full sample of 70 economies, demonstrating that global emissions reductions were led by reductions in developed economies. By contrast, across emerging economies, the two primary mechanisms for emission reductions were advances in economic efficiency (41%) and electrification (20%). We find that the importance of these two mechanisms in global CO₂ reductions has grown steadily since the 1980s, reflecting the rise of emerging economies and their increasingly influential role in global emission trends (Fig. 2d).

For over 70% of the observed occurrences of simultaneous CO₂ decline and GDP growth over 1970-2013, our model also predicts net emission reductions. Such consistency is most notable for a range of advanced and transition economies, namely, Sweden, Denmark, France, Switzerland, Germany, the United Kingdom, Finland, Luxembourg, Poland, Bulgaria, and Uruguay, where the estimated outcomes of net emissions reductions match repeated occurrences of emissions decline (≥ 10 years) coupled with GDP growth observed in the data. As Fig. 2d shows, in Denmark and the UK, CO₂ emissions reductions during periods of GDP growth were mainly driven by energy system transformations. In Poland, these reductions were led by energy system transformations and economic development over time.

Desirable GDP growth rate for stabilizing or declining CO₂ emissions

If the same mechanisms held in the near future, we can identify GDP growth rates that are compatible with stabilizing or declining CO₂ emission rates based on (1) plausible and internally consistent dynamics of the economic and energy developments captured in our data and (2) statistically significant empirical relationships we estimated for GDP growth, productivity, service growth, decarbonization, and electrification (see [Supplementary Information E](#)). Our analytical approach thus assumes that future CO₂ emissions will be influenced by the same mechanisms as in the past. This assumption appears plausible considering that we found no apparent trends in our sample over the 44-year period: national spending on emission abatement programs remains low and stagnant ([1](#)) and abatement technologies such as carbon capture and sequestrations (CCS) are commercializing and deploying at a very slow rate ([36](#), [37](#)).

Under these assumptions, we estimate that stabilizing or declining CO₂ emissions, accompanied by varying rates of positive economic growth, can be achieved in roughly 40% of countries in our sample ([Fig. 3a](#)). These countries currently account for 35% of the global population and for more than half of global economic output and CO₂ emissions ([Fig. 3b](#)). The viability of achieving economic growth while stabilizing or reducing CO₂ emissions drops dramatically for higher economic growth targets. If GDP grows by >1%, >2%, >4%, and >6%, stabilized or reduced same-year CO₂ emissions can be expected in roughly 30%, 20%, 10%, and 5% of countries in our sample, respectively ([Fig. 3a](#)). The percentage of countries that can sustainably achieve economic growth while stabilizing or reducing their carbon emissions is higher among developed economies than among emerging economies ([Fig. 3c](#)). We find little evidence that the prospect for sustainable economic growth has increased over time ([Fig. 3d](#)).

Fig. 3. GDP growth rates compatible with stabilizing or declining CO₂ emission rates under future “business-as-usual” development. **a.** Percentile distribution of the maximum annual GDP growth rates compatible with zero or negative emission growth rate in the same year. The maximum desirable annual GDP growth rates are equivalent to the emission reduction outcomes of the same-year changes of economic efficiency, deindustrialization, energy system decarbonization, and electrification observed during 1970-2013. Shadings represent the range between the best possible and worst possible conditions based on the observed changes and the 95% confidence interval of the estimated emission effects. Low to high annual GDP growth rates that are compatible with zero or negative emission growth rates in the same year, **b-d** show the corresponding distribution of global population, GDP, and CO₂ emissions of fossil fuel combustions and industrial processes (**b**), country-year observations among developed (OECD countries in 1990) and developing (non-OECD countries in 1990) countries, respectively (**c**), and country-year observations in four-year groups (**d**). Emissions reductions associated with economic recession (GDP growth rate < 0) are not the focus of this analysis and thus not shown here.

Our estimates of future emissions outcomes are based on historical patterns, assuming similar future trends. Countries may reduce their future emissions, however, by deploying emerging CO₂ abatement strategies, such as bioenergy with carbon capture and sequestration (BECCS). According to recent IAM-based analyses, these technologies are essential for meeting the 1.5°C target (38, 39). Emissions outcomes from economic development can also be altered if more mechanisms are included, such as emission reductions by a shift from transport equipment to intangible, knowledge-based assets, or emission reductions as a result of GDP losses in response to warming (40).

Conclusion

This analysis provides empirical explanations and verifications of key carbon mitigation mechanisms able to offset the driving impact of GDP growth. Our findings suggest that energy system transitions indeed reduce CO₂ emissions, a fact that has been disputed by previous empirical analysis (41), and that these transitions have been most important in developed economies. In developing economies, decarbonization can be assisted by increases in economic efficiency and electrification. Previously, knowledge on how to reduce CO₂ emissions during economic growth was predominantly derived using an *ex-ante* approach, such as the recent development of emissions scenarios associated with alternative socio-economic developments (e.g., Shared Socioeconomic Pathways (SSPs)) (42). Key parameters of the *ex-ante* analyses, such as the emissions outcome of electrification, decarbonization and other energy system transformations, are commonly estimated from energy engineering computations within IAMs (37, 43). However, *ex-ante* engineering estimates can differ considerably from *ex-post* estimates of actual emissions and economic outcomes (44). In this particular case, our analysis confirms and provides a crucial empirical basis for the findings from *ex-ante* models that, without unprecedented transformations, few countries can sustainably achieve economic growth while stabilizing or reducing their carbon emissions. Our statistical approach can be used to form evidence-based explanations of the driving forces behind emissions reductions in individual countries, and thereby complements other forms of analysis, such as index decomposition approaches (45).

Data and Methods

Our empirical analyses are based on a strongly balanced panel data set that contains annual CO₂ emissions and a variety of economic, energy-system, and temperature variables estimated for 70 countries over 44 years, from 1970 to 2013. CO₂ emissions related to fossil-fuel combustion and industrial processes are obtained from the Emissions Database for Global Atmospheric Research (EDGAR v4.3.2) (26). Anthropogenic CO₂ emissions from the combustion of fossil fuels have been the main contributor to the rising CO₂ levels in the atmosphere, and CO₂ emissions are the largest component of anthropogenic GHG emissions (46). The EDGAR inventory provides comprehensive and consistent emission estimates over a long time series. Our data on GDP, capital stocks, population, and human capital are from the Penn World Table (PWT) 9.0 (27). Value added by sectors are collected from the United Nations National Accounts Main Aggregates Database (47). Energy data is obtained from the International Energy Agency (IEA) (32). Climate data for monthly average temperature are collected from the Climatic Research Unit Time-series (CRUCY v3.23) (48).

After omitting countries with short time series, each of the 70 countries kept in our sample has at least 42 years of data for all variables used in our model. The only exception is Zimbabwe, for which only 35 years of data are available. Iraq and Argentina are excluded from our sample due to concerns about data reliability. The data set covers 82% of the CO₂ emissions by fossil fuel combustion and industrial processes, 87% of total primary supply, 80% of population, and 89% of GDP in the world over 1970-2013. Detailed descriptions of the data set and country sample are available in the [Supplementary Information B1](#) and [Table S2 a-b](#).

Empirical framework and benchmark model

Eq. 1 provides the overarching structure of the benchmark model. CO₂ represents annual CO₂ emissions related to fossil fuel combustion and industrial processes in a country/region. The level of economic output is measured by *GDP*. For every unit of economic activity, Ω units of CO₂ are generated.

$$CO_2 = GDP \cdot \Omega \quad (1)$$

Methodologically, our model specification circumvents common challenges of endogeneity, non-stationarity, and cross-sectional heterogeneity that have undermined the estimation consistency in many prior studies. By developing a two-equation simultaneous equation model (SEM, *Eqs. 2-3*) and estimating it using three-stage-least-square estimator (3SLS), we ensure consistency of the estimates threatened by endogeneity – that GDP affects CO₂ emissions could be in part because they both depend on capital formation and technological changes. By specifying how CO₂ emissions are affected by growth-related and non-growth-related mechanisms while controlling for GDP changes, we allow heterogeneous responses of CO₂ emissions, across the countries, to the same rate of economic growth. Given CO₂ emissions and GDP are non-stationary (15, 49), we apply first differencing to all variables (*Eqs. 4-5*). Results from a range of statistical tests indicate our model circumvents or greatly alleviates several critical estimation problems related to the properties of our analyzed data: non-stationarity, endogeneity, and cross-sectional correlation ([Supplementary Information C5](#)).

Fig. S1 provides an illustration of our empirical framework. Below we explain the development of the benchmark two-equation SEM describing CO₂ emissions and GDP. Robustness checks using alternative estimation procedures are explained in [Supplementary Information C1-C4](#).

