Quantitative analysis of renewable energy system structure based on the weather condition in Cambridge, London, and Oxford

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Abstract. Renewable resources have been a rising star in energy generation and consumption. This paper is going to talk about the data sets of the solar and wind energy in three different cities, and find the patterns to those data sets using contribution factors, probabilities, and normal distributions.

1. Introduction
The earth’s natural ability to provide fossil energy won’t persist. Due to the fast increase of energy demand, constant greenhouse impact, and growing usage of existing energy techniques, countries have started to pay attention to renewable energy production and use [1].

The primary energy source nowadays is fossil fuel, which is plentiful and inexpensive. The usage of fossil fuel, plenty in supply and cheap in price. Coal-fired power plants are now providing about 40% of the electricity globally, with some country’s way beyond the average line. For instance, 93% of the electricity generation in South Africa is done by coal, followed by Poland and PR China with the number of 87% and 79% [2]. The utilization of fossil fuel is also crucial to environment. Most fossil fuel use directly contributes to increasing greenhouse gas emissions in the atmosphere. According to NOAA, global temperatures have risen by one degree Celsius since 1880. According to US Energy Information Administration [3], CO₂ emissions make approximately 80% of the total emission of the greenhouse gas in the US in 2019. About 74% of all greenhouse gas emissions come from fossil fuel combustion. The remaining 16% comes from human-made carbon dioxide emissions.

Nuclear power generation is also a non-renewable way of electricity generation. Report in IEA shows that in the past five decades, the generation of nuclear power reduce over 600 billion tons of CO₂ emission, it's about two years of worldwide energy-related emissions. [4] Other advantages of nuclear power includes the small cover area and the low consumption it needs. Nuclear power is not considered to be a safe way of electricity generation for the following reasons. Nuclear waste disposal must be meticulous. Although the volume of spent nuclear fuel is minimal, due to the radioactivity, it must be approached with caution. It is quite possible that if it is handled incorrectly, it will have a disastrous impact on the environment and life. Nuclear waste's radioactivity cannot be removed using standard physical, chemical, or biological procedures. The only way to lessen it is for radionuclides to decay.

One of the renewable sources of energy is hydropower. The global potential for technological hydropower is projected to be approximately 15 000 TWh. A large portion of the mass of producible hydrocarbon resources in Europe has already been utilized [5]. Research from BP Statistical Review of World [6] shows that in 2020, China produces the most hydroelectric electricity, with 1355.2 terawatt-
hours produced every hour, subsequently after is the US, Canada, and Brazil with each about 300 to 385 terawatts per hour. China has increased about 1000TWh in the past two decades with other countries remain the same. The cost of generating electricity is cheap. Hydropower does not need the usage of additional power sources. In comparison to hydroelectric power plants, thermal power generating stations have an annual operating cost that's 10-15 times higher due to fuel usage. The project's all-around advantage should also be taken in consideration. Because damming creates a large artificial lake and regulates the flow of water, the building of hydroelectric stations has numerous advantages, including flood control, agriculture, shipping, water supply, and tourism. In terms of nature, massive reservoirs can generate surface activity and even earthquakes.

Biomass power generation is also a renewable electricity generation method. Globally, 596 TWh of biopower were produced in 2017, an increase of 25 TWh (+4%) over the prior year. Biomass energy production had increased by 3.6-fold during the 17 years. In big scale electricity alone and combined heat/power plants, main solid biofuels such as wood chips, wood pellets, and so on accounted for 65 percent of biopower output [7]. Biofuels are made from a variety of basic sources. Crop straw, forestry processing leftovers, animal manure, organic wastewater from the food processing sector, urban rubbish, and low-quality soil may all be used to grow a variety of energy plants for biofuels. Biofuels are created through the harmless and resource-efficient use of farming, forest cultivation, and biotic wastes. All biofuels' living components can join the earth's system, and indeed the emitted carbon dioxide will be returned to the soil and function in the earth's cycle, resulting in zero emissions. Biomass power generation will cause environmental problems. Production is heavily reliant on enormous amounts of water and oil. Biofuel production facilities have historically caused widespread pollution and damage to water supplies. Carbon and hydrogen both produce greenhouse gases and contribute to global warming when biofuels are made.

