Retrospective Analysis of Global Carbon dioxide Emissions and Energy Consumption

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Abstract. The international climate emergency has triggered actions for understanding and controlling the Green House Gases(GHGs) all over the world to achieve the net zero 'dream'. It is important to understand the global trend in the GHG emissions, particularly focusing on Carbon dioxide. This paper investigates the trends in carbon dioxide emissions between 1965 and 2019. A retrospective look at this data will help us understand the major global trends and help designing better strategies to work towards the zero carbon target. This data analysis will look at breakdown of carbon emissions by geographical regions, which could provide a greater insight into the regions experiencing a rise in carbon emissions. The relationship between energy consumption and carbon emissions are also tested. The work also aims to provide a forecast of future energy consumption based on the learning from this analysis.

Keywords: Data Analysis, Carbon Emissions, Energy Consumption, Renewable Energy, Statistics

1 Introduction

The Green House Gases (GHGs), mainly carbon dioxide, (CO_2) traps heat in the atmosphere which is a natural phenomena to keep the Earth warm and maintain the balance of life. CO_2 is very abundant and stays longer in the atmosphere compared to the other GHGs like methane or nitrous oxide. Recently, this balance of temperature and life on Earth has been tampered with by the unprecedented increase in the amount of CO_2 emissions in the atmosphere. According to the National Oceanic and Atmospheric Administration (NOAA),the levels of atmospheric CO_2 is at its highest point in 3 million years. The temperature at that point in time was $2°–3°C(3.6°–5.4°F)$ higher and sea levels 15-25 meters higher than today. CO_2 has been increasing at a rate of 100 times faster in the past 60 years compared to normal increase in the 11,000-17,000 years. This increase has resulted in trapping additional heat in Earth's atmosphere and slowly increasing the global temperature.

Carbon dioxide is a colourless and odourless naturally occurring gas in the earth's atmosphere which is made up of one carbon atom and two oxygen atoms [1]. The negative connotations of carbon dioxide often lead to the misconception of it being harmful. However, a natural amount of CO_2 plays a crucial part in maintaining our ecosystem. It only causes damage to the environment when there is an excess of CO_2, usually generated by man-made activities such as fossil fuel use [13]. Excess CO_2 can be a problem because it acts like a "greenhouse gas". Due to its molecular structure, CO_2 absorbs and emits infrared radiation, warming the Earth's surface and the lower levels of the atmosphere [3]. Scientists and experts believe that carbon emissions need to be reduced or there may be irreversible harm to the global ecosystem, it is therefore necessary to measure emissions of carbon dioxide so that progress (or lack of progress) can be identified and the necessary changes can be implemented.

The main contribution of atmospheric CO_2 is from burning fossil fuels. The energy industry has been keen to look at this information. BP plc was one of the first companies to gather this data in terms of global energy consumption and release of CO_2 [7]. The data since 1965 is available for analysis. This data analysis aims to explore carbon dioxide emissions data from this dataset. This paper will first look at some related literature followed by analysis and some insights from this analysis.

2 Literature Review

A group of scientists in the 19^{th} century discovered that atmospheric gases produce a "greenhouse effect", a natural process in which the accumulation of gases in the atmosphere absorb energy and contributes to a rise in temperature of the earth. However, this was even seen as beneficial, as per the Swedish scientist, Svante Arrhenius whose perspective was that it could lead to higher agricultural yield in colder climates. The concept of climate change was largely dismissed until the 20^{th} century, at which point several studies of climate change began to emerge. The study of carbon isotopes by Hans Suess [10] revealed that carbon dioxide was not absorbed by the ocean immediately. Another significant study was conducted by the Stanford research institute in 1968. It was predicted that: "If the Earth's temperature increases significantly, a number of events might be expected to occur, including the melting of the Antarctic ice cap, a rise in sea levels and a warming of the oceans" [8].

Carbon dioxide emissions have increased for several reasons; however, it is widely regarded that human activities, including the production and consumption of oil, natural gas and coal are the main cause of rising carbon emissions. These activities are linked to economic growth and industrialisation in emerging economies. However it has been discovered that higher income levels increases the demand for policies which promote environmental protection, reducing emissions in developed countries [11]. Another paper which investigates the relationship between carbon emissions, energy consumption and economic growth in China [15], concludes that the government of China is able to implement policies aimed at reducing carbon emissions without compromising economic growth. Although this paper finds that China is one of the world's major emitters of carbon dioxide, contradicting its findings. Developed countries face different challenges to the rest of the world, for example, countries such as the UK have experienced structural change in their economy. A shift towards the service sector means that the manufacturing and agricultural sector have declined, meaning a larger proportion of goods consumed by UK households are produced abroad. This increases transport related carbon emissions [2].

