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CO_2 Emission Drivers and Decoupling across Net-Zero Commitment Clusters

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Abstract

Background: Progress toward net-zero emissions requires evidence of whether economic growth is becoming less carbon-intensive across countries with different levels of net-zero commitment.
Objective: This study identified the main drivers of changes in CO_2 emissions and compared economic-growth decoupling across net-zero-emission commitment clusters.
Methods: Secondary panel data for 27 high-emitting countries, selected from six net-zero commitment-status clusters, were analyzed for 2008–2023. Logarithmic Mean Divisia Index (LMDI) decomposition was used to estimate the contributions of economic activity, population, energy intensity, carbon intensity, and the energy mix; Tapio analysis was used to classify emission–growth decoupling before and after the Paris Agreement.
Results: Economic activity and population were the principal drivers of emissions, whereas improvements in energy and carbon intensity generally offset part of the increase. Commitment clusters with targets embedded in law or policy documents showed more stable decoupling outcomes than declaration and proposed clusters; only Gabon, in the achieved cluster, reached strong decoupling in the post-Paris period.
Conclusion: Integrating LMDI and Tapio analyses shows that the credibility and institutionalization of net-zero commitments are associated with more stable decoupling patterns, while improvements in efficiency and decarbonization remain essential for offsetting growth-related emissions.

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INTRODUCTION

Global warming has been a concern for many countries in recent years. Based on data from the National Centers for Environmental Information (NOAA), 2024 was the warmest year since global temperature records began in 1850. The global average surface temperature was 2.32 degrees Fahrenheit (1.29 degrees Celsius) above the 20th-century average of 57.0 degrees Fahrenheit (13.9 degrees Celsius) and 2.63 degrees Fahrenheit (1.46 degrees Celsius) above the pre-industrial average, which NOAA defines as the period from 1850 to 1900.

One of the causes of global warming is the increase in greenhouse gas emissions. Data from Climatewatchdata (2024), as shown in Figure 1, show that the largest contributor to greenhouse gas emissions is the energy sector, with total emissions of 38.37 Gt globally, accounting for 76% of total emissions. Several energy subsectors contribute to these emissions, including electricity and heat (29.7%), transportation (13.7%), manufacturing and construction (12.7%), and other sectors.

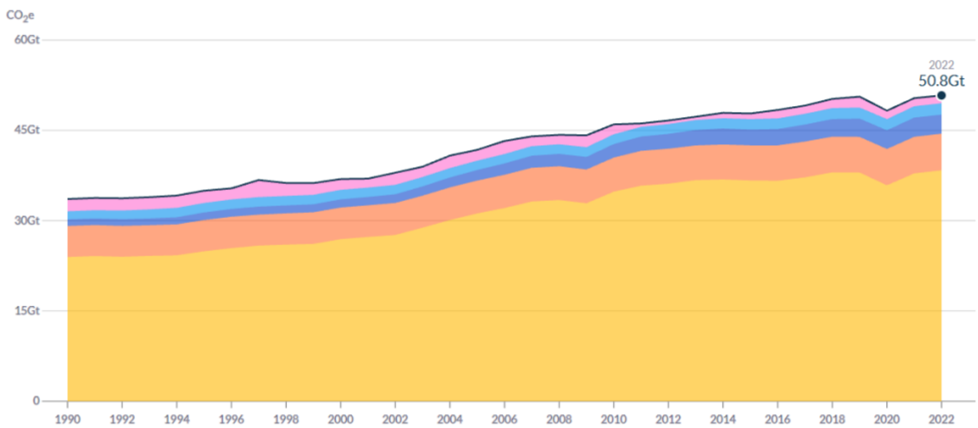


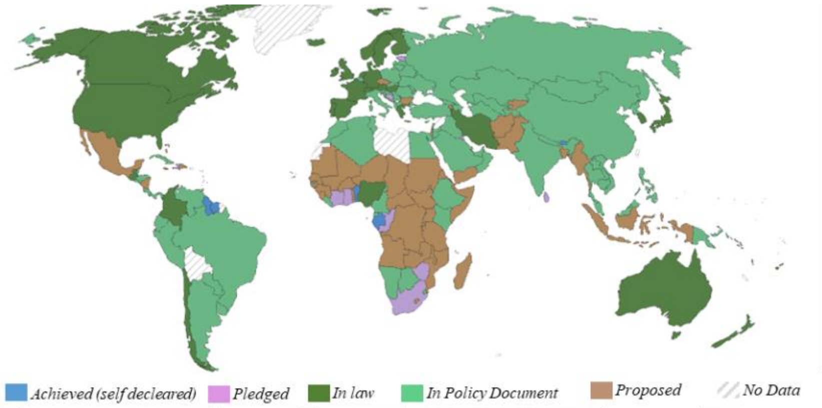
Figure 1. Emission levels from various sectors
Source: climatewatchdata (2024)

Global warming and high emission levels have become major concerns for many countries seeking long-term solutions (Jacobson et al., 2022; Santos et al., 2022; Singh, 2021). The formation of international cooperation and joint commitments through the Paris Agreement in 2015 represents one such effort. The Paris Agreement was adopted by 195 Parties at the 21st Conference of the Parties (COP21) in Paris, with the main goal of limiting the increase in the global average temperature to well below 2°C above pre-industrial levels while pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Furthermore, COP21 established a framework for achieving long-term climate neutrality. Rather than requiring the complete elimination of emissions, the Paris Agreement seeks to achieve a balance between anthropogenic greenhouse gas (GHG) emissions by sources and removals by sinks in the second half of the century.

Achieving this balance can involve several measures, such as reforestation of degraded forests, restoration of peatlands and other ecosystems, reductions in GHG emission rates, transitions to cleaner energy sources, and the development of environmentally friendly technologies with lower emissions. These measures are crucial for limiting global temperature rise to 1.5°C above pre-industrial levels and reducing the risk of severe climate impacts. To align with the 1.5°C temperature goal, global GHG emissions need to decline substantially; the IPCC has indicated that global GHG emissions would need to be reduced by approximately 43% by 2030 relative to 2019 levels, while earlier assessments commonly expressed the requirement as a 45% reduction by 2030 relative to 2010 levels. Thus, the 45% reduction figure should not be presented as a target to be achieved by 2050.

Figure 2 shows a map of the distribution of countries according to their net-zero commitment status. Of the countries assessed globally, the 2024 Net Zero Stocktake classified countries according to the status and strength of their net-zero targets, including targets that had been achieved or were in progress. Because the classification of "achieved" depends on the criteria and source used, the number and identity of countries in this category should be reported directly according to the dataset underlying Figure 2 rather than stated as a universal count. The same applies to the number of countries with legally binding net-zero targets and those without net-zero targets. If the figure is based specifically on a 2024 Net Zero Tracker dataset, the country counts should therefore be cross-checked against that dataset before publication.

To achieve these targets, long-term policies and strategies are needed across all countries. One of the major drivers of GHG emissions is the high level of fossil-fuel consumption. Many countries remain highly dependent on fossil fuels as their primary energy sources and as an important driver of economic growth. According to Our World in Data (2024), fossil-fuel consumption remains particularly high in Asia, with China being the world's largest consumer of coal and the United States among the world's largest consumers of oil. Fossil-fuel consumption comprises energy derived from coal, oil, and natural gas; therefore, comparisons should specify the fuel type and unit of measurement rather than referring generally to "fossil energy consumption" (Khalid et al., 2021; Q. Wang et al., 2020).



