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The Variation of Renewable Energy in the Context of Global Economic and Social Well-Being

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Abstract

As renewable energy (RE) rapidly integrates into society to meet the growing demand for affordable and clean energy (SDG 7, United Nations' Sustainable Development Goal 7), it is crucial to analyze the merits and flaws of renewable energy generation by assessing its impact on the global economy and social wellbeing. This paper performs an investigative study on the correlation and causality between renewable energy, economy, and environmental indicators. The data was gathered from diverse sources, including The Center for Climate and Energy Solutions, National Aeronautics and Space Administration Goddard Institute for Space Studies (NASA GISS), and Our World in Data, for the temperature, carbon dioxide (CO2) emissions, and gross domestic product (GDP) data. Significant Granger p-values were obtained for RE generation's ability to forecast CO2 emissions and temperature while discovering a strong positive correlation between CO2 and RE generation. The findings revealed that RE has limited effects on the global economy but has considerable implications on social and ecological wellbeing.

Keywords Renewable energy, CO_2 emissions, Average global real GDP per capita, Temperature, COVID-19 Pandemic

1 Introduction

As the global population rapidly approaches the carrying capacity of the logistic growth curve [1], the need for reliable energy sources becomes an urgent concern. According to the Klass Model [2], fossil fuel reserves for oil, coal, and gas are projected to deplete in approximately 35, 107, and 37 years, respectively. On the contrary, RE is inherently diversified, abundant, and mostly sustainable [3]. Therefore, the study of RE is crucial in ensuring the longevity of reliable energy sources for the future. On that account, it is critical for the scientific community to investigate the economic and environmental aspects of affordable and clean energy in pursuit of a sustainable future, which is the main purpose of the United Nations' Sustainable Development Goal 7: to ensure access to affordable, reliable, sustainable and modern energy for all [4]. The consistent performance of RE sectors before and during the Pandemic could attest to the degree of its resiliency during volatile times. Hence, the objective of this study is to analyze the relationship between RE, climate, and economic indicators before and amid the Pandemic. Discovering potential correlations between these variables will lead to a better understanding of the implications and feasibility of RE sources as it would inevitably become an integral component to the operation of future society. In our research, we have focused on the global data surrounding the generation of RE and its connection to CO_2 emissions, GDP, and global temperature.

2 Materials & Methods

2.1 Data

The global air temperature gridded data from the *NASA GISS Surface Temperature Analysis* [5] The dataset has a spatial resolution of 2x2 from 1980 to 2021. Data used in this table are from *Our World in Data.* Data includes the GDP per capita, PPP (constant 2017 international dollar), the global mean temperature anomalies (degrees Celsius), CO_2 emissions per capita (Tons), the energy produced by all the renewable sources (TWh), consisting of Wind, Solar, Hydro, Geo, Biomass, Waste, Wave, and

Year(World infomation)	GDP per capita, PPP (constant 2017 international $)	Global Mean Temperature Anomalies/degC	Co2 per capita tons	Wind - TWh	Solar - TWh	Geo, Biomass and Others - TWh	Hydro - TWh	Sum of all the renewables sources - TWh
2000	11079.91	0.39	4.11	31.42	1.12	185.97	2651.96	2870.48
2001	11191.49	0.54	4.09	38.39	1.40	191.80	2583.89	2815.48
2002	11350.06	0.63	4.13	52.33	1.76	206.29	2631.85	2892.23
2003	11627.15	0.62	4.29	62.91	2.26	217.85	2627.60	2910.63
2004	12065.98	0.54	4.43	85.12	2.97	235.21	2820.75	3144.04
2005	12461.04	0.68	4.53	104.08	4.16	254.51	2916.44	3279.19
2006	12941.19	0.64	4.62	132.86	5.72	271.63	3027.68	3437.88
2007	13445.27	0.67	4.70	170.68	7.76	294.65	3079.34	3552.43
2008	13635.75	0.54	4.72	220.60	12.61	315.31	3257.39	3805.91
2009	13381.81	0.66	4.60	276.02	20.94	338.82	3252.50	3888.28
2010	13890.51	0.72	4.79	346.47	33.67	381.03	3435.77	4196.94
2011	14260.36	0.61	4.90	440.39	65.18	402.65	3501.09	4409.30
2012	14539.90	0.65	4.91	530.55	101.16	436.16	3649.81	4717.69
2013	14843.54	0.68	4.89	635.49	138.94	471.07	3795.93	5041.43
2014	15177.20	0.75	4.87	705.81	197.76	510.48	3894.24	5308.29
2015	15510.00	0.90	4.81	831.43	256.36	546.64	3885.01	5519.44
2016	15829.68	1.02	4.75	962.23	328.39	560.68	4018.67	5869.97
2017	16242.88	0.92	4.76	1140.31	446.05	593.79	4066.72	6246.87
2018	16636.85	0.85	4.80	1269.52	576.95	632.17	4176.69	6655.33
2019	16915.29	0.98	4.76	1418.17	707.92	663.13	4227.88	7017.11
2020	16194.04	1.02	4.47	1591.21	855.72	700.07	4296.80	7443.81