The lack of technology meant that more quantitative research and analysis was not undertaken until recently. There are now several publications looking at several different aspects of carbon emissions. Bulent Tumez [12] looked at Trends in energy emissions. The work uses Trend Analysis to predict future emissions, however, it concludes that carbon emissions have several influencing factors which should be considered alongside the projections provided in the paper. The effects of the COVID-19 Pandemic demonstrates this. Recent studies by Liu et.al. [4] reveals the effect of Covid19 pandemic situation on global CO_2 emissions. The research finds that there was an 8.8% drop in carbon dioxide emissions in the first half of 2020 compared to the same period in 2019. This outlines the difficulty in accurately predicting future carbon emissions. Chi Xu [14], investigates the distribution of human populations and its environmental niche. The study states that global warming will change human health, food and water supply and economic growth. A strength of this analysis is that it was funded by reputable bodies such as the European research council and uses various graphical techniques to visualise their findings. However, it is not clear if the paper offers an balanced view of the facts. The projection for MAT's (Mean Annual Temperatures) for 2070 has been referred to as a 'worst case scenario' by many scientists. Mark Maslin, an earth science professor at UCL, claims that the study does not consider the dynamic and adaptable nature of human technology and society [5]. Nevertheless, the paper provides several valid arguments and exemplifies the need to study carbon emissions and its effects in greater detail.

The effect of carbon emissions on global warming is one of the recurring themes of carbon emissions analysis that can be found online, and research has been conducted by major organisations and government institutions. NASA has created a "Global Climate Change Website" [6] which provides interactive visualisations, appealing to those from a non-science backgrounds, for visitors to view. The presence of freely available and comprehensible information has piqued the interest of the public. A survey conducted by the UK Government Department for Business, Energy and Industrial Strategy found that 76% of respondents were somewhat concerned about global warming [9]. It is therefore worthwhile, to investigate the relationship between carbon dioxide emissions and global warming in greater detail. This paper will also explore, using time series analysis, the reasons behind changes in carbon emissions and will conclude with 'attempting' to forecast when renewable energy will account for all of the world's energy consumption, something that is seen as a crucial objective yet is lacking from previous research and analysis on this topic.

The data for carbon emissions from the burning of fossil fuels have been published by BP Plc [7]. The company has also analysed this dataset and publishes an annual report which provides insights into world energy production and consumption. Its main focus is analysis of the world energy market from the previous year. The 2020 edition analyses world energy data and trends prior to the COVID-19 pandemic covering areas such as the oil, natural gas and coal markets. Renewable energy is also becoming a prominent feature in recent annual reports as it continues its rapid growth. Despite being a highly detailed report, carbon emissions form only a very small fraction of the total analysis and therefore it can't be considered a very comprehensive analysis of carbon emissions data. This proposed research will analyze the details in the same dataset. The dataset seems quiet exhaustive. The main findings in the report does refer to China being the "biggest driver of energy" and "accounting for more than three quarters of net global growth" [7]. This research will validate these claims on the BP dataset and at the same time look at new insights to be gained from the dataset. To the best of our knowledge, there has not been any other analysis of the carbon dioxide and energy consumption section of the dataset making this paper the most comprehensive analysis of BP's carbon dioxide and energy consumption data.

3 Data Analysis

3.1 Carbon Emissions Introductory Analysis

This Data Analysis was performed using python and various libraries. We will begin by investigating the overall trend of carbon emissions between 1965 and 2019. Below is a time series graph demonstrating this:

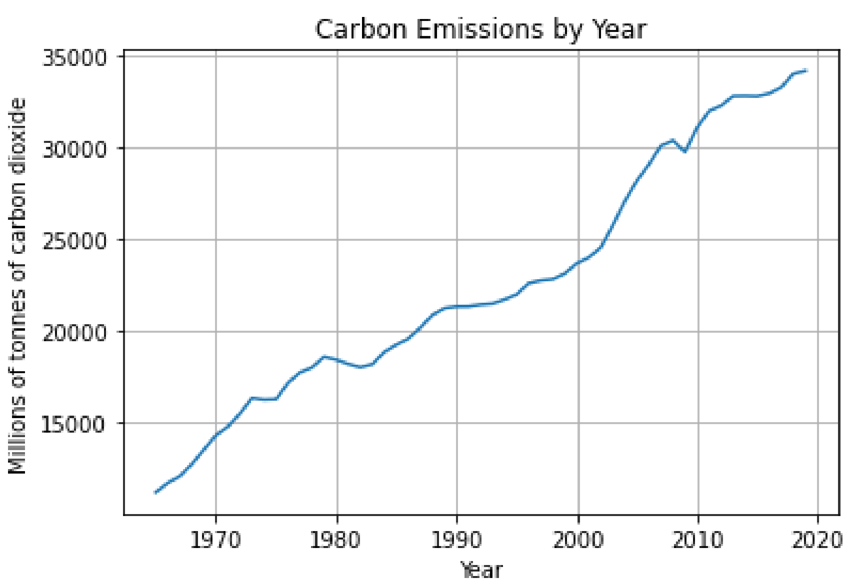

Fig. 1. Carbon Emissions 1965-2019

We can draw the following key findings from Figure 1

- There is a clear upwards trend with some minor fluctuations
- The largest increase happened between 2009 and 2010, however, the largest decrease happened the year before in 2008 - the year of the global recession. Carbon emissions could have reduced due to lower energy consumption as a result of higher prices for oil and gas. This suggests that the main reason for the sharp increase in carbon emissions the following year were due to the world recovering from the event.
- Carbon emissions reached their highest ever point in 2019, with a value of 34169 million tonnes of carbon

