How do the relationship and trend of the economic development (measured using GDP per capita) and the carbon dioxide emissions per capita during 2002 - 2022 vary across countries?

ESS SL Internal Assesment

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1 Introduction and background knowledge

Climate change is one of the most concerned issues in the modern world. Due to the rapid growth in population and industrialization, emissions of green house gases (GHGs) have increased steeply and resulted in may serious problems. Beyond sea-level rise (Hansen, Sato, Russell, & Kharecha, 2013), consequences include threats to food security and human health (D. Wang et al., 2025), increased risk of heavy metal contamination in soil (X. Wang, Zhang, Shan, & Guo, 2023), and harm to microbes and the ecosystem (Yu & Chen, 2019). Carbon dioxide is a side-product of grazing, fossil fuel combustion and other industrial practices, which is considered the most siginificant GHG that is responsible for global warming, which requires urgent attention and action (Solomon, Plattner, Knutti, & Friedlingstein, 2009).

Human society has made many major progresses since then. Kyoto Protocal (1997) binded emissions reduction targets for developed countries and marked the first time that global warming is globally recognized as a international issue. In Paris Agreement (2015), nearly all nations committed to "Nationally Determined Contributions" (NDCs) to reduce emissions, marking a full-scale recognition of the urgency of mitigating global warming. Many recent technology development and policies favoring green energy and decarbonization also played a major role in the reduction of GHG emission. However, many challenges are still present on the path to full solution of global warming.

Economic development is another factor commonly considered when talking about GHG emissions, as GHG emissions and pollution are commonly considered side effects of economic development, especially at low levels of development (Shafik & Bandyopadhyay, 1992). In this study, the economic development is measured using GDP per capita, which is a common indicator of economic development. GDP per capita provides a simple, standardized way to compare the average economic output per person across countries and has a strong correlation with the material affluence of a nation (United Nations Development Programme, 2024).

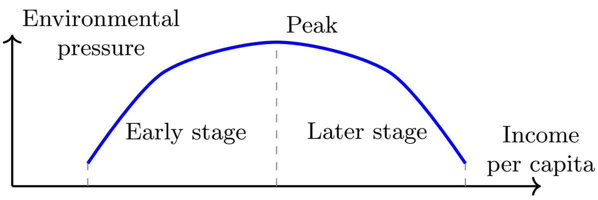


Figure 1: Schematic Kuznets curve

The Environmental Kuznets Curve (EKC) is an inverted-U-shaped curve that prostulates and predicts the relationship between different pollutants and per capita income (Dinda, 2004). It suggests that environmental pressure increases up as income goes up; after that, it decreases, as is shown in Figure 1. EKC suggests that early stage of economic development is generally accompanied with the emissions of pollutants, which is the opposite of the trend of the later stages. There are multiple explanations for that. For instance, individual preferance for environmental quality can play a vital role (Roca, 2003). Research and development (R&D) funding in developed countries may also result in mitigation of emission issues (Komen, Gerking, & Folmer, 1997).

Research question: How do the relationship and trend of the eco-

nomic development (measured using GDP per capita) and the carbon dioxide emissions per capita during 2002 - 2022 vary across countries?

2 Strategy (carbon budget)

Humans have set multiple critical values to limit the global warming, the most famous one being the 1.5°C from the 2015 Paris Agreement. To achieve that, only a certain amount of green house gases can be released to the atmosphere. A *carbon budget* is estimated the total amount of carbon dioxide (CO_2) that humanity can emit while still having a specified probability of keeping global warming under a certain threshold, calculated using the approximately linear relationship between the rise in golbal average temperature and the amount of CO_2 emitted (Avakumović, 2024). When such budget is calculated, countries can hold conferences and negotiations to allocate the budget, and divide them further inside the nations. If all countries follow the agreement and manage to control the carbon emissions within the budget, the global warming can be kept under control.

This strategy provides a quantifiable solution with some consideration for different economic statuses. It sets boundaries and helps governments plan green technology investments and carbon taxes while encouraging international cooperation. However, there are still flaws of the action that prevents it from fully taking place.

