The change of renewable energy and zero-carbon economy in an anthropogenically warming climate

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Abstract. Anthropogenetic global warming has led to increasingly significant environmental issues, biodiversity losses, and socioeconomic impacts. There is a rising demand for transition from fossil fuels to renewable energy (RE), reducing carbon emissions, and thus realizing zero-carbon economy. Nevertheless, it remains a challenge to achieve the carbon-free economy and mitigate global warming, without fully understanding the ongoing RE development. The major objectives of this research are to (1) investigate the changes of different RE types compared with fossil fuels in the U.S., U.K., Mexico, Canada, and China; (2) examine the relationships between RE, temperature anomalies, and GDP; and (3) propose potential strategies for zero-carbon economy and climate change. The annual mean energy, temperature, and GDP data in these five selected countries during 1980 to 2021 are collected for analysis, and their relation-ships are addressed through Pearson's correlation analysis, along with significance test. The results suggest an increasing trend of RE and rising RE-fossil fuels ratio during the past four decades. All five countries either showed exponential or linear increasing trends in GDP and RE. The correlation analysis suggests a significantly positive correlation between RE and GDP in both countries. For example, different from the U.S., the synchronized growth in RE and fossil fuels in China leads to a significantly positive correlation between these two. All five countries provide their unique data of renewable development, which can stimulate the research and enable further study. This study will shed light over possible strategic plans for an optimized use of renewable energy, ensuring below 1.5°C temperature rise, and reaching carbon neutrality by 2050.

Keywords: Renewable Energy, Fossil Fuels, Carbon Emission, Zero-Carbon Economy, Global Warming.

1. Introduction

Global warming is defined as the long-term warming of the Earth's surface due to human activities observed since pre-industrial era, which increases the levels of heat-trapping greenhouse gases in the Earth's atmosphere. The anthropogenic global warming has impacted the Earth's environment tremendously, including: (a) the melting of glaciers that causes the sea level rise [1], threatening countries with lower coastal altitudes or areas with more developed economies; (b) the increased frequency of extreme weather, such as extreme drought, flood, wildfires, hurricanes, etc., affecting the survival of organisms and agriculture [2]; and (c) the rising impacts on the global ecosystem, changing the ecological environment and accelerating the rate of biological extinction [3, 4]. There are multiple reasons for the global warming to occur nowadays on earth, which includes the generation of electricity

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from fossil fuels which releases a numerous amount of greenhouse gases, mass production, over-explicitness, over-consumption. All kinds of greenhouse gases are mainly owing to the usage of fossil fuels.

By definition, fossil fuels are fuels generated naturally, which are formed by decomposition of animals and plants with coal, natural gas, and petroleum, and Orimulsion (fuel derived from the bitumen that occurs naturally in large reserves in the 700 km long Orinoco oil belt in Venezuela). Fossil fuels are the only fuel in the world for centuries, but there is a new type of energy called renewable energy emerging nowadays [5]. Renewable energy is energy extracted from natural resources that is replenished at a higher rate than consumed. Sunlight and wind, for example, are such resources that are constantly being replenished. Compared with fossil fuels, renewable energy sources are much cleaner and "greener", such as solar, wind, hydropower, geothermal, and biomass, etc. The renewables can not only purify our environment, and it can even push our economy forward more [6]. Without the up limit to the amount of energy usage, the society can utilize the maximum of renewables, differentiating from fossil fuels, they have an up limit, and the globe needs to consider the exhaustion of fossil fuel. Nonetheless, the world has only started the transition from fossil fuels to renewables, and all the techniques are under development, the unpredictable future troubles and complex prospects are exactly the beauty of this research, which is what attracts people and to choose this topic. Beside the comparison and the push of energy transition, it is also important to understand the changes of energy utilization in the world. This comparison includes the renewable energy generation, GDP, carbon emission, and climate change in five typical countries with a specific focus on greenhouse gas emission.

However, it remains a challenge to achieve a carbon-free economy and mitigate global warming, without fully understanding the ongoing development of renewable energy, that will also get aided in this research. As stated by Chen and Wang [7], low carbon economy refers to the green ecological economy based on low energy consumption and low pollution; yet current fossil fuel-dominated energy structure in most countries fails to achieve this specific economic development objective. The United Nations has announced recently that carbon neutrality by 2050 is the world's most urgent mission and many countries have already set targets to reach net zero to balance any emissions by absorbing an equivalent amount from the atmosphere (e.g., [8, 9]). Given the global target to achieve carbon neutrality, there is an increasing demand for better understanding the past and future changes in renewable energy.

Moreover, the accurate relationship between renewable energy and economic factors such as GDP is still not well understood, which requires further investigation. A recent paper by Shahbaz et al. [10] summarized the renewable energy-GDP relationship in literature, pointing out the ongoing debate on how renewable energy affects economics. Haseeb et al. [11], for example, argued that renewable energy had a positive impact on economic growth based on renewable energy data from 1980 to 2016 in Malaysia. This is consistent with research by Muhammad et al. [12], who analyzed renewable energy and economic data in 29 countries. In the meanwhile, Maji and Sulaiman [13] reported that renewable energy consumption might reduce economic growth based on 15 countries in West Africa. Therefore, this study further explores the GDP-renewables relationship.

Specifically, the primary objectives of this study are to address the following questions: (1) How have different sources of renewable energy and fossil fuels changed during the past four decades in the U.S., U.K., Mexico, Canada, and China? (2) What are the relationships between renewable energy, carbon emission, GDP, and climate factors? (3) How can we propose an applicable strategy to approach the goal of carbon neutrality or zero-carbon economy considering the transfer of energy use from fossil fuels to renewables? The evolution of renewables will be discussed within the context of global warming and economic development, thereby improving the structure and security of energy consumption, lowering the emission of greenhouse gases, and accomplishing the ultimate goal of the carbon-free economy globally.

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2. Data and Method

2.1. Data Description

The annual data of renewable energy, fossil fuels, and carbon emission from 1980 to 2021 are obtained from the publicly available data archive of OurworldinData (www.ourworldindata.org). The GDP data in the U.S. and China between 1980-2021 are downloaded from the website of the World Bank (www.data.worldbank.org); and the annual mean temperature anomalies in U.S., U.K., Mexico, Canada and China from 1980 to 2021, with respect to a baseline climatology of 1951-1980, are derived from the Food and Agriculture Organization of the United Nations (www.fao.org/faostat/en/#data/). The collected data in the five typical countries (U.S., China, U.K., Mexico, and Canada) are presented in Tables S1-S5, respectively. The data included the trend of temperature, carbon dioxide emission, population, renewables of each country respectively. Moreover, several economic factors are considered for the five selected countries with different development level, such as GDP and productivity (www.data.worldbank.org), which can represent different economic growth status, thus better formulating the strategies to achieve net-zero carbon emission targets.

2.2. Method

2.2.1. Selection method of typical countries. The reason for selecting these five countries have two main reasons, first of all that America and China are the two main economic bodies in nowadays society, and represents the main developments of the world which will be crucial for the future study and renewable energy development. All other three countries represents the different stages of development in the renewable stages which is that UK is the one that is in the middle of development and we have Canada as one country that is highly developed in renewable phase while having Mexico as a poorly renewable country and by the comparison between the five countries with their own typical points, we can obtain different data that cooperates to each other and better build up a conclusion which will result to our goal of zero carbon economy and its strategy.