National Energy Administration in China stated that geothermal power is a black horse in renewable resources [8], and according to NS Energy [9], in the United States, 2020, it is the world's biggest geothermal energy producer, providing 16.7 billion KWh of geothermal energy during the year, which is about 0.4% of the total electricity generation [10]. Indonesia is right after in the second place with 1948MW of output in 2018. Geothermal energy can constantly transfer power; it is completely unaffected by the climate and may be used 24 hours a day if there is a geothermal source. This has the potential to supply consistent and massive base load power, which is beyond the capabilities of most renewable energy sources. It is not widely used because geothermal energy is typically utilized in seismic zones due to topographical restrictions. It is a type of resource that regenerates slowly. The geothermal steam generating area can only be used for a limited duration, which can range between 30 and 3000 years.

Tidal power generation is a renewable resource that is rarely affected by the weather, similar to geothermal power. Scientific advancement has increased the quantity of energy produced by the ocean. The 2019 growth rate was 13%, which was much greater than the rate of increase in the previous three years [11]. It is a generally steady and consistent source of energy, with little influence from climate, hydrology, or other natural causes. The yearly total power generation is constant, and wet and dry years, as well as wet and dry seasons have no effect on the amount of power generated by tidal power. There is no need to construct huge dams for tidal power plants. Even if the dams are damaged by natural calamities like earthquake, they will not cause significant harm to downstream cities, farms, people's lives, or property.

Many people are concerned about global warming and what this means for renewable energy, including wind, ocean, solar, biofuels, and geothermal energy. Wind and solar power have developed at a rapid rate in the past decade. These are both clean, abundant energy sources [12].

PV electricity is now widely utilized in rural communities all over the world, notably in hybrid systems involving diesel generators. The advantages of PV powers including short periods required for the design, installation, and start-up of a new facility. In contrast to dynamic wind turbines, the PV system for solar electricity is stationary, does not require strong tall towers, creates no disturbance or sound, and does not require active cooling [13]. It produces no pollutants and emits no carbon emissions.
after construction. Because of its light weight, it is also very portable and very mobile. However, every energy source has its drawbacks. The preliminary cost of acquiring a solar system is rather significant. This covers the purchase of solar cells, a transformer, chargers, cabling, and construction. It also requires a lot of space to produce solar power in a large amount.

Wind power is cost-effective. After the production tax credit, land-based utility-scale wind is one of the most affordable energy sources accessible today, costing 1–2 cents per kilowatt-hour. Wind energy reduces the price uncertainty that fuel expenses contribute to traditional sources of energy since electricity from wind farms is sold at a set price over a lengthy period and its fuel is free [14]. Also, wind turbines do not emit pollutants into the atmosphere that contribute to acid rain or carbon emissions. On current fields or pastures, wind turbines can be installed. This has a significant economic impact on remote areas, which have the majority of the best wind sites. Rural communities could farm usually because wind turbines take up just a small portion of it. Wind power will also have an impact on wildlife. Birds have died after colliding with whirling turbine blades. Wind turbine blades have also killed bats, and research is continuing to discover and enhance methods to limit the impact of wind turbines on these species. Wind projects, like other energy sources, can modify the environment on which they are built, which may affect the suitability of that habitat for species.

2. Background
To better optimizing the renewable energy in places in UK, background research is done to investigate UK policies in recent years.

According to Office of Gas and Electricity Markets [15], Introducing the Renewable Obligation in 2002 massively increase the effective price per unit energy in kWh, from almost £0.00 to over £1.80 in 2017. and greenhouse gas emissions from over 200 MTCO2e to 125 MTCO2e [16]. According to Sun and Nie (2015) [17], global programs such as RO are successful in decreasing carbon emissions and opened a path for UK renewable resource generation.