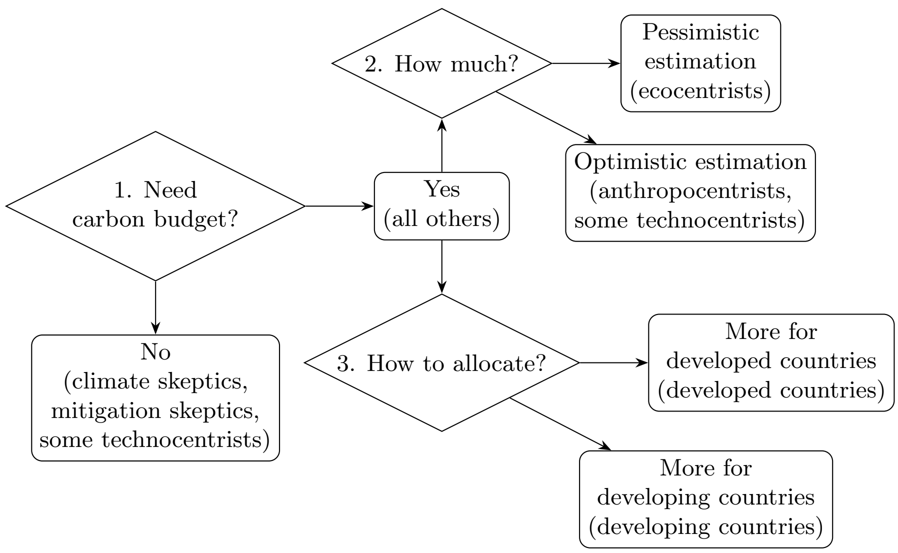


Figure 2: Carbon budget issues

First, not every stakeholder agrees with the carbon budget policy. Climate skeptics,mitigation skeptics, and some technocentrists may argue that carbon budget is unnecessary (Gap, 2023); they might want the right for full utilization of sources like fossil fuels. Others generally agree with the policy, but may have different views on implementation details.

Moreover, it is challenging to accurately estimate the budget (Friedlingstein et al., 2023). Unlike fossil fuels, the emissions of GHGs due to deforestation, grazing and permafrost thawing is hard to be considered into the budget. Different stakeholders may have different views on how much the budget should be set and how much it is actually spent. For instance, ecocentrists may tend to give a conservative estimation on the budget available and take all possible release of carbon dioxide into consideration. But technocentrists may tend to give a more optimistic estimation.

Last but not the least, it is difficult for countries to reach an agreement on the budget. Developed countries may argue that they provided the most advanced green technology and pioneered in the climate acts, and should therefore be granted more carbon budgets, while developing countries may have an economy heavily dependent on fossil fuel and took up much less historical carbon budget, and demand for the right to emit more carbon dioxide (Beckerman, 1992). Finally, it is hard to monitor if one country is following the agreement or not, as there is no central authority that can enforce the budget without the consent of the countries.

3 Hypothesis and reasoning

3.1 Cross-sectional Hypothesis

Generally speaking, we divide a country's economy into three catogories: primary (agriculture), secondary (industry) and tertiary (service). Nowadays, not only is energy highly dependent on fossil fuel in most countries, but it also plays a pivotal role in most countrie's industry and production. This demonstrates close connection between carbon dioxide emissions per capita and GDP per capita.

Primary sector-dominant economies are countries that did not undergo industrialization. They generally constitute of a large amount of farming, grazing and fishing. These economic practices are natural and require little fossil fuel. However, these industries also tend to be less productive, which would result in low GDP per capita. These countries tend to be low-income or developing countries at an early stage, like Afganistan, Chad, or some sub-Saharan countries.

Secondary sector-dominant economies are emerging or newly industrialized countries. They typically feature rapid industrial growth, especially in manufacturing and construction, and decline in agriculture. This transition from primary to secondary sector, however, requires a large amount of energy and chemical ingredients that comes from fossil fuel, which can significantly increase the carbon dioxide emissions per capita. These economies are generally middle-income or developing countries, like China, India, or Brazil, with moderate GDP per capita.

Tertiary sector-dominant economies are generally developed countries, with mechanized mass production of agriculture and automated industry being the primary and secondary sections and service industry being the dominat tertiary section. With advanced technology and high productivity, these economies are generally high-income or developed countries, like the US, UK, or Japan, with high GDP per capita. Although these economies can produce GDP way more efficiently and the governments are generally more aware of the environmental issue, the carbon dioxide emissions per capita can still be high due to large number of devices consuming energy and expensive lifestyle.