Source: Ourworldindata (2025)
Figure 2. Net Zero Emission Progress of All Countries

One related concept to net-zero emissions is carbon neutrality; both share the goal of achieving an emissions balance but differ in scope (Chen et al., 2026). According to the European Parliament (2019), carbon neutrality means achieving a balance between carbon emissions and carbon absorption from the atmosphere through carbon sinks. The process of removing carbon dioxide from the atmosphere and storing it is known as carbon sequestration (Rackley, 2017). Unlike net-zero emissions, carbon neutrality generally focuses on carbon dioxide emissions, whereas net-zero emissions is broader, accounting for all greenhouse gas emissions, including methane, SF_6, and nitrous oxide. This research focuses primarily on carbon neutrality as part of the transition toward net-zero emissions.

The energy transition from fossil fuel use to renewable energy sources has been undertaken by many countries. Alternative energy resources have been widely developed, reaching their highest levels in 2023 at 21,436.24 TWh and in 2024 at 22,345.99 TWh. Renewable energy sources such as wind, biomass, solar, and hydropower constitute the most widely used renewable energy sources. Nevertheless, global use of fossil energy sources continues to increase each year. An article on The Guardian website (2024) states that although renewable energy consumption peaked in 2023, fossil energy consumption also increased. Coal consumption rose by 1.6%, while oil demand rose by 2%, reaching 100 million barrels per day for the first time. A report released by KPMG also mentioned that this increase was driven by rising fossil fuel consumption in India, which increased by 8% from the previous year, matching the overall increase in energy demand and reaching 89% of total energy use. This also means that, for the first time, more coal was used in India than in Europe and North America combined (The Guardian, 2024).

The Kaya identity operationalizes the IPAT proposition by expressing CO_2 emissions as the product of population, economic activity per capita, energy intensity, and carbon intensity; the present study additionally captures changes in the fossil-energy share through an energy-mix effect. LMDI decomposes changes in total emissions into these drivers, whereas Tapio decoupling evaluates whether the resulting emissions trajectory separates from economic growth. Together, the two methods create a coherent analytical sequence from emission drivers to the development–emission relationship.

LMDI was used to quantify the contributions of population, economic activity, energy intensity, carbon intensity, and energy mix to observed CO_2-emission changes. The resulting component effects provide the empirical basis for interpreting each country's Tapio decoupling status rather than treating decoupling solely as a descriptive ratio.

Tapio decoupling was then used to assess whether changes in CO_2 emissions were separated from economic growth. This second step connects the driver-based LMDI results with a comparable classification of country performance across periods and commitment clusters.

Previous research has applied decomposition and decoupling methods to sectors and geographically bounded settings, including industrial sectors in China Dong et al. (2021), tourism in European Union countries Driha et al. (2025), and university activities in the United Kingdom (Shaikh & Jacob, 2021). These studies demonstrate the utility of these methods but do not compare countries according to the legal and policy maturity of their net-zero commitments, nor do they jointly assess pre- and post-Paris Agreement patterns across these commitment categories.

This study makes three measurable contributions. First, it classifies high-emitting countries into six net-zero commitment-status clusters rather than by region or income group, allowing comparison of policy-commitment maturity. Second, it integrates LMDI decomposition with Tapio decoupling so that the contributions of emission drivers can be interpreted alongside the emission–growth relationship. Third, it compares 2008–2014 and 2015–2023 to examine how these patterns changed before and after the Paris Agreement. This classification is important because the legal and policy status of a net-zero pledge may indicate differences in implementation capacity that regional and income classifications do not capture.

This study aims to quantify the contributions of emission drivers and classify country-level decoupling outcomes across net-zero commitment clusters. The findings provide theoretical evidence on the Kaya–IPAT mechanism and practical evidence for policymakers regarding which levers (energy efficiency, carbon intensity, or energy-mix transition) require priority action.

METHOD

This quantitative, longitudinal comparative study used deterministic Logarithmic Mean Divisia Index (LMDI) decomposition and Tapio decoupling analysis. LMDI estimated the contributions of economic activity, population, energy intensity, carbon intensity, and energy mix to annual changes in CO_2 emissions, whereas the Tapio method classified the relationship between changes in CO_2 emissions and GDP.

Operational Definition and Variable Measurement

Carbon Dioxide (CO_2) Emissions

CO_2 emissions refer to the release of carbon dioxide into the atmosphere, primarily resulting from human activities such as the combustion of fossil fuels in the energy, industrial, agricultural, and waste sectors, excluding land use, land-use change, and forestry (LULUCF). CO_2 is a major contributor to global warming because it is a greenhouse gas that traps heat in the atmosphere. In this study, CO_2 emissions are defined as the annual emissions of each sampled country resulting from fossil-fuel and energy use, expressed in $MtCO_2$.

Income Level (GDP)

Gross domestic product (GDP) is the most commonly used measure of a country's overall economic activity. GDP represents the total monetary value of final goods and services produced within a country over a specific period, such as one year, measured at constant prices. In this study, GDP is measured as the total GDP of each sampled country in U.S. dollars (US$).

Population

Total population is based on the *de facto* population definition, which counts all residents regardless of legal status or citizenship. The data are expressed in millions of people.

Energy Intensity

Energy intensity is the amount of energy required to produce one unit of economic output. In this study, energy intensity is calculated as the ratio of total primary energy consumption to GDP. A lower energy-intensity ratio indicates greater energy efficiency in generating economic output, whereas a higher ratio indicates that more energy is required to generate the same level of economic output.

Carbon Intensity

Carbon intensity is a measure of the amount of carbon dioxide emissions generated per unit of energy consumed or economic output produced. In this study, carbon intensity is calculated as the ratio of total CO_2 emissions to total primary energy consumption and is expressed in $MtCO_2$ per unit of energy. A lower carbon-intensity value indicates lower CO_2 emissions per unit of energy consumed and therefore a lower carbon burden associated with energy use.

Energy Mix Level

The energy mix represents the combination of energy sources used to meet a country's energy demand. It reflects the composition of energy consumption according to the types of energy resources used, including fossil fuels such as coal and oil and renewable energy sources. In this study, the energy mix is represented by the share of fossil-fuel consumption in total energy consumption. A decline in the fossil-fuel share indicates a shift toward cleaner energy sources and greater use of renewable energy, whereas an increase indicates greater reliance on fossil fuels. Within the LMDI framework, the resulting energy-mix effect captures the contribution of changes in the energy composition to changes in CO_2 emissions.

Type and Source of Data

The study used annual secondary panel data for 2008–2023. The sampling frame comprised countries classified according to their net-zero commitment status in Our World in Data. Within each of the six clusters, countries with the highest emission levels and complete data were selected to ensure that the analysis captured major contributors while maintaining representation across clusters. The initial sampling frame contained 29 countries; Yemen and Myanmar were excluded because complete published data were unavailable, resulting in a final analytical sample of 27 countries.

GDP data were obtained from the International Monetary Fund, while data on CO_2 emissions, population, energy intensity, carbon intensity, and energy mix were compiled from the World Bank's World Development Indicators, the U.S. Energy Information Administration, and Our World in Data. The series were checked for consistent country coverage, annual units, and temporal availability before analysis. Only complete country-year observations were retained.