2.2.2. Pearson's Linear Correlation. The Pearson's linear correlation is a statistical method of measuring the strength and direction of the linear relationship between two variables, which is applied to diagnose possible relationships between two variables. The formula for estimating the Pearson's linear correlation coefficient is given below:

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

$r =$ correlation coefficient

$x_i =$ values of the $x -$ variable in a sample

$\bar{x} =$ mean of the values of the $x -$ variable

$\mathrm{y} =$ mean of the values of the $y -$ variable

$\bar{y} =$ mean of the values of the $y -$ variable

The correlation coefficient (*r*) ranges from -1 to 1, where -1 indicates a strong negative relationship, 0 indicates no relationship, and 1 indicates a strong positive relationship. Pearson's linear correlation can be used in conjunction with Student's t-test, which is a statistical test used to determine whether there is a significant difference between the means of two groups. Moreover, the linear regression analysis is applied to estimate the trend and make forecasts of future state in time series of annual temperature anomalies, carbon emission, GDP, and energy generation/consumption.

3. Results and Discussion

3.1. Global warming

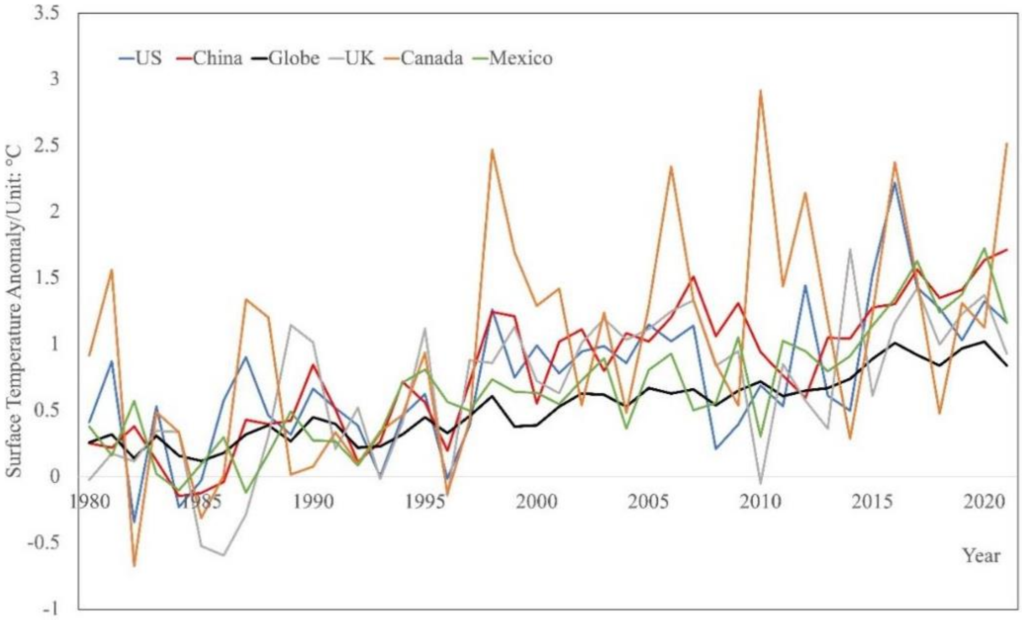

Figure 1. Annual Temperature Anomalies in China, the U.S., the UK, Canada, Mexico, and global mean values. The X-axis represents the surface temperature anomaly in degrees Celsius, and the Y-axis represents the year from 1980 to 2021.

To analyze the graph and understand the trends, we compare the variations and trends of surface temperature anomalies for the five selected countries. Figure 1. clearly demonstrates an upward trend in surface temperature anomalies over time for all countries and the global average, indicating a global pattern of increasing surface temperatures. In 2021, China stands out with the highest surface temperature anomaly among the countries shown, reaching around 1.5 degrees Celsius. The global average, the United States, and Canada follow closely behind with values around 1.2-1.3 degrees Celsius in 2021. The United Kingdom and Mexico exhibit lower surface temperature anomalies, around 1 degree Celsius in 2021, still representing a significant increase from the 1980 baseline.

Interestingly, there is a consistent gap between China's surface temperature anomaly and those of the other countries in the graph, suggesting a potentially more rapid temperature increase in China. At the beginning of the graph in 1980, China had the lowest temperature compared to the global average and the United States. However, by 2021, China has surpassed all other countries with the highest temperature anomalies. Despite fluctuations caused by factors like Earth's orbit wobbles, known as Milankovitch cycles, which contribute to climate variations by altering sunlight at mid-latitudes by up to 25 percent, the overall trend of rising annual temperature anomalies aligns with global warming trends. These variations can exaggerate the fluctuation in temperature records within individual countries and globally. However, the significantly upward trend in annual temperature anomalies indicates the dominant role of human activities, particularly the combustion of fossil fuels and the release of significant amounts of carbon dioxide in recent decades.

In general, Figure1. provides robust evidence of the increasing global surface temperatures, with variations in the rate of change between different countries. China experiences a particularly intense temperature increase compared to the United States and the rest of the world. These findings highlight the importance of understanding and addressing the impact of human activities, especially the combustion of fossil fuels and the release of tremendous amounts of carbon dioxide, on climate change.

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3.2. Changes of GDP in five typical countries

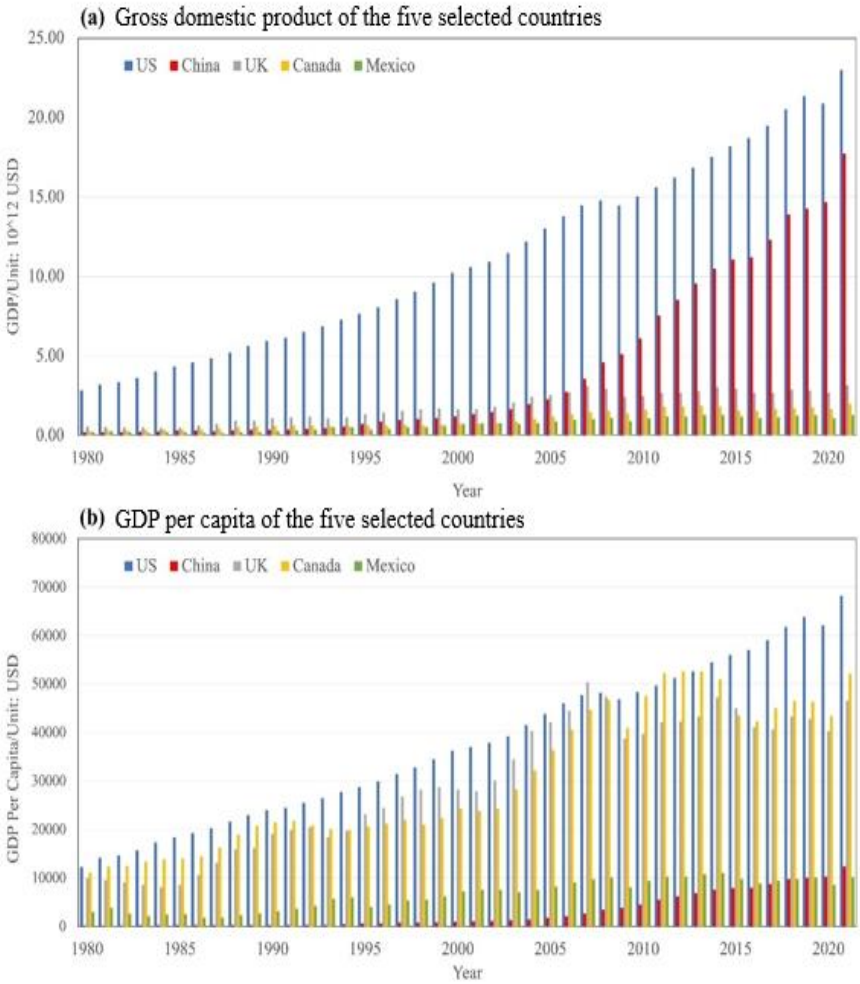

Figure 2. GDP and GDP per capita for five selected countries: the United States, China, the United Kingdom, Canada, and Mexico. (a) Gross domestic product of the five selected countries. (b) GDP per capita of the five select-ed countries. The X-axis represents the GDP in billions of dollars, and the Y-axis represents the year from 1980 to 2021.