Some countries may not fit perfectly into these catogories. The resource rich-countries like Qatar or Saudi Arabia have high GDP per capita but did not go through a typical industrialization path. Tourism-dependent countries can develop strong tertiary industry without a developed secondary section. So outliers of the three catogories are also possible.

By summarizing the three catogories, we can see that GDP per capita and carbon dioxide emissions per capita are expected to be positively correlated nationwise.

3.2 Longitudinal Hypothesis

Despite having economical crisis and the Covid pandemic, the economy during the 2002 - 2022 period is generally developing, so we can naturally hypothesize that GDP per capita is expected to exhibit an increasing trend in all of the countries studied.

The carbon dioxide emissions per capita is expected to show different trends. During 2002 - 2022, developing countries like China and India are shifting from primary sector, which mostly involved natural growth and little carbon dioxide emission, to energy-intensive, CO2-emitting secondary sector. This change in economical emphasis is expected to result in an increase in carbon dioxide emissions per capita. On the contrary, developed countries like the US and the UK are shifting to the tertiary sector and their carbon dioxide emissions per capita is expected to be higher but decreasing. LDCs are expected to remain low in carbon dioxide emission.

In fact, the Kuznet curve is commonly used to describe some side-effect of the economy increase which is expected to be limited by further growth, like inequality (as is used in Kuznet's original studies) and GHG emissions (as is used in this study). Kuznet curve hypothesizes an inverted U-shape curve on the emission-GDP graph. This means that the carbon dioxide emissions per capita is expected to be strongly correlated with GDP per at the early stage of development, but becomes less relevant and even negatively correlated in the later stage.

4 Methodology

This study requires large dataset around the world that can not be reproduced in laboratory conditions or revealed through survery, so secondary data is adopted to carry out the research.

This study uses secondary data obtained from `ourworldindata.org`, which is shown in Figure 3. The dataset is publicly available and anonymized, ensuring no personally identifiable information is included. Data were used in compliance with the source's terms of use and citation requirements. No modifications were made to the original data. Therefore,

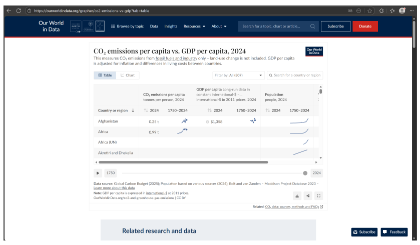


Figure 3: Screenshot of the dataset.

no additional safety and ethical precautions are required.

Ourworldindata is generally considered a reliable source and both the variables can be calculated by commonly researched topics. The ultimate data sources are Global Carbon Budget (2024) and Bolt and van Zanden - Maddison Project Database 2023. Both are reliable enough to be used in this study.

Sample raw data is listed in the Appendix. The full raw data has 64344 rows and can not fit in the paper.

The data is recorded in a `.csv` file and processed using Python using `csv`, `scipy` and `matplotlib` libraries.

The follwing procedures are used to process the data:

Steps for cross-sectional analysis

1. Read the data form the `co2-emissions-vs-gdp.csv` file. Select the data in 2002, 2012 and 2022.
2. Highlight the typical countries (e.g., China, India, USA).
3. For each year:
   - Plot all countries as circles sized by population.
   - Add GDP on the x-axis, CO_2 on the y-axis.
   - Draw unweighted and population-weighted trend lines.
   - Label highlighted countries in distinct colors.
4. Visualize the data side by side.

Steps for longitudinal analysis

1. Read the data form the `co2-emissions-vs-gdp.csv` file.
2. Collect yearly GDP and CO_2 data (2002-2022) for selected typical countries.
3. Compute efficiency ratio: GDP per CO_2 emitted.
4. For each country:
   - Plot GDP vs. time, CO_2 vs. time, and GDP/CO_2 vs. time.
   - Adjust the scale if necessary. Keep the color consistent.
5. Visualize the data size by side.

5 Results and analysis

5.1 Cross-sectional results

The cross-sectional analysis is done by the scatter plot and linear-fit, as is shown in Figure 4. Data from 2002, 2012 and 2022 are chosen for analysis. Each country is represented by a dot, whose size is proportional to its total population in the graph. Some typical countries are highlighted in the graph.