Table 1: Data used in research

Tidal.

2.2 Tools

In this paper, Python version 3.8 is utilized for data analysis and visualization. Several Python modules such as NumPy, Pandas, Matplotlib, and sci-kit-learn are applied to plot the maps and the estimate of linear correlation. The time series were plotted using R version 4.1.2. The Pearson linear correlation is applied to estimate the relationship between RE use and other factors, including global mean surface temperature, CO_2 emissions, and GDP during the past decades. The Granger causality test is also used to determine causality between each variable.

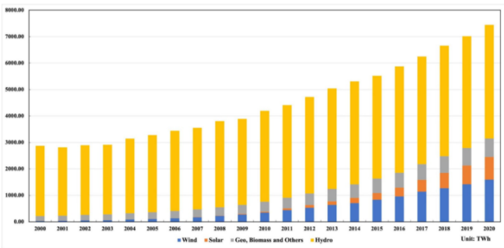

Figure 1: Contributions of wind, solar, hydro, geo, biomass, waste, wave and tidal.

2.3 Reducing Bias

The variables that we analyze are reputable social, ecological, and economic welfare indicators over the past two decades. We chose total global RE generation (terawatt hours) each year to gain a holistic insight into the prevalence of RE by factoring out outliers from particular countries. We did not choose to analyze the efficiency or price of RE because these indicators are more susceptible to measurement errors given the diverse nature of RE. Figure 1 shows the contribution of each major RE source to the total RE (in terawatt-hours) from 2000-2020 used in our calculations. Average global real GDP per capita (in constant 2017 international dollars) is the standard we chose to gauge worldwide economic activity. Real GDP accounts for current-year domestic output at current prices, thus neglecting inflation (whose increase does not signal real economic growth). Due to extreme economic disparities, the total real GDP is divided by the total global population to adjust for outliers. Environmentally, CO_2 emissions account for the highest concentration of greenhouse gas released into the atmosphere [6], hence providing a reliable quantitative measure of greenhouse gas emissions from human activities (notably due to the burning of fossil fuels). We gathered data of mean global temperature (in degrees Celsius) worldwide plotted by dividing longitude and latitude for our surface temperature and CO_2 emissions correlation map, ensuring reliable data over a large sample of regions. Throughout the paper, the average real global GDP per capita will be referred to as GDP, and total global RE generation annually may be abbreviated as RE.

3 Results

3.1 Time Series for CO_2, GDP, and RE respectively

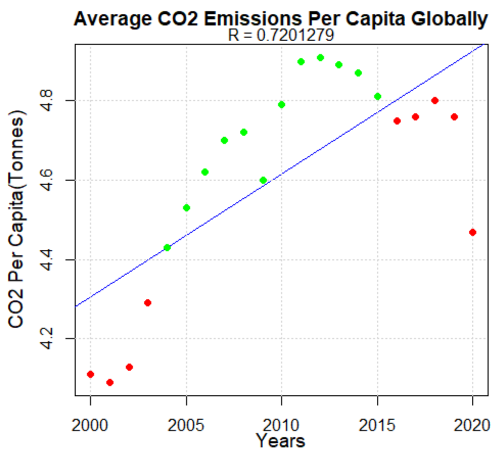

Figure 2: Average CO_2 emissions per capita globally in tonnes from 2000-2020 [7]. (Where red points represent the points below the expected values, and green points represent the points above the expected values)

