

Towards a Sustainable Net-Zero Future: Energy and Economic Transition Amid Global Warming

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Abstract. As global temperatures continue to rise, there is an alarming increase in the severity and frequency of extreme climate hazards. The United Nations, responding to these dire changes, has advocated for a target of net-zero carbon emissions, a strategy aimed at pursuing efforts “to limit the temperature increase to 1.5°C above pre-industrial levels” (The Paris Agreement) and mitigating the devastating effects of global warming. This research delves into economic implications of these targets, leveraging comprehensive data that encompass carbon emissions, temperature, renewable energy, and vital economic indicators. Utilizing the RCP scenarios, we provide a nuanced projection of future climate under varying socio-economic and radiative conditions. The analysis of economic indicators can help predict the overall level and change trend of carbon emissions more reasonably, which can provide important decision-making support for the government to formulate environmental protection policies and enterprises to carry out carbon emission reduction work. At the same time, economic indicators can also help assess the changes in the carbon trading market, and play an important guiding role for enterprises and investors to conduct carbon emissions trading. Our findings underscore the intricate relationship between stringent carbon management practices and their potential economic ramifications, which include both the promise of increased market value for businesses and bolstered resilience against climate-induced threats. Bridging historical observations with future-orientated projections, this study serves as a beacon for policymakers and stakeholders alike. It emphasizes the critical need to advance sustainable development within a net-zero carbon framework, ensuring a comprehensive strategy for global warming adaptation and mitigation.

1. Introduction

The growing burning of fossil fuels has brought huge economic growth to the world and promoted the overall development of the world, but it has also brought potential hidden dangers. A large number of greenhouse gases produced after the burning of fossil fuels, mostly carbon dioxide and sulfur oxides, have a huge impact on the world, including: (a) Melting glaciers are driving sea level rise, posing a global threat to coastal areas [1], which directly threatens some countries at lower altitudes, and even some islands have been submerged; (b) The recurrent incidence of extreme weather events, prolonged droughts, frequent wildfires, and floods, coupled with the regular onset of El Niño, contributes significantly to escalating economic losses in human productive activities [2]. (c) Its profound influence on the global ecosystem alters the native ecological environment of regions, rendering original organisms incapable of adapting to the changes and ultimately facing extinction [3,4]. Therefore, how to achieve sustainable development has become an important problem in front of human development.

Sustainable development is defined as the development that can meet the needs of the present generation without endangering the ability of future

generations to meet their needs. Renewable energy sources not only contribute to environmental purification but also propel economic advancement, creating a dual benefit for both our planet and our financial prosperity [5]. It requires economic and social development under the premise of strict population control, improving the quality of the population, protecting the environment and sustainable use of resources. In 1991, the International Union for Conservation of Nature (IUCN), the United Nations Environment Program (UN-EP) and the World Wildlife Fund (WWF) jointly published "Caring for the Earth: A Strategy for Sustainable Survival". A Strategy for Sustainable Living defines sustainable development as "improving the quality of human life while living within the capacity of maintaining the ecosystem", and puts forward nine basic principles for sustainable human survival. This is undoubtedly a good strategy at a time when the world is still warming, but whether countries can follow the policy implementation of this strategy is still a question.

Nowadays, the planet is already about 1.1°C warmer than it was at the end of the 19th century, and emissions continue to rise. To limit global warming to no more than 1.5°C, as required by the Paris Agreement, emissions need to be reduced by 45% by 2030 and reach net zero by 2050. Many nations are striving for net-zero goals, aiming to

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offset greenhouse gas emissions by absorbing an equivalent amount of carbon. The advent of renewable energy marks a pivotal transformation in the global energy landscape, enabling countries to diversify their energy mix, prioritize renewable sources, and curtail reliance on fossil fuels. This shift holds the potential to enhance energy sustainability while mitigating the environmental impact of traditional energy consumption [6,7]. Hence, it is important for every country to see how to achieve a balance between economic growth and greenhouse gas emissions. This paper focuses on the analysis the following questions: (1) How have different renewable energy sources and fossil fuels changed in some countries of the world over the past 30 years? (2) What is the relationship between renewable energy, carbon emissions, GDP, and climate factors? (3) What impact does carbon reduction have on the world economy?