Figure 4: Scatter plot of GDP per capita and carbon dioxide emissions per capita.

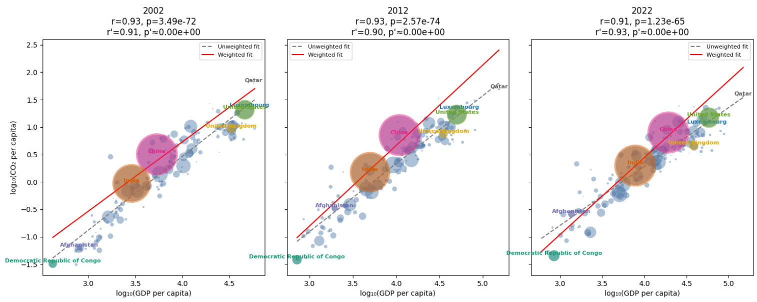


Figure 4 shows very strong correlation between the two variables. Almost every country is displayed close to the linear fit line, proving the strong correlation. Statistical tests support the trend, as a Pearson correlation coefficient of $r = 0.93(2002), 0.93(2012), 0.91(2022)$ is calculated for unweighted data and $r' = 0.91(2002), 0.90(2012), 0.93(2022)$ for weighted data. All the coefficients are significantly higher than the common 0.75 for a strong correlation in social sciences. Additionally, the p test for each set of data is less than 10^{-64}, indicating that the correlation is statistically significant.

We can also notice that the pattern of the scatter plot, especially the relative position of the typical countries chosen, does not change much over years. Afganistan and D.R. Congo are the examples of war-torn, foreign-exploited third-world countries, displayed in the left-bottom of the graph. China and India are the examples of large developing economies, occupying the center of the graph. The US, the UK and Luxembourg epitomizes developed nations at the right top of the graph, while Qatar, as the resource-rich fossil fuel exporter, being the outlier at the very right top corner.

However, some transition can also be noticed in the graph. There used to be a clear boundary between the developing and the developed world in the left figure, but the gap is getting smaller and less significant as the countries in the center are moving up-right as they get industrialized, probably because of technology development and globalization. China and India both occupied a position further to the right and higher up in 2022 compared to 2002, due to the industrialization and structural economy change to secondary industry. Unlike most other countries, the UK showed a decline in CO2 per capita during the process, largely thanks to the policies in favour of decoupling CO2 from economic development. The energy generation, manufacturing, water supply, and transport played vital roles during the process (Syed, 2019). However, some of the reduction is dependent on offshoring energy-intensive manufacturing to developing countries (Peters, Minx, Weber, & Edenhofer, 2011).

5.2 Longitudinal results

The longitudinal analysis is done by plotting GDP per capita, carbon dioxide emissions per capita and their ratio over time, as is shown in Figure 5.

Figure 5: Variables' change over time

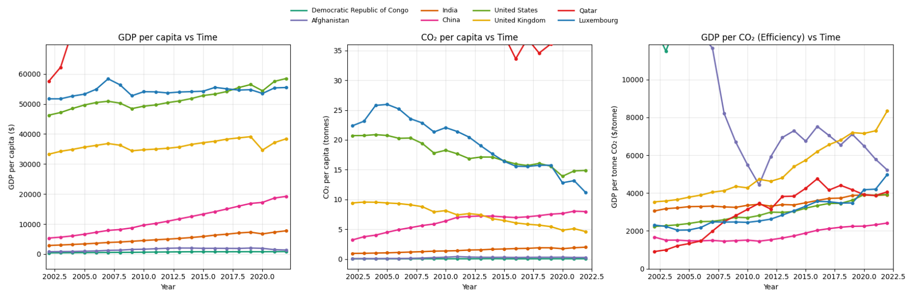


Figure 5 shows various information about the trend of the two variables. Most countries showed constant growth throughout the period except for 2008 (2008 financial crisis) and 2020 (Covid-19 pandemic) which resulted in an abrupt downturn. This supports our prediction on GDP per capita. There is a significant gap between the developing and developed countries chosen in the graph. Despite all growing, the US, China and India showed a quicker increase in GDP per capita as the US benefited greatly from the globalization and China and India industrialized rapidly. Qatar's oil industry grew so rapidly that it was one of the country that had the highest GDP per capita and increase in GDP per capita during the period. D.R. Congo and Afganistan remains poor due to lack of source for economical growth.