To gain a better understanding of this time series data, a rate of change graph can be plotted to find outliers, which in this case are specific years with higher than usual growth. In a statistical sense, an appropriate definition is: "a point which is 2 standard deviations away from the mean." Standard deviation is a measure of variance, which in simple terms is the extent to which individual data points are spread out from the mean. In a normal distribution, around 68% of the data lies within one standard deviation of the mean and approximately 95% of the data is within 2 standard deviations. Therefore by defining an outlier as being two standard deviations away from the mean, it is very likely to be an outlier. Figure 2 confirms the earlier point on the exceptional rate of change in 2009.

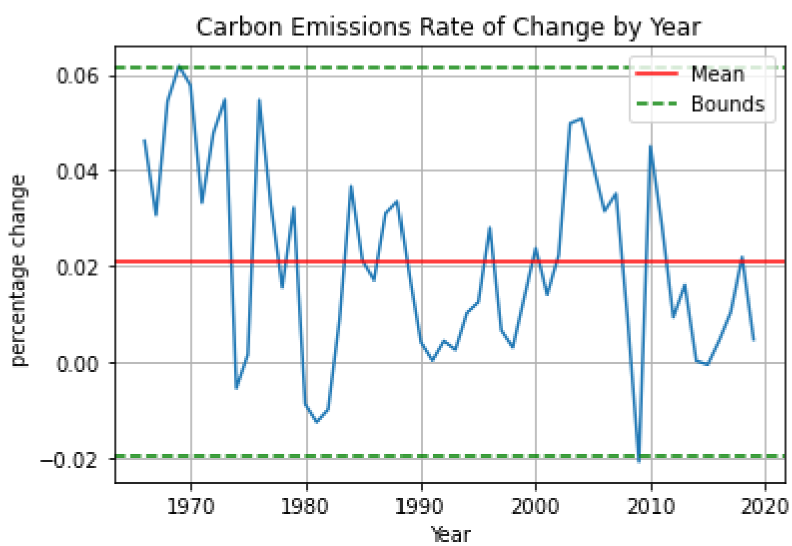

Fig. 2. Carbon Emissions Rate of Change 1965-2019

3.2 Carbon Emissions Breakdown by region

A breakdown of carbon emissions by region will provide a greater insight into what geographical regions are experiencing a rise in carbon emissions. For this breakdown, countries are placed into 7 different regions based on their geographical location. The regions are listed as follows: "North America, South and Central America, Europe, CIS, Middle East, Africa and Asia Pacific.