2. Data and Methods

2.1. Data

Annual data on renewables, fossil fuels and carbon emissions from 1990 to 2021 is drawn from the open data archive at *Ourworldindata* platform (www.ourworldindata.org). Country GDP data for 1990-2021 are available on the World Bank website (www.data.worldbank.org); We obtain national average annual temperature anomalies for 1990-2021, relative to baseline climate data for 1951-1980, from the Food and Agriculture Organization of the United Nations (www.fao.org/faostat/en/#data/). We also have global surface temperature trends from National Oceanic and Atmospheric Administration (<https://www.climate.gov/>). In addition, for the five selected countries with different levels of development, several economic factors such as GDP and productivity (www.data.worldbank.org) are considered to comprehensively analyze different economic growth conditions, which provides a good reference for designating reasonable strategies.

2.2. Regression and Correlation analysis

Regression analysis serves as a powerful linear simulation technique, allowing for accurate predictions based on historical data patterns. In this research, the Pearson's linear correlation is employed to gauge the magnitude and direction of the linear association between two variables, aiding in the identification and assessment of potential relationships. The formula used for calculating the Pearson's linear correlation coefficient is as follows:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (1)$$

r = correlation coefficient

x_i = values of the x – variable in a sample

\bar{x} = mean of the values of the x – variable

y = mean of the values of the y – variable

\bar{y} = mean of the values of the y – variable

The correlation coefficient (r), ranging from -1 to 1, serves as a comprehensive indicator: -1 signifies a robust negative relationship, 0 implies no relationship, and 1 denotes a strong positive relationship. In tandem with Pearson's linear correlation, the study integrates Student's t-test, a statistical tool crucial for discerning significant differences between the means of two groups. Additionally, linear regression analysis is deployed to model trends and forecast future states in time series data encompassing temperature anomalies, carbon emissions, GDP, and energy.

2.3. RCP Scenarios

RCP scenarios are a set of potential future greenhouse gas (GHG) concentration trajectory models. They are used as inputs to climate models to predict and study the potential impacts of climate change on various aspects of the environment, society, and economy over a period. The model develops the RCP scenario by integrating information from a variety of sources, such as socio-economic trends, energy use patterns, and policies related to greenhouse gas emissions. These scenarios represent the different levels of greenhouse gas concentrations in the atmosphere that are likely to occur based on different emission reduction policies and socioeconomic trends. It is of great value to climate observation. They provide concrete models for assessing possible future climate change associated with different GHG concentration pathways. By using these scenarios, governments as well as researchers can understand the potential scope of climate impacts, develop strategies to respond to greenhouse gas emissions accordingly, and assess the effectiveness of action for policy implementation.

3. Results and Discussion

3.1. Global warming and carbon emission

As shown in Figure 1 (a), we can obtain annual data points for each country, and thus obtain temperature rise patterns or trends. What we can see from this is that there is a clear upward trend for all countries and the global average between 1990 and 2021, which indicates that the global surface temperature is on an upward trend, which is clearly not a good trend. Of the five countries selected, China has the highest surface temperature anomaly, with a 2021 temperature value of about 1.5 degrees Celsius, followed by the global average temperature of 1.1 to 1.3 degrees Celsius in the United States and Canada, and a lower temperature of about 1 degree Celsius in the United Kingdom and Mexico. This is a significant increase in temperature relative to 1990. It is worth noting that China's surface temperature is somewhat different from that of other countries, suggesting that China may be experiencing more rapid surface temperature warming. The significant upward trend in annual temperature anomalies indicates the dominant role of human activities, especially the burning of fossil fuels and the release of large amounts of carbon dioxide in recent decades. Figure 1 (b) shows the temperature change (degrees Celsius per

century) from 1900 to 2014. Grey areas indicate that there is not enough data to find a long-term trend. We can clearly see the change of the world's surface temperature.

There is no doubt that the surface temperature is on the upward trend.