Figure 2a. shows an evident increasing trend in GDP over time for all countries, with China and the United States having the highest GDP values in 2021. An upward change in GDP per capita is also shown in Figure 2b. over time for all countries, with the United States having the highest GDP per capita value in 2021, followed by the United Kingdom and Canada. The United States and China have significantly higher GDP values compared to the other countries shown in the graph, with values of over 20 trillion dollars in 2021. This suggests that the United States and China have very rapid economic development compared to the others. Despite of a smaller values of GDP, the United Kingdom and Canada have higher GDP per capita values compared to China and Mexico, indicating that the individual citizen in these countries has a higher level of economic well-being on average. Mexico has the lowest GDP per capita value among the countries shown in the graph, indicating that the average citizen in Mexico has a lower level of economic well-being compared to the other countries. Overall, the graph suggests that there is significant variation in GDP and GDP per capita between different countries, with the United States and China having the largest economies but the United Kingdom and Canada having higher levels of economic well-being per capita.

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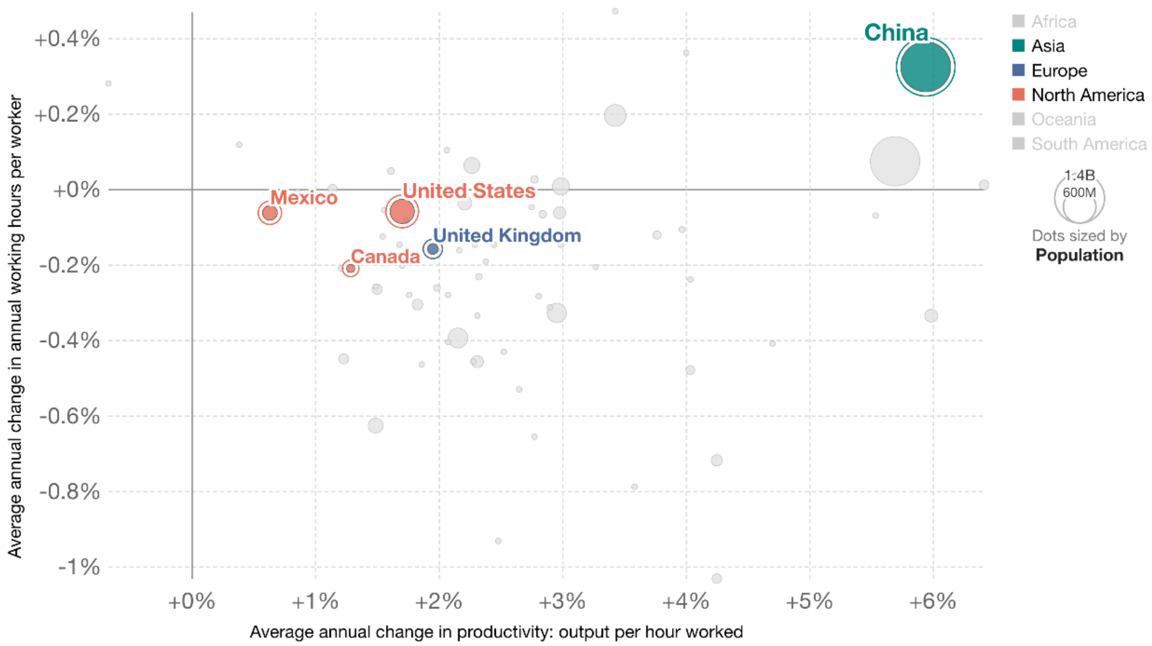

Figure 3. Annual working hours vs. labor productivity in the five selected countries, estimated during 1990 and 2019. This figure is adapted from Feenstra et al. [14]. Labor productivity is measured as GDP per hour of work. GDP is adjusted for inflation and for differences in the cost of living between countries.

As shown in Figure 3, Mexico shows a slight decrease in annual working hours per worker, with an average annual change of around -0.1%. Meanwhile, Mexico also has the lowest increase in labor productivity, with an average annual change of around 0.5%, suggesting that there may not be a strong positive correlation between longer working hours and increased productivity in Mexico. The United States and Mexico have similar levels of change in annual working hours per worker, while Canada and the United Kingdom show a decrease rate of approximately 0.2%. Further, the United States has a slightly higher increase in labor productivity, with an average annual change of around 1.5%, compared to Canada's average annual change of around 1.1%. This suggests that there may be a positive correlation between longer working hours and increased productivity in the United States, but the relationship may be weaker in Canada. However, the United Kingdom has the highest increase in labor productivity, with an average annual change of around 2%, indicating a strong positive correlation between increased productivity and shorter working hours in the United Kingdom. Notably, the average annual change in annual working hours per worker in China, compared to the other four typical countries, shows an increasing rate of 0.32%, accompanied by a rising annual change in productivity (around 6%). All the five countries display an enhancement of productivity possibly due to the development of economy and technology.

3.3. *Changes of Carbon Emission in Five Typical Countries*

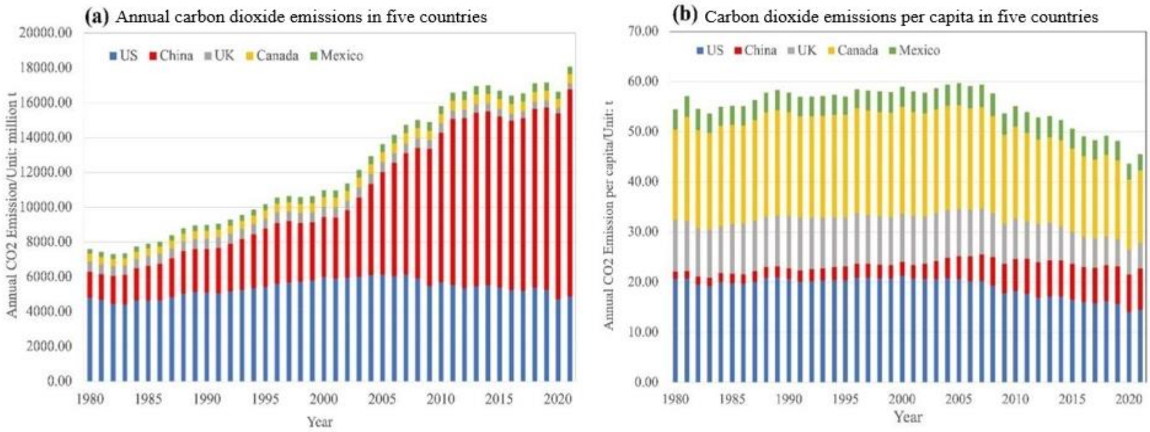

Figure4. Annual CO_2 emissions and CO_2 emissions per capita for several countries: the United States, China, the United Kingdom, Canada, and Mexico. The X-axis represents the annual CO_2 emissions in million metric tons, and the Y-axis represents the year from 1980 to 2021.

Figure 4. demonstrates a clear upward trend in CO_2 emissions over time for all countries, with China leading with the highest annual CO_2 emissions in 2021. The graph also reveals an increasing trend in CO_2 emissions per capita, with the United States having the highest CO_2 emissions per capita in 2021. It is noteworthy that despite its smaller population, the United States has the highest CO_2 emission per capita compared to other countries shown in the graph. Examining the CO_2 emissions data for additional countries, we observe varying levels. China stands out as the largest contributor to global CO_2 emissions, surpassing 10,000 million metric tons in 2021. The United Kingdom showcases the lowest annual CO_2 emissions among the countries presented, indicating progress in reducing its carbon footprint. However, it's essential to note that the graph doesn't provide a comprehensive representation of all countries' emissions.