As is hypothesized, developed countries, namely the US, the UK and Luxembourg transitioning from secondary economy to tertiary economy decreased their carbon dioxide emissions per capita thanks to technology development, policy reformation and relocation of the secondary industry to developing areas. Developing countries, especially China which just get industrialized, showed very rapid growth in carbon dioxide emissions per capita, even exceeding some developed countries like the UK. Qatar's oil industry remains to contribute to the highest carbon dioxide emissions per capita, while D.R. Congo and Afganistan remains low in carbon dioxide emissions due to lack of industry.

We can also notice that the GDP made from each tonne of CO2 is also increasing over time. This may attribute to the development of green technology and the prosperous tertiary econonomy that does not produce as much green house gases. Such growth is more prominant in developed countries as they tend to have more advanced technology and more efficient production.

As we can conclude from these trends, the carbon dioxide emissions can be the side effect of one source of GDP growth (as in manufacturing and energy generation), but the developed countries have already been decoupling carbon dioxide emissions from GDP growth, which yield some fruitful results. This possibilty of decoupling CO2 from GDP growth showed that the carbon dioxide emissions per capita is not a necessary indicator of GDP per capita and there positive correlation, though prevalent on a global scale, can be mitigated using technology and active policy making.

6 Conclusion

To conclude, the research on data showed clear trends and successful statistical tests supporting the initial hypothesis. The cross-sectional analysis studied the similarity and differences across nations and revealed the strong correlation between carbon dioxide emissions per capita and GDP per capita. Such correlation testified the role of fossil fuel in the past economical development that shaped the international society nowadays. On the other hand the longitudinal analysis partially strengthened the correlation between the two variables with data from developing countries but also highlighted the decoupling of these two factors and predicted future less significant or negative correlation between the two variables. The outcome fits with the Kuznet model and indicated that most of the countries are still climbing the "peak" of the Kuznet curve in the past decades.

7 Evaluation

- **Limited time range:** 2002 - 2022 was selected because of data availability and simplicity of analysis, as some data prior to 2002, especially the one of LDCs are not available for analysis. This can result in some historical factors and trends being not included in the analysis. It would be better if more data is available. Some analysis on the limited areas where data is available can be conducted as well.

- **Log-log scale:** Log-log scale is used because the exceptional high value of some developed countries make developing countries squeeze together in the graph. Subsequently, the linear-fit is conducted on the log-log scale to avoid distortions near the origion. Despite showing strong connection between the two variables, it does not necessarily show *linear* correlation as the best fit line is not a straight line but a curve on the linear axis. Additional study on the linear scale can be conducted to compensate the flaw.

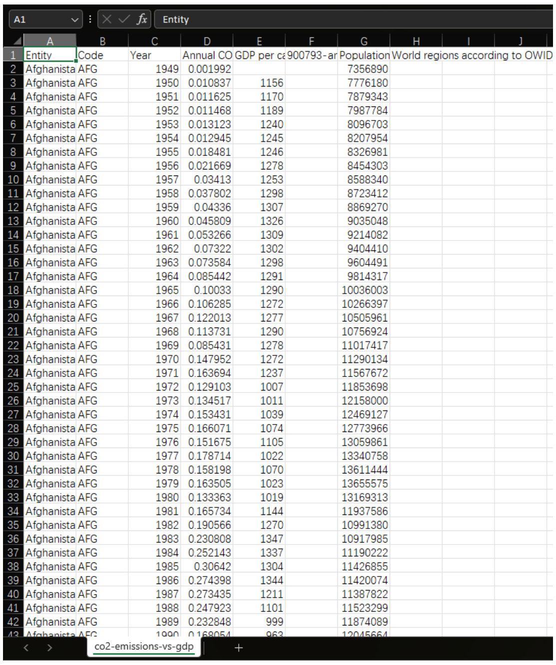
- **Nationwise data:** Data is collected country by country. This method can result in small countries such as Luxembourg having equal effect in data as the large countries such as the US, neglecting the large countrie's significance in carbon dioxide emissions and economy. This flaw is fixed by additional study on the data weighted according to the population. However, both studies focus on the cross-country comparisons while overlooking the intra-country differences. This can underestimate the regional and financial impact of carbon dioxide emissions within one country, especially large countries like the US or China. This could be improved if more detailed data is available.