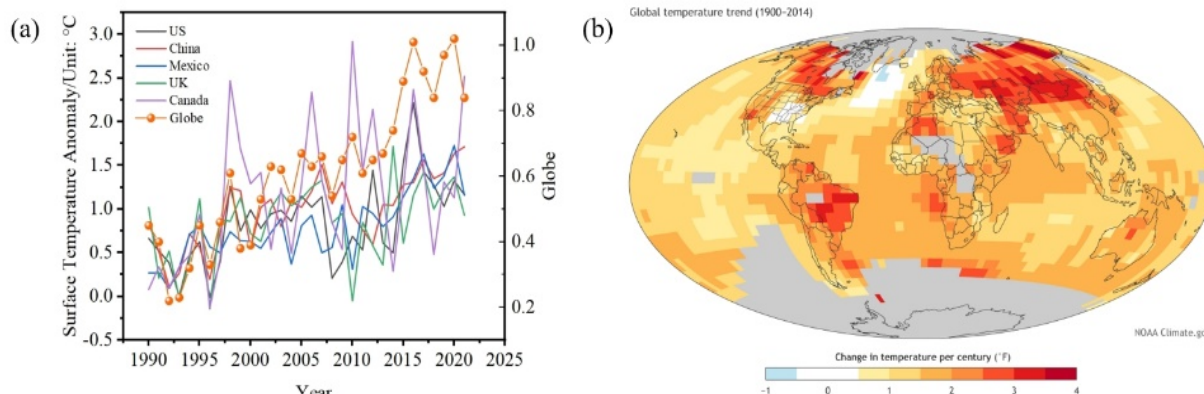


Fig. 1. Variation and trend of surface temperature. a) Surface temperature changes in selected countries and globally between 1990 and 2021. b) Global temperature trends.

In general, Figure 1 provides the overall change of global surface temperature. The change rate of different countries is different, but the global change shows the trend of global warming in general, and China has a higher temperature increase than other countries. These findings require humanity to summarize and address the damage of human activities to the climate, especially the consumption and post-treatment of fossil fuels.

We also can see from Figure 2 that the CO₂ emissions of the selected countries have a clear upward trend over time, with China's annual CO₂ emissions in 2021 reaching the highest among the five countries. At the same time, we can see the increasing trend of per capita CO₂ emissions

from Figure 2 (b). Despite the small population of the United States, compared with other countries shown in the figure, per capita CO₂ emissions in the United States have reached the highest level. By analyzing CO₂ emissions data from other countries, we observe different levels. China's carbon emissions will exceed 1 billion tons by 2021, making it the largest contributor to global carbon dioxide emissions. In contrast, the UK's annual carbon dioxide emissions are the lowest among the five countries, indicating that the UK's emission reduction policies have played a certain effect. However, it is important to note that the figure does not accurately reflect individual countries' emissions.

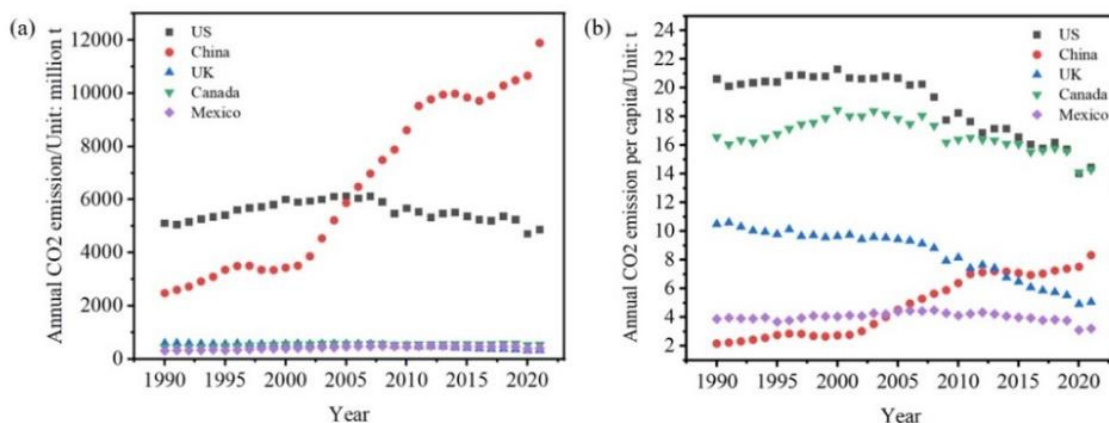


Fig. 2. Carbon emissions of selected countries. a) Annual CO₂ emissions for five countries from 1990 to 2021. b) Annual per capita CO₂ emissions for the five countries from 1990 to 2021.