GDP (Eq. 2). Based on the one-sector augmented Solow model, economic output (*GDP*) is produced via capital stock *K*, effective labor (human capital augmented labor, *H·L*), and productivity or technological progress represented by total factor productivity *TFP* (50). Because estimates of labor *L* (the product of number of persons engaged *emp* and average annual hours worked by persons engaged *avh*) are unavailable for most developing countries, we use population (*Pop*) as a substitute of labor in our model. The capital stock comprises different assets (*Kc_**) that may have different growth implications. Specifically, in PWT 9.0 (27), capital stock *K* is disaggregated into four asset classes. *Kc_Structfr*, *Kc_Machfr*, *Kc_TraEqfr*, and *Kc_Intangfr* represent the fraction of structural assets (residential and non-residential), machinery (including computers, communication equipment, and other machinery), transport equipment, and intangible assets (including software, intellectual property products, and cultivated assets). Given the fractions of the four assets sum up to unity, *Kc_TraEqfr* is dropped from Eq. 2 because its value will be default when the values of other three are set. Since there are missing data for many countries for total labor supply *L* in PWT 9.0, total population *P* is used instead. Other determinants of *GDP* are captured by ε_1 , including country characteristics (e.g., political institutions, geography, and culture) and common contemporaneous shocks (e.g., global financial crisis). They are not specified either due to the lack of data or because they change very slowly and are considered as time-invariant.

$$GDP = TFP^{\alpha_1} \cdot K^{\beta} \cdot Kc_Structfr^{\delta_1} \cdot Kc_Machfr^{\lambda_1} \cdot Kc_Intangfr^{\theta_1} \cdot (H \cdot Pop)^{\eta} \cdot \varepsilon_1 \quad (2)$$

Ω (Eq. 3). Emission intensity of the economy, Ω , depends on multiple growth-related and non-growth-related forces that are observable and unobservable, $\mathbf{x}$ and ε_2 , respectively:

$$\begin{aligned} \Omega = f(\mathbf{x}, \varepsilon) = & TFP^{\alpha_2} \cdot H^{\zeta} \cdot VA_Indfr^{\omega} \cdot Kc_Structfr^{\delta_2} \cdot Kc_Machfr^{\lambda_2} \cdot Kc_Intangfr^{\theta_2} \\ & \cdot TPES_FFfr^{\rho} \cdot TPES_coalFFfr^{\varphi} \cdot TPES_oilFFfr^{\eta} \\ & \cdot Electrification^{\sigma} \cdot Pl_eng^{\kappa} \cdot Openness^{\epsilon} \cdot Netimportfr^{\zeta} \\ & \cdot Lowtemp^{\tau} \cdot Hightemp^{\psi} \cdot kyoto^{\chi} \cdot \varepsilon_2 \end{aligned} \quad (3)$$

Growth-related factors. Firstly, the composition of the economic output matters for emission intensity of the economy. The process of industrialization, which historically has been energy-intensive, is regarded as an important driver for the increase of fossil CO₂ emissions (6). In comparison, the energy or CO₂ implications of a growing service sector has been speculated but there has been less certainty about its role (45). Industrialization is commonly represented by the fraction of total value added (*VA*) by industrial activities, *VA_indfr*. To explore the emission implications of the capital asset mix, we include the disaggregation of the capital stock in the emission intensity equation, as we did in the GDP equation, Eq. 2. Besides economic “composition,” Ω can be affected by the overall productivity or efficiency of economic production represented by *TFP* and human capital *H*.

Energy system transformation and price level. Electrification (1, 37) and less carbon-intensive fuels (25, 37, 45, 51) have been identified as the main reasons of falling energy intensity observed in many countries. Here, we specify and estimate the effects of decarbonizing energy supplies by (1)

displacing fossil fuels by non-fossil fuels, (2) displacing coal and coal products by natural gas and natural gas products, and (3) displacing oil and oil products by natural gas and natural gas products. Three variables: *TPES_FFfr* (fraction of fossil fuels in total primary energy supply), *TPES_coalFFfr* (fraction of coal and coal products in total fossil primary energy supply), and *TPES_oilFFfr* (fraction of oil and oil products in total fossil primary energy supply) are used to measure the decarbonizing processes. 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 (45, 52, 53). We use the annual global energy price level obtained from (54) as a proxy for the energy price signal. 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 non-growth factors. The trade-emission linkages have received considerable attention in recent research, e.g., (18, 20). We test the emission effects of globalization and trade deficit (or “outsourcing”) using two variables, *Openness* and *Netimportfr*, respectively. *Openness* measures the total trade (imports plus exports) as a fraction of total GDP; *Netimportfr* is the ratio of net import to GDP, representing a country’s trade balance. Low or high temperature may affect energy demand and thus the emission intensity Ω . We use the lowest and the highest monthly average temperature in a year (*Lowtemp* and *Hightemp*) to estimate the emission effects of winter warming and summer warming, respectively. Ω may be affected by climate policy interventions. One of the few interventions that are comparable across countries and have a long enough sample period is the ratification of the Kyoto Protocol, which features common but differentiated emission reduction commitments by developed and developing countries. We use a dummy variable to represent the commitment of binding emission reduction targets by Annex B countries (*kyoto* = 1 since year 2005; the Annex B countries are denoted in Supplementary Table S2). Other determinants of emission intensity Ω are captured by ε_2 , including country characteristics (e.g., political institutions, geography, and culture) and common contemporaneous shocks (e.g., global financial crisis). They are not specified either because of a lack of data or because they change very slowly and are considered time-invariant.

Using the 44-year longitudinal sample of 70 countries around the world, we take first differences of the natural log of *CO₂*, *GDP*, *Pop*, *TPES*, *TFP*, *K*, *H*, *Pl_eng* and first difference of *Kc_Strucfr*, *Kc_Machfr*, *Kc_Intangfr*, *VA_Indfr*, *Openness*, *Netimportfr*, *TPES_FFfr*, *TPES_coalFFfr*, *TPES_oilFFfr*, *Electrification*, *Lowtemp*, and *Hightemp*. Based on Eqs. 1-3, our benchmark two-equation SEM are (Eqs. 4-5):

$$\dot{GDP}_{i,t} = \alpha_1 \dot{TFP}_{i,t} + \beta \dot{K}_{i,t} + \delta_1 \dot{Kc_Strucfr}_{i,t} + \lambda_1 \dot{Kc_Machfr}_{i,t} + \theta_1 \dot{Kc_Intangfr}_{i,t} + \eta(H_{i,t} \cdot \dot{Pop}_{i,t}) + u_{1i} + y_{1t} + \varepsilon_{1i,t} \quad (4)$$

$$\begin{aligned} \dot{CO}_{2,i,t} = & \gamma \dot{GDP}_{i,t} + \alpha_2 \dot{TFP}_{i,t} + \xi \dot{H}_{i,t} + \omega \dot{VA_Ind}_{i,t} + \delta_2 \dot{Kc_Strucfr}_{i,t} + \lambda_2 \dot{Kc_Machfr}_{i,t} + \theta_2 \dot{Kc_Intangfr}_{i,t} \\ & + \rho \dot{TPES_FFfr}_{i,t} + \phi \dot{TPES_coalFFfr}_{i,t} + \vartheta \dot{TPES_oilFFfr}_{i,t} + \sigma \dot{Electrification}_{i,t} + \kappa \dot{P_engl}_{i,t} \\ & + \epsilon \dot{Openness}_{i,t} + \zeta \dot{Netimportfr}_{i,t} + \tau \dot{Lowtemp}_{i,t} + \psi \dot{Hightemp}_{i,t} + \chi \dot{kyoto} + u_{2i} + y_{2t} + \varepsilon_{2i,t} \end{aligned} \quad (5)$$

Each observation is identified by country/region *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). Both *CO₂* emissions

and *GDP* are endogenously determined by various exogenous variables, including a common set of growth-related variables (i.e. Kc_{*} and *TFP*). In both equation specifications, the country-fixed effects (u) capture the aggregated effects of the time-invariant variables and the year-fixed effects (y) capture the aggregated effects of global common time trends. They are not specified further due to the lack of data or the fact that they change very slowly and are considered as time-invariant. $\varepsilon_{i,t}$ is the error term in each equation. All statistical analyses are coded and performed in Stata/MP (55).