- **GDP per capita:** GDP per capita fails to consider or can underestimate factors like equality, non-market work, social well-being and technology development of a country. These are also significant factors that can affect the overall development and carbon dioxide emissions per capita. To put those factors into consideration, additional study on other factors like HDI (Human development index), GNI (Gross national income), GII (Global innovation index), etc. can be conducted.

Appendix

Table 1: CO_2 Emissions and Economic Data by Country

Entity	Year	Annual CO_2 emissions (per capita)	GDP per capita	Population (historical)
Afghanistan	2022	0.26017997	1357.9878	40578847
Afghanistan	2021	0.2567944	1485.547	40000410
Afghanistan	2020	0.29706252	1928.4547	39068977
		⋮		
Afghanistan	2002	0.062727444	796.8166	21378123
Albania	2022	1.8295889	12978.101	2827614
		⋮		
Zimbabwe	2002	0.98413074	2025.3177	12087661



	A	B	C	D	E	F	G	H	I	J
1	Entity	Code	Year	Annual CO	GDP per ca	900793-ar	Population	World regions according to OWID		
2	Afghanista	AFG	1949	0.001992			7356890			
3	Afghanista	AFG	1950	0.010837	1156		7776180			
4	Afghanista	AFG	1951	0.011625	1170		7879343			
5	Afghanista	AFG	1952	0.011468	1189		7987784			
6	Afghanista	AFG	1953	0.013123	1240		8096703			
7	Afghanista	AFG	1954	0.012945	1245		8207954			
8	Afghanista	AFG	1955	0.018481	1246		8326981			
9	Afghanista	AFG	1956	0.021669	1278		8454303			
10	Afghanista	AFG	1957	0.03413	1253		8588340			
11	Afghanista	AFG	1958	0.037802	1298		8723412			
12	Afghanista	AFG	1959	0.04336	1307		8869270			
13	Afghanista	AFG	1960	0.045809	1326		9035048			
14	Afghanista	AFG	1961	0.053266	1309		9214082			
15	Afghanista	AFG	1962	0.07322	1302		9404410			
16	Afghanista	AFG	1963	0.073584	1298		9604491			
17	Afghanista	AFG	1964	0.085442	1291		9814317			
18	Afghanista	AFG	1965	0.10033	1290		10036003			
19	Afghanista	AFG	1966	0.106285	1272		10266397			
20	Afghanista	AFG	1967	0.122013	1277		10505961			
21	Afghanista	AFG	1968	0.113731	1290		10756924			
22	Afghanista	AFG	1969	0.085431	1278		11017417			
23	Afghanista	AFG	1970	0.147952	1272		11290134			
24	Afghanista	AFG	1971	0.163694	1237		11567672			
25	Afghanista	AFG	1972	0.129103	1007		11853698			
26	Afghanista	AFG	1973	0.134517	1011		12158000			
27	Afghanista	AFG	1974	0.153431	1039		12469127			
28	Afghanista	AFG	1975	0.166071	1074		12773966			
29	Afghanista	AFG	1976	0.151675	1105		13059861			
30	Afghanista	AFG	1977	0.178714	1022		13340758			
31	Afghanista	AFG	1978	0.158198	1070		13611444			
32	Afghanista	AFG	1979	0.163505	1023		13655575			
33	Afghanista	AFG	1980	0.133363	1019		13169313			
34	Afghanista	AFG	1981	0.165734	1144		11937586			
35	Afghanista	AFG	1982	0.190566	1270		10991380			
36	Afghanista	AFG	1983	0.230808	1347		10917985			
37	Afghanista	AFG	1984	0.252143	1337		11190222			
38	Afghanista	AFG	1985	0.30642	1304		11426855			
39	Afghanista	AFG	1986	0.274398	1344		11420074			
40	Afghanista	AFG	1987	0.273435	1211		11387822			
41	Afghanista	AFG	1988	0.247923	1101		11523299			
42	Afghanista	AFG	1989	0.232848	999		11874089			

Figure 6: Raw Data Screenshot

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