3.2. Evaluation and Prediction of Macroeconomic Indicator

Figure 3 shows a clear trend in GDP growth for all countries, with China and the United States significantly outpacing the rest in 2021. At the same time, Figure 3 (b) also shows the increase and change of per capita GDP of

all countries over time. Due to the small population base of the United States, the per capita GDP of the United States in 2021 is the highest, followed by the United Kingdom and Canada. Although China's GDP is relatively high, exceeding 20 trillion US dollars in 2021, its per capita GDP is not significant. From the graph, we can analyze that the economic development of America and China is very fast.

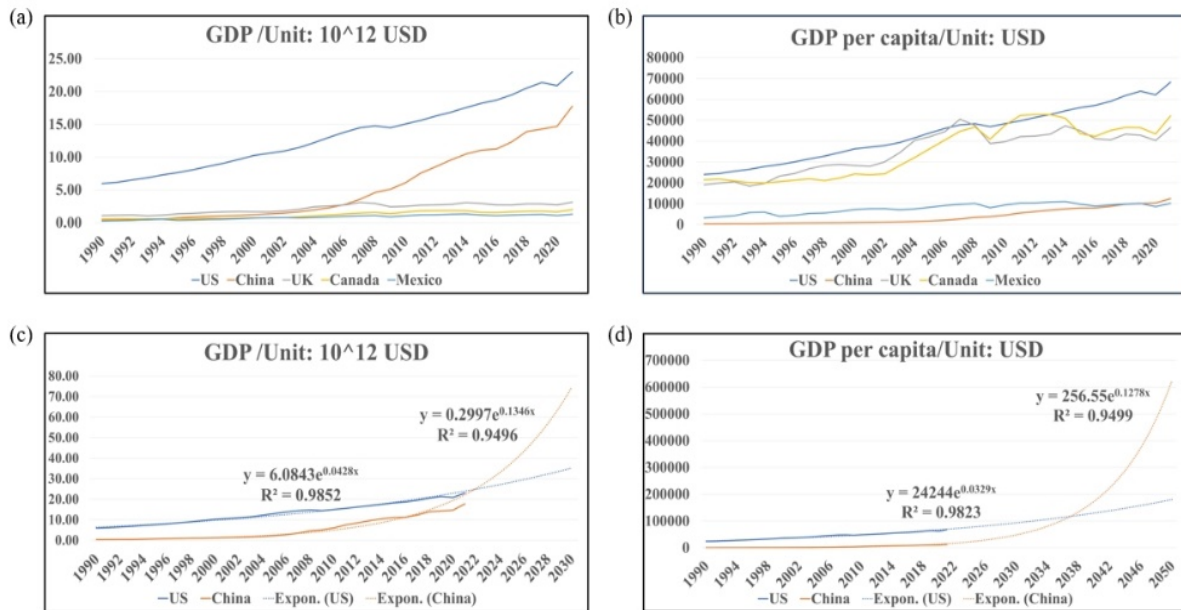


Fig. 3. Total annual GDP and per capita of the five selected countries. a,b) GDP and per capita data for the five countries. c,d) China and the United States GDP data and trend lines.

From Figure 3 (c, d), we can find that the GDP and per capita of China and the United States are both in a stage of rapid growth, and from the forecast trend line and equation, China's GDP and per capita will catch up with the United States in the near future. Overall, the graph shows that GDP and GDP per capita differ significantly among different countries, with the US and China having the largest economies, the UK and Canada having higher levels of economic welfare per capita, and China's overall economic development being greater than that of the US.

consumption increased two decades ago, peaked around 2005, and then gradually declined over the next few decades, in line with U.S. carbon emissions. China, on the other hand, has seen rapid growth in fossil fuel consumption and GDP over the past four decades. In Canada and Mexico, there is a slight upward trend in fossil fuel consumption. In the UK, fossil fuel consumption has shown a sharp downward trend between 1981 and 2020, which may be significantly linked to improvements in its energy consumption structure.