According to UK National Renewable Energy Action Plan [18], the electricity generation in UK need to be increased. As they think forwards, they must make much use of renewable resources to establish a strong foundation for UK, because the demand is non-stopping. When in 2009, it was only about 3 percent of total energy are renewables, the renewable energy directive sets a goal to make the proportion up to 15% [19]. Through the recent work in promoting renewable resources across the country, the significant outcome is shown. In the energy trends data from BEIS [20], the renewables were 47% of the total electricity generation for its first time in 2017, Britain generated more power from renewables than it is from fossil fuels, a trend that has maintained in recent years.

In the field of wind energy, Prime Minister also set plans in 2020 to massively enhance the offshore wind capacity, which is already the greatest in the world and already provides 10% of the total power demand. £160 million will be allocated to modernize the foundational system [21]. Those will be creating more jobs, decrease greenhouse emissions, and uplift the trading. The government also want to achieve that by 2030, offshore wind power is capable for all electricity generation, from today’s 30 GW to 40GW.

According to LawReviews.co.uk [22], UK is encouraging residential renewable energy alongside the big powerplants. The design of spread generating capacity for self, which provides considerable economic benefits to consumers. In London, Solar Action Plan is launched to promote Londoner to install solar panels to help with the London's zero carbon target by 2050. The London government are also working with companies, regulator, and electricity operators to best benefiting the households and meeting the target [23].

3. Motivation
Two types of renewable energy are existing in today’s global market, classified by whether the energy source is weather dependent. In this paper, only weather-dependent renewable energy will be considered.

According to National Oceanic and Atmospheric Administration [24], wind and solar power's unpredictability present problems for those who must maintain a continual balance between energy
requirements to maintain a reliable electric power system. But until energy storage becomes cost-effective, the power grid's "flexibility" is critical to its efficient operation. Better forecasting for variable renewables along a variety of time periods will give crucial flexibility and make weather-dependent renewables integration easier.

Renewable energy output is unlikely to match demand due to its poor timing. Weather unpredictability affects any wind power. Solar energy decreases in the evenings when demand is highest. Solar produces roughly 1/9th of its production in the winter.

According to US EIA data in 2020 [25], showing that UK has a capacity of around 35 gigawatts of weather-dependent energies by the end of 2019, and have a running cost of £62 billion. However, gas-fired energy production is by far the most cost-effective energy source, costing less than £1 billion per Gigawatt, which its combustion emits far less CO₂ than other fossil fuels.

Now, technologies are improved to make more accurate forecast to optimise the production in weather dependent renewables. Climate research from sub-seasonal to seasonal timescales include projections for up to six weeks and seven months ahead, respectively, are much longer compare to forecasts for up to 10 days ahead, which most people are used to hearing on the news and conceive of as long-term forecasts. For 1-15 days of weather forecast, it could help with setting energy prices for energy traders, and planning cleaning and maintenance for plant operators. For climate predictions including sub-seasonal and seasonal forecast, they could help planning for maintenance works, especially wind power, predict the return on investments, and giving advice on resource management and strategies. Lastly, for long term climate prediction, from 2 to 100 years, they could help the politicians to decide the energy mix, and the site for building power plants [26].

4. Methodology and modelling

All the data is downloaded from National Aeronautics and Space Administration’s Prediction of Worldwide Energy Resources (POWER) website [27]. The POWER Data Access Viewer includes meteorological and solar-related characteristics that have been developed for the purpose of evaluating and developing renewable energy systems. In single point data access, daily averaged data may be obtained for specified date ranges and characteristics in a selected location, including humidity, temperature, wind speed at multiple heights, and solar insolation. Interactive charts or data tables may be used to display the information. For researching the solar power, the number of daily insolation clearness index (KT) from 2016 to 2020 was downloaded. KT is dimensionless, it is measured by surface radiation budget, which is the average net radiative flux density over a particular location on the earth's surface during a certain time. The downward shortwave, the upward shortwave, the downward longwave, and the upward longwave are the core elements of the surface radiation budget. For wind speed data, the number of wind speed at 50 metres altitude from 2016 to 2020 was downloaded. The source of the data in metre pre second was from the second Modern-Era Retrospective analysis for Research and Applications (MERRA2), which is the updated version of MERRA, is providing meteorological re-analysis from 2016.