Table 1

Net Zero Emission Status

Achieved	No Target	Declaration	Submission	Drafting/ Legislation	Already has Legislation
Togo (TGO)	United States (USA)	Indonesia (IDN)	Pakistan (PAK)	China (CHN)	India (IND)
Gabon (GAB)	Poland (POL)	Saudi Arabia (SAU)	Myanmar (MMR)	Japan (JPN)	Russia (RUS)
Suriname (SUR)	Iran (IRN)	South Africa (ZAF)	Sudan (SDN)	Mexico (MEX)	Germany (DEU)
Guyana (GUY)	Egypt (EGY)	Uzbekistan (UZB)	Yemen (YEM)	Brazil (BRA)	South Korea (KOR)
	Iraq (IRQ)	Kuwait (KWT)	Kyrgyzstan (KGZ)	Turkey (TUR)	Canada (CAN)

Data Collection Method

Data were collected through documentary retrieval from the cited institutional databases. The analytical flow proceeded from data harmonization to LMDI decomposition of emission change, to Tapio decoupling classification, and finally to comparison across commitment clusters and the pre- and post-Paris Agreement periods. This sequential design links the accounting of emission drivers to the interpretation of country-level decoupling outcomes.

Data Analysis Technique

Decomposition Calculation

LMDI-I decomposition was used because it provides additive factor contributions without residual terms. The model assumes that the selected Kaya identity factors adequately represent the accounting relationship among emissions, economic activity, population, energy intensity, carbon intensity, and energy mix. It estimates contributions rather than causal effects.

$$\Delta C = C_t - C_0 = \Delta CI + \Delta EM + \Delta EI + \Delta EA + \Delta P \qquad (3.1)$$

The calculation for each emission factor effect can be described as follows:

$$\Delta CI = \sum_i \left(\frac{C_i^t - C_i^0}{ln\ C_i^t - ln\ C_i^0}\right) x \ln\left(\frac{CI^t}{CI^0}\right) \quad (3.2)$$

$$\Delta EM = \sum_i \left(\frac{C_i^t - C_i^0}{ln\ C_i^t - ln\ C_i^0}\right) x \ln\left(\frac{EM^t}{EM^0}\right) \quad (3.3)$$

$$\Delta EI = \sum_i \left(\frac{C_i^t - C_i^0}{ln\ C_i^t - ln\ C_i^0}\right) x \ln\left(\frac{EI^t}{EI^0}\right) \quad (3.4)$$

$$\Delta EA = \sum_i \left(\frac{C_i^t - C_i^0}{ln\ C_i^t - ln\ C_i^0}\right) x \ln\left(\frac{EA^t}{EA}\right) \quad (3.5)$$

$$\Delta P = \sum_i \left(\frac{C_i^t - C_i^0}{ln\ C_i^t - ln\ C_i^0}\right) x \ln\left(\frac{P^t}{P^0}\right) \quad (3.6)$$

Where, in the above equations, CI represents carbon intensity, EM represents the energy mix level, EI represents energy intensity, EA represents economic activity measured by GDP per capita, P represents population, and t denotes the year of observation.

For the decomposition calculation, the analysis was performed for each country. Comparisons were also made between the periods 2008–2014, representing the period before the Paris Agreement, and 2015–2023, representing the period after the Paris Agreement entered into force, to examine each country's commitment to implementing energy transition and reducing emissions.

Decoupling Index Calculation

The Tapio decoupling index was used to classify the elasticity between changes in CO$_2$ emissions and GDP. The method assumes comparable annual changes in the variables and interprets the resulting decoupling categories as descriptive performance states; it does not establish that net-zero commitments caused the observed emission trajectories.

$$D_C = D_{CI} + D_{EM} + D_{EI} + D_{EA} + D_P \quad (3.7)$$

The individual decoupling index calculation for each factor is as follows:

$$D_{CI} = \frac{(CI^t - CI^0)/C^0}{(G^t - G^0)/G^0} \quad (3.8)$$

$$D_{EM} = \frac{(EM^t - EM^0)/C^0}{(G^t - G^0)/G^0} \quad (3.9)$$

$$D_{EI} = \frac{(EI^t - EI^0)/C^0}{(G^t - G^0)/G^0} \quad (3.10)$$

$$D_{EA} = \frac{(EA^t - EA^0)/C^0}{(G^t - G^0)/G^0} \quad (3.11)$$

$$D_P = \frac{(P^t - P^0)/C^0}{(G^t - G^0)/G^0} \quad (3.12)$$

Tapio categories were interpreted as descriptive combinations of changes in emissions and economic growth. Strong decoupling denotes declining emissions alongside economic growth, whereas weak decoupling denotes growth in both variables, with emissions increasing more slowly than GDP. Expansive negative decoupling denotes emissions increasing faster than GDP. Recessive decoupling and the negative-decoupling categories represent contractionary economic contexts and require interpretation alongside the underlying LMDI effects.

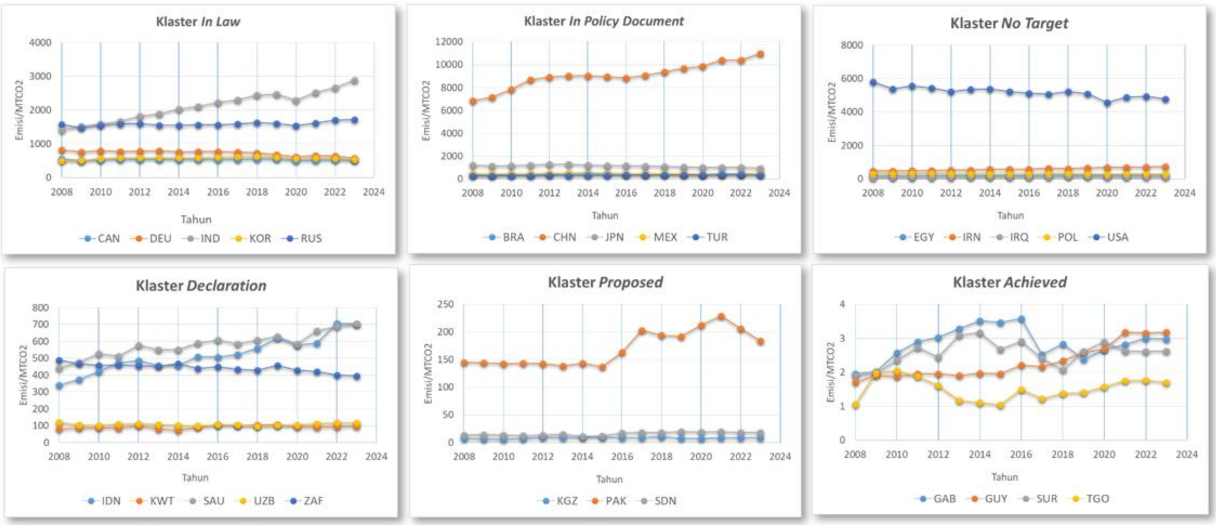
RESULTS AND DISCUSSION

Overview of Research Objects

Carbon Emission Level Trends

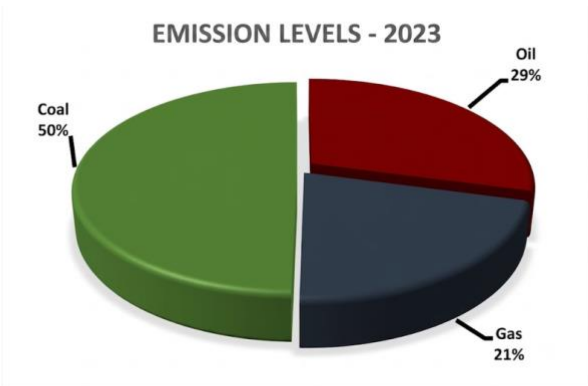
In this study, the emissions considered are those originating from fossil fuel use, with carbon emissions measured in MtCO$_2$e. Throughout the 2008–2023 study period, carbon emissions in the 27 countries examined fluctuated annually. In 2023, global emissions reached their highest level, with cumulative emissions from the 27 countries accounting for 78% of total emissions, or 27,901 MtCO$_2$e. Based on data from the past five years, Gabon (25%), Guyana (22%), Togo (22%), India (17%), and Uzbekistan (12%) recorded the largest percentage increases in emissions, although their overall emission levels remain relatively small. Meanwhile, Germany (−16%), South Africa (−14%), South Korea (−11%), Japan (−10%), and Iraq (−10%) recorded the largest reductions in emissions over the same five-year period.