3.3. Changes in fossil fuels and renewable energy

We can see from Figure 4 that the pattern of fossil fuel and renewable energy mix is different for each country from 1981 to 2020. For the United States, fossil fuel

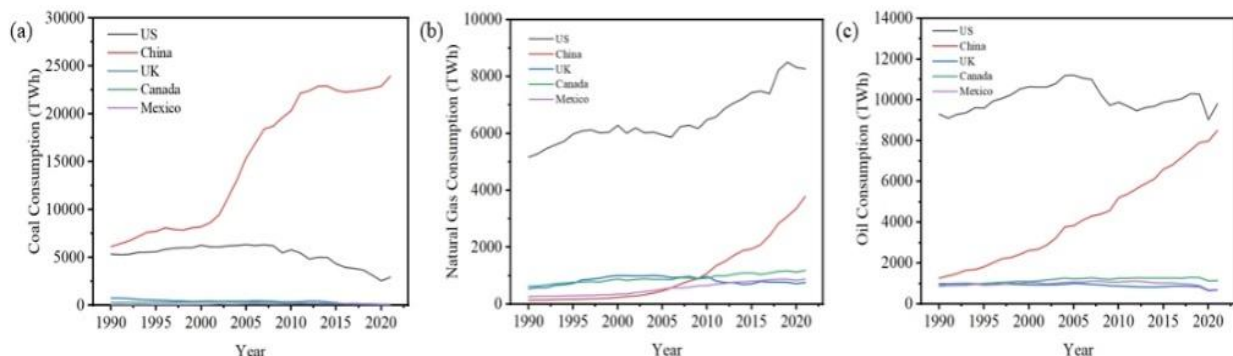


Fig. 4. Consumption of the world's major fossil fuels in selected countries, including coal, natural gas and oil.

In terms of renewable energy, we can see from Figure 5 that the five countries selected show an increasing trend, especially solar and wind energy. At the beginning of the study, hydropower dominated all types of renewable energy. From 1981 to 2021, in terms of total renewable energy, the total renewable energy in the United States, the United Kingdom and China has an exponential growth trend, while Mexico and Canada have an overall linear

growth trend. This different pattern of renewable generation growth appears to be consistent with changes in GDP over the study period. We can clearly see that renewable energy is becoming increasingly important for global development. This energy improves the mix of energy consumption, without the greenhouse gas emissions of fossil fuels, and greatly reduces air pollution.

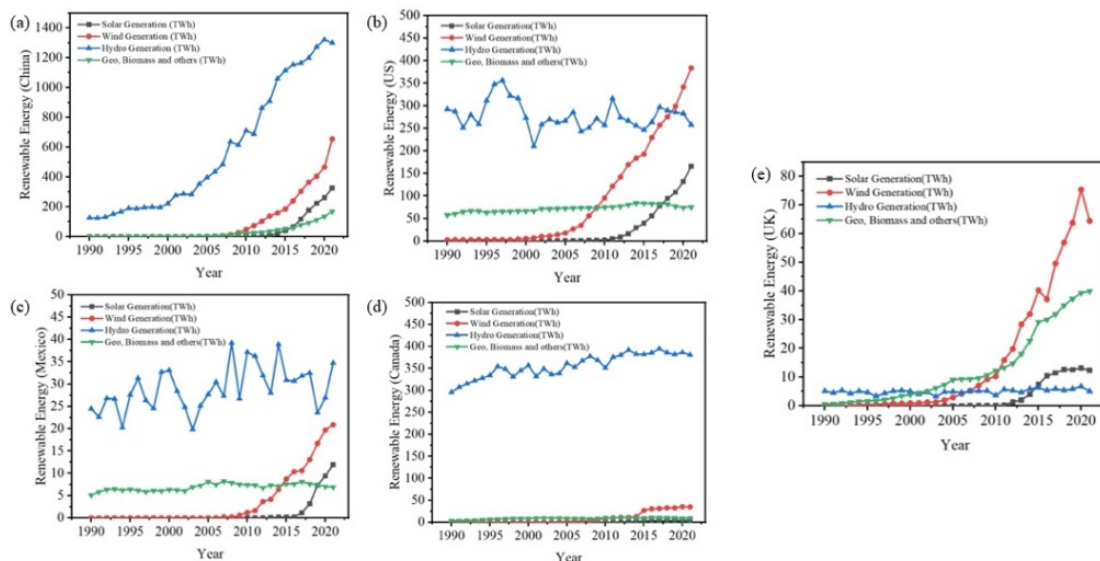


Fig. 5. Annual generation of different types of renewable energy in selected countries.