The most significant deviations from the regression lines are in the years 2000-2003 and 2020. In the years 2000-2003, the deviation from the expected values was due to the exponential growth of CO_2 emissions largely attributed to the sudden rising demand for energy. In 2020, amid the COVID-19 outbreak, there was a decrease in the use of transportation and a decrease in economic activity, thereby decreasing CO_2 emissions [8].

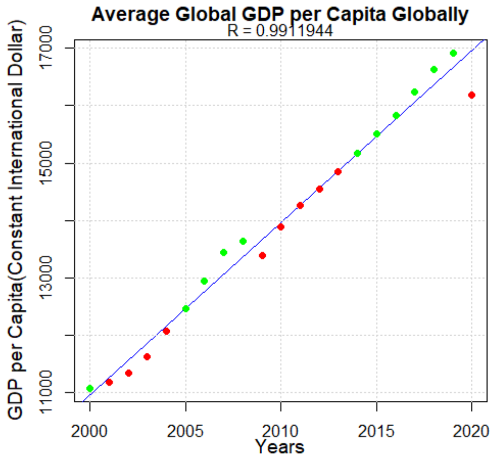

Figure 3: Average global GDP per capita from 2000-2020 [9].

The largest deviation in GDP per capita globally seems to be in 2020, which could mostly be explained by the decrease in economic activity due to the COVID-19 Pandemic.

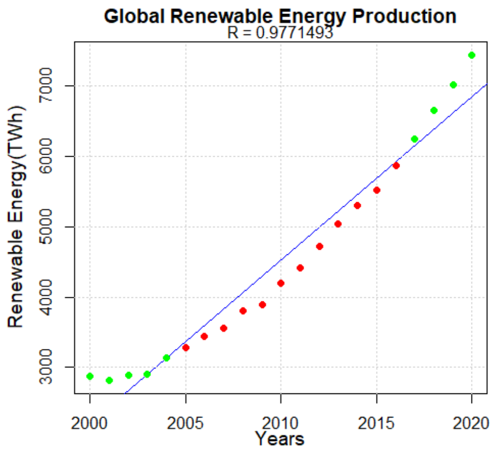

Figure 4: Global RE production in terawatt-hours from 2000-2020 [10].

There are no significant outliers in the data. However, despite the strong fit of the regression line, the data points seem to fit a growth curve whose increasing slope suggests that RE production worldwide has experienced accelerated growth over the past two decades.

3.2 Pearson Correlation

A correlation graph of RE, GDP, surface temperature, and CO_2 emissions suggests that these variables show a strong correlation and an upward trend. The data is normalized so that the standard deviations of each variable are compared for differences. Evidently, GDP and total RE are almost perfectly linear and correlated. Surface temperature and CO_2 emissions show

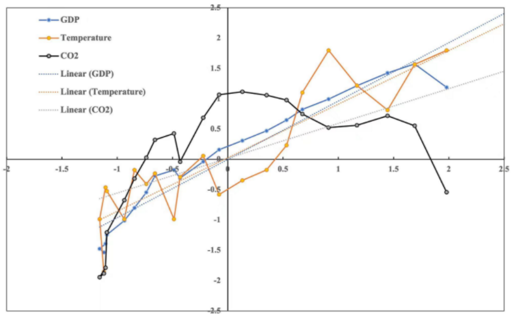

Figure 5: Standard deviations of CO_2 emissions per capita globally, average global GDP per capita, surface temperature (y-axis) with respect to standard deviation of global RE production (x-axis).

more substantial fluctuations but seem to also adhere to the general upward trend. Figure 5 depicts the standard deviation of RE (x-axis) with respect to CO_2 emissions, GDP, and temperature (y-axis). The data is normalized so that the variability of CO_2 emissions, GDP, and temperature can be compared to the variability of RE under a standard unit (the Z-score value). The least-squares regression lines are plotted for each variable. The sum of GDP residuals is significantly lower than that of CO_2 emissions and temperature. Therefore, the variability between RE and GDP is very similar, with few outliers whose presence could be attributed to external factors unrelated to RE that year.