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Supplementary Information

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This Supplementary Information includes 14 sections, with additional treatment of the following topics:

A review of prior studies on CO₂-GDP elasticity

A.1 Selected literature

A.2 Elasticity estimates and empirical methods

Data and methods

B.1 Panel data set description

B.2 A graphic illustration of the empirical framework

Robustness and generalizability of the main result

C. 1 Statistical results of the benchmark model

C. 2 Various specifications of growth-related effects

C. 3 Additional equation for primary energy supply

C. 4 Alternative data sources and influence of cyclical variations

C5. Testing for non-stationarity, serial correlation and cross-sectional correlation

Assessments of historical emission impacts

D. 1 Equation for computing annual emission changes

D. 2 Equation for computing total emission changes

D. 3 Observed and computed desirable trends

Explorations of climate-compatible economic growth rates

E. 1 Equations and assumptions

A A review of prior studies on CO₂-GDP elasticity

A.1 Selected literature

We conducted an extensive literature review of quantitative empirical research that estimated the CO₂-GDP elasticity, published between 1990 and 2017. In the literature, CO₂-GDP elasticity is considered to represent the ‘net’ emission effect of economic growth, i.e., without separately specifying the influence of other factors such as structural change, total factor productivity, changes in the energy system, or similar factors. Based on this reduced-form specification, prior estimates of CO₂-GDP elasticity ranged widely, which have been attributed to differences in country samples, data sources, as well as the neglect of econometric problems that are essential for obtaining reliable empirical estimates. Emission effects of other factors are also explored in some studies and treated as independent from those of economic growth. Here, we selected 21 studies for a detailed review. Those studies estimated CO₂-GDP elasticity for a range of developed and developing countries and represent publications at different time points between 1994 and 2017, including a number of most widely-cited studies.

A.2 Elasticity estimates and empirical methods

Supplementary Table S1: **A of review selected literature: CO₂-GDP elasticity, sample, data source, and treatment of economic issues methods of the 21 selected publications** (by year of publication in descending order):.

Ref.	Dependent variable*	GDP per capita (GDP/p) or GDP*		Sample		Econometric issues addressed***		
		linear	quadratic	Time period	Country/region	NS	E	CD
(20)	CO ₂ /p	0.66		1997,2001,	66+12 region clusters	N	Y	N
	CO ₂ /p**	0.786		2004,2007, 2011				
(56)	CO ₂ **	1.075	0.077	1995-2011	40 major economies	Y	N	N
	CO ₂ /p**	1.147	0.083	1995-2011	40 major economies	Y	N	N
	CO ₂ **	1.11	0.156	1995-2011	27 EU countries	Y	N	N
	CO ₂ /p**	1.013	0.128	1995-2011	27 EU countries	Y	N	N
	CO ₂ **	1.043	0.062	1995-2011	40 major economies	Y	N	Y
	CO ₂ **	1.016	0.05	1995-2011	40 major economies	Y	N	Y
	CO ₂ /p**	0.997	0.042	1995-2011	40 major economies	Y	N	Y
	CO ₂ /p**	1.011	0.043	1995-2011	40 major economies	Y	N	Y
	CO ₂ **	1.102	0.129	1995-2011	27 EU countries	Y	N	Y
	CO ₂ **	0.976	0.101	1995-2011	27 EU countries	Y	N	Y
	CO ₂ /p**	0.963	0.088	1995-2011	27 EU countries	Y	N	Y
	CO ₂ /p**	0.953	0.073	1995-2011	27 EU countries	Y	N	Y
(17)	CO ₂ /p	0.534	-0.035	1990-2015	40 top emitters (top 10 emitters per region)	Y	Y	Y
		1.093	-0.061					
(18)	CO ₂	0.76	-0.06	1970-2014	183 countries	Y	N	N
	CO ₂ /p	0.78						
(19)	CO ₂ /p	0.155	0.002	1950-2000	151 countries	N	Y	N
		0.11	0.002					

		0.199	0.002					
(15)	CO ₂	0.52		1961-2010	189 countries	Y	Y	N
		0.65		1961-2010	OECD countries	Y	Y	N
		0.57		1961-2010	Non-OECD countries	Y	Y	N
		0.65		1961-2010	189 countries	Y	Y	N
		0.71		1961-2010	189 countries	Y	Y	N
		0.68		1961-2010	189 countries	Y	Y	N
(16)	CO ₂ /p	0.57		1971-2011	26 OECD countries	Y	N	Y
	CO ₂ /p	0.75		1971-2011	26 OECD countries	Y	N	Y
	CO ₂ /p	0.97		1971-2011	54 Non-OECD countries	Y	N	Y
	CO ₂ /p	0.96		1971-2011	54 Non-OECD countries	Y	N	Y
	CO ₂	0.81		1971-2011	All (26+54)	Y	N	Y
	CO ₂	0.87		1971-2011	All (26+54)	Y	N	Y
	CO ₂	0.58		1971-2011	26 OECD countries	Y	N	Y
	CO ₂	0.71		1971-2011	26 OECD countries	Y	N	Y
	CO ₂	0.89		1971-2011	54 Non-OECD countries	Y	N	Y
	CO ₂	0.83		1971-2011	54 Non-OECD countries	Y	N	Y
(14)	CO ₂ /p	0.9147		1971-2010	134 countries	Y	Y	N
		0.9074			97 countries			
(13)	CO ₂	1.023		1960-2005	86 (DC+LDC) countries	Y	N	N
	CO ₂	0.986		1960-2005	22 DC countries	Y	N	N
	CO ₂	1.003		1960-2005	64 LDC countries	Y	N	N
	CO ₂ /p	0.467		1960-2005	86 (DC+LDC) countries	Y	N	N
	CO ₂ /p	0.757		1960-2005	22 DC countries	Y	N	N
	CO ₂ /p	0.388		1960-2005	64 LDC countries	Y	N	N
(10)	CO ₂ /p	1.612		1960-2000	24 OECD countries	Y	N	N
		1.509		1950-2000	100 countries			
(9)	CO ₂ /p	1.96	0.08	1959-2001	109 countries	Y	N	Y ^d
		10.91	0.56	1959-2001	G7 countries	Y	N	Y ^d
		10.76	0.56	1959-2001	EU15 countries	Y	N	Y ^d
		8.91	0.45	1959-2001	OECD countries	Y	N	Y ^d
		0.29	0.04	1959-2001	Non-OECD countries	Y	N	Y ^d
		0.16	0.02	1959-2001	40 poorest countries	Y	N	Y ^d
(57)	CO ₂ /p	0.687		1975	85 countries	--	N	N
		0.688		1980	85 countries	--	N	N
		0.662		1985	85 countries	--	N	N
		0.666		1990	85 countries	--	N	N
		0.702		1995	85 countries	--	N	N
		0.741		2000	85 countries	--	N	N
		0.722		2005	85 countries	--	N	N
(11)	CO ₂	0.376		1975-2005	99 countries	Y	N	N
		2.498		1975-2005	23 low-income countries	Y	N	N
		0.987		1975-2005	43 middle-income countries	Y	N	N
		0.829		1975-2005	33 high-income countries	Y	N	N
(8)	CO ₂ /p	0.84	-0.42	1973-2000	88 countries	N	Y	N
(7)	CO ₂ /p	0.731	0.202	1950-2000	100 countries	Y	Y	Y
		0.589	0.290					
(58)	CO ₂	0.68		1975-2000	208 countries	N	N	N
		0.57		1975-2000	55 high-income	N	N	N
		0.33		1975-2000	40 upper-middle income	N	N	N
		0.44		1975-2000	54 lower-middle income	N	N	N

		0.26		1975-2000	59 low-income	N	N	N
(5)	CO ₂	0.892		1975-1998	86 countries	Y	N	N
(4)	CO ₂ /p	0.4083	0.1428	1950-1992	132 countries	N	N	N
		-0.28		1950-1990	income: \$200-629/year	N	N	N
		0.31		1950-1990	income: \$629-932/year	N	N	N
		1.29		1950-1990	income: \$932-1283/year	N	N	N
		0.79		1950-1990	income: \$1283-1728/year	N	N	N
		1.1		1950-1990	income: \$1728-2352/year	N	N	N
(3)	CO ₂ /p	0.66		1950-1990	income: \$2352-3190/year	N	N	N
		0.54		1950-1990	income: \$3190-4467/year	N	N	N
		0.71		1950-1990	income: \$4467-6598/year	N	N	N
		0.07 ^(e)		1950-1990	income: \$6598-9799/year	N	N	N
		-0.3		1950-1990	income: \$9799-19627/year	N	N	N
(28)	CO ₂ /p	0.5204		1951-1986	130 countries	N	N	N
(59)	CO ₂ /p	1.62		1960-1989	153 countries	N	N	N

*: Data sources of CO₂ and GDP:

- (1). CO₂ fossil fuel combustion (GTAP Database); per capita GDP in constant PPP: WDI Database.
- (2). CO₂: fossil fuel combustion, cement, minerals, refineries (WIOD Database); GDP: WIOD, constant 1995 US\$
- (3). CO₂: fossil fuel combustion and cement production, excluding other emissions such as from land use change and forestry (CDIAC Database); GDP: PWT Data set (version unknown) or WDI.
- (4). CO₂: fossil fuel use and industrial processes (cement production, carbonate use of limestone and dolomite, non-energy use of fuels and other combustion), excluding short-cycle biomass burning (such as agricultural waste burning) and large-scale biomass burning (such as forest fires) (EDGAR); GDP PPP: IMF.
- (5). CO₂: fossil fuel consumption and cement production (Boden et al. 2010, i.e. CDIAC); GDP: WDI.
- (6). CO₂: fossil fuel combustion and cement production, excluding other emissions such as from land use change and forestry (CDIAC); GDP: WDI, constant 2005 US\$.
- (7). CO₂: fossil fuel combustion (IEA); GDP: (IEA, then converted to USD via PPP).
- (8). CO₂: combustion of fossil fuels, gas flaring, and cement production (CDIAC, i.e. Boden et al 2013); GDP growth rates: rgdpna, GDP level: cgdp (PWT 8.0).
- (9). CO₂: fossil fuel combustion, gas flaring, and cement manufacturing, excluding emissions from land use change or bunker fuels used in international transportation; WRI's Climate Analysis Indicators Tool (CAIT) which compiles data from CDIAC, IEA, and EIA; GDP: constant 2000 US\$ (WDI).
- (10). CO₂: fossil fuel combustion and cement production, excluding other emissions such as from land use change and forestry (CDIAC); GDP: real GDP per capita (Maddison Project <http://www.gdcd.net/maddison/maddison-project/home.htm>).
- (11). CO₂: combustion of fossil fuels, gas flaring, and cement production (Marland et al 2007, CDIAC); GDP: 1990 International 'Geary-Khamis' dollars (Maddison 2002).
- (12). CO₂: fossil fuel combustion, gas flaring, and cement manufacturing (CDIAC, Boden et al. 2009); GDP: constant 2000 PPP (UNDP).
- (13). CO₂: fossil fuel combustion (IEA); GDP: 2000 PPP (World Bank, missing data filled by IEA data).
- (14). CO₂: combustion of fossil fuels, gas flaring, and cement production (Marland 2000 et al, CDIAC); GDP: measured in real dollars (PWT 6.1).
- (15). CO₂: fossil fuel combustion and cement production, excluding other emissions such as from land use change and forestry (CDIAC); GDP: real GDP per capita (Maddison Project <http://www.gdcd.net/maddison/maddison-project/home.htm>).
- (16). CO₂: from industrial process stemming from the burning of fossil fuels and the manufacture of cement (Statistical Information Management and Analysis (SIMA) of the World Bank); GDP: constant 1995 US\$ (Statistical Information Management and Analysis (SIMA) of the World Bank).
- (17). CO₂: WDI (World Bank); GDP WDI (World Bank).
- (18). CO₂: all major anthropogenic sources of emissions with the exception of those associated with gas flaring or land use changes (such as deforestation) (Boden et al 1995, CDIAC); GDP: PPP (PWT 5.6).
- (19). CO₂: excluding the carbon emissions associated with bunker fuel and gas flaring (CDIAC, Marland et al. 1989); GDP: RGDPCH, chained 1985 PPP (PWT 5.5).
- (20). CO₂: fossil fuel consumption and cement manufacture (ORNL 1992); GDP: RGDPCH, chained 1985 PPP (Penn Mark V World Tables in Summers and Heston 1991).
- (21). CO₂: fossil fuel consumption and cement manufacture (Marland 1989, ORNL) GDP: RGDPCH, chained 1985 PPP (Penn Mark V World Tables in Summers and Heston 1991).

** : consumption-based CO₂ emissions (commonly known as carbon footprint)

***Treatment of major econometric issues (Y: yes; N: no): NS. CO₂ and GDP non-stationarity, E. endogeneity, and CD. Cross-sectional dependence.

B Data and methods

B.1 Panel data set description

Sample composition of the data set are presented in Supplementary Tables S2a. Descriptive statistics of the panel data set, before and after first differencing, are provided in Table S2b and Tables S3a-b, respectively.

Supplementary Table S2a **Country sample**

Country/Region name	Frequency	Geographic region	RC 5 Region	Annex B countries
Australia	43	East Asia & Pacific	1. OECD-1990	1
Austria	43	Europe & Central Asia	1. OECD-1990	1
Belgium	42	Europe & Central Asia	1. OECD-1990	1
Bulgaria	43	Europe & Central Asia	2. Economies in Transition (EIT)	0
Bahrain	42	Middle East & North Africa	4. Middle East and Africa (MAF)	0
Brazil	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	1
Canada	42	North America	1. OECD-1990	1
Switzerland	43	Europe & Central Asia	1. OECD-1990	0
Chile	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
China	42	East Asia & Pacific	5. Asia	0
Cameroon	42	Sub-Saharan Africa	4. Middle East and Africa (MAF)	0
Colombia	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Costa Rica	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Cyprus	43	Europe & Central Asia	2. Economies in Transition (EIT)	1
Germany	42	Europe & Central Asia	1. OECD-1990	1
Denmark	42	Europe & Central Asia	1. OECD-1990	0
Dominican Republic	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Ecuador	43	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Egypt, Arab Rep.	43	Middle East & North Africa	4. Middle East and Africa (MAF)	1
Spain	43	Europe & Central Asia	1. OECD-1990	1
Finland	43	Europe & Central Asia	1. OECD-1990	1
France	42	Europe & Central Asia	1. OECD-1990	1
United Kingdom	42	Europe & Central Asia	1. OECD-1990	1
Greece	42	Europe & Central Asia	1. OECD-1990	0
Guatemala	43	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Hong Kong SAR, China	42	East Asia & Pacific	5. Asia	1
Hungary	42	Europe & Central Asia	2. Economies in Transition (EIT)	0
Indonesia	42	East Asia & Pacific	5. Asia	0
India	43	South Asia	5. Asia	1
Ireland	42	Europe & Central Asia	1. OECD-1990	0
Iran, Islamic Rep.	43	Middle East & North Africa	4. Middle East and Africa (MAF)	0
Iceland	42	Europe & Central Asia	1. OECD-1990	0
Israel	43	Middle East & North Africa	4. Middle East and Africa (MAF)	1
Italy	42	Europe & Central Asia	1. OECD-1990	0
Jamaica	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Jordan	42	Middle East & North Africa	4. Middle East and Africa (MAF)	1
Japan	42	East Asia & Pacific	1. OECD-1990	0
Kenya	43	Sub-Saharan Africa	4. Middle East and Africa (MAF)	0
Korea, Rep.	42	East Asia & Pacific	5. Asia	0
Kuwait	42	Middle East & North Africa	4. Middle East and Africa (MAF)	1

Luxembourg	42	Europe & Central Asia	1. OECD-1990	0
Morocco	42	Middle East & North Africa	4. Middle East and Africa (MAF)	0
Mexico	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Malta	43	Europe & Central Asia	2. Economies in Transition (EIT)	0
Mozambique	43	Sub-Saharan Africa	4. Middle East and Africa (MAF)	0
Malaysia	42	East Asia & Pacific	5. Asia	0
Nigeria	43	Sub-Saharan Africa	4. Middle East and Africa (MAF)	1
Netherlands	42	Europe & Central Asia	1. OECD-1990	1
Norway	42	Europe & Central Asia	1. OECD-1990	1
New Zealand	42	East Asia & Pacific	1. OECD-1990	0
Peru	43	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Philippines	42	East Asia & Pacific	5. Asia	1
Poland	42	Europe & Central Asia	2. Economies in Transition (EIT)	1
Portugal	42	Europe & Central Asia	1. OECD-1990	0
Qatar	42	Middle East & North Africa	4. Middle East and Africa (MAF)	1
Romania	42	Europe & Central Asia	2. Economies in Transition (EIT)	0
Saudi Arabia	42	Middle East & North Africa	4. Middle East and Africa (MAF)	0
Senegal	43	Sub-Saharan Africa	4. Middle East and Africa (MAF)	0
Singapore	43	East Asia & Pacific	5. Asia	1
Sweden	43	Europe & Central Asia	1. OECD-1990	0
Thailand	42	East Asia & Pacific	5. Asia	0
Trinidad and Tobago	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
Tunisia	42	Middle East & North Africa	4. Middle East and Africa (MAF)	0
Turkey	42	Europe & Central Asia	1. OECD-1990	0
Tanzania	43	Sub-Saharan Africa	4. Middle East and Africa (MAF)	0
Uruguay	43	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	1
United States	43	North America	1. OECD-1990	0
Venezuela, RB	42	Latin America & Caribbean	3. Latin America & Caribbean (LAM)	0
South Africa	42	Sub-Saharan Africa	4. Middle East and Africa (MAF)	0
Zimbabwe	33	Sub-Saharan Africa	4. Middle East and Africa (MAF)	0