Figure 4. potentially indicates the relationship between carbon emissions and GDP (Figure 2.) for the United States and China. The bar graph depicts relatively stable carbon emissions for the United States, potentially reaching a peak around 2005 and declining thereafter. In contrast, China's carbon emissions display a gradual increase in the first two decades from 1980, followed by a rapid surge after 2000. Regarding GDP, the United States demonstrates a linear increasing trend, while China's economic growth exhibits an exponential pattern. The graph provides labeled evolutionary functions for GDP in both countries, enabling GDP forecasts based on linear regression. Notably, if the current economic development trend continues, it is anticipated that China's GDP may surpass that of the United States in the coming years.

Overall, these figures highlight significant variations in CO_2 emissions and their relationship with GDP among countries. China emerges as the largest emitter of CO_2, while the United States has the highest CO_2 emissions per capita. The United Kingdom demonstrates progress in reducing emissions, and other countries not shown in the graphs likely have their unique emission profiles. These findings underscore the importance of addressing CO_2 emissions and promoting sustainable economic development worldwide. By implementing effective strategies, countries can work towards reducing emissions while fostering economic growth in a more environmentally conscious manner.

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3.4. Changes of fossil fuels and renewable energy in the five selected countries

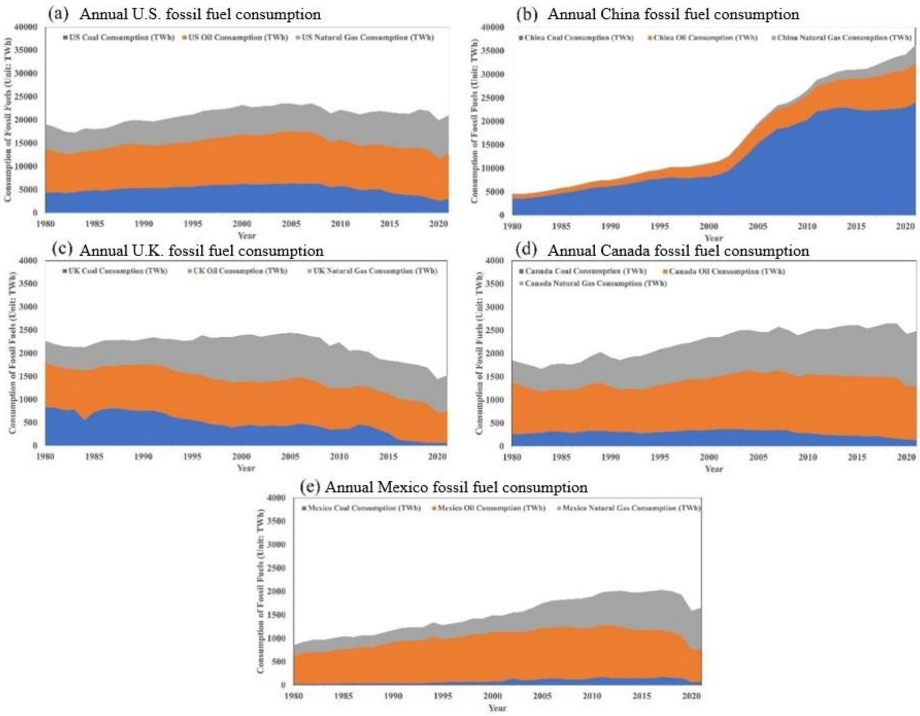

Figure 5. Annual consumption of fossil fuels in several countries: the United States, China, the United Kingdom, Canada, and Mexico. The X-axis represents the annual consumption of fossil fuels in terawatt-hours (TWh), and the Y-axis represents the year from 1980 to 2021.

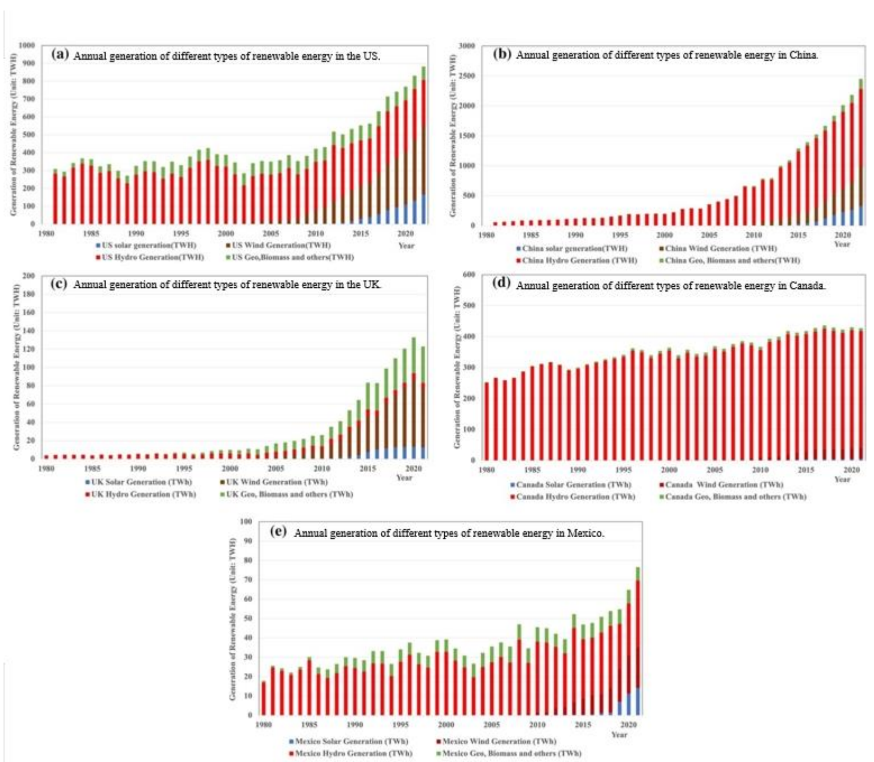

Figure 6. Annual generation of different types of renewable energy in the five selected countries.

As shown in Figure 5 and 6, different countries have different patterns of change in fossil fuels and renewable energy from 1981 to 2020. In the United States, it is seen that the consumption of fossil fuels increases in the first two decades, reaching the maximum in around 2005, then it decreases in the following decades. This is general-ly consistent with the changes of carbon emission in the U.S., maximizing around 2005 (see Figure 4. and Figure S1). Fig. S1 specifically compares the GDP and carbon emission in the U.S. and China, the world's two largest economies. Compared with the U.S., China shows a rapid increase in fossil fuel consumptions during the last four decades, accompanied with a upward trend in carbon emission and GDP (Figure S1). In Canada and Mexico, we have demonstrated a slightly rising trend of fossil fuel consumption, while in the U.K., a dramatic downward trend of fossil fuels is identified during 1981 and 2020 (Figure 5).

In terms of renewable energy, all the five selected countries represent an increasing trend, especially for solar power and wind power during the last decade (Figure 6). Hydropower, in particular, dominates among all types of renewable energy in early years of the research period. Interestingly, hydropower remains the largest source of renewable energy to supply electricity in Canada, China, and Mexico; meanwhile, wind power becomes dominant in the U.S. and the U.K. Considering the sum of renewable energy, the U.S., U.K., and China show a nearly exponential change from 1981 to 2021, while Mexico and Canada exhibit generally a linearly increasing trend. This different increasing patten of renewable energy generation seems to be consistent with the GDP changes during the research period.

In order to have a comprehensive comparison between the U.S. and China, Figure 2 shows the carbon dioxide emitted due to fossil fuel consumption in these two largest economies over the world, which brings a closer look to the relationship of each kind of fossil fuels and carbon emission and allows us to observe which type of fossil fuels will cause the most carbon emission. It is clearly shown that in China, annual carbon emission due to coals is dominant, reaching 8 billion ton in 2020. There is also an increasing trend in terms of carbon emission due to oil. In the U.S., however, carbon emission due to different kinds of fossil fuels is flattened during the past decades. Carbon emission due to coals and oil is comparable in the U.S. and started to decrease from 2005. Figure 5. displays the new form of energy which is the renewables in both Country. Renewables have become more and more crucial to the global development. The energy produces no greenhouse gas emissions from fossil fuels and reduces some types of air pollution. As suggested in Figure 5a, before the year 2007 the renewable energy in America is stable which do not have big influence. After 2007, there is a little boost and considerable development of solar, wind, and biomass. We can clearly see that wind power was very week before the year 2005, but has become the topset renewable energy since 2010s in the U.S. On the other hand, China has an extremely poor development in all four kinds of renewables before 2009. Nevertheless, there is a quick boost in renewables after 2009, given the rapid development of technology and economics related to renewables. Notably, hydropower dominates in China nowadays, while wind becomes the leading renewable energy source in the U.S.