During the study period, 2008 and 2009 recorded the lowest emission levels. In 2008, emissions totaled 22,525 $MtCO_2e$, before declining by 0.95% in 2009. The 2008–2009 period coincided with the global financial crisis, which affected numerous sectors and contributed to reductions in economic activity, energy consumption, and income levels worldwide. A further decline occurred in 2015–2016, driven by several factors, including the economic slowdown in China, declining coal consumption in China, and the increasing use of renewable energy sources, particularly solar energy. This period also coincided with the adoption of the Paris Agreement in 2015 and its entry into force in 2016. Finally, emissions decreased by 3.95% in 2020 as the COVID-19 pandemic caused a substantial decline in global economic activity.



Source: Ourworldindata (2024)
Figure 3. Carbon emission level trends

Based on data from Our World in Data (2024), among the three fossil energy sources used by the 27 countries, coal remains the largest contributor to emissions, compared with oil and gas. A total of 13,876 $MtCO_2e$, accounting for 50% of total emissions, comes from coal use. Meanwhile, oil accounts for 29% of total emissions, equivalent to 8,158 $MtCO_2e$, while gas accounts for 21%, equivalent to 5,902 $MtCO_2e$.



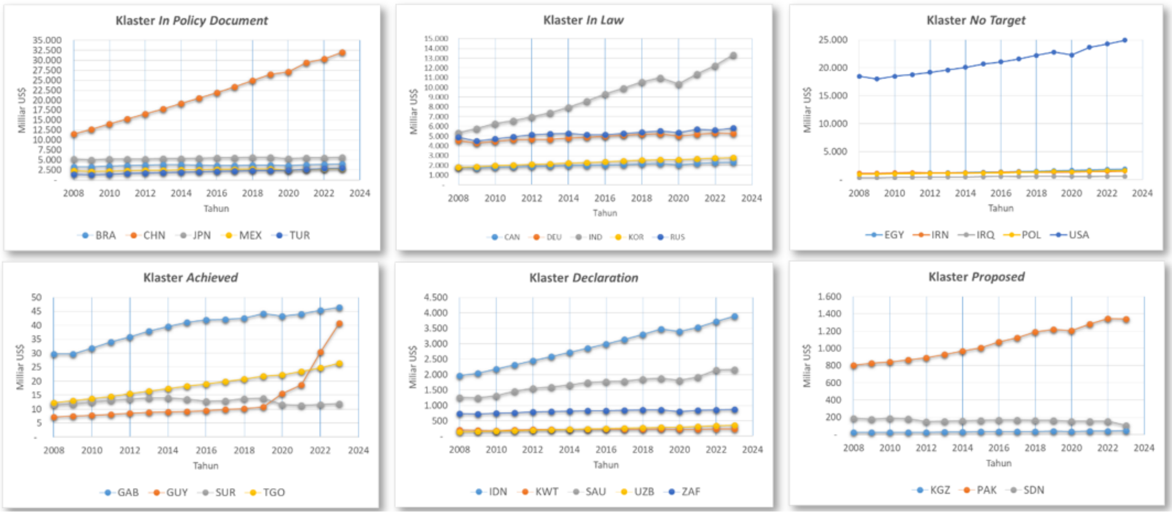
Source: Ourworldindata (2024)
Figure 4. Percentage of fossil emissions from 27 countries

Income Level Trends

Income data in this study were obtained from the World Bank website (2024), using gross national income (GNI) in current US$ to show the growth trend in the income levels of the countries studied. Global GNI has fluctuated but has continued to show an overall growth trend.

In 2023, global GNI was US$116,927,928,837,000. Compared with the 27 countries studied, these countries accounted for 70% of global GNI, with the United States, China, Japan, Germany, and India having the highest GNI levels. Over the last five years, from 2019 to 2023, the countries with the highest percentage growth in GNI were Guyana (276%), Turkey (26%), Uzbekistan (24%), India (21%), and Togo (21%).

During the research period, there were two years in which GNI declined: 2009 and 2020. In 2009, GNI decreased by 0.77% from 2008, when it was US$69,740,881,113,935. This decline occurred, as explained above, due to the global economic crisis. Similarly, in 2020, due to the COVID-19 pandemic, the GNI of the 27 countries studied fell by 1.63% from the previous year. Among these countries, Russia (−8%), Kuwait (−7%), Mexico (−6%), Japan (−6%), and Germany (−6%) experienced the largest declines in GNI in 2009. Meanwhile, in 2020, the five countries with the largest decreases were Suriname (−16%), Iraq (−12%), Mexico (−8%), Kyrgyzstan (−7%), and South Africa (−6%).

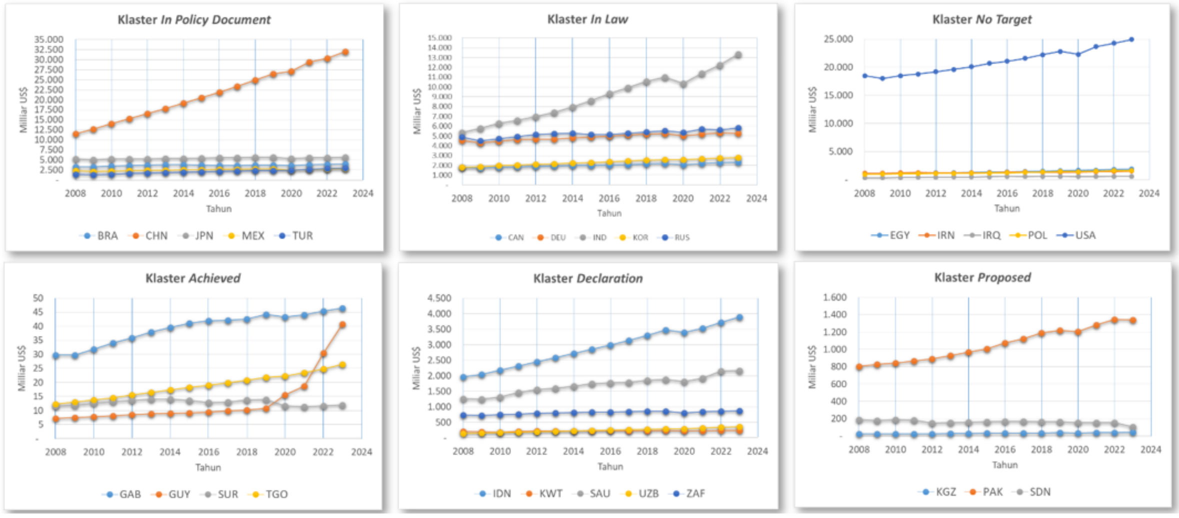


Source: World Bank (2024)

Figure 5. Income level trends

Population Trends

The population count is based on the de facto definition, which counts all residents regardless of legal status or citizenship. Data were obtained from the World Bank website (2024) and subsequently processed and presented graphically in Figure 4.3 below. Across the 27 countries, the total population in 2023 was 5,079,241,277. The average population growth from 2008 to 2023 was 0.88%, with the population continuing to increase each year and reaching its highest level in 2023. Poland (-3.4%), Japan (-1.7%), Russia (-1.1%), and Korea (-0.1%) experienced population declines over the last five years. Several factors may have contributed to these declines, including low fertility rates, cultural changes related to marriage in each country, and rising living costs, which have caused many citizens to delay marriage.