Oxford is the administrative capital, non-metropolitan area, and city status of the county of Oxfordshire in southeast England. It has a location 51.752022, -1.257677 [28] It has a population of 151,584 people, with 74% born in the UK. [29] The distribution of monthly average precipitation in a year is highly balanced, owing to the influence of the Atlantic Ocean. In January 1982, the lowest temperature recorded in Oxford was 16.6 °C (2.1 °F). In August 2003, the maximum temperature recorded was 35.6 °C (96 °F). [30] Between 2005 and 2014, Oxford's total carbon emissions were decreased by 27%, mostly in industry. [31] The London Borough of Bexley is in south-east London and have a coordinate 51.4399° N, 0.1543° E. In 2021, it has about 25 thousand residents. Like Oxford, it has 1/3 population under 25 years old and 1/6 over 65. Bexley inhabitants have a higher employment rate than residents of London and the rest of the United Kingdom. Bexley residents work in occupations that need a comparable mix of low, middle, and high abilities. [32] In Bexley, electrical aggregation in thriving, with the support of city councils, so that the goal of “green Bexley” could be reached. [33] Whittlesey (52.5581° N, 0.1301° W) is a town in the English county of Cambridgeshire, which has a
population of more than 16 thousand people. [34] The railway station there could transport to Cambridge, Birmingham, Liverpool, and Leicester as well as Stansted Airport. [35] According to the switch-plan.co.uk, the average Whittlesey home uses 3,529.39 kWh per year. That identical household's median usage would be 3,090.43 kWh [36].

Figure 1. Location for three cities in Google map [37].

Figure 1 is an image drawn in Google map, showing the geographical locations for the three cities, at the top is Whittlesey, with Oxford on the left and Bexley at the bottom.

Figure 2 shows that in Bexley, London, maximum kt is from 2018 and 2020, which is 0.71 in 2020 Mar 25th, May 6th, May 29th, May 30th, and 2018 May 6th. The rest of the years are all 0.7 for maximum kt. The minimum kt is in 2020 Mar 9th, June 27th, October 28th, and December 14th. This shows a wide diversity of the range of the kt. Which the minimum kt could be exist in different time of the year, and barely affected by the season. It is also clear that the range of kt has expanded in 2020, especially the minimum limit, where from 2016 to 2019, the minimum value was 0.06 or 0.08. The graph shows a periodicity, where most of the bigger values are a little before the middle of the year, and the smaller values are at the start and the end of the year.

Figure 2. Time serial trend chart of kt values in Bexley from the start of 2016 to the end of 2020.

Figure 3. Time serial trend chart of wind speed (m/s) in Bexley from the start of 2016 to the end of 2020.

Figure 3 demonstrates the wind speed in Bexley. The maximum wind speed was 21.19 in 2020 Feb, 9th. With the second maximum 18.82 in 2016, and the rest of the years not beyond 17m/s. The difference
between the first two maximums is 2.37, which is a big variance. The minimum value was 1.41 in 2016 Jun 7th, followed by 1.46 in 2020. From the graph, there’s no clear periodicity shown. Neither dates nor seasons indicate a trend for wind speed, although it seems that wind speed is higher at the start of the year and lower mid-year.