3.5. Relationship between energy, carbon emission, and economic factors

We can clearly see in Table 1 that renewable energy has a significantly high correlation with the Economic GDP in the U.S., U.K., Mexico, Canada, and China. In China, the correlation reaches up to 0.99, which reveals how renewables can affect both the environment and have a positive effect on the annual change of GDP. Compared with China, a relatively lower correlation coefficient (0.85) between renewable energy and GDP is detected in the U.S. Basically, the results presented here demonstrate the close renewable energy-GDP relationship, which is consistent with several previous studies[11,12]

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Table 1. The correlation coefficients between energy, climate, carbon emission and GDP in the five selected countries.

Countries	Correlation Coefficients	Energy		Climate	Carbon Emission	Economics
		Renewable Energy	Fossil Fuels	Surface Temperature Anomalies	Annual CO_2 emission	GDP
US	Renewable Energy	1.00	0.17	0.51	0.11	0.85
	Fossil Fuels	0.17	1.00	0.43	0.96	0.59
	Surface Temperature Anomalies	0.51	0.43	1.00	0.28	0.64
	Annual CO_2 emission	0.11	0.96	0.28	1.00	0.36
	GDP	0.85	0.59	0.64	0.36	1.00
China	Renewable Energy	1.00	0.91	0.73	0.92	0.99
	Fossil Fuels	0.91	1.00	0.79	1.00	0.94
	Surface Temperature Anomalies	0.73	0.79	1.00	0.77	0.71
	Annual CO_2 emission	0.92	1.00	0.77	1.00	0.94
	GDP	0.99	0.94	0.71	0.94	1.00
UK	Renewable Energy	1.00	0.93	0.46	0.97	0.70
	Fossil Fuels	-0.93	1.00	0.28	0.96	-0.45
	Surface Temperature Anomalies	0.46	0.28	1.00	0.41	0.66
	Annual CO_2 emission	0.97	0.96	0.41	1.00	-0.65
	GDP	0.70	0.45	0.66	-0.65	1.00
Canada	Renewable Energy	1.00	0.89	0.44	0.83	0.91
	Fossil Fuels	0.89	1.00	0.51	0.98	0.89
	Surface Temperature Anomalies	0.44	0.51	1.00	0.51	0.50
	Annual CO_2 emission	0.83	0.98	0.51	1.00	0.80
	GDP	0.91	0.89	0.50	0.80	1.00

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Table 1. (continued).

Mexico	Renewable Energy	1.00	0.71	0.75	0.63	0.82
	Fossil Fuels	0.71	1.00	0.74	0.98	0.96
	Surface Temperature Anomalies	0.75	0.74	1.00	0.69	0.77
	Annual CO_2 emission	0.63	0.98	0.69	1.00	0.94
	GDP	0.82	0.96	0.77	0.94	1.00

Moreover, the correlation between fossil fuels and GDP in the U.S. (0.59) is also smaller than that in China, with a coefficient reaching 0.85. Both fossil fuels and GDP in China grow exponentially, leading to this significantly positive correlation be-tween these two. While in the U.S., there is a linear increasing trend in GDP and a relatively flattened variation in fossil fuel consumption. The renewable energy shows a slightly negative correlation with carbon emission in the U.S., highlighting the benefit of renewable energy in terms of its near-zero carbon emission. Not limiting on the two countries, the correlation between fossil fuels and GDP in UK, Mexico, and Canada is -0.45, 0.89, and 0.96 respectively. Also, the correlation between renewables and GDP is 0.70, 0.90 and 0.82. respectively. Comparing with the status of US and China, as well as their current renewable development or progress towards the zero carbon economy, we can observe that UK is the nation that possessed the dominance in the transition from the negative relation between fossil fuel and GDP, but unlike China it trend tend to be more linear as well as Mexico and Canada, which all provide that the ongoing transition from fossil fuel to renewable energy is beneficial not only to the environment but as well as economic factors. This is also one of the dominant reasons for the ongoing transition from fossil fuels to renewable energy, given the global goal of carbon-free economy [15]. Specifically, carbon emission holds a -0.11-correlation coefficient with renewable energy and a positive 0.96 correlation with fossil fuels.

It is worth noting that the U.S. has reached carbon peak around 2005 as well as the UK. In addition, Canada and Mexico peak in 2018 while carbon emission in China continues to increase during the past decades. The increasing trend of carbon emission and fossil fuels in China contributes to the high positive correlation between these two variables. High correlation is also detected between fossil fuels and renewable energy in China, which can be derived. In a nutshell, the U.S. and China, as two largest economic bodies in the world, have shown different developmental phases of renewable energy and GDP. And UK, Mexico, and Canada have shown a stability between the transition on a different energy in different stages of development which heavily corporates with GDP.

4. Conclusion

In this research, the investigation of the changes in renewable and fossil fuel energy have drawn the conclusion that in America it has already reached the peak of car-bon dioxide emission. In recent years, carbon dioxide emission starts to decrease in the U.S., implying its potential to reach carbon neutrality. Similar to the carbon di-oxide emission, the utilization of fossil fuel also reached its peak around the year 2005 and starts to decrease afterwards. The renewables in the U.S. also have an in-creasing trend after the year of 2005, before that time the amount of renewable energy is rather stable. In the meanwhile, China shows a tremendously rapid development of renewable energy between the year of 2003 and 2015, with an continuously increasing trend in recent years. In 2021, China revealed a similar amount in fossil fuel usage comparing to the US. Furthermore, the renewable energy in China shows an exponential increasing trend which went on the track of the year 2005 and starts to develop rapidly. Interestingly, at the initial of renewable development, US, China, Mexico, and Canada were dominated by hydropower generation, but in recent years, wind generation become a more important and dominating factor in the US, and China, Mexi-co, and Canada remain the same. Hydropower generation only dominated UK at the years that renewables weren't developed which is until 2010 and wind generation quickly took over the dominance. The benefits of renewable energy on economic is expressed by the high correlation with GDP in both America and China. In the US, it has a 0.85 correlation and in China it holds a 0.99. Also, renewables will also reduce the carbon dioxide emission, with a 0.17 correlation coefficient in the U.S. Moreover, the relation between surface temperature anomalies also points out the importance and effect that renewable energy has on our nowadays society, comparing to fossil fuels, it has much less effect on the temperature in the whole globe.

Moreover, this study summarizes the change of renewable energy and zero-carbon economy in an anthropogenically warming climate during the past four decades. The complicated relationships between renewable energy and other factors, such as temperature anomalies, GDP, carbon emission, are explicitly examined (see details in Section 3.5). This provides useful scientific information for us to propose strategies to reach the carbon neutrality or zero/low carbon economy. To put it simply, the strategy is basically the replacement of renewable with fossil fuels which was the main source of energy in the past years. However, it is more important to analyze the development of renewable energy and the economy of the whole globe. From the correlation, it is obvious that renewable energy will not harm the economy (GDP), and even have a positive effect. The reason is mainly due to, the benefit for companies that uses renewable as their energy source, and the unlimited using of renewables allows company or business to prove much more comparing the ones using fossil fuels.