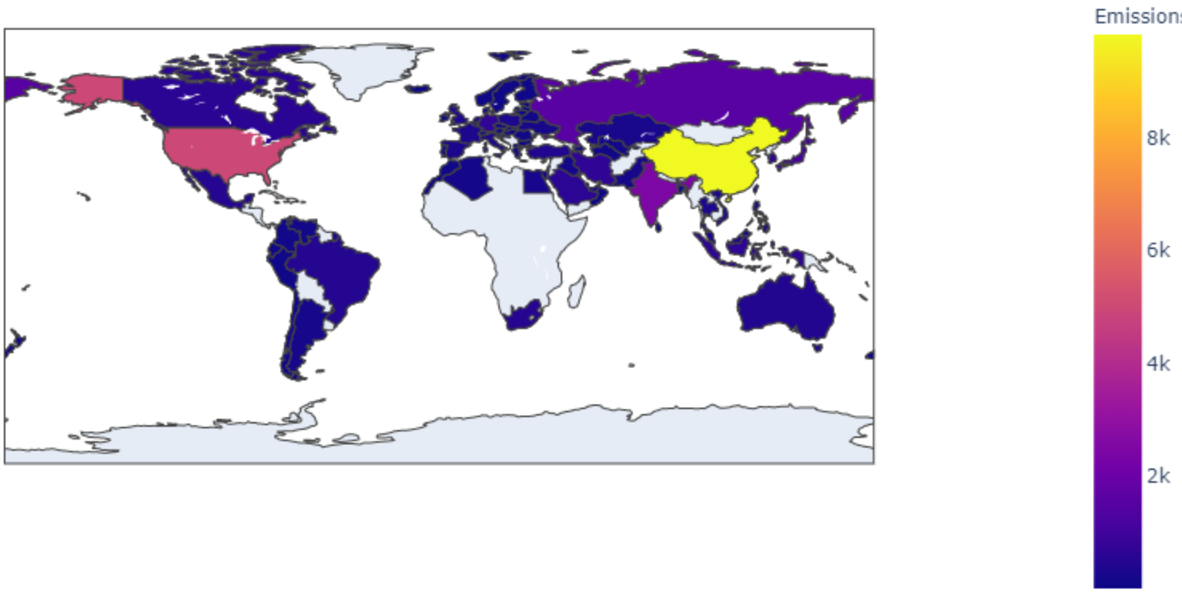

Fig. 3. Choropleth Map of Carbon Emissions

Figure 3 is a choropleth map which are used to represent data through shading patterns on geographical areas. In this case it shows the variability of carbon emissions across the world, the legend on the right hand side translates the various shading patterns to numerical data. This type of visualisation does well to illustrate how carbon emissions vary around the world and is easy to understand for the reader. A disadvantage of this is that it is difficult to identify exact values

Figure 4 is a nested pie chart, it does well to summarise a dataset in visual form and is more detailed than a traditional pie chart as it has more than one 'level'. For example, we can see that Asia Pacific is the biggest contributor of carbon emissions and China is the biggest contributor in Asia Pacific. The reader can make an immediate analysis at a glance. However, like the previous visualisation it is difficult to get an exact value.

Figure 5 is an ECDF plot (Empirical Cumulative Distribution Function). It allows the plotting of data from the lowest value to the greatest value and visualise the distribution of the dataset. It also shows the percentage of data

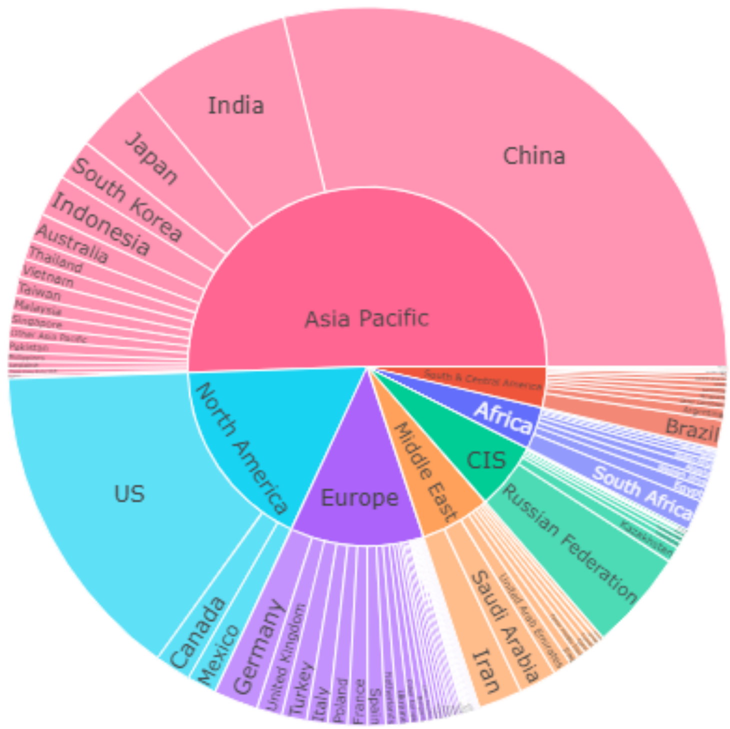

Fig. 4. Nested Pie Chart of Carbon Emissions

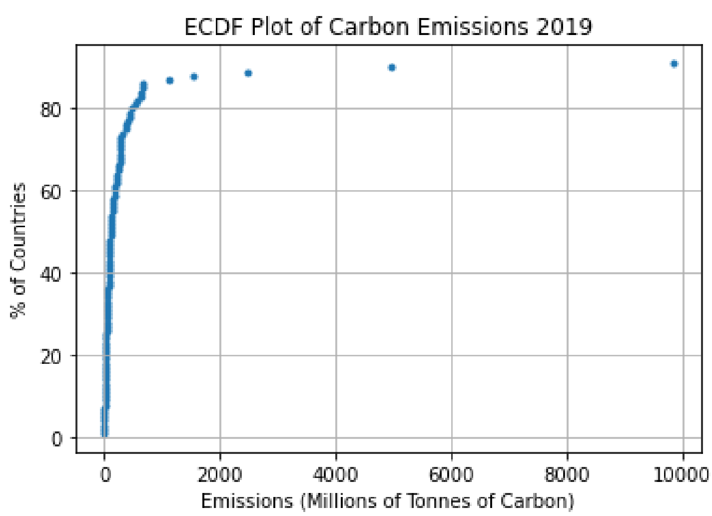

Fig. 5. ECDF Plot of Carbon Emissions of Carbon Emissions

that has a particular x value. For example, Figure 5 shows that almost 90% of countries had carbon emissions below 1000 million tonnes of carbon in 2019 with a handful of countries exceeding that threshold.

Figure 6 is a time series graph of carbon emissions between 1965 and 2019 showing growth by region. it is clear that Asia Pacific's emissions are rising whereas the other regions have levelled off. Another interesting observation is that in 1965 they were among the lowest emitters of carbon dioxide.