3.4. Complex Relationships between carbon emission, GDP, and energy

From Table 1, we can clearly analyze that from 1990 to 2021, renewable energy in the United States and China has a high correlation with economic GDP. For China, the correlation coefficient is as high as 0.99, and the data proves that renewable energy can not only bring environmental friendliness, but also have a very positive effect on the economy. Compared with China, the correlation coefficient between renewable energy and GDP in the United States is relatively low (0.86). The findings of this study essentially corroborate the strong correlation between renewable energy and GDP, aligning with outcomes observed in various prior research endeavors [8, 9].

Moreover, the correlation of fossil fuels to GDP in the US (0.16) is much smaller than in China (0.94). This shows that both fossil fuels and GDP in China are growing

exponentially, and there is a significant positive correlation between the two. In the United States, where GDP growth is linear, fossil fuel consumption tends to be flatter. In the United States, renewable energy has a significant negative correlation with carbon emissions, reaching a correlation of -0.57, highlighting the advantage of renewable energy in near-zero carbon emissions. Given the aspiration for a global carbon-free economy, the transition from fossil fuels to renewable energy emerges as a cornerstone objective [10].

It is worth noting that the United States peaked its carbon emissions in the mid-2000s, while China's carbon emissions have continued to increase over the past few decades. The increasing trend of carbon emissions and fossil fuels in China leads to a high positive correlation between these two variables. All in all, the United States and China, as the two largest economies in the world, are at different stages of development in terms of renewable energy and GDP.

Table 1. The correlation coefficients between energy, climate, carbon emission and GDP in the USA & China

Country	Correlation Coefficients	Energy		Climate	Carbon Emission	Economics
		Renewable Energy	Fossil Fuels	Surface Temperature Anomalies	Annual CO2 emission	GDP
US	Renewable Energy	1.00	-0.22	0.50	-0.57	0.86
	Fossil Fuels	-0.22	1.00	0.18	0.92	0.16
	Surface Temperature Anomalies	0.50	0.18	1.00	-0.05	0.60
	Annual CO2 emission	-0.57	0.92	-0.05	1.00	-0.19
	GDP	0.86	0.16	0.60	-0.19	1.00
China	Renewable Energy	1.00	0.91	0.68	0.91	0.99
	Fossil Fuels	0.91	1.00	0.68	1.00	0.94
	Surface Temperature Anomalies	0.68	0.68	1.00	0.65	0.66
	Annual CO2 emission	0.91	1.00	0.65	1.00	0.94
	GDP	0.99	0.94	0.66	0.94	1.00

3.5. Future projections of climate and impacts

Within the context of global warming and economic growth, our understanding sharpens when we look through

the lens of Representative Concentration Pathway (RCP) scenarios. While predicting exact future carbon emissions remains tricky, these scenarios provide a roadmap to track the changing trends in emissions caused by human activities. By reading these trends, we can make informed

predictions about future global warming and, crucially, take effective steps to prevent it. As shown in Figure 6, human activities pump out more carbon emissions, the temperature keeps rising. This link between what we do, and the warming Earth is hard to ignore. Now, picture a world where our growth and economic well-being are

tightly linked. To understand how much carbon, we are spewing into the air, we turn to RCP methods. These methods help us measure the carbon footprint of our social and economic activities, giving us a heads-up on what our actions mean for the planet.