Uncertainty remains in this study. One specific caveat is that only five representative countries are included and discussed in this study. More countries or regions will be addressed in further studies in order to provide a more comprehensive analysis of the relationship between renewable energy and economic development. Moreover, the analytical method – Pearson's linear correlation analysis – cannot derive the causality between renewable energy, GDP, other factors. However, this research presents the changes of renewable energy in an anthropogenically warming climate, shedding light on potentially useful strategies for renewable energy innovation and zero-carbon economy.

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Appendix

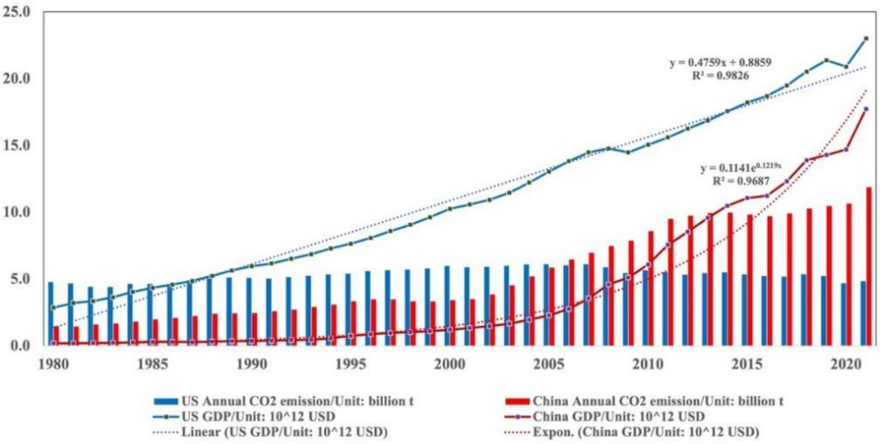

Figure 1. S1 Annual CO_2 emission and GDP in the U.S. and China.

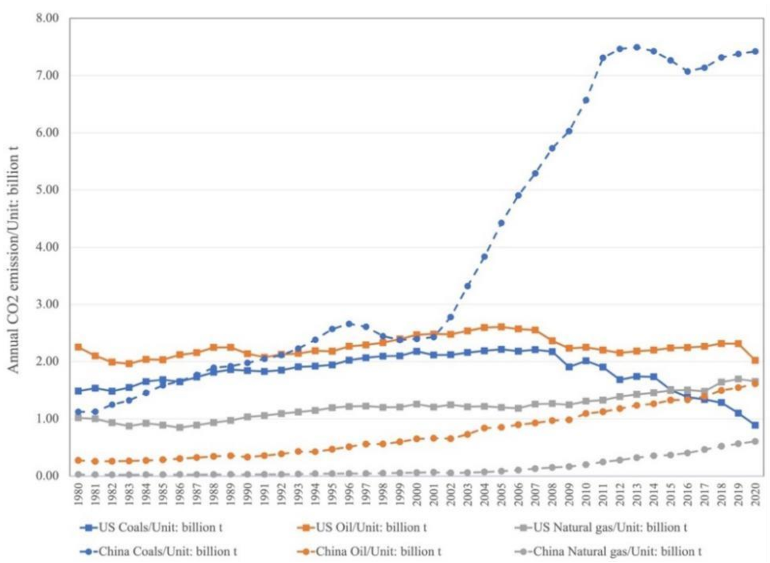

Figure 2. S2 Annual CO_2 emission due to fossil fuels (Coal, Oil, Natural Gas) in the U.S. and China.

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Table S1. Annual data of surface temperature anomalies, CO_2 emission, GDP, fossil fuel, and renewable energy from 1980 to 2021 in the U.S.

U.S.	Climate	Low-carbon Economy		Fossil Fuels			Renewable Energy			
Year	**Surface Temper -ature Ano-maly/ Unit: °C**	**Annual CO_2 emissio-n/Unit: billion t**	**GDP/ Unit: 10^12 USD**	**Coal Consu-mption (TWh)**	**Oil Cosumpti-on (TWh)**	**Natural Gas Consum-ption (TWh)**	**Solar Genera -tion (TWh)**	**Wind Gener -ation (TWh)**	**Hydro Generat -ion (TWh)**	**Geo, Biom-ass and others (TWh)**
1980	0.41	4.81	2.86	4293.98	9453.47	5337.38	0.00	0.00	282.00	26.66
1981	0.87	4.69	3.21	4428.93	8812.75	5208.63	0.00	0.00	266.51	27.38
1982	-0.34	4.45	3.34	4265.80	8350.53	4841.71	0.00	0.00	315.53	26.41
1983	0.53	4.43	3.63	4425.29	8311.48	4542.24	0.00	0.00	338.68	29.80
1984	-0.23	4.66	4.04	4752.76	8573.32	4851.57	0.01	0.01	327.59	35.60
1985	-0.03	4.65	4.34	4866.30	8540.44	4669.54	0.01	0.01	287.18	36.39
1986	0.58	4.66	4.58	4805.60	8955.59	4376.20	0.01	0.00	296.97	38.70
1987	0.90	4.83	4.86	5013.87	9142.15	4652.74	0.01	0.00	255.41	42.67
1988	0.46	5.05	5.24	5247.14	9520.88	4866.02	0.01	0.00	22838	42.39
1989	0.32	5.13	5.64	5309.36	9517.53	5170.22	0.25	2.13	274.72	48.85
1990	0.67	5.11	5.96	5338.00	9306.91	5170.61	0.37	2.82	292.28	57.46
1991	0.52	5.06	6.16	5287.61	9108.51	5283.97	0.48	2.98	28733	60.55
1992	0.39	5.17	6.52	5324.03	9297.39	5463.51	0.41	2.92	251.43	64.82
1993	0.00	5.27	6.86	5522.45	9376.04	5599.42	0.48	3.04	279.25	66: 92
1994	0.46	5.36	7.29	5543.14	9619.75	5731.08	0.50	3.48	259.34	66.35
1995	0.63	5.42	7.64	5593.05	9597.53	5979.83	0.51	3.20	311.22	63.27
1996	-0.01	5.61	8.07	5847.30	9947.14	6088.90	0.54	3.27	347.55	64.83
1997	0.39	5.69	8.58	5970.78	10079.77	6125.32	0.53	3.32	355.97	65.82
1998	126	5.73	9.06	6029.34	10251.11	6021.79	0.52	3.06	322.09	65.62
1999	0.75	5.80	9.63	6020.10	10537.09	6042.63	0.52	4.53	316.61	66.48
2000	0.99	6.01	10.25	6286.54	10654.13	6283.91	0.52	5.65	272.76	66.58
2001	0.78	5.90	10.58	6101.32	10636.85	6006.58	0.57	6.81	210.24	66.83
2002	0.95	5.95	10.93	6098. 45	10642.41	6201.11	0.60	10.46	258.17	71.79
2003	0.99	6.01	11.46	6214.54	10803. 68	6021.90	0.61	1130	269.97	71.33
2004	0.86	6.11	12.22	6254.98	11197.87	6046.28	0.70	14.29	262.55	71.95
2005	1.15	6.13	13.04	6346.96	11214.08	5951.93	0.75	17.99	266.43	72.60
2006	1.02	6.05	13.82	6249.68	11070.91	5865.78	0.82	26.86	285.54	73.08
2007	1.14	6.13	14.47	6333.85	11001.76	6241.38	1.10	34.80	243.04	73.87
2008	0.21	5.91	14.77	6233.05	10273.70	6288.91	1.63	55.92	251.05	73.55
2009	0.40	5.48	14.48	5482.38	9737.24	6176.28	2.08	74.63	271.53	73.16
2010	0.69	5.68	15.05	5800.54	9891.23	6481.93	3.01	95.61	257.27	75.06

Table S1. (continued).