We can deduct the following key findings from these visualisations:

– Asia Pacific is responsible for approximately half of the world's carbon emissions- a significant part of this is China.
– The US accounts for more than 70% of North America's carbon emissions.
– South and Central America is the region with the lowest carbon emissions.
– Around 90% of countries had individual carbon emissions below 1000 million tonnes of carbon in 2019. Perhaps if the other 10% took action to reduce their carbon emissions, it could help to bring worldwide emissions down.
– Asia Pacific's emissions are rising whereas other regions have stabilised, this implies that the Asia Pacific region is the main driving force for the increase in global carbon emissions.
– African data may not be valid as there are several countries not included in the data (choropleth map has several blank spaces on the African region).

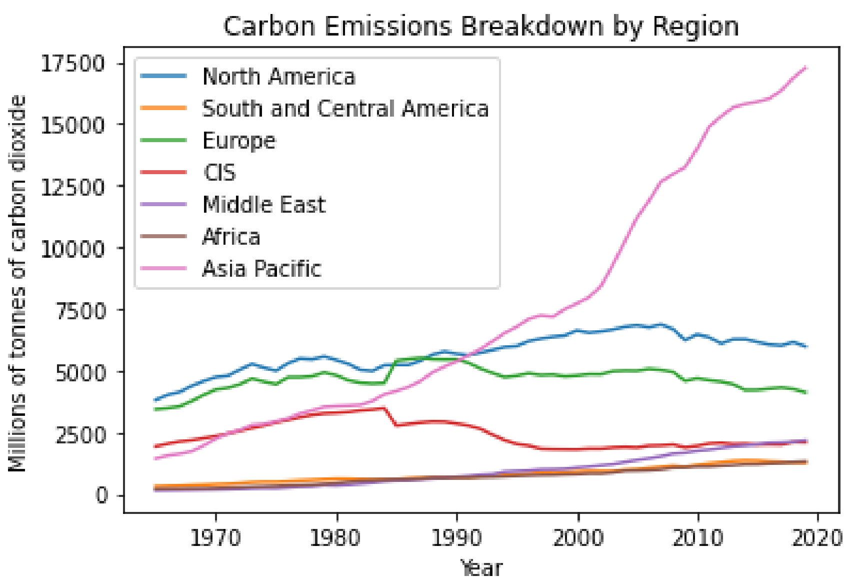

Fig. 6. Carbon Emissions Breakdown by Region 1965-2019

3.3 Energy Consumption

It is widely considered that energy consumption and carbon dioxide emissions are related, to test this relationship, Pearson's correlation coefficient can be used. This measures the statistical relationship between two continuous variables, it gives information about the magnitude of the association, or correlation, as well as the direction of the relationship.

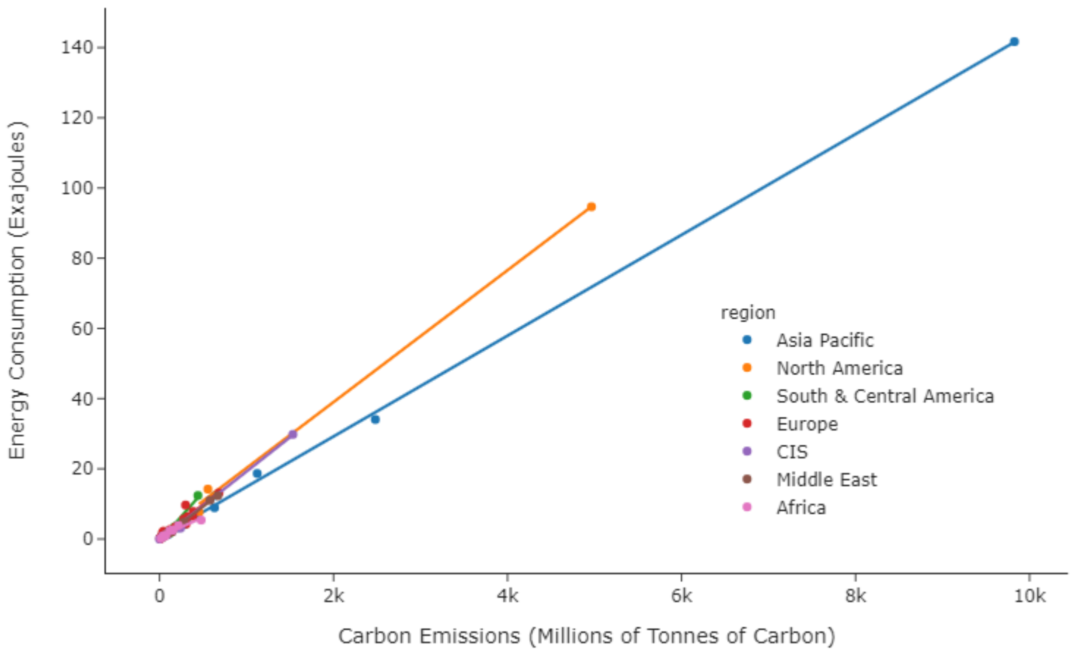

Fig. 7. Relationship Between Energy Consumption and Carbon Emissions by Region

Plotting energy consumption and carbon emissions results in a clear linear relationship consistent with all geographical regions (as shown in Figure 7). Using Pearson's correlation coefficient to test the magnitude of the relationship results in a coefficient of 0.99, where 1 is an exact linear relationship and 0 is no relationship, implying a very strong association.