Supplementary Table S2b **Descriptive statistics**

Variable	Unit	Observations	Mean	Std. Dev.	Min	Max	Global coverage
CO_2^a	petagram	3,080	0.27	0.83	0.00	10.50	82%
GDP^b	Million 2011 US\$	3,080	0.65	1.59	0.00	16.10	89%
$TPES^c$	10^9 toe	3,036	0.10	0.29	0.00	2.91	87%
Pop^d	million people	3,080	59.30	175.47	0.11	1362.51	80%
K^e	10^9 2011 US\$	3,080	2.17	5.17	0.00	60.94	--
$Kc_Strucfr^f$	dimensionless	3,080	0.80	0.07	0.39	0.98	--
Kc_Machfr^f	dimensionless	3,080	0.13	0.06	0.01	0.43	--
$Kc_TraEqfr^f$	dimensionless	3,080	0.04	0.02	0.00	0.16	--
$Kc_Intangfr^f$	dimensionless	3,080	0.02	0.03	0.00	0.23	--
TFP^g	dimensionless	3,080	0.98	0.23	0.45	3.59	--
H^h	dimensionless	3,080	2.39	0.66	1.06	3.73	--
VA_Indfr^i	dimensionless	3,080	0.33	0.11	0.07	0.79	--
$Openness^j$	dimensionless	3,080	0.74	0.66	0.04	4.83	--
$Netimportfr^k$	dimensionless	3,080	0.00	0.15	-1.07	1.87	--
$TPES_FFfr^l$	dimensionless	3,080	0.75	0.25	0.05	1.04	--
$TPES_coalFFfr^m$	dimensionless	3,080	0.17	0.20	0.00	0.89	--

<i>TPES_oilFFfr</i> ^m	dimensionless	3,080	0.65	0.26	0.02	1.00	--
<i>Electrification</i> ⁿ	dimensionless	3,080	0.15	0.09	0.00	0.62	--
<i>PI_eng</i> ^o	dimensionless	3,080	53.76	30.56	10.98	125.56	--
<i>Lowtemp</i> ^p	°C	3,080	9.78	11.49	-27.70	27.00	--
<i>Hightemp</i> ^p	°C	3,080	23.82	5.98	7.20	38.60	--

- CO₂: carbon dioxide emissions related to fossil fuel combustion and industrial processes (26);
- GDP: real gross domestic product at constant U.S. dollars, “*rgdpna*” in (27);
- TPES: total primary energy supply (32);
- Pop: total population (27), representing total labor supply in our analysis;
- K: capital stock, “*rkna*” in (27);
- Kc_*: capital stock composition; *Kc_Structfr*, *Kc_Machfr*, *Kc_TraEqfr*, and *Kc_Intangfr*: fraction of structural assets (residential and non-residential), machinery, transport equipment, and intangible assets (including software, intellectual property products, and cultivated assets) in capital stock (27);
- TFP: total factor productivity, “*rkna*” in (27);
- H: human capital (27);
- VA_Indfr: fraction of total value added (VA) by industrial sectors (ISIC G-P) (47);
- Openness: fraction of GDP by total trade (import plus export (54)) ;
- Netimportfr: ratio of net import to GDP, representing the level of a country/region’s trade deficit;
- TPES_FFfr: fraction of fossil fuels in primary energy supply (32);
- TPES_coalFFfr and TPES_oilFFfr: fraction of coal & coal products and oil & oil products in fossil primary energy supply, respectively (32);
- Electrification: fraction of electricity in final energy consumption (32);
- PI_eng: price level of energy supply (54);
- Lowtemp and Hightemp: the lowest and highest monthly temperature each year, respectively (48).

Descriptive statistics of the first differenced variables and their correlations are presented in Supplementary Table S3.

Supplementary Table S3a **Descriptive statistics of the first differenced panel data set**

Variable	Observations	Mean	Std. Dev.	Min	Max
Δ CO ₂	3,010	0.0245	0.0780	-1.0258	0.8393
Δ GDP	3,010	0.0355	0.0473	-0.5278	0.6033
Δ TPES	2,966	0.0288	0.0712	-1.2191	1.1872
Δ Pop	3,010	0.0156	0.0153	-0.1990	0.1762
Δ K	3,010	0.0429	0.0298	-0.0220	0.2850
Δ Kc_Structfr	3,003	0.0000	0.0121	-0.1043	0.1418
Δ Kc_Machfr	3,003	-0.0004	0.0089	-0.1218	0.0720
Δ Kc_TraEqfr	3,003	0.0000	0.0042	-0.0298	0.0467
Δ Kc_Intangfr	3,003	0.0004	0.0032	-0.0380	0.0594
Δ TFP	3,000	0.0014	0.0426	-0.5459	0.5945
Δ H	3,010	0.0096	0.0065	-0.0073	0.0411
Δ VA_Indfr	3,010	-0.0014	0.0152	-0.3316	0.2475
Δ Openness	3,010	0.0104	0.0892	-2.2955	1.2537
Δ Netimportfr	3,010	0.0004	0.0654	-1.9205	1.9435
Δ TPES_FFfr	2,966	-0.0006	0.0159	-0.1150	0.1184
Δ TPES_coalFFfr	2,966	-0.0001	0.0195	-0.2136	0.2027
Δ TPES_oilFFfr	2,966	-0.0040	0.0279	-0.2027	0.2873
Δ Electrification	2,966	0.0027	0.0152	-0.2083	0.5002
Δ PI_eng	3,010	0.0592	0.2573	-0.6603	0.9983

Δ Lowtemp	3,010	0.0212	1.6073	-9.6000	9.5000
Δ Hightemp	3,010	0.0273	1.0311	-4.6000	5.3000

Supplementary Table S3b **Correlation coefficients**

		(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(0)	Δ CO ₂														
(1)	Δ GDP	0.49													
(2)	Δ VA_Indfr	0.37	0.89												
(3)	Δ Kc_Strucfr	0.34	0.45	0.45											
(4)	Δ Kc_Machfr	-0.09	-0.13	-0.05	-0.03										
(5)	Δ Kc_Intangfr	0.07	0.09	0.03	0.02	-0.90									
(6)	Δ TPES_FFfr	0.01	0.05	0.01	0.01	-0.42	0.15								
(7)	Δ TPES_coalFFfr	0.51	0.18	0.11	0.09	-0.05	0.03	0.00							
(8)	Δ TPES_oilFFfr	0.10	-0.01	-0.02	0.01	-0.01	0.01	0.02	0.07						
(9)	Δ Electrification	-0.08	-0.05	-0.05	-0.15	0.00	0.00	-0.01	-0.09	-0.52					
(10)	Δ Openness	-0.31	-0.11	-0.13	-0.06	0.00	0.00	0.00	-0.19	0.09	-0.06				
(11)	Δ Netimportfr	-0.01	0.03	0.01	-0.10	-0.01	-0.01	0.03	0.04	0.03	0.06	0.03			
(12)	Δ PI_eng	-0.18	-0.19	-0.26	-0.40	-0.05	0.03	0.03	0.06	0.00	0.19	0.14	0.29		
(13)	Δ Lowtemp	0.05	0.12	0.08	0.05	0.03	-0.03	-0.02	0.03	0.05	-0.05	0.02	0.10	0.02	
(14)	Δ Hightemp	-0.10	0.00	-0.02	0.00	0.00	0.01	-0.02	-0.07	-0.05	0.05	0.04	0.00	0.01	-0.03

B. 2 A graphic illustration of the empirical framework

We specify and estimate main growth-related and non-growth-related factors that determine CO₂ emissions. An illustration of the empirical framework is provided in Fig. S1.

Supplementary Figure S1. A schematic overview of the growth-related ('blue arrows') and non-growth-related ('green arrows') channels determining CO₂ emissions.

C Robustness and generalizability of the main result

C. 1 Statistical results of the benchmark model

In the main manuscript (Table 1), only statistically significant empirical estimates removed from the CO₂ equation are presented. In Supplementary Table S4, statistical results of the benchmark model, for both the CO₂ and GDP equations are presented. Most country- and year- fixed effects are not statistically significant so they are omitted from the table. For variables included in Table 1, bias-corrected and accelerated (BCa) 95% confidence interval are estimated from 1000 times' bootstrap runs, which further validate the robustness of the most crucial empirical relationships we recovered from the benchmark model and used in later analyses.