2011	0.53	5.54	15.60	5473.07	9694.56	6582.11	4.74	121.39	316.10	75.78
2012	1.45	5.34	16.25	4838.40	9472.59	6881.23	9.04	142.24	274.03	77.04
2013	0.61	5.47	16.84	5022.27	9627.55	7070.23	16.04	169.54	26655	80.67
2014	0.50	5.52	17.55	5010.86	9693.27	7222.60	29.22	183.49	255.75	84.07
2015	1.53	5.37	18.21	4329.08	989072	7435.79	39.43	192.65	246.45	83.74
2016	2.22	5.25	18.70	3960.74	9961.58	7490.99	55.42	22929	263.76	82.72
2017	1.43	5.21	19.48	3852.59	10057.78	7399.92	78.06	256.87	296.81	82.80
2018	1.27	5.38	20.53	3689.46	10299.73	8217.15	94.31	275.42	289.51	81.89
2019	1.03	5.26	21.37	3150.46	10283.93	8506.92	107.97	298.87	285.47	76.82
2020	133	4.71	20.89	2556.18	9032.40	8319.03	132.04	34135	282.78	74.31
2021	1.17	4.87	23.00	2936.55	9813.04	8267.17	165.36	383.60	257.69	75.49

Table S2. Same as Table S1, but for China.

CN.	**Climate**	**Low-carbon Economy**		**Fossil Fuels**			**Renewable Energy**			
Year	**Surface Temper-ature Ano-maly/ Unit: °C**	**Annual CO_2 emissio-n/Unit: billion t**	**GDP/ Unit: 10^12 USD**	**Coal Consu-mption (TWh)**	**Oil Cosumpti-on (TWh)**	**Natural Gas Consum-ption (TWh)**	**Solar Genera-tion (TWh)**	**Wind Gener-ation (TWh)**	**Hydro Generat-ion (TWh)**	**Geo, Biom-ass and others (TWh)**
1980	0.25	1.49	0.19	3539.02	972.53	143.82	0.00	0.00	58.22	0.00
1981	0.22	1.48	0.20	3520.20	921.53	128.40	0.00	0.00	65.51	0.00
1982	0.38	1.61	0.21	3724.84	911.75	120.24	0.00	0.00	74.41	0.00
1983	0.12	1.69	0.23	3989.00	930.10	123.06	0.00	0.00	86.42	0.00
1984	-0.15	1.84	0.26	4338.27	964.89	125.28	0.00	0.00	86.81	0.00
1985	-0.12	2.00	0.31	4736.26	1010.60	130.32	0. .00	0.00	92.39	0.00
1986	-0.04	2.10	0.30	4951.42	1074.42	138.68	0.00	0.00	94.55	0.00
1987	0.43	2.26	0.27	5372.24	1142.23	139.99	0.00	0.00	100.02	0.00
1988	0.40	2.43	0.31	5771.22	1229.36	143.72	0.00	0.00	109.17	0.00
1989	0.42	2.46	0.35	6046.90	1287.73	151.67	0.00	0.00	118.41	0.00
1990	0.85	2.48	0.36	6134.52	1274.57	154.18	0.00	0.00	126.74	0.06
1991	0.51	2.61	0.38	6433.43	1379.14	156.12	0.00	0.01	124.69	0.06
1992	0.11	2.73	0.43	6731.50	1495.91	159.14	0.00	0.13	130.69	0.11
1993	0.27	2.92	0.44	7170.36	1663.78	168.97	0.00	0.21	151.85	0.12
1994	0.72	3.10	0.56	7641.67	1690.64	176.97	0.00	0.38	167.43	0.46
1995	0.56	3.36	0.73	7736.85	1825.63	178.80	0.01	0.62	190.58	3.01
1996	0.20	3.50	0.86	8095.39	2023.03	187.36	0.01	0.09	187.97	1.53
1997	0.72	3.51	0.96	7931.91	2221.55	197.99	0.01	0.20	195.98	2.72

Table S2. (continued).

1998	1.25	3.36	1.03	7871.72	2287.59	204.16	0.01	0.36	198.89	2.48
1999	121	3.35	1.09	8099.03	2437.24	216.63	0.02	0.47	196.58	2.52
2000	0.55	3.44	1.21	8211.41	2626.90	246.96	0.02	0.59	222.41	2.54
2001	1.02	3.51	1.34	8635.75	2683.25	276.46	0.03	0.72	277.43	2.55
2002	1.11	3.87	1.47	9467.46	2895.60	294.14	0.05	0.84	287.97	2.55
2003	0.80	4.55	1.66	11283.06	3234.76	341.75	0.06	1.00	283.68	2.54
2004	1.09	5.22	1.96	13155.28	3777.77	399.84	0.08	128	353.54	2.53
2005	1.02	5.88	2.29	15405.11	3838.49	469.75	0.08	1.95	397.02	5.32
2006	121	6.49	2.75	1691838	4116.77	577.84	0.09	3.71	435.79	7.13
2007	1.51	6.98	3.55	18423.91	4313.57	710.78	0.11	5.48	485.26	9.86
2008	1.06	7.50	4.59	18715.92	4408.09	819.33	0.15	13.10	636.96	14.87
2009	131	7.89	5.10	19605.02	4580.30	902.24	0.28	27.61	615.64	20.86
2010	0.94	8.62	6.09	20339.11	5214.49	1088.74	0.70	49.40	71138	24.90
2011	0.76	9.53	7.55	22140.64	539073	1351.63	2.61	74.10	688.04	27.63
2012	0.60	9.78	8.53	22418.49	5654.30	1508.78	3.59	103.05	862.79	30.13
2013	1.05	9.95	9.57	22897.41	5907.47	1718.79	8.37	138.26	909.61	37.13
2014	1.04	9.99	10.48	22911.17	6142.52	1883.63	23.51	159.76	1059.69	46.27
2015	128	9.85	11.06	22477.21	6609.90	1946.90	39.48	185.59	1114.52	54.07
2016	1.31	9.72	11.23	22273.85	6823.58	2094.41	66.53	240.86	1153.27	62.13
2017	1.57	9.92	12.31	22377.88	7183.17	2412.52	117.80	304.60	1165.06	79.60
2018	1.35	10.29	13.89	22514.79	7534.66	2839.26	176.90	365.80	1198.89	93.73
2019	1.41	10.49	1428	22694.04	7915.18	3083.77	224.00	405.30	1272.54	112.73
2020	1.64	10.67	14.69	22882.26	7984.45	3366.17	261.10	466.50	1321.71	135.63
2021	1.71	11.90	17.73	23936.06	8499.58	3786.94	327.00	655.60	1 300.00	169.93

Table S3. Same as Table S1, but for the UK.

Year	Surface Temperature Anomaly /Unit: °C	Annual CO_2 emission/ Unit: billion t	GDP /Unit: 10^12 USD	Sum of Fossil Fuel Consumption (TWh)	Sum of Renewable Energy Generation (TWh)
1980	-0.02	579.04	0.56	2264.38034	3.954
1981	0.18	560.55	0.54	2194.38727	4.419
1982	0.12	548.24	0.52	2146.98496	4.536
1983	0.35	545.49	0.49	2139.3246	4.536
1984	0.34	529.11	0.46	2126.83432	4.537010101
1985	-0.52	559.63	0.49	2205.67299	3.955210101
1986	-0.59	568.55	0.60	2275.31523	4.769310101
1987	-0.28	571.67	0.75	2283.81689	4.1868

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Table S3. (continued).