**Figure 4.** Time serial trend chart of kt values in Whittlesey from the start of 2016 to the end of 2020.

Figure 4 is the solar irradiance In Whittlesey, Cambridge. The Maximum kt is 0.7, which maintained from 2017 to 2020 (2020 Apr 7th, 22th, 30th, Jun 25th, 2019 May 15th, 2018 May 6th, 7th, 2017 May 10th) and in 2016, the maximum was 0.69. As the analysis shown above, in 2020, few dates hit the maximum kt, and the time span was expanded greatly. The minimum kt is 0.05 in 2017 Dec 27th, and 2019 Dec 26th, 0.06 in 2016 Nov 21th, 0.08 in 2018 Nov 28th, and 2020 Dec 3rd. Although the minimum kt is fluctuated by year, but it doesn’t have a particular trend of increasing or decreasing, rather it’s stable. The graph indicate that it has a periodicity of a year, with most smaller results among the start or the finish of the year, and bigger results at the middle of the year. It is shown in Figure 5, that the maximum wind speed in Whittlesey was 20.71 in 2020 Feb, 9th. The highest speed in previous years was 17.63 in 2016. The difference between each year’s minimum is only 0.54. It is suggested that the value of wind speed at the start of the year is usually high, and that it is mostly low in the middle of the year.

**Figure 5.** Time serial trend chart of wind speed (m/s) in Whittlesey from the start of 2016 to the end of 2020.

For Oxford, shown in Figure 6, the maximum kt is 0.71 in 2018 May 6th and 2020 Mar 25th, May 6th, May 29th, and May 30th, and all the other years, the maximum values are all 0.7. comparing the data

**Figure 6.** Time serial trend chart of kt values in Oxford from the start of 2016 to the end of 2020.

**Figure 7.** Time serial trend chart of wind speed (m/s) in Oxford from the start of 2016 to the end of 2020.
from 2018 and 2020, it is shown that the dates that meet the maximum value increased a lot. In 2020, there are 7 dates which have the value 0.7, meaning the kt values are increasing through years. The minimum kt number is 0.06 from 2016 Jan 3rd, Nov 21th, 2019 Dec 10th, and 2020 Feb 15th, and 0.08 from 2017 and 2018. In this graph, the values among Jan 2021 were generally smaller than other values, which has a small trend of decrease. The graph also indicates the periodicity, with most smaller results among the start or the finish of the year, and bigger results before the middle of the year. While in Figure 7, the maximum wind speed is also in 2020 Feb 9th, and in that day, the wind speed is 20.73m/s. It is followed by 18.41m/s in 2016 Feb 8th. The minimum speed is 1.39 in 2020 Sep 1st. There’s no pattern showing the wind speed would vary from dates or seasons, but it is implied that the value of wind speed at the start of the years is mostly high, and when in the middle of the years, it is mostly low.

Figure 8. Time serial trend chart comparison among the kt values for three cities.

In Figure 8, there’s a clear pattern for all the cities that in the beginning and the end of the years, which is winter, the kt values are the lowest of the year, while in the beginning of summer, which is the middle of the year, the kt values are the highest. All the trends are similar, it’s because the latitude of Oxford (51.7520° N), Bexley (51.4399° N), and Whittlesey (52.5581° N) is very close, so it doesn’t have a big difference in the angle of the sun. Figure 9 directly shown the key numbers for the cities. Whittlesey is placed in 2, and it has the lowest maximum and minimum values, while the interquartile range is slightly wider than Bexley and Oxford. Looking at the maximum, Whittlesey is around 0.7 and the others are all a lot over. The median of Whittlesey is also the highest, while Bexley and Oxford are almost the same.

Figure 9. Box plot of three cities’ kt values.

Figure 10 is an XBAR control chart. it is shown that the actual process mean is about 0.4, with upper control limit about 0.5 and lower control limit above 0.3. As the diagram presents, most data are out of the control limit, hence the process is not stable. There are similar number of values that are bigger than
the upper control limit to the values that are smaller than the lower limit. 6 comparisons and 3 bar charts are shown in Figure 11. On the top right and bottom left is the analysis for Bexley and Oxford. Straight lines imply that there is only slight difference between the two cities. A possible explanation is that the latitude between Bexley and Oxford is closer than the latitude to Whittlesey, so that the amount of sun irradiance would be similar compared to the value in Whittlesey.