3.3 Granger Causality Test

Using the Granger Significance test, we found no significant evidence that the explanatory variable (RE production) can predict the response variable (GDP per capita globally), where the p-value is 0.0849 is above the alpha level we chose of 0.05. Inversely, the GDP per capita globally cannot predict RE production, where the p-value is 0.256. However, we did find significant evidence that RE production can forecast CO_2 emissions per capita, where the p-value is 0.02372. The CO_2 emissions per capita cannot predict RE production, as we obtained a p-value of 0.1362. We found that RE production can forecast the global mean temperature, with a p-value of 0.0040238. Inversely, global mean temperature cannot predict RE production, as the test yielded a p-value of 0.091372.

3.4 Variable Anomalies

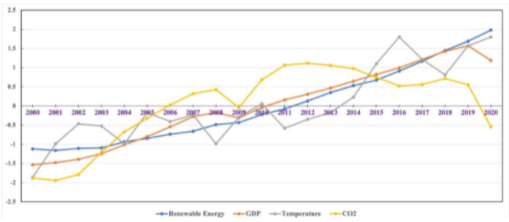

Figure 6: Graph of standard deviations of CO_2 emissions per capita globally, average global GDP per capita, surface temperature (y-axis) each year (x-axis).

There seems to be an "equilibrium relationship between green energy use, carbon emissions, and economic growth" [11]. Such a relationship can be shown in Figure 5. For example, economic growth, carbon emissions, temperature, and RE production all share a common upward trend. Also, the relationship between carbon emissions and green energy production shows that whenever the residual of one variable is negative, the residual of the other tends to be positive. In the years 2005 to 2015, the residuals for CO_2 emissions per capita globally were positive, shown by the green colour of the points, meanwhile, the residuals for RE generation globally were negative, shown by the red colour of the points. Both trends seem to occur at similar times, where the residuals for RE were negative from 2005 to 2016, while the residuals for CO_2 emissions were positive from 2004 to 2015.

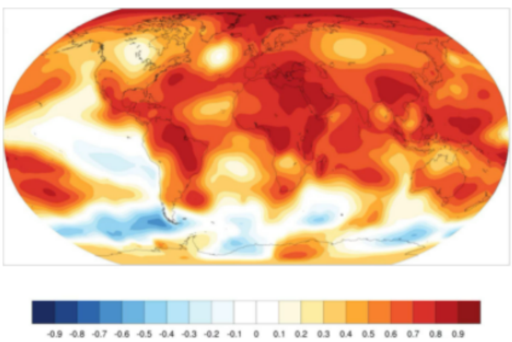

Figure 7: Correlation Map between Surface Temp. and CO_2 Emissions globally

4 Discussion

4.1 Connection Between RE, GDP and CO_2 Emissions

Rapid advancements in technology through the 21st century have significantly boosted economic growth through improved education, labour productivity, and ease of trade. Concurrently, the increasing worldwide population and CO_2 emissions of greenhouse gases have stimulated the growth of the RE sector [12]. Therefore, RE, GDP, and CO_2 have been overall trending upwards for the past two decades. However, Figure 5 depicts that GDP and CO_2 have experienced significant deviations from the steadily increasing trend since 2019. GDP has decreased to its 2017 levels while CO_2 emissions have fallen to 2010 levels. These outliers are primarily due to the effects of the COVID-19 Pandemic [13]. The Pandemic has disrupted trade, caused workplace absenteeism, and undermined job security worldwide [14]. Overall the economic implications of the Pandemic have been detrimental, which could explain why GDP has decreased since 2019 in Figure 3. CO_2 emissions have also declined sharply as manufactured products from fossil fuel combustion and cement production, accounting for roughly 29% of the global CO_2 emissions, has reduced significantly due to COVID-19 [15]. Evidently, the Pandemic has underscored the volatility of the fossil fuel industry. However, despite the economic downturn and weakening fossil fuels industry, RE production has demonstrated its resiliency by continuing its steady upward trend in production (shown in Figure 4). Extrapolating from these findings, perhaps RE could continue to display reliability as it integrates into society as an indispensable source of energy for the future.