More specifically, it is the consumption of fossil fuels such as oil, coal and gas that is the main contributor to carbon emissions. By plotting the consumption of each of these fossil fuels against carbon and calculating the correlation coefficient for each relationship, we can determine which fossil fuel has the closest relationship with carbon (Figure 8). it seems that coal and oil seem to have the closest correlation to carbon consumption, to verify this, Pearson's correlation coefficient has been used. Coal and oil have a close to perfect positive correlation with carbon (correlation coefficients are 0.95 and 0.94 respectively), with gas having a slightly lower but still strong relationship with carbon (correlation coefficient of 0.76). Some fossil fuel plots have more outliers than others. This study uses only what was provided in the BP dataset and did not look for other factors contributing to emissions which might give a better understanding of these correlations. The distribution of usage of different types of fossil fuels varies for each country or region which could explain the high variance.

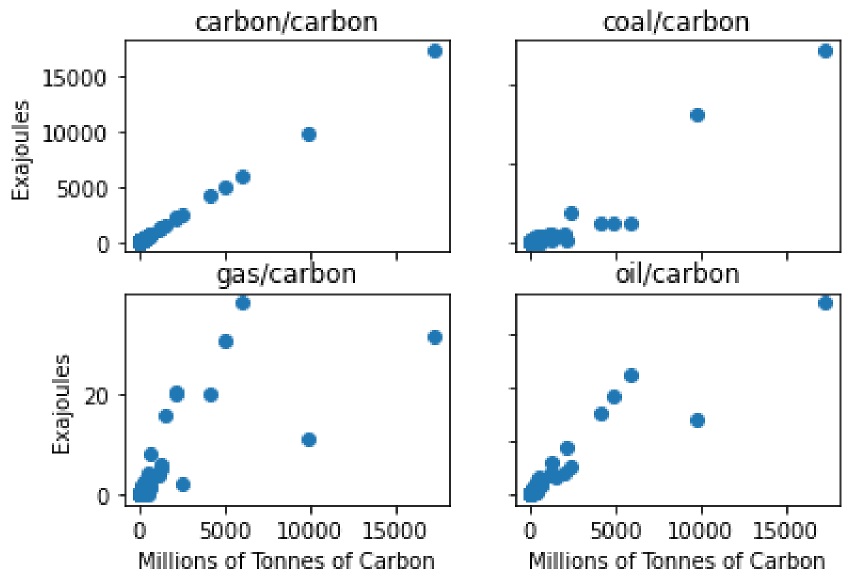

Fig. 8. Correlation between Oil, Coal Gas and Carbon Dioxide Emissions

3.4 Renewable Energy Consumption

Whilst this paper is mostly focused on analysing carbon emissions and the reason why they might be increasing. it is also worthwhile to explore renewables consumption data as many scientists believe that by switching to renewable energy, carbon emissions can be brought down. As a result, analysis of renewables consumption is relevant.

Figure 9 is a simple time series graph of renewables consumption between 1965 and 2019. We can see that there was slow growth between 1965 and 2000 and then a steep rise until 2019. By breaking down figure9 and show renewables consumption by region (figure 10), we can see that the Asia Pacific region is experiencing the greatest growth. This is interesting as it is also responsible for the steepest rise in carbon emissions. Europe and North America are following closely behind.