![Figure 12. Time serial trend chart comparison among the wind speeds for three cities.](image)

![Figure 13. Box plot of three cities’ wind speeds.](image)

The time serial trend chart in Figure 12. In general, these three cities’ wind speeds are very similar, and they have a vague pattern that the windspeed is the highest in the start and the end of the year, while it is the slowest in the middle of the year. All the maximum values in different cities are in 2020 Feb 9, which are obvious outliers. It is because the storm Ciara arrived in those places with a high wind speed and heavy rain. From the box plot in Figure 13, it is implied that the wind speeds in Bexley, London and Whittlesey, Cambridge have more similarities. They have close median and interquartile ranges, but the maximum and minimum values for Whittlesey is all closer to the range than Bexley. In Oxford, it has the lowest minimum, maximum, median, and interquartile ranges, and the range between the first quartile and the third quartile is the smallest.

![Figure 14. XBAR control chart of wind speeds.](image)

![Figure 15. Comparison of wind speeds between the two of the three cities.](image)

XBAR control chart is shown above in Figure 14. The actual process mean is about 6.5 m/s, with upper control limit about 9m/s and lower control limit about 4m/s. As the diagram presents, most data are out of the control limit, hence the process is not stable. There are a greater number of values that are bigger than the upper control limit to the values that are smaller than the lower limit. Figure 15 is a comparison of wind speeds for all the cities. The difference between the cities is alike, with no two cities
close to the same or very different. The difference between Bexley and Oxford is smaller compared to others.

Combining Figures 16-18, it is implied that the contribution factor is starting with a slightly thin positive tail, with normal till about 0.43, and positively skewed afterwards. This is because of the quickly changing wind speed in the beginning of the year.

Figure 16 is two time series trend charts, which shows solar and wind contribution factors. Solar contribution factor was calculated by the $kt$ values times by the percentage of solar energy to the total renewable energy, then times by the percentage of renewable energy to the total energy supply. Wind contribution factor is used in the same method. For solar contribution factors, the difference between the maximum and the minimum is about 0.235. At the start and the end of the chart, the solar contribution factor is lower than the middle part. There’s also a major decrease in the mid-point. Wind contribution factors has a huge increase in the first 50 days, which the rest of the contribution factors relatively stable. The range difference is about 1.6. Comparing solar and wind together, the wind contribution factors are generally higher than solar, it’s because the percentage share in 2016 for wind energy (including onshore and offshore) is much more than solar energy. Scatter-hist diagram in Figure 17 shows that the solar contribution factors are close to a normal distribution, but the wind contribution factors bar chart shows a long tail, which is a clear skewed distribution. Normal probability plot in Figure 19 can tell that the red data set, which is the wind, is positively skewed, with data above 0.4 starting to skew. The largest value is 1.6 with a long tail. The solar contribution factors are slightly negatively skewed, it become is normal until over 0.2. Figure 20 is a box plot of wind and solar contribution factors. Comparing the 2 box plots, it is clear that the median of the two contribution factors are similar, with wind a little higher. Wind contribution factors has a lot of outliers, the interquartile range is bigger, and the maximum have
a larger difference to the third quartile compared to the difference between the first quartile and the minimum. The medium is closer to the first quartile. For solar contribution factor, the interquartile range, maximum and the minimum are evenly arranged among the median. The bar chart is shown in Figure 21, with the percentage of solar and wind energy to the total energy. At the highest point, it is close to 2 percent, and the average percentage around the year is about 0.5 to 0.6 percent.

5. Conclusions
In this study, the data sets of the solar and wind energy in three different cities are used to find the patterns by using contribution factors, probabilities, and normal distributions. The number of solar and wind contribution components is shown by using a normal probability plot to represent the data. The box plots of the solar contribution factors are smaller than the interquartile range of the weight contribution factors which shows that the wind contribution factors have a lot of variety compared to the solo contribution factor. The wind contribution factor has a higher median then the solar contribution factors and it has a very large range from the maximum to the first quartile. The wind contribution factors contribute a lot of the pattern of the chart because it has a greater variety and range.

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