1988	0.31	570.29	0.91	2291.18326	4.885610101
1989	1.15	581.58	0.93	2271.0197	4.7773
1990	1.02	600.34	1.09	2304.76976	5.815799983
1991	0.21	608.43	1.14	2345.41546	5.317900007
1992	0.52	592.88	1.18	2308.48735	6.404199989
1993	-0.02	578.64	1.06	2303.99446	5.717999954
1994	0.41	574.64	1.14	2272.32543	6.94849997
1995	1.12	566.57	1.35	2279.95317	6.871600013
1996	-0.14	588.19	1.42	2390.41896	5.6846
1997	0.88	562.33	1.56	2329.80148	6.9498001
1998	0.86	567.60	1.66	2349.66912	8.654200077
1999	1.13	561.11	1.69	2345.66214	9.619100037
2000	0.72	567.59	1.67	2392.8995	9.921799936
2001	0.63	576.31	1.65	2406.43545	9.556000023
2002	1.01	560.07	1.79	2352.21607	11.13010006
2003	1.19	571.47	2.06	2394.10885	10.69369986
2004	1.04	572.90	2.42	2423.8179	14.14390019
2005	1.12	569.96	2.54	2441.97563	16.93229969
2006	1.25	567.57	2.71	2422.5615	18.10690029
2007	1.33	559.24	3.09	2371.05853	19.68450104
2008	0.84	544.50	2.93	2341.67377	21.92927769
2009	0.95	493.89	2.42	2160.8191	25.2449477
2010	-0.05	511.63	2.49	2232.80651	26.18296806
2011	0.85	469.45	2.67	2058.21621	35.20379414
2012	0.58	487.52	2.71	2070.15063	41.24799706
2013	0.36	477.39	2.79	2027.22765	53.21489082
2014	1.72	438.54	3.07	1879.66042	64.52124634
2015	0.61	422.34	2.93	1845.15372	83.35897598
2016	1.16	399.34	2.70	1819.88166	82.99553459
2017	1.42	387.57	2.68	1776.48386	98.87837265
2018	1.00	381.89	2.88	1747.394125	110.06612
2019	1.23	369.01	2.86	1688.30693	120.4994199
2020	1.37	329.58	2.70	1440.675307	132.9622809
2021	0.93	340	3.13	1521.203113	123.087

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Table S4. Same as Table S1, but for Canada.

Year	Surface Temperature Anomaly /Unit: °C	Annual CO_2 emission/Unit: billion t	GDP /Unit: 10^12 USD	Sum of Fossil Fuel Consumption (TWh)	Sum of Renewable Energy Generation (TWh)
1980	0.92	442.85	0.27	1856.98525	252.448
1981	1.56	429.63	0.31	1789.41713	267.913
1982	-0.67	414.45	0.31	1736.72088	259.9339999
1983	0.49	408.34	0.34	1669.3005	268.037
1984	0.34	425.23	0.36	1764.49308	288.4599999
1985	-0.31	421.72	0.36	1782.31451	305.323
1986	0.01	404.71	0.38	1758.20209	312.501
1987	1.34	430.98	0.43	1815.983	318.519
1988	1.20	455.67	0.51	1944.692	309.9209999
1989	0.02	462.89	0.57	2032.37037	293.92774
1990	0.08	458.22	0.59	1916.01553	299.6392392
1991	0.34	449.96	0.61	1860.17956	311.2619192
1992	0.10	463.76	0.59	1928.25952	319.7007028
1993	0.34	464.31	0.58	1946.97089	327.0919525
1994	0.47	478.73	0.58	2009.35591	333.6496524
1995	0.94	491.39	0.60	2095.3997	341.2604281
1996	-0.13	507.51	0.63	2139.8799	362.1884796
1997	0.43	521.84	0.65	2201.377	356.9167969
1998	2.47	529.65	0.63	2231.21047	339.9292894
1999	1.69	544.06	0.68	2293.15608	354.1192118
2000	1.29	566.69	0.74	2356.57712	364.1170427
2001	1.42	558.78	0.74	2350.00815	340.0221497
2002	0.54	564.05	0.76	2428.9887	357.5261044
2003	1.24	581.31	0.90	2495.3929	344.3372945
2004	0.49	579.59	1.03	2508.97281	348.1945263
2005	1.28	574.65	1.17	2469.9327	369.0454136
2006	2.34	568.45	1.32	2464.81482	360.7480465
2007	1.33	593.52	1.47	2579.5756	375.9410774
2008	0.85	576.56	1.55	2506.0173	385.4889662
2009	0.54	543.97	1.37	2392.13881	380.6420567

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Table S4. (continued).

2010	2.92	556.56	1.62	2471.7078	367.0575578
2011	1.44	567.05	1.79	2535.3963	392.8437842
2012	2.14	568.22	1.83	2528.76443	399.4438193
2013	1.18	572.61	1.85	2576.81794	418.1656102
2014	0.29	569.84	1.81	2607.89447	412.8952452
2015	1.23	574.3	1.56	2617.32677	417.9271788
2016	2.37	560.53	1.53	2544.80048	427.5495228
2017	1.48	571.54	1.65	2591.32082	436.230481
2018	0.48	584.37	1.73	2653.2673	429.171605
2019	1.31	584.71	1.74	2648.0542	422.6572844
2020	1.13	534.86	1.65	2421.13201	430.2952634
2021	2.52	545.63	1.99	2483.22027	427.1759066

Table S5. Same as Table S1, but for Mexico.

Year	Surface Temperature Anomaly /Unit: °C	Annual CO_2 emission/Unit: billion t	GDP /Unit: 10^12 USD	Sum of Fossil Fuel Consumption (TWh)	Sum of Renewable Energy Generation (TWh)
1980	0.38	267.74	0.21	853.724595	17.82500002
1981	0.16	283.71	0.26	926.551	25.58199999
1982	0.57	303.91	0.18	972.85086	24.22
1983	0.02	277.57	0.16	967.499927	22.08600005
1984	-0.10	276.65	0.18	1006.991805	25.02700003
1985	0.10	287.37	0.20	1045.680565	30.06829203
1986	0.30	293.41	0.13	1028.06741	24.69150005
1987	-0.12	306.02	0.15	1067.337058	23.70319422
1988	0.17	305.67	0.18	1067.749437	26.4691109
1989	0.49	323.48	0.22	1120.536404	30.02919519
1990	0.27	317.04	0.26	1177.41728	29.60694407
1991	0.27	330.13	0.31	1226.2199	28.46077538
1992	0.09	332.78	0.36	1236.79861	33.18321686
1993	0.33	338.07	0.50	1240.87428	33.15969063
1994	0.71	351.53	0.53	1338.828683	26.49984541
1995	0.81	331.6	0.36	1283.75195	34.02511049
1996	0.57	345.77	0.41	1319.72901	37.53283205

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Table S5. (continued).

1997	0.50	368.64	0.50	1352.03366	32.26334342
1998	0.74	388.36	0.53	1425.04532	30.75353104
1999	0.64	390.52	0.60	1419.99915	38.79632137
2000	0.63	396.07	0.71	1495.73237	39.18864496
2001	0.55	410.7	0.76	1488.388424	34.49749708
2002	0.73	411.97	0.77	1548.02023	30.80106018
2003	0.89	437.76	0.73	1571.815035	26.65971275
2004	0.37	438.86	0.78	1650.9272	32.24183415
2005	0.81	463.99	0.88	1751.33767	35.54751888
2006	0.93	476.57	0.98	1805.72379	37.6473867
2007	0.50	479.79	1.05	1823.53426	35.51991322
2008	0.56	492.98	1.11	1836.30426	46.96615822
2009	1.05	475.9	0.90	1852.32925	34.60706907
2010	0.31	463.78	1.06	1894.15066	45.50604969
2011	1.03	484.16	1.18	1983.09464	44.96692429
2012	0.95	501.57	1.20	2007.303	42.09093531
2013	0.80	495.49	1.27	2016.59201	39.32226086
2014	0.91	484.11	1.32	1977.47974	52.25663435
2015	1.14	479.52	1.17	1984.57361	46.93215399
2016	1.35	479.79	1.08	2011.49707	47.73929155
2017	1.63	465.62	1.16	2035.17199	50.84381744
2018	1.24	475.27	1.22	2007.14032	53.83814806
2019	1.38	472.19	1.27	1929.12364	54.74220804
2020	1.73	391.71	1.09	1588.75353	64.78456831
2021	1.16	407.21	1.29	1657.60404	76.50603447