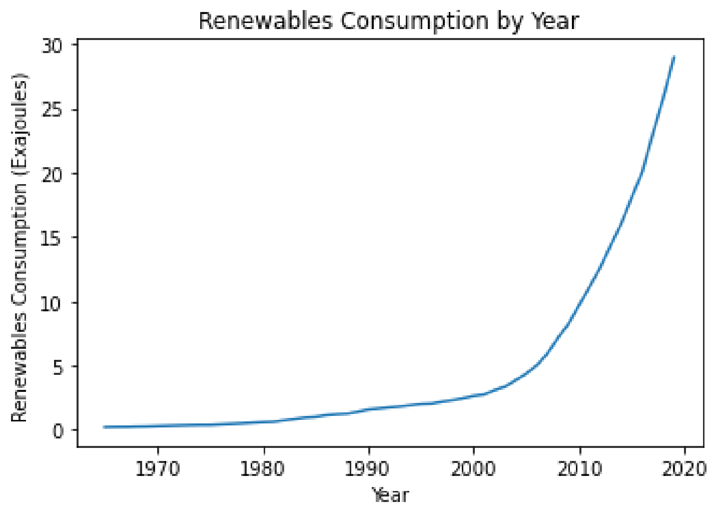

Fig. 9. Renewable Energy Consumption 1965 - 2019

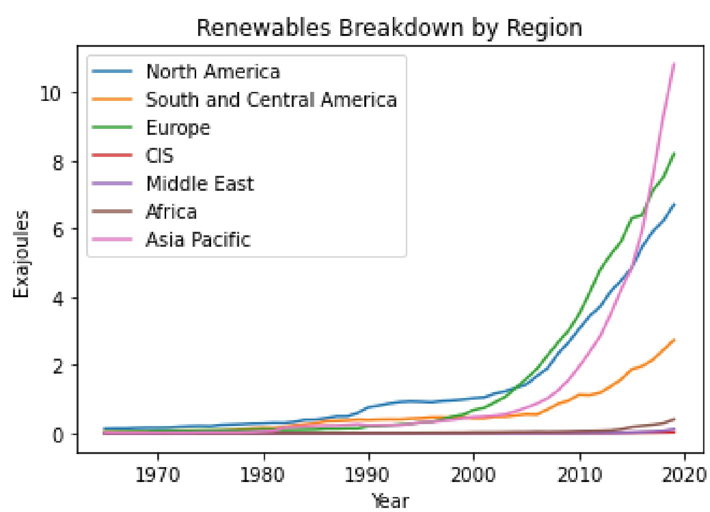

Fig. 10. Renewable Energy Breakdown by Region

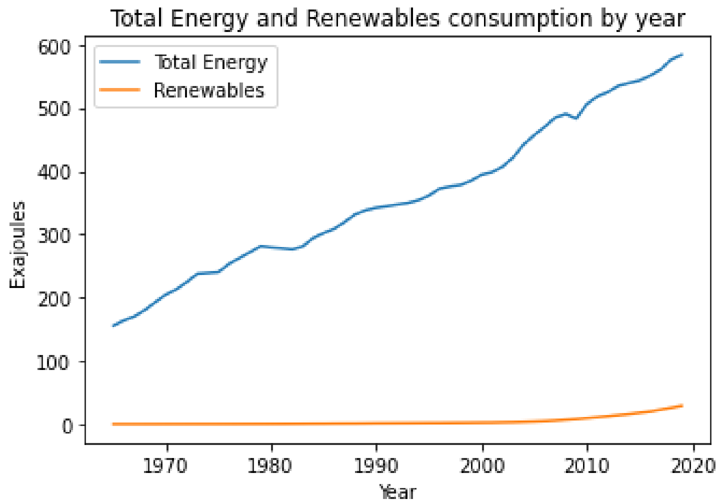

Fig. 11. Total Energy and Renewable Energy Consumption 1965-2019

Whilst the growth in renewables consumption has been close to exponential in recent years, it is still insignificant compared to total energy consumption. As shown in Figure 11 forecasting total energy consumption and renewable energy consumption can provide an insight into how the current trend will progress into the future. the "prophet" library, an open source library which uses an additive regression model, produced some interesting results. This is shown in Figure 12.

The dark blue line represents the most likely forecast and the light blue shaded area represents the bounds. We can see that growth in total energy consumption is mostly linear, although the shaded area underneath the line is unlikely to be valid as scientists predict that energy consumption is unlikely to reduce as developing and emerging economies industrialise and the world's population increases.

The forecast for renewable energy shows growth even in a worst-case scenario (figure 13), however, the forecast is mostly linear which is unexpected. it also never reaches the level of total energy consumption which is what scientists predict will happen in the next 30 years. This disparity is likely since this forecast is predicting the next 46 years using historical data which only accounts for 55 years. The model also assumes that there will not be a drastic rate of change in renewables consumption, whereas scientists feel that there will be, this leads to the problem of overfitting. Whilst this forecast is likely not valid, it is still interesting to see how the current trend would play out in the future if there is no action by countries to increase investment and consumption in renewable sources of energy