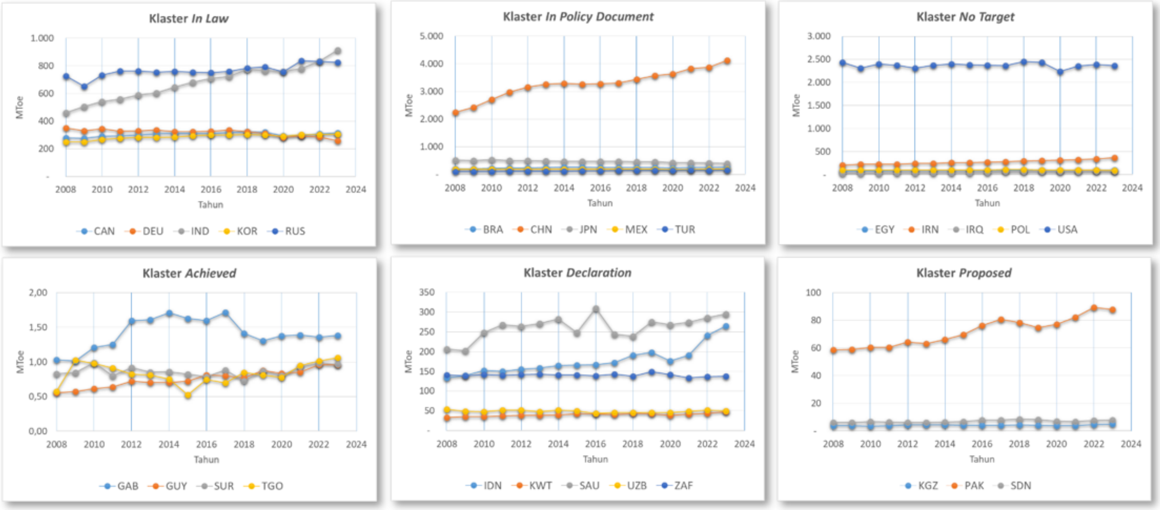
Source: World Bank (2024)
Figure 6. Population trends

Energy Consumption Level Trends

Energy consumption is one of the driving factors behind changes in carbon emission levels (Chang et al., 2019; Duan et al., 2022; Xiong et al., 2025). This study uses primary energy consumption data obtained from the Our World in Data (2024) website. The data, originally reported in TWh, were converted to million tonnes of oil equivalent (Mtoe). According to the Energy Information Administration (2025), primary energy consumption refers to energy consumption in the form in which it is first accounted for in the statistical energy balance, before any transformation into secondary or tertiary energy forms. This includes fossil fuels such as coal, natural gas, and oil, as well as energy from renewable and other sources, such as biomass, nuclear, geothermal, and wind (Kalair et al., 2021).

The graph shows that the highest levels of energy consumption are still dominated by China, which ranked first with 4,121,324,528 toe (approximately 4,121 Mtoe), followed by the United States in second place with 2,360,991,945 toe (approximately 2,361 Mtoe). India ranked third with 913,028,742 toe, followed by Russia with 824,749,759 toe and Japan with 404,406,068 toe. Across all countries included in the study, the highest aggregate energy consumption occurred in 2023, reaching 11,640,186,152 toe (approximately 11,640 Mtoe), or 78.6% of global primary energy consumption.

As with changes in global emission and income levels, a decrease in energy consumption was observed among the countries included in the study. In 2015, China experienced a decrease of 0.7%. The adoption of the Paris Agreement in 2015, followed by its entry into force in 2016, may have contributed to the increased adoption of renewable energy, particularly solar energy, although this relationship should not be interpreted as a direct causal effect without further empirical evidence. In addition, the global pandemic in 2020 led to a decline in economic activity worldwide, which also affected energy consumption across the 27 countries included in the study.



Source: Ourworldindata (2025)

Figure 7. Energy consumption level trends

When viewed in terms of the rate of change between 2019 and 2020, the largest declines in primary energy consumption occurred in Sudan (-13.3%), Indonesia (-10.7%), Mexico (-9.8%), Iraq (-9.8%), and Germany (-9.7%). Of the 27 countries, only Gabon (5.2%), Pakistan (3.2%), Iran (2.4%), and China (1.7%) did not experience a decrease in energy consumption in 2020. This decrease was only temporary, as consumption in each country increased again from 2021 to 2023, following the subsiding of the COVID-19 pandemic, and reached its highest level in 2023.

Summary of Statistical Results

Table 2 below presents statistical data for 27 countries analyzed over a 15-year research period, from 2008 to 2023, resulting in a total of 405 observations. The main variables used as the basis for the calculations in this study are emissions levels, income levels, population, and energy consumption levels. As shown in the table below, the average emissions level across the 27 countries is 940.01 MtCO$_2$e, with a minimum value of 1.05 MtCO$_2$e (Togo in 2008) and a maximum value of 11,008.45 MtCO$_2$e (China in 2023).

Table 2

Descriptive statistics of variables from 27 countries

Variable	Unit	Observations	Mean	Std. Dev.	Min	Max
Emissions	MtCO2e	405	940.01	1,910.06	1.05	11,008.45
Income	Billion US$ PPP constant 2021	405	3,383.29	5,640.14	7.20	32,004.88
Population	Millions of people	405	177.48	343.39	0.54	1,438.07
Energy Consumption	Mtoe	405	381.89	734.69	0.53	4,121.32
Economic Activity	US$/Capita	405	13.96	15.36	0.58	66.36
Energy Intensity	MToe/US$	405	268,506.25	169,029.48	50,265.89	1,031,980.25
Carbon Intensity	MTCO2/MToe	405	0.000003	0.0000004	0.000002	0.000004
Energy Mix	Percent (%)	405	0.92	0.07	1.03	0.67

For the income level variable, the highest value is China's income in 2023, at US$26,445,072,845. From the data above, the average population of the 27 countries is 177,480,000 people, with Suriname in 2008 having the lowest population at 537,245 people and India having the highest population at 1,438,069,596. Furthermore, for the energy consumption variable, the average primary energy consumption of the 27 countries is 381.89 Mtoe. By country, Togo had the lowest primary energy consumption, at 0.53 Mtoe in 2015, while China had the highest primary energy consumption, at 4,121.32 Mtoe in 2023.

The economic activity variable shows an average value of 13.96 US$/person, with the lowest value recorded by Guyana in 2023 at 50,265.89 Mtoe/US$. The higher the energy intensity, the more inefficient a country is, as it requires more energy to produce a given level of economic output. The carbon intensity variable shows a relatively small difference between the maximum and minimum values and their standard deviations. This may indicate that the emission characteristics of the countries do not differ substantially. A similar pattern can be observed for the energy mix variable. The energy mix variable has an average value of 0.92, with a standard deviation of 0.07. The minimum value of 0.67 and maximum value of 1.03 indicate that differences in the energy structures among countries are relatively small compared with those observed for other variables.

Discussion

Analysis of Decoupling Results

The annual Tapio results showed substantial cross-country variation. Canada displayed relatively stable weak to strong decoupling states, although crisis periods were associated with recessive decoupling states. This pattern should be interpreted in conjunction with the LMDI results: changes in economic activity and population exerted upward pressure on emissions, while improvements in energy intensity and carbon intensity moderated that pressure.

Figure 8. Yearly decoupling trends

Across the 27 countries, strong decoupling, weak decoupling, and expansive negative decoupling were the most frequent states. The strongest aggregate period was 2021–2022, when 12 countries achieved strong decoupling and nine achieved weak decoupling; the 2008–2009 and 2019–2020 crisis periods generated the most adverse categories. These findings indicate that decoupling performance depends on whether efficiency and carbon-reduction gains can offset the Kaya–IPAT pressures created by income growth and population.