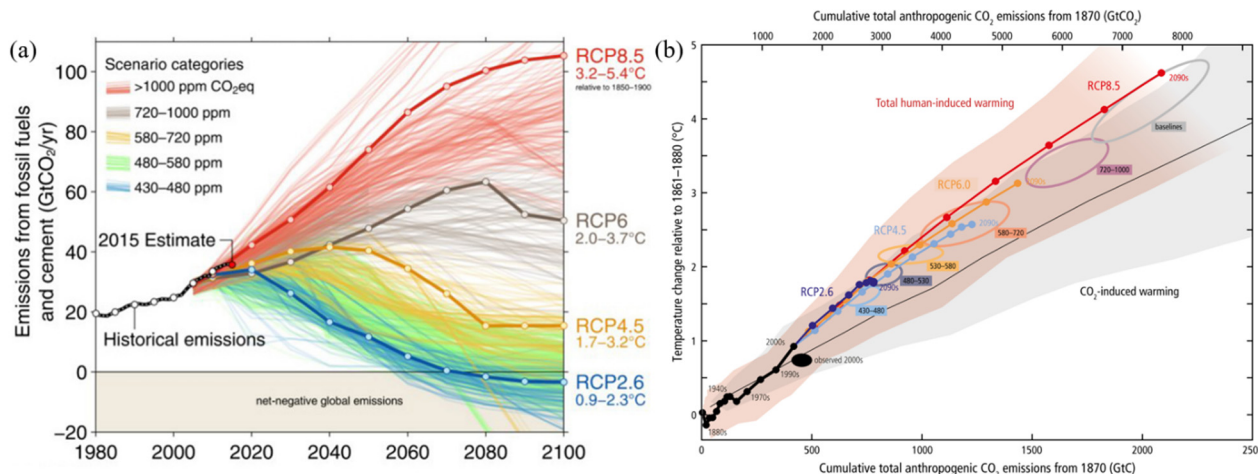


Fig. 6. RCP as scenarios & RCP scenarios future projection of CO₂ and Global warming (Image Credit: Neil Craik, University of Waterloo & https://ar5-syr.ipcc.ch/topic_futurechanges.php)

In the game plan against global warming, sustainable development is the MVP. Look at businesses: for them to play a responsible role, they've got to take sustainability into consideration. Business decision maker need to consider the environment when making their business plans. This isn't just about being eco-friendly; it's about making sure our economic growth doesn't come at the cost of our planet. Here's where RCP steps in as a helpful guide. It's like a map for big companies, showing them how to reduce their carbon footprint and keep things balanced as they grow. By following RCP's advice, businesses can cut down on how much they're contributing to global warming. It's a win-win, allowing economic growth without wrecking the planet. In a nutshell, RCP scenarios give us a peek into the future of global warming tied with our economy. Armed with this foresight, businesses can shift towards a future where growth and looking out for the environment go hand in hand. Thanks to RCP, we're not just hoping for a better future; we're actively working towards one where we tackle global warming while still thriving economically.

4. Conclusion

In the study, an analysis of data on changes in renewable and fossil fuel energy in individual countries concluded that the United States has already reached peak CO₂ emissions. From 1990 to 2021, carbon dioxide emissions in the United States have gradually decreased, which means that the United States has achieved some progress in carbon neutrality. Similarly, fossil fuel use in the United States peaked in the mid-2000s and has since declined. Renewable energy also showed an increasing trend after 2005, before which the amount of renewable energy was stable.[11] At the same time, China's renewable energy has developed rapidly between 2003 and 2015, and there

is a trend of continuous growth. At the same time, China's consumption of fossil fuels is also huge, and by 2021, China's reported use of fossil fuels will equal that of the United States. However, it is worth mentioning that China's renewable energy is also growing exponentially and began to develop rapidly along the track of 2005.[12] Interestingly, at the beginning of the development of renewable energy, the United States, China, Mexico and Canada were dominated by hydropower, but in recent years, wind power has become more important and dominant in the United States, and China, Mexico and Canada have remained unchanged. Until 2010, when renewable energy sources were not yet developed, hydropower was dominant in the UK, and wind power quickly became dominant. The economic benefits of renewable energy in China and the United States are highly correlated with GDP.

In addition, the paper also summarizes the changes of renewable energy and zero-carbon economy in the context of climate warming in the past 30 years. This provides us with useful scientific information to come up with strategies to achieve a carbon neutral or zero carbon/low carbon economy.[13] In short, the strategy is basically to replace fossil fuels, which have been the main source of energy in the past few years, with renewables in large part, but which undeniably pose a huge threat to the world's environment. From a correlation point of view, renewable energy does not harm the economy (GDP) and can even have a positive impact.

The future projection of CO₂ emissions and global warming indicates a complex interplay of risks and opportunities for economic development. The extent to which these factors impact the economy will depend on the effectiveness of mitigation and adaptation strategies, global cooperation, technological advancements, and societal responses to the challenges posed by climate

change. Addressing these issues proactively may lead to a more sustainable and resilient economic future.

But there are still uncertainties in the study. Only five representative countries are included and discussed in this study. If more countries or regions are involved, a broader and more specific analysis of the relationship between renewable energy and economic development may not be available. Moreover, the analytical method - Pearson linear correlation analysis - is unable to derive a clear causal relationship between renewable energy and factors such as GDP. However, this study demonstrates how renewable energy varies under different climate patterns, providing potentially useful strategies for renewable energy innovation and a zero-carbon economy.

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