Supplementary Table S4 **Detailed results of the benchmark model**

	Coefficients	95% confidence interval		Bca 95% bootstrap confidence interval	
CO ₂ equation					
Δ GDP ^a	1.0443*** ^b	[0.9005	1.1881]	[0.8808	1.2262]
Δ TFP	-0.5967***	[-0.7420	-0.4514]	[-0.7881	-0.4261]
Δ Kc_Strucfr	-0.3147	[-0.8223	0.1929]	--	--
Δ Kc_Machfr	-0.2416	[-0.8681	0.3849]	--	--
Δ Kc_Intangfr	-0.7515^	[-1.6123	0.1093]	[-1.7255	0.2259]
Δ VA_Indfr	0.4695***	[0.3008	0.6381]	[0.2040	0.7873]
Δ H	-0.0422	[-0.4421	0.3576]	--	--
Δ Openness	0.0052	[-0.0190	0.0294]	--	--
Δ Netimportfr	-0.1770***	[-0.2147	-0.1392]	[-0.2690	-0.0994]
Δ TPES_FFfr	1.8412***	[1.7099	1.9725]	[1.6689	2.0215]
Δ TPES_coalFFfr	0.5072***	[0.3789	0.6356]	[0.2936	0.6680]
Δ TPES_oilFFfr	0.1617***	[0.0718	0.2516]	[0.0418	0.3507]
Δ Electrification	-1.0367***	[-1.1683	-0.9051]	[-1.6612	-0.4881]
Δ Pl_eng	0.3589	[-3.5239	4.2417]	--	--
Δ Lowtemp	-0.0035***	[-0.0048	-0.0023]	[-0.0046	-0.0026]
Δ Hightem	-0.0007	[-0.0027	0.0014]	--	--
Kyoto	0.0014	[-0.0083	0.0111]	--	--
Constant	-0.0107	[-0.0301	0.0087]		
R-sq					0.53
GDP equation					
Δ K	0.6046***	[0.5826	0.6266]	--	--
Δ Kc_Strucfr	-0.0406	[-0.1603	0.0791]	--	--
Δ Kc_Machfr	-0.0224	[-0.1702	0.1254]	--	--
Δ Kc_Intangfr	-0.0695	[-0.2736	0.1346]	--	--
Δ H·P ^b	18.8528***	[16.6041	21.1015]	--	--
Δ TFP	0.9612***	[0.9498	0.9726]	--	--
Constant	0.0023	[-0.0025	0.0072]	--	--
R-sq					0.93
n_countries					70
N_observations					2995

a. Δ is the first difference operator; b. [^] $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; b. the high coefficient for the labor variable is a result of the multiplication by human capital (*H*)

C. 2 Various specification of the growth-related effects

Our estimates for the CO₂-GDP elasticity and other emissions effects are robust to various specifications of growth-related effects in the model (Supplementary Table S5), specifically

- (1) adding 1-year lag of GDP growth rate to the CO₂ equation
- (2) adding 1-year and 2-year lags of GDP growth rate to the CO₂ equation
- (2) adding 1-year, 2-year and 3-year lags of GDP growth rate to the CO₂ equation
- (4) testing for asymmetric effects: GDP expansion vs. GDP recession in the CO₂ equation
- (5) using sample of OECD countries only
- (6) using non-OECD countries only
- (7) adding trade activities to the GDP equation

Supplementary Table S5 **Results of various model specifications of growth-related effects.** The main differences from the critical emission effects estimated using the benchmark model and shown in Table 1 are highlighted in red.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
CO ₂ equation							
ΔGDP^a	1.0150*** ^b	0.9695***	0.9852***	1.0497***	1.0385***	1.0408***	1.0434***
ΔGDP_{t-1} (1-year lag)	0.0279	0.0141	0.0082				
ΔGDP_{t-2} (2-year lag)		0.0627*	0.0729**				
ΔGDP_{t-3} (3-year lag)			-0.0438 [^]				
$\Delta GDP+$ (expansion)				-0.0286			
$\Delta GDP+$ (recession)				-0.0272			
ΔTFP	-0.5738***	-0.5185***	-0.5313***	-0.5944***	-0.5924***	-0.5981***	-0.5951***
$\Delta Kc_Strucfr$	-0.3225	-0.3189	-0.3692	-0.3124	-0.7935*	-0.2282	-0.3150
ΔKc_Machfr	-0.2594	-0.2273	-0.2757	-0.2387	-0.5759	-0.1587	-0.2416
$\Delta Kc_Intangfr$	-0.7353 [^]	-0.6301	-0.6609	-0.7521 [^]	-1.1996**	-0.7771	-0.7502 [^]
ΔVA_Indfr	0.4734***	0.4531***	0.4464***	0.4658***	0.2012 [^]	0.5035***	0.4697***
ΔH	-0.0199	0.0666	0.0127	-0.0406	-0.8764**	0.0805	0.0428
$\Delta Openness$	0.0044	0.0042	-0.0006	0.0047	0.0609 [^]	0.0041	0.0018
$\Delta Netimportfr$	-0.1772***	-0.1825***	-0.1828***	-0.1759***	-0.1442*	-0.1790***	-0.1742***
$\Delta TPES_FFfr$	1.8403***	1.8389***	1.8395***	1.8410***	1.4048***	2.0352***	1.8413***
$\Delta TPES_coalFFfr$	0.5111***	0.5047***	0.5015***	0.5076***	0.6995***	0.3473***	0.5072***
$\Delta TPES_oilFFfr$	0.1632***	0.1673***	0.1650***	0.1616***	0.0207	0.1889**	0.1617***
$\Delta Electrification$	-1.0402***	-1.0310***	-1.0162***	-1.0354***	-1.3272***	-0.9995***	-1.0367***
ΔPl_eng	0.4467	0.5410	0.9570	0.3733	0.0206	0.4388	0.3600
$\Delta Lowtemp$	-0.0036***	-0.0035***	-0.0036***	-0.0035***	-0.0039***	-0.0028 [^]	-0.0035***
$\Delta Hightem$	-0.0007	-0.0003	-0.0003	-0.0007	-0.0006	-0.0016	-0.0007
<i>kyoto</i>	0.0017	0.0023	0.0023	0.0013	-0.0027	0.0019	0.0014
<i>Constant</i>	-0.0109	-0.0121	-0.0124	0.0178	-0.0041	-0.0282*	-0.0107
R-sq	0.532	0.533	0.527	0.532	0.702	0.487	0.532
GDP equation							
ΔTFP	0.9612***	0.9602***	0.9583***	0.9612***	0.9386***	0.9647***	0.9597***
$\Delta Kc_Strucfr$	-0.0648	-0.0741	-0.0595	-0.0696	-0.4389**	0.0913	-0.0402
ΔKc_Machfr	-0.0202	-0.0272	-0.0335	-0.0224	-0.2000	0.0607	-0.0226
$\Delta Kc_Intangfr$	-0.0384	-0.0468	-0.0467	-0.0406	-0.2898*	0.0606	-0.0724
$\Delta H \cdot P$	18.7788***	18.7605***	18.7215***	18.8584***	47.7122***	17.3529***	18.9355***
ΔK	0.6060***	0.6086***	0.6114***	0.6046***	0.5894***	0.6159***	0.6054***
<i>dopenness</i>							0.0063*
<i>Constant</i>	0.0022	0.0022	0.0021	0.0023	0.0041	-0.0122***	0.0023

N_Observations	2931	2862	2793	2955	1284	1671	2955
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a. Δ is the first difference operator; b. $^{\wedge}p<0.10$, $*p<0.05$, $**p<0.01$, $***p<0.001$

All estimates CO₂-GDP elasticity in Supplementary Table S5 are not statistically different from 1 ($p<0.001$). Overall, the critical emission effects shown in Table 1 and used in later analyses are consistently estimated by different model specifications, within the 95% CI derived from the benchmark model. For developed countries, the statistical significance and emission effects estimated for (de-)industrialization and natural gas decarbonization of oil are both lower, suggesting their economic productions are less carbon-intensive and oil use more efficient than those in developing countries.

C. 3 Additional equation for primary energy supply

Supplementary Table S6 Detailed results of the three-equation simultaneous model.

Independent variables	CO ₂ equation			Energy equation			GDP equation		
	Coef.	95% Confidence Interval		Coef.	95% Confidence Interval		Coef.	95% Confidence Interval	
ΔGDP^a				1.0302*** ^b	0.935	1.1254			
$\Delta TPES$	0.9332***	0.8431	1.0233						
ΔTFP				-0.6402***	-0.7373	-0.5432	0.9617***	0.9503	0.9731
$\Delta Kc_Strucfr$	0.2270	-0.2542	0.7082	-0.4763 [^]	-0.988	0.0353	-0.0423	-0.1619	0.0774
ΔKc_Machfr	0.2330	-0.3591	0.8251	-0.3913	-1.0239	0.2413	-0.0239	-0.1716	0.1239
$\Delta Kc_Intangfr$	-0.4769	-1.283	0.3292	-0.5017	-1.3667	0.3633	-0.0682	-0.2722	0.1359
ΔVA_Indfr	0.0661***	0.027	0.1053	0.2998***	0.1368	0.4627			
$\Delta Openness$	0.0294*	0.0064	0.0523	-0.0296*	-0.054	-0.0052			
$\Delta Netimportfr$	0.0526**	0.014	0.0912	-0.2425***	-0.2808	-0.2042			
$\Delta TPES_FFfr$	1.1289***	0.9838	1.2741	0.7349***	0.6036	0.8662			
$\Delta TPES_coalFFfr$	0.3207***	0.1971	0.4442	0.2337***	0.1038	0.3636			
$\Delta TPES_oilFFfr$	-0.0735	-0.1621	0.0151	0.2390***	0.1475	0.3306			
$\Delta Electrification$	0.0023	-0.1575	0.1621	-1.1084***	-1.2435	-0.9732			
ΔPI_eng				-3.2272	-7.2223	0.7679			
$\Delta Lowtemp$				-0.0037***	-0.0049	-0.0025			
$\Delta Hightem$				-0.0010	-0.003	0.001			
$\Delta H\text{-}P$							18.773***	16.528	21.018
ΔK							0.6038***	0.5819	0.6257
kyoto	-0.0031	-0.0115	0.0054						
Constant	0.0068	-0.0057	0.0193	-0.0098 [^]	0.0207	0.0010	0.0024	-0.0024	0.0072
n_countries			70			70			70
N_observations			2995			2995			2955
R-sq			0.51			0.41			0.93

a. Δ is the first difference operator; b. $^{\wedge}p<0.10$, $*p<0.05$, $**p<0.01$, $***p<0.001$