4.2 Social Implications of Hydroelectricity

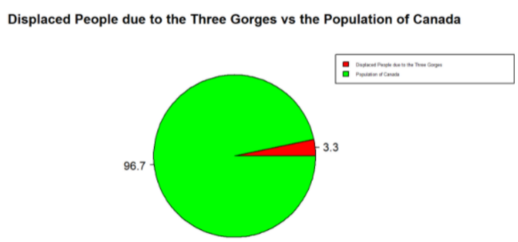

Figure 8: Pie chart showing the percentage of people displaced by flooding from the Three Gorges to the total population of Canada [16].

From Figure 1, it can be seen that hydroelectricity is by far the most used form of RE today, making up around 16% of the total global energy consumption [17]. However, the prevalence of hydroelectric dams has yielded negative social externalities. For example, the Three Gorges Dam in China, although is an indispensable energy source generating 88.2 billion kWh annually

[18], has become a major social concern. Along with the flooding of 13 cities, 140 towns, and 1350 villages, totaling 1.3 million residents being displaced [16]. Farmers and fishermen who lived near the Yangtze River (where the dam is located) were moved to cities, where they were structurally unemployed. As shown in Figure 8, the number of people displaced by the flooding of the Three Gorges Dam is equivalent to 3.3% of the entire population of Canada in 2021. Other hydroelectric dams worldwide also face similar problems. Therefore, the social implications of RE should be thoroughly considered before increasing generation capacity.

4.3 Socially Responsible RE Production

The Granger causality test proves that increased RE production could potentially be used to forecast rising temperatures, albeit the effect may be weak due to other confounding variables (such as greenhouse gas emissions, melting ice caps, etc.). Regardless, this result could potentially impose significant implications on how RE can be used in the future as a sustainable source of energy. Statistically, a p-value of 0.02372 supports that the RE generation trend could forecast CO_2 emission trends. In addition, the operation and creation of hydroelectricity present many environmental issues, one being the rise in temperature. Hydropower may seem sustainable when looking at its carbon footprint. However, water storage and hydroelectricity production emit millions of tons of methane, which has 86 times more warming power than CO_2. According to the *Environmental Defense Fund*, there are over 100 hydroelectric facilities in the world whose greenhouse gas emissions cause more significant warming than fossil fuel plants [19]. As a result, diversification in RE is crucial in ensuring its sustainability. Another form of RE that further adds to the global warming issue is biomass energy. Biomass energy is collected through the burning or decomposition of organic matter. Although biomass energy is renewable, it is not necessarily a sustainable energy source. According to *The Partnership for Policy Integrity*, biomass energy production emits 150% more CO_2 than coal energy production and 300 - 400% more than natural gas production [20]. Furthermore, biomass energy is usually a byproduct of mass deforestation; therefore, the energy itself is indirectly non-renewable as its collection methods pose significant threats to the environment. Consequently, it can be seen that biomass energy production leaves a large carbon footprint and contributes to global warming as it emits significantly more CO_2 than many larger non-renewable energies. The positive correlation and significant casualty results between RE and temperature could imply potential issues with current RE generation (predominantly hydroelectric facilities). However, it is unlikely that the strong, positive correlation between RE production and CO_2 emissions is entirely a cause-and-effect relationship. On the contrary, the shape of the RE generation data points has displayed accelerated growth whose slope is increasing as time increases while the CO_2 emissions trend generally has a decreasing slope. It is very likely that the increased diversification of RE production in recent years (shown in Figure 1) has led to this result. Therefore, socially responsible production of RE should involve a variety of RE sources (such as solar, wind, etc.) so negative externalities can be mitigated.