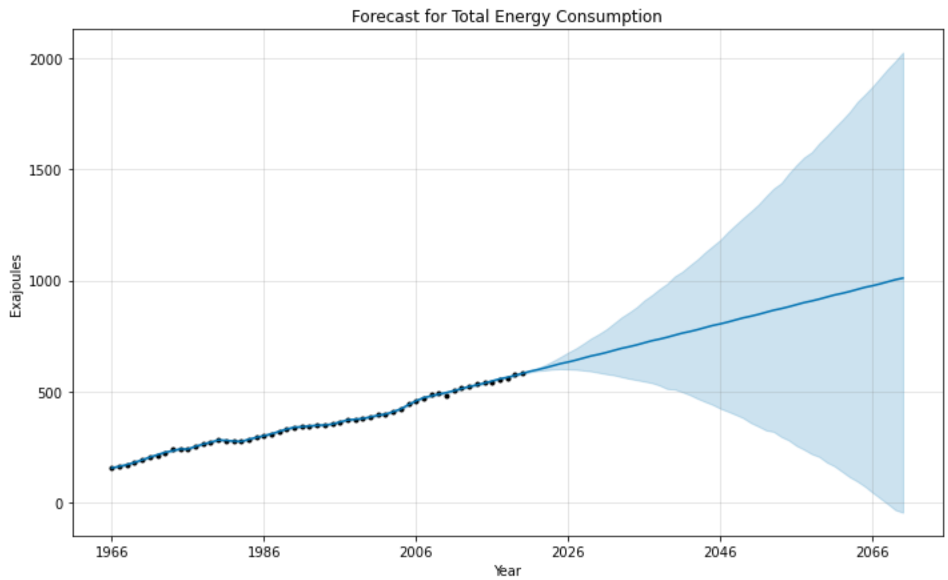

Fig. 12. Forecast for Total Energy Consumption

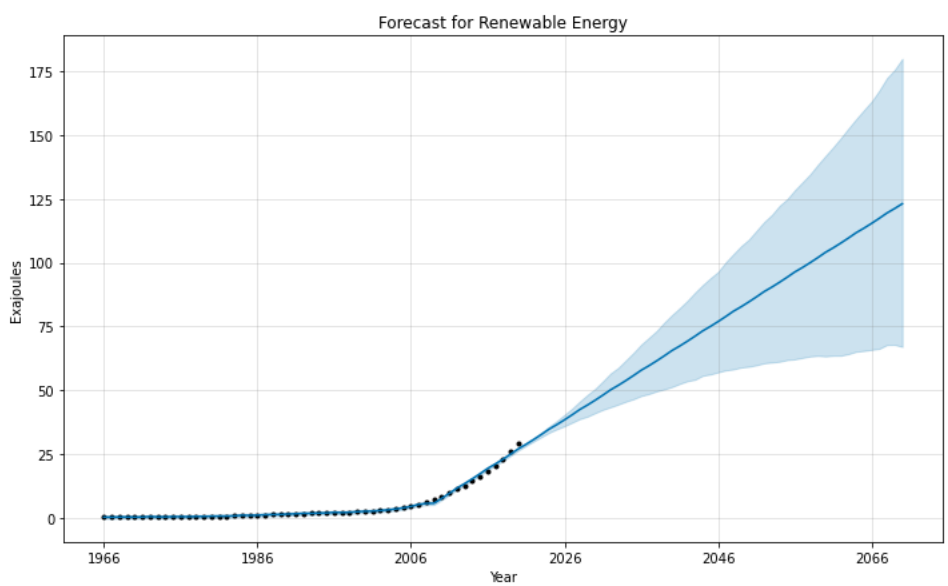

Fig. 13. Forecast for Renewable Energy Consumption

4 Conclusion

Through the analysis of this data, we can conclude the following:

- Carbon emissions have maintained a constant upwards trend since 1965 with an average rate of change of 2% The financial crisis in 2008 led to the largest reduction in carbon emissions between 1965 and 2019, this was quickly followed by a large increase in carbon emissions due to the world recovering from the event. Carbon emissions reached an all time high in 2019, suggesting that the world has not done enough to reduce their carbon footprint
- Asia Pacific account for around half of the worlds carbon emissions, China is a major contributor - having almost as many emissions as North America and Europe combined. Asia Pacific has experienced a sharp rise in carbon emissions whereas every other region has levelled off, implying that Asia Pacific is the main driving force for the rise in the worlds carbon emissions in recent years
- The top 5 carbon dioxide emitting countries (China, US, India, Russia and Japan) are responsible for 58% of the worlds carbon emissions, this suggests that changes in environmental policy in these countries can be effective in reducing global emissions. 90% of countries have emissions below 1000 million tonnes of carbon.
- Energy Consumption has a very strong correlation with carbon emissions, implying that higher energy consumption is one of the main causes of higher carbon emissions. More specifically, coal and oil consumption is very strongly associated with carbon emissions. Using alternative sources of energy can go a long way in reducing energy related carbon emissions
- Renewable energy consumption, which is widely regarded as crucial in reducing carbon emissions, has rapidly increased in the last 15 years. Asia Pacific has experienced more growth than any other region. This suggests that they acknowledged their contribution to carbon emissions and are taking action to reduce it. Despite this rapid growth, renewable energy is still an insignificant proportion of total energy consumption as many countries are still reliant on fossil fuels such as oil, coal and gas. Forecasting the next 46 years with historical data between 1965 and 2019, shows that even in a best-case scenario, renewable energy does not account for total energy consumption in that period, despite many scientists predicting that the world is on track to reach 100% renewable energy by 2050. However, the forecast does not account for external factors such as drastic changes in environmental policy and investment in renewable energy which means that it is not completely valid.
- The coronavirus pandemic has drastically reduced carbon emissions this year due to lower industrial activity and transport use and it is not clear what effect this may have regarding carbon emissions and renewable energy consumption in the future. During previous crises, the growth rate of carbon emissions has recovered, however, this pandemic has reduced Carbon dioxide emissions by more than any other event in history

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