Indirectly, we can derive a proportional CO₂-GDP elasticity from Supplementary Table S6 ($p<0.001$). Estimates in the table are highly consistent with those derived from the benchmark model (Table 1 and Supplementary Table S4). Using primary energy supply to bridge GDP and CO₂, we can further elucidate the emission reduction mechanisms, i.e. whether by affecting primary energy use or the emission intensity of energy supplies or

emissions from industrial processes. Those nuances are discussed in the main manuscript. Although estimated at relatively low statistical significance level, trade openness (or globalization) appears to reduce a country's emissions by reducing its primary energy supply while increase the emissions by increasing the carbon intensity of the energy supply or the emissions from industrial processes. The two opposite emissions effects cancel each other out.

C. 4 Alternative data sources and influence of cyclical variations

Overall, our main results are also robust to the usage of different data sources for CO₂ and GDP and the removal of cyclical variations (Supplementary Table S7), specifically:

- (1) Using fossil-fuel CO₂ emissions obtained from Carbon Dioxide Information Analysis Center (60);
- (2) Using real GDP estimates (in constant 2010 US dollars) obtained from (54)
- (3) Using both alternative data sources in (1) and (2)
- (4) Based on 5-year averages: averaging the original data in the panel data set of every 5-year interval and take first differences of the transformed data set
- (5) Based on 5-year averages: averaging the first differenced data

Supplementary Table S7 **Results of using alternative data sources and considering the influence of cyclical variations.** The main differences from the critical emission effects estimated using the benchmark model and shown in Table 1 are highlighted in red.

	(1)	(2)	(3)	(4)	(5)
CO2 equation					
ΔGDP^a	0.8834*** ^b	1.0027***	0.9364***	0.9432***	0.9496***
ΔTFP	-0.5984***	-0.4922***	-0.5021***	-0.5232***	-0.5036***
$\Delta Kc_Strucfr$	-0.6728	-0.2919	-0.6530	-0.0021	0.0271
ΔKc_Machfr	-0.6901	-0.1389	-0.4956	-0.0223	-0.0563
$\Delta Kc_Intangfr$	-1.0170	-0.5517	-0.7380	-1.4026*	-1.4689*
ΔVA_Indfr	1.0238***	0.3351***	0.6558***	0.7396***	0.5435**
ΔH	-0.1392	-0.1011	-0.1935	0.3534^	0.2165
$\Delta Openness$	-0.0184	0.0179	0.0027	-0.0116	-0.0626*
$\Delta Netimportfr$	-0.2070***	-0.0652**	-0.0704	0.0175	0.0865
$\Delta TPES_FFfr$	2.1395***	1.8032***	2.0814***	1.5813***	1.5517***
$\Delta TPES_coalFFfr$	0.3099**	0.5087***	0.4569***	0.7888***	0.5490***
$\Delta TPES_oilFFfr$	0.1201	0.1719***	0.2737**	0.0755	0.0886
$\Delta Electrification$	-0.4725***	-0.8617***	-0.4688***	-0.4571^	-0.3214^
ΔPl_eng	1.2613	0.5735	1.7175	0.0256	0.0231
$\Delta Lowtemp$	-0.0038***	-0.0037***	-0.0039***	0.0026	-0.0067**
$\Delta Hightem$	0.0003	-0.0004	0.0004	-0.0018	-0.0031
<i>kyoto</i>	-0.0103	0.0037	-0.0067	-0.0046	-0.0010
<i>Constant</i>	0.0028	-0.0134	-0.0025	-0.0729**	-0.0134*
R-sq	0.288	0.479	0.261	0.662	0.598
GDP equation					
ΔTFP	0.9617***	0.8582***	0.8586***	0.9574***	0.9484***
$\Delta Kc_Strucfr$	-0.0387	-0.0325	-0.0312	-0.3182*	-0.2782^
ΔKc_Machfr	-0.0201	-0.0840	-0.0823	-0.2227	-0.1734
$\Delta Kc_Intangfr$	-0.0680	-0.1557	-0.1552	-0.4614^	-0.3602
$\Delta H-P$	18.8669***	18.8405***	18.9901***	6.9296***	32.2812***
ΔK	0.6051***	0.5787***	0.5787***	0.5270***	0.5365***

<i>Constant</i>	0.0023	0.0046	0.0046	0.0273***	0.0055***
<i>N</i>	2934	2778	2757	574	646

a. Δ is the first difference operator; b. $^{\wedge}p<0.10$, $^*p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

All estimates CO₂-GDP elasticity in Supplementary Table S7 are not statistically different from 1 ($p<0.001$). Most of the critical emission effects shown in Table 1 and used in later analyses are maintained (within the 95% CI derived from the benchmark model). In comparison to the main results from the benchmark model (Table 1), here, emission effects of (de-)industrialization are estimated higher and electrification lower. Besides, the emission effects of trade surplus and displacing oil by natural gas appear less certain.

C5. Testing for nonstationarity, serial correlation and cross-sectional correlation

The presence of non-stationarity, serial correlation and cross-sectional correlation in panel data models may lead to inconsistent estimates, or even spurious results. Accordingly, we tested for those issues in our benchmark model using different methods, which are available as commands in Stata/MP (55). We found no evidence of panel non-stationarity, which is likely due to our first differencing approach. For most of the panel series in our data sample, there is no evidence of autocorrelation (or serial correlation). We also found that our model specification significantly reduced the extent of cross-sectional correlation.

Testing for panel non-stationarity. We ran a few panel non-stationarity tests using different methods. Consistently, the results reject the null hypothesis of non-stationarity in all panel series. Table S8 shows the results of the Maddala and Wu (1999) and Pesaran (2007) tests, carried out using the ‘multipurt’ command. multipurt performs 1st and 2nd generation panel unit root tests for multiple variables and lags 1 (61).

Supplementary Table S8 **Results of panel non-stationarity test.**

	Maddala and Wu (1999) Fisher Test		Pesaran (2007) CIPS Test	
Lags	Constant		Constant	
	Δ CO2	Δ GDP	Δ CO2	Δ GDP
0	2181.25 (.00)	1304.26 (.00)	-34.37 (.00)	-22.54 (.00)
1	1114.28 (.00)	949.33 (.00)	-20.56 (.00)	-16.31 (.00)
2	731.10 (.00)	586.32 (.00)	-13.05 (.00)	-9.68 (.00)
4	543.71 (.00)	510.77 (.00)	-8.74 (.00)	-7.48 (.00)

Testing for serial correlation. We also tested for serial correlations. The Wooldridge test for serial correlation in panel-data models has been widely used, available through Stata command xtserial (62, 63) but it cannot be applied to a structural model, such as our benchmark model. Thus we tested for autocorrelation for each of the 70 panel series in our data sample using the C-H test, available through the Stata command ‘actest’ (64). Unlike many other tests for serial correlations, the C-H test is still applicable when the model contains endogenous repressors, which is our case. Out of the 70 panel series included in our

data sample, the null hypothesis of serial correlation, MA (1), exists in the residuals of the CO₂ model is rejected in most of them. The few exceptions are New Zealand, Mexico, Morocco, and Ireland ($p < 0.05$); Greece, Ecuador, China, Norway, Philippines, Malta, Iran ($0.05 < p < 0.1$).

Testing for cross-sectional correlation. The Pesaran CD-test was employed here, using Stata command “xtcd”. The results (Table S9) show very high average absolute correlation coefficients for the data in log levels. The coefficients were greatly reduced in the first differenced data and further reduced to a low level in the residuals of the benchmark model (65).