	2008 - 2009	2009 - 2010	2010 - 2011	2011 - 2012	2012 - 2013	2013 - 2014	2014 - 2015	2015 - 2016	2016 - 2017	2017 - 2018	2018 - 2019	2019 - 2020	2020 - 2021	2021 - 2022	2022 - 2023
Iraq	Expansive negative decoupling	Expansive coupling	Weak decoupling	Weak decoupling	Weak decoupling	Strong decoupling	Weak decoupling	Weak decoupling	Strong negative decoupling	Expansive negative decoupling	Weak decoupling	Recessive decoupling	Strong decoupling	Expansive negative decoupling	Expansive negative decoupling
Jepang	Recessive coupling	Expansive coupling	Expansive negative decoupling	Expansive negative decoupling	Weak decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Recessive decoupling	Recessive decoupling	Weak decoupling	Strong decoupling	Strong decoupling
Kyrgyztan	Strong decoupling	Recessive decoupling	Expansive negative decoupling	Strong negative decoupling	Strong decoupling	Expansive coupling	Weak decoupling	Strong decoupling	Strong decoupling	Expansive negative decoupling	Strong decoupling	Recessive coupling	Expansive negative decoupling	Strong decoupling	Weak decoupling
Korea Selatan	Expansive negative decoupling	Expansive negative decoupling	Expansive negative decoupling	Weak decoupling	Weak decoupling	Strong decoupling	Weak decoupling	Weak decoupling	Expansive coupling	Expansive coupling	Strong decoupling	Recessive decoupling	Weak decoupling	Strong decoupling	Strong decoupling
Kuwait	Strong negative decoupling	Strong negative decoupling	Strong decoupling	Expansive negative decoupling	Strong decoupling	Strong decoupling	Expansive negative decoupling	Expansive negative decoupling	Recessive coupling	Expansive coupling	Expansive coupling	Recessive decoupling	Strong decoupling	Weak decoupling	Strong negative decoupling
Mexico	Weak negative decoupling	Strong decoupling	Expansive negative decoupling	Expansive coupling	Strong decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Weak decoupling	Weak negative decoupling	Recessive coupling	Weak decoupling	Expansive negative decoupling	Expansive negative decoupling
Pakistan	Strong decoupling	Strong decoupling	Weak decoupling	Strong decoupling	Strong decoupling	Expansive coupling	Strong decoupling	Expansive negative decoupling	Expansive negative decoupling	Strong decoupling	Strong decoupling	Strong negative decoupling	Expansive coupling	Strong decoupling	Recessive decoupling
Poland	Strong decoupling	Expansive negative decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Weak decoupling	Expansive coupling	Weak decoupling	Strong decoupling	Strong decoupling	Recessive decoupling	Expansive negative decoupling	Strong decoupling	Strong decoupling
Rusia	Recessive coupling	Expansive coupling	Weak decoupling	Weak decoupling	Strong decoupling	Expansive coupling	Strong negative decoupling	Strong decoupling	Expansive coupling	Expansive coupling	Strong decoupling	Recessive decoupling	Expansive coupling	Strong negative decoupling	Weak decoupling
Saudi Arabia	Strong negative decoupling	Expansive negative decoupling	Strong decoupling	Expansive negative decoupling	Strong decoupling	Weak decoupling	Expansive negative decoupling	Expansive negative decoupling	Strong decoupling	Expansive negative decoupling	Expansive negative decoupling	Recessive decoupling	Expansive negative decoupling	Weak decoupling	Expansive negative decoupling

Figure 9. Yearly decoupling trends - continued

Gabon, Guyana, Suriname, and Togo, which are countries in the achieved-emission-balance cluster, show relatively volatile results in the decoupling analysis. The matrix indicates that these four countries are predominantly characterized by the expansive negative decoupling level. Only Togo is relatively more stable during the 2009–2014 period, while the other countries have not yet achieved a better level of decoupling. Based on the decomposition results, this can be attributed to economic growth rates that are slower than the increases in emission levels in these countries. Furthermore, energy intensity and carbon intensity also contribute to this pattern, reflecting the relatively low efficiency of production technologies associated with the still-low level of modern industrialization in these countries.

	2008 - 2009	2009 - 2010	2010 - 2011	2011 - 2012	2012 - 2013	2013 - 2014	2014 - 2015	2015 - 2016	2016 - 2017	2017 - 2018	2018 - 2019	2019 - 2020	2020 - 2021	2021 - 2022	2022 - 2023
Sudan	Strong negative decoupling	Strong decoupling	Recessive decoupling	Strong negative decoupling	Expansive negative decoupling	Strong decoupling	Expansive negative decoupling	Expansive negative decoupling	Expansive negative decoupling	Strong negative decoupling	Strong negative decoupling	Weak negative decoupling	Strong negative decoupling	Recessive decoupling	Weak negative decoupling
Suriname	Expansive coupling	Expansive negative decoupling	Expansive negative decoupling	Strong decoupling	Expansive negative decoupling	Expansive negative decoupling	Recessive decoupling	Strong negative decoupling	Strong decoupling	Strong decoupling	Expansive negative decoupling	Strong negative decoupling	Recessive decoupling	Strong decoupling	Weak decoupling
Togo	Expansive negative decoupling	Weak decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Expansive negative decoupling	Strong decoupling	Expansive negative decoupling	Weak decoupling	Expansive negative decoupling	Expansive negative decoupling	Weak decoupling	Strong decoupling
Turki	Strong negative decoupling	Strong decoupling	Weak decoupling	Expansive coupling	Strong decoupling	Expansive coupling	Expansive coupling	Expansive negative decoupling	Weak decoupling	Strong decoupling	Strong decoupling	Weak decoupling	Expansive coupling	Strong decoupling	Strong decoupling
Amerika Serikat	Recessive decoupling	Expansive negative decoupling	Strong decoupling	Strong decoupling	Expansive coupling	Weak decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Expansive coupling	Strong decoupling	Recessive decoupling	Expansive coupling	Weak decoupling	Strong decoupling
Uzbekistan	Strong decoupling	Strong decoupling	Expansive negative decoupling	Weak decoupling	Strong decoupling	Strong decoupling	Strong decoupling	Expansive coupling	Strong decoupling	Strong decoupling	Expansive coupling	Weak decoupling	Expansive coupling	Weak decoupling	Strong decoupling
Afrika Selatan	Recessive decoupling	Strong decoupling	Weak decoupling	Strong decoupling	Strong decoupling	Expansive negative decoupling	Strong decoupling	Expansive negative decoupling	Strong decoupling	Strong decoupling	Expansive negative decoupling	Recessive coupling	Strong decoupling	Strong decoupling	Strong decoupling

Figure 10. Yearly decoupling trends - continued (2)

Analysis of Decoupling Results – Scope of the Paris Agreement

The period 2008–2014 represents the phase before the ratification of the Paris Agreement. In 2014, the emission level of the 27 countries was 25,463.305 tons of CO_2, a 13% increase from the total emissions in 2008 (22,525.433 tons of CO_2). The decomposition results show that, in almost all countries during the 2008–2014 period, the economic activity effect and population effect had positive impacts, driving up emission levels. Energy intensity and carbon intensity were factors that mitigated the increase in emission levels. Japan, Germany, and Sudan showed favorable energy intensity performance compared with other countries, while, in terms of carbon intensity, Canada, Kuwait, and Russia had the most favorable carbon intensity effects during this period. The energy mix effect calculation results show that most countries were still dependent on fossil fuels for energy consumption.