Linear Correlation	GDP		Temperature		CO2	
	Coefficient	R-square	Coefficient	R-square	Coefficient	R-square
Total Renewable Energy	0.96	0.93	0.89	0.78	0.53	0.33
Wind	0.93	0.87	0.9	0.79	0.44	0.23
Solar	0.83	0.67	0.87	0.70	0.23	0.08
Hydro	0.99	0.98	0.83	0.71	0.7	0.54
Geo, Biomass and Others	0.98	0.96	0.88	0.79	0.59	0.40

Table 2: Correlation Coefficients for each variable

4.4 Pearson Regression Analysis

Numerically, the linear correlation table shows that total RE production and GDP per capita share an R-squared value of 0.93. The linearity (stability) of GDP per capita is partially attributed to the large sample size as the real GDP per capita is average across the globe so singular outliers would not have significant impacts on the mean. Namely, the GDP per capita in 2008 had a Z-score of -0.5 despite the Great Recession in the U.S. (the world's leading power) that year. On the other hand, total RE and surface temperature share a relatively weaker correlation, although they still appear to be strongly correlated with an R-squared value of 0.78. This relationship aligns with a previous study, *The Economics of Renewable Energy*, stating that "if the worst impacts of rising temperatures and climate alteration are to be avoided, society needs to switch to renewable energy sources" [21]. Thus, they imply that rising temperature is closely correlated with insufficient RE usage, lining up with our results. We hypothesized that CO_2 emissions and RE would yield a negative correlation such that increased RE is accompanied by decreased CO_2 emissions as RE would replace the carbon-emitting fossil fuels. However, our results suggest a weak correlation between these two variables, where the R-squared value is 0.33. This result can imply that RE in the short-run (20 years) is not a perfect substitute for fossil fuels, or there may be other confounding variables (not analyzed by this paper) affecting CO_2 emissions, thus contributing to the weak correlation. We speculate that the increase in RE simply satisfies the continuously increasing demand for energy sources rather than substitutes for existing non-RE sources such as fossil fuels.

4.5 Potential Sources of Error

Given the limited scope of our research, there would inevitably be other variables not taken into account that may contribute to confounding errors. For example, the world's ecosystem and economy contain countless more intertwining variables than those explored in this paper. Therefore, relationships discovered through this paper are not solely dependent on the variables in the study, but may also be affected by other confounding variables. We encourage further experimental studies to validate and expand upon our results.

4.6 Summary and Conclusion

The implications of increased future RE production are clouded with uncertainty. This paper investigates how RE production impacts society economically and socially. Variable anomalies, using normalized data for each indicator, suggest that increased RE production correlates positively with GDP, CO_2 emissions, and temperature. Upon performing the Granger causality test on the time series for each variable, we obtained significant p-values(below 0.05) for RE generation's ability to forecast only CO_2 emissions and temperature, but not for GDP. Evidently, these findings suggest that there are limited global economic implications for RE generation(according to variations in GDP). Interestingly, RE generation's impact on CO_2 emissions is ambivalent. The increasing generation of RE is correlated with the simultaneously increasing CO_2 emissions. However, it could also be interpreted that the decline of CO_2 emissions in recent years (or, during some years, its decelerating upward trend) could be attributed to marginally increasing RE generation (increasing at an increasing rate). We hypothesize that other confounding factors, such as the combustion of hydrocarbon fuels, cause CO_2 emissions to increase while increased RE production slows the upward trend, although we lack empirical evidence to make this conclusion. However, we can safely conclude that dependence upon undiversified RE production yields detrimental negative social externalities. For example, the prevalent use of hydropower has led to the loss of many lives and displaced many others due to flooding (which is also due to rising temperatures). In conclusion, the RE generation's economic, environmental, and social implications explored in this paper should be considered as the era of rapid RE generation is on the horizon. In addition, future research is required to understand the relationship between RE generation and CO_2 emissions (to resolve our ambivalent results), and the magnitude of RE generation's effect on CO_2 and temperature should be further investigated.

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