Supplementary Table S9 **Results of testing cross-section dependence in macro panel data.**

	CD-test	p-value	corr ¹	abs (corr) ²
ln CO ₂	122.93	0.000	0.385	0.747
ln GDP	293.55	0.000	0.915	0.915
Δ CO ₂	36.07	0.000	0.113	0.178
Δ GDP	49.21	0.000	0.152	0.225
residuals_CO ₂ equation	-2.02	0.044	-0.006	0.134
residuals_GDP equation	-3.1	0.002	-0.010	0.153

¹corr: averaged correlation coefficient; ²abs(corr): averaged absolute correlation coefficient

D Assessments of historical emission impacts

D. 1 Computing annual emission change and reduction

We use our data sample and the 9 statistically significant empirical relationships recovered using the benchmark model (Table 1) to quantify the emission contributions made by the already-observed trends of the 9 emission driving factors. As mentioned before, we bootstrap the benchmark model 1000 times and obtained 1000 sets of estimates for the 9 empirical relationships: $\beta^1, \beta^2, \beta^3, \dots, \beta^{1000}$, with β^N being a 1×9 vector. $x_{i,t}^j$ represents the change of any emission driving factor j observed in country i , year t . Thus, in country i , year t , factor j 's contribution to annual emission change ($AEC_{i,t}^{N,j}$) is computed as:

$$AEC_{i,t}^{N,j} = \beta^{N,j} \cdot x_{i,t}^j \quad (6)$$

For each emission driving factor j , we then calculate the median value of all $AEC_{i,t}^{N,j}$ ($N=1, 2, 3, \dots, 1000$) and obtained the 95% confidence interval to represent uncertainty range of our sample. The median values of each of the nine factors are plotted as yellow lines in Fig. 2a, *left*. To illustrate the distribution of the factors' impacts on emission changes, they are plotted in a “visually-weighted” fashion based on (66): darker areas represent values for which emission changes were more common.

To illustrate the annual emission reduction (*AER*) effects of the emission disabling trends of factor j (Fig. 2b, *left*), we only account for the emission reduction effect (Eq. 7). The median values and uncertainty ranges are obtained and plotted as described above. The emission reduction effects of GDP reductions are not accounted in the figure, since GDP reduction is not considered as a desirable emission disabling pathway in this analysis.

$$AER_{i,t}^{N,j} = \beta^{N,j} \cdot x_{i,t}^j \quad \forall \quad \beta^{N,j} \cdot x_{i,t}^j < 0 \quad (7)$$

D. 2 Computing total emission change and reduction

The total emission changes contributed by the nine emission driving factors are plotted in Fig 2a, *right*. Factor j 's contribution to total emission change (TEC^j) is computed as:

$$TEC^j = \beta^{*,j} \cdot \sum_t \sum_i x_{i,t}^j \quad (8)$$

$\beta^{*,j}$ is emission factor j 's regression coefficient in Table 1. The uncertainty ranges, illustrated by the error bars in the figure, are calculated using the Bca ("bias-corrected and accelerated") 95% bootstrap confidence interval (see Supplementary Table S4).

Similar to annual emission reduction (*AER*), total emission reduction (*TER*) of the emission disabling trends of factor j (Fig. 2b, *right*) only account for the emission reduction effects:

$$TER^j = \beta^{*,j} \cdot \sum_t \sum_i x_{i,t}^j \quad \forall \quad \beta^{*,j} \cdot x_{i,t}^j < 0 \quad (9)$$

Like *TEC*, the uncertainty ranges of *TER* are calculated using the Bca ("bias-corrected and accelerated") 95% bootstrap confidence interval (Supplementary Table S4) and illustrated by error bars in the figure.

D. 3 Observed and computed desirable trends

There is a good agreement between the observed CO₂ decline and the computed net CO₂ reduction outcome during GDP growth. Such agreement is most notable for 14 advanced and transition economies, namely, Austria, Belgium, Bulgaria, Switzerland, Germany, Denmark, Finland, France, United Kingdom, Iceland, Luxembourg, Poland, Sweden, and Uruguay, where the computed outcomes of net emission reduction match repeated occurrences (≥ 10 years) of CO₂ decline observed during years of GDP growth. While this is only illustrated for three countries (Denmark, United Kingdom, and Poland) in Fig. 2d, it is presented for all 14 countries in Supplementary Fig. S2.

Supplementary Figure 2 Observed and computed desirable trends for 14 countries where occurrences of CO₂ (–) decline were observed during GDP (+) growth repeatedly (≥ 10 years). “Circles” indicate CO₂ reduction was observed during GDP growth; “Colored circles” suggest computed results show CO₂ emission reduction in the same year. The Color indicate the dominant emission reduction force: deindustrialization and economic efficiency (red), decarbonization and electrification (blue), and trade surplus and winter warming (grey). Quantities of CO₂ and GDP are normalized to 1 at 1971.

E Explorations of climate-compatible economic growth rates

E. 1 Equations and assumptions

Assuming the future mimics the past, we calculate the GDP growth rates that are compatible with stabilizing or declining CO₂ emission rates based on our data set and the statistically-significant empirical relationship we derived from the benchmark model. The data set represents plausible and internally-consistent dynamics of the economic and energy developments. The use of the empirical relationships assumes future CO₂ emissions are influenced by those anthropogenic activities in a similar fashion as they were before. As discussed in the manuscript, the climate change implications of winter warming and trade surplus are less certain. Thus, in the further explorations, we only investigate how emissions

are shaped by seven factors: (1) GDP growth rate, (2) overall economic efficiency, (3) deindustrialization, (4-6) three decarbonization pathways, and (7) electrification.

First, we obtain the emission impacts of factors (3)-(7), $e1$, in country i , year t :

$$e1_{i,t} = \sum_{j=3}^7 \beta^{*,j} \cdot x^j_{i,t} \quad (10)$$

Annual changes of GDP and TFP are related and such relation varies across country and across time. For instance, in a country i , TFP increases by 2% and GDP grows by 3% in year t ; TFP increases by 2% and GDP grows by 2.2% in year $t+1$; and in the following year, TFP increases by 3% and GDP decreases by 0.2%. We preserve the plausible and internally-consistent GDP-TFP dynamics described by our data sample by computing the average TFP growth rate associated with every 1% of GDP growth:

$$\overline{\Delta TFP_{i,t}} = \frac{\Delta TFP_{i,t}}{\Delta GDP_{i,t}} \cdot 1\% \quad (11)$$

Based on Eq. 11, we can calculate the net emission effects of factors (1) and (2) when GDP grows by 1%, $e2$, in country i , year t :

$$e2_{i,t} = \beta^{*,1} \cdot 1\% + \beta^{*,2} \cdot \overline{\Delta TFP_{i,t}} \quad (12)$$

The desirable GDP growth rate ($GDP_{i,t}^d$) that allows for stabilizing or reducing CO₂ emission rate is then calculated:

$$GDP_{i,t}^d = \frac{-e1_{i,t}}{e2_{i,t}} \cdot 1\%$$

Eq. 11 represents a simplified construction of the GDP-TFP relationship. We only compute $\overline{\Delta TFP_{i,t}}$ when both $\Delta TFP_{i,t}$ and $\Delta GDP_{i,t}$ are positive as it makes the construction more likely to be reasonable. If $\Delta TFP_{i,t}$ and/or $\Delta GDP_{i,t}$ are negative, the observation is considered a case where simultaneous CO₂ reduction and GDP growth is unlikely to be achieved. We also exclude $\Delta TFP_{i,t}$ outliers (when $\Delta TFP_{i,t}/\Delta GDP_{i,t} > 2$) from further analysis. In both cases, the desirable GDP growth rate ($GDP_{i,t}^d$) that allows for stabilizing or reducing CO₂ emission is assumed to be “0”, making our analysis a conservative estimate of the climate-compatible GDP growth rate.

The percentile results presented in Fig. 3 are based on $GDP_{i,t}^d$ computed for all 2955 samples. Detailed results for Fig. 3b-d are presented in the table below.

Supplementary Table S10 **Detailed results for Fig. 3b-d**. Fractions reflect the fraction of countries which have may obtain indicated GDP growth rates while keeping emissions from

rising, except for rows population, GDP, and CO₂, where the share of global total for each of the three indicators is represented.

Desirable GDP growth rate	>=0%	>=1%	>=2%	>=3%	>=4%	>=5%	>=6%
OECD1990	55%	41%	30%	20.7%	15.1%	10.5%	7.2%
non-OECD1990	55%	36%	20%	14.3%	10.2%	7.2%	5.4%
Population	35%	19%	9%	5%	4%	2%	1%
GDP	50%	31%	13%	8%	5%	3%	2%
CO ₂	51%	31%	12%	7%	4%	3%	1%
1970s	59%	44%	30%	19%	13%	8%	6%
1980s	57%	43%	32%	25%	20%	16%	12%
1990s	53%	35%	20%	15%	12%	9%	6%
2000-2014	52%	37%	24%	17%	10%	7%	5%

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