Although a global economic crisis occurred in 2008–2009, the decoupling results show that nine countries achieved a strong decoupling level: Canada, Germany, Kuwait, Pakistan, Poland, Russia, the United States, Uzbekistan, and South Africa. Collectively, these countries experienced decreases in emission levels. This indicates a strong separation of economic growth from carbon-emission pressures, with the decline in emissions not being caused by weakening economic activity but rather by improved energy efficiency, lower carbon intensity, and the transformation toward cleaner, lower-emission production technologies and energy systems.

According to the decoupling calculation results, China, Egypt, Guyana, Iraq, Mexico, Saudi Arabia, Togo, and Turkey were at the weak decoupling level during the pre-Paris Agreement period. This means that these countries were in a phase of economic growth accompanied by rising emissions, but the increase in emissions was still slower than the rate of economic growth. Countries at this level can be categorized as being in the early phase of transition toward strong decoupling, as indicated by improvements in carbon intensity and energy intensity.

	2008 - 2014						
	DEA	DEP	DEI	DCI	DEM	DCE TOT	D Status
Brazil	0,75	0,33	0,56	0,19	0,17	2,00	*Expansive negative decoupling*
Kanada	0,34	0,60	0,09	-2,04	0,84	-0,16	*Strong decoupling*
China	0,83	0,06	-0,22	-0,15	-0,03	0,49	*Weak decoupling*
Jerman	1,19	-0,26	-2,41	-0,10	0,11	-1,46	*Strong decoupling*
Mesir	0,30	0,66	-0,16	-0,19	0,00	0,61	*Weak decoupling*
Gabon	0,32	0,85	0,90	0,26	0,07	2,40	*Expansive negative decoupling*
Guyana	0,96	0,00	0,04	-0,39	-0,01	0,60	*Weak decoupling*
Indonesia	0,76	0,23	-0,34	0,25	-0,01	0,88	*Expansive coupling*
India	0,78	0,21	-0,14	0,09	-0,03	0,90	*Expansive coupling*
Iran	0,14	0,92	1,84	-0,60	-0,06	2,24	*Expansive negative decoupling*
Iraq	0,39	0,57	0,06	-0,23	-0,01	0,78	*Weak decoupling*
Jepang	1,34	-0,34	-5,87	0,20	6,22	1,56	*Expansive negative decoupling*
Kyrgyztan	0,55	0,48	-0,33	0,95	-0,32	1,34	*Expansive negative decoupling*
Korea Selatan	0,82	0,17	-0,33	0,11	0,08	0,85	*Expansive coupling*
Kuwait	-3,03	3,94	1,19	-3,40	0,00	-1,29	*Strong decoupling*
Mexico	0,04	0,93	-0,95	0,26	-0,05	0,22	*Weak decoupling*
Pakistan	0,32	0,59	-0,33	-0,54	-0,08	-0,04	*Strong decoupling*
Poland	0,90	-0,02	-0,91	-0,24	-0,10	-0,36	*Strong decoupling*
Rusia	0,82	0,14	-0,35	-0,68	-0,09	-0,15	*Strong decoupling*
Saudi Arabia	0,28	0,69	0,14	-0,33	0,00	0,78	*Weak decoupling*
Sudan	1,92	-0,96	-1,28	1,05	0,76	1,49	*Recessive decoupling*
Suriname	0,77	0,42	-0,97	2,66	0,22	3,09	*Expansive negative decoupling*
Togo	0,46	0,41	-0,18	-0,34	-0,21	0,13	*Weak decoupling*
Turki	0,67	0,24	-0,35	-0,12	-0,04	0,41	*Weak decoupling*
Amerika Serikat	0,39	0,53	-1,07	-0,47	-0,18	-0,80	*Strong decoupling*
Uzbekistan	0,57	0,16	-0,81	-0,21	0,00	-0,29	*Strong decoupling*
Afrika Selatan	0,20	0,72	-0,94	-0,34	-0,04	-0,40	*Strong decoupling*

Figure 11. Pre-Paris Agreement decoupling results

India, Indonesia, and South Korea were at the expansive coupling level, where the economic growth ratio and emissions growth ratio increased simultaneously, and their magnitudes were almost equal. Based on the energy mix effect calculations, India and Indonesia showed negative values; however, these values were still much lower than those of the economic activity effect and population effect, resulting in increased energy consumption and greater emissions. The opposite occurred in Brazil, Gabon, Iran, Japan, Kyrgyzstan, and Suriname, where emissions increased faster than economic growth. This situation also reflects inefficient economic activity, the continued dominance of fossil energy sources in the energy production process, and high carbon intensity. Sudan can be considered the worst-performing country during this period; the recessive decoupling level indicates that Sudan experienced a decline in economic growth while simultaneously experiencing an increase in emissions and a deterioration in environmental quality. This also reflects inadequate environmental policies and an economic crisis. During the

2008–2014 period, no countries were found at the recessive coupling, weak negative decoupling, or strong negative decoupling levels.

The Paris Agreement was adopted by 195 Parties in 2015, with the goal of reducing global emissions and preventing further global warming. However, based on emissions data from the 27 countries in 2023, total emissions increased by 8.72% compared with 2014, reaching 27,901.270 tons of CO_2. The decoupling analysis results show that, although the number of countries at the strong decoupling and weak decoupling levels increased compared with the pre-Paris Agreement period, several countries experienced a decline in their decoupling levels, and two countries fell to the weak negative decoupling and strong negative decoupling levels.

Kuwait, Pakistan, Russia, and Uzbekistan, which were previously at the strong decoupling level, shifted to the expansive coupling and weak decoupling levels during the 2015–2023 period. Kuwait's increase in emissions was associated with a rise in energy intensity to 1.59 and a 131% increase in the population effect, reaching 5.16. Meanwhile, Pakistan and Uzbekistan were driven by increases in the economic activity effect, population effect, and carbon intensity, which contributed to increases in emissions, whereas Russia was driven by the economic activity effect and carbon intensity. Iraq and Togo also experienced similar situations, shifting from weak decoupling to expansive negative decoupling, in which energy intensity and population effects played larger roles than the other effects. These countries experienced significant increases in emissions compared with 2014, although their 2023 emissions levels were not the highest recorded during the research period.

	2015 - 2023						
	DEA	DEP	DEI	DCI	DEM	DCE TOT	D Status
Brazil	0,42	0,50	-0,93	-0,14	-0,85	-1,01	Strong decoupling
Kanada	0,20	0,71	-0,86	-0,26	0,00	-0,21	Strong decoupling
China	0,84	0,04	-0,42	0,03	-0,09	0,40	Weak decoupling
Jerman	0,54	0,29	-3,37	-0,82	0,07	-3,29	Strong decoupling
Mesir	0,57	0,36	-0,68	0,33	-0,02	0,56	Weak decoupling
Gabon	-0,53	1,40	-2,03	0,91	-0,83	-1,08	Strong decoupling
Guyana	0,52	0,03	-0,45	0,08	0,00	0,18	Weak decoupling
Indonesia	0,78	0,23	0,50	-0,39	-0,08	1,03	Expansive coupling
India	0,76	0,17	-0,32	0,07	-0,02	0,66	Weak decoupling
Iran	0,60	0,40	0,39	-0,39	0,00	1,00	Expansive coupling
Iraq	-0,15	1,18	3,65	-3,47	0,15	1,36	Expansive negative
Jepang	1,42	-0,53	-4,74	0,60	-2,21	-5,46	Strong decoupling
Kyrgyztan	0,41	0,41	-0,30	-0,62	-0,07	-0,16	Strong decoupling
Korea Selatan	0,80	0,06	-0,69	-0,49	-0,09	-0,41	Strong decoupling
Kuwait	-4,16	5,16	1,59	-1,34	-0,08	1,17	Expansive coupling
Mexico	0,24	0,71	-1,07	0,28	-0,10	0,06	Weak decoupling
Pakistan	0,55	0,46	-0,18	0,43	-0,20	1,05	Expansive coupling
Poland	0,93	-0,10	-1,01	0,00	-0,07	-0,25	Strong decoupling
Rusia	1,03	-0,04	-0,27	0,07	-0,06	0,72	Weak decoupling
Saudi Arabia	0,43	0,54	-0,22	0,01	0,00	0,76	Weak decoupling
Sudan	2,35	-0,81	-2,12	-1,11	0,11	-1,58	Strong negative decoupling
Suriname	1,71	-0,65	-2,38	1,23	0,28	0,18	Weak negative decoupling
Togo	0,50	0,56	0,97	-0,63	-0,01	1,40	Expansive negative
Turki	0,67	0,20	-0,53	-0,02	-0,06	0,26	Weak decoupling
Amerika Serikat	0,66	0,21	-0,91	-0,32	-0,06	-0,42	Strong decoupling
Uzbekistan	0,58	0,30	-0,87	0,38	-0,02	0,37	Weak decoupling
Afrika Selatan	-1,15	2,07	-1,32	-1,47	-0,17	-2,03	Strong decoupling

Figure 12. Post-Paris Agreement decoupling results

Brazil, Gabon, Japan, Kyrgyzstan, and South Korea successfully reduced their emissions in the post-Paris Agreement period. This was also accompanied by an improvement in the Tapio decoupling status of these countries, with their status rising to strong decoupling. The energy-mix effect of these five countries shows negative values, although the values are not significant compared with those of the other effects. Additionally, improvements in energy intensity and carbon intensity also played major roles in suppressing emission rates. Only Japan showed a decrease in the population effect, while Gabon also showed a negative economic-activity effect. In

2023, India reached its highest emission level throughout the research period. Even so, India's decoupling status improved to weak decoupling, meaning that India was in a phase of economic growth in which emissions increased more slowly than economic output. From India's decomposition results, it is also evident that the economic-activity effect was the main factor driving increases in emissions.

Unlike the previous period, in the second period, there were two countries at the weak negative decoupling and strong negative decoupling levels. Suriname experienced a decline in national income of 14.8% in the second period, followed by a 17.2% decrease in emissions. This indicates that Suriname experienced both an emission decrease and an economic contraction. This also means that the emission decrease was not necessarily due to the success of environmental policies but rather to weakening economic activity. The decomposition results show that the economic-activity, carbon-intensity, and energy-mix effects were positive, indicating that economic activity and energy use contributed to emissions. Sudan experienced strong negative decoupling, the worst category on the Tapio scale, in which economic growth declined while environmental quality worsened as emission levels increased. Although the population effect, energy intensity, and carbon intensity were negative and acted as factors slowing the emission rate, these improvements were not strong enough to overcome emission pressures in the context of Sudan's economic instability.

Country clusters with commitments embedded in law or policy documents displayed comparatively more stable weak-to-strong decoupling patterns after the Paris Agreement, whereas declaration and proposed clusters were more volatile. The results do not establish a causal policy effect, but they are consistent with the proposition that more formalized commitments may be accompanied by stronger energy-efficiency, carbon-intensity, and energy-transition measures.

Declaration and proposed clusters, including Indonesia, Saudi Arabia, and Pakistan, showed greater volatility. Their LMDI profiles indicate that improvements in energy or carbon intensity were often insufficient to offset economic-activity and population effects, consistent with evidence that growth-related drivers remain dominant when structural energy transition is incomplete (Karmellos et al., 2021; Q. Wang & Su, 2020).

Poland and the United States maintained strong decoupling, while Egypt maintained weak decoupling despite the absence of a formal net-zero target in the classification. These cases show that legal commitment status is not the sole determinant of decoupling; technology, energy efficiency, energy structure, and country-specific institutional conditions also shape outcomes.

In the achieved cluster, Togo, Gabon, Guyana, and Suriname showed varying decoupling results. The decomposition results also show that, although the emission levels and fossil-fuel consumption of these countries were much lower than those of the other countries, only Gabon was able to reach the strong-decoupling level.

This indicates that low emissions are not necessarily the result of effective environmental policies, energy efficiency, or energy-structure transformation, but may instead be associated with low economic activity, limited industrialization, and substantial natural carbon sequestration in these countries. In this cluster, in addition to the substantial forest cover that contributes to high carbon sequestration, low emissions are also driven by the relatively low use of fossil energy sources. The four countries rely primarily on oil and have relatively little or no use of coal or natural gas. Additionally, these countries still depend on traditional energy sources such as biomass and hydropower. This cluster may potentially experience significant increases in emissions in the future if economic and industrial expansion occurs without corresponding improvements in energy efficiency.

Broadly, the decoupling levels of the 27 countries, both before and after the ratification of the Paris Agreement, show that increases in emission levels were driven primarily by the economic-activity and population effects (Karmellos et al., 2021; Q. Wang & Su, 2020). Of the 27 countries, only Kuwait consistently showed a negative economic-activity effect in both periods, while Japan showed a negative population effect during both periods. Energy intensity was the main factor mitigating and offsetting emission increases, followed by carbon intensity (Q. Wang & Su, 2020). The number of countries with negative energy-intensity effects increased in the second period, while for carbon intensity, the number of countries showing negative values decreased from 17 to 15. Changes in the energy-mix structure have also improved, with an increasing number of countries reducing their fossil-fuel consumption levels. This has become one of the factors mitigating emission rates, although its contribution remains relatively small compared with those of the other factors, and substantial time is required to transform the energy structure toward renewable energy sources (Z. Wang et al., 2020).

The post-Paris period showed more countries in the strong- or weak-decoupling categories, while total emissions still increased in absolute terms. This apparent tension reinforces the Kaya–IPAT interpretation: improvements in energy intensity, carbon intensity, and the energy mix can mitigate emissions but may remain smaller than the pressures exerted by economic activity and population. Policy should therefore combine efficiency standards, accelerated renewable-energy deployment, fossil-fuel phase-down planning, and transparent monitoring of cluster-specific net-zero milestones.

CONCLUSION

Across the 27-country sample, economic activity and population were the principal sources of upward CO_2-emission pressure, whereas energy intensity and carbon intensity generally moderated that pressure. The integrated LMDI–Tapio approach shows that net-zero commitment clusters with targets embedded in law or policy documents had comparatively more stable decoupling outcomes, while early-stage commitment clusters remained volatile. The findings support the Kaya–IPAT proposition that growth-related pressures must be counterbalanced by sustained improvements in energy efficiency, decarbonization, and the energy mix.

For policymakers, net-zero targets should be accompanied by enforceable implementation instruments, measurable energy-efficiency and carbon-intensity benchmarks, and an accelerated shift away from fossil fuels. Future studies should use panel econometric, STIRPAT, or dynamic-panel models to test the causal relationships among economic growth, energy transition, policy commitment, and emissions.

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AUTHOR CONTRIBUTION STATEMENT

Yosafat Mathias Sihombing contributed to the study conceptualization, methodology, data collection and curation, formal analysis, and initial manuscript drafting. Deni Kusumawardani contributed to the research design, interpretation of findings, critical manuscript revision, supervision, and final approval of the submitted version. Both authors are responsible for the integrity and accuracy of the study.

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