Constructing a Global Electricity Supergrid Based on Renewable Energy Sources: A Qualitative Analysis

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Energy has become a necessity in our modern society. As the world economy and population grows, energy consumption also increases. Humans have relied on fossil fuels as their primary energy source after the Industrial Revolution, but fossil fuels have a limited supply. For this reason and in efforts to reduce climate change, energy consumption from renewable energy sources is becoming much more popular. The downfall of renewable energy sources is that they are unreliable, as they depend on nature. A solution to this problem is a global supergrid, a large electrical grid that connects the entire world's energy supply. It would allow energy to be transported through the grid, making the grid balanced, even on a 100% renewable energy system. This manuscript discusses how to formulate the ideal global supergrid in the section titled 'Results'. It also gives a brief overview on the disadvantages of each renewable energy source and provides a detailed background on the global supergrid. Its purpose is to give detailed information on a 100% renewable energy based system specific to each region. This manuscript was written in 2021.

Introduction

Climate change is the result of human alteration since the Industrial Revolution. It is driven by human-induced greenhouse gas emissions[1]. Examples of greenhouse gasses are carbon dioxide, methane, and nitrous oxide[2]. These allow solar radiation to penetrate the atmosphere and heat the Earth, but trap the reflected radiation from Earth's surface, which results in the increase of global average temperatures[2]. As some parts of Earth naturally receive more heat than others, and this disparity is heightened by global warming, climate change also constitutes large-scale shifts in weather patterns, affecting many ecosystems and habitats[3]. The energy sector is the largest contributor to greenhouse gas emissions[4]. Carbon dioxide makes up a majority of greenhouse gas emissions, as it makes up 76 percent of greenhouse gas emissions[5]. Trees, like all green plants, take up carbon dioxide from the atmosphere and release oxygen during photosynthesis, but when forests are cut down, this stored carbon dioxide is released into the atmosphere once again[3].

Wind mills, water mills, and solar panels have been used for centuries, but since the popularization of coal during the industrial revolution, they were only used rarely, until recently. These are examples of renewable energy sources because they come from natural sources that are constantly being replenished and reproduced[6]. Renewable energy sources offer a cleaner, long term alternative to a predominantly fossil fuel energy sector. Some examples of renewable energy are solar, wind, tidal, hydro, biomass, and geothermal energy[7]. Many countries have started using renewable energy as an alternative to fossil fuels (such as coal, oil, and natural gas) which emit carbon dioxide and have a limited number of resources[8]. One way to reduce greenhouse gas emissions is to convert to using 100% renewable energy on a global scale and supplying the remaining percentage by nuclear power, which only emits water vapor. However, nuclear energy should only be used as a last resort, as it also produces radioactive waste, which can be extremely dangerous to the environment if it's not stored properly[9].

Advantages of Renewable Energy

The recent drive to fight climate change has motivated more research and advancements in the renewable energy sector, making it significantly cheaper and more accessible. Prices of solar photovoltaic (PV) and wind energy per MWh are dropping drastically (82% and 69%, respectively)[10]. All fossil fuels are more expensive than solar and wind power today[11]. Therefore, a grid made up of a 100% renewable energy system has the potential to be cheaper than a system dependent on fossil fuels as the predominant source of energy[12]. In addition to the higher prices of fossil fuels, they also have the potential to run out during our lifetime, as crude oil reserves are predicted to last for only 53 years, coal reserves for 150 years, and gas reserves for 52 years[8].

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Disadvantages of Renewable Energy

However, renewable energy has the disadvantage of being inconsistent, as it depends on climate or geography [13]. For example, a drawback of wind energy is that winds are unpredictable and can overwhelm a grid with too much energy as well as provide no energy on calm days. Furthermore, wind turbines restrict views and can be a danger to some kinds of wildlife [14]. Wind and solar farms are also costly to build and can leave a carbon footprint. The most common drawback of solar energy is that its standard forms do not work at night [15]. Hydro power also has some limitations. If a dam were to break down it would result in significant flooding in the area [8]. It could damage ecosystems and landscapes further as waste leaks into the water. Additionally, the construction itself carries a carbon footprint. Finally, there is significant pushback against dams in parts of the world as they disrupt certain water ecosystems, such as breeding salmon in Canada [16]. Tidal energy is costly, as it is a fairly new discovery, and researchers are not completely sure how it would damage marine ecosystems [14]. Similarly to tidal energy, geothermal energy is costly and cannot be applied evenly throughout the world [14]. Lastly, the downfall with biomass energy is maintenance costs and permits from a local authority [14]. However, it is important to consider that even with these disadvantages to renewable energy, the energy sector's carbon footprint would be significantly reduced with a predominantly renewable-based system.

Possible Suggestions

An inconsistent system with unpredictability cannot satisfy day-to-day energy demands. Certain energy sources are better in certain locations and worse in others. Energy generation from 100% renewable energy has therefore the potential for blackouts based on weather conditions in each area. A potential solution to this problem would be implementing a global electrical grid, also known as a global supergrid. A supergrid would allow for energy to be transported within the grid ensuring that all areas are supplied with energy and making the grid balanced [17]. For example, if one area is not receiving enough sun, their usual source of energy, extra energy from another area can be delivered so that no area is left without energy, preventing blackouts and eliminating the unpredictability of renewable energy [18]. It's likely that some regions may be left with extra energy based on weather patterns, solar radiation, and the water cycle, and because energy storage technology is not well developed [19], it could be transported to places that aren't meeting their energy demands. Additionally, with a global supergrid, the amount of energy stored can be cut down by 50% [17]. The grid would need to be balanced on a 24 hour cycle, as some renewables are not available at all times during the day. It would be best if during the day, solar energy would primarily be used, while at night the other renewables would supply energy. Storage is one way to ensure that all renewables are not used equally at all times, however storage technologies are costly and difficult to operate.

Presently, there are dozens of regional grids around the world, so why not keep them and just convert to a 100% renewable system? A global supergrid would ensure that all or nearly all the energy that's produced would get consumed, avoiding wasteful practices such as paying wind farm operators to curtail production or dumping energy that's not immediately needed [17]. Moreover, a global supergrid would minimize consumption of natural resources, maximize economic useful life, recycling rate, and ensure effective usage of natural resources [20]. For example, connecting just the three regional grids in the United States could lead to carbon dioxide reductions of 80 percent than what the US releases today [21]. Not only that, but maintaining a balance between electricity supply and demand becomes easier with a larger grid [17]. A global supergrid provides more regions for extra energy to be supplied to and places for extra energy to be produced when compared with regional grids. This manuscript focuses on creating an outline for a custom electrical grid that provides energy to a region based on its own climate and geographical location. A 100% renewable energy based supergrid would allow the entire world to operate off of clean energy, significantly reducing carbon emissions.

Research Question

This analysis focuses on answering the following question: What is the ideal composition of an electric supergrid to meet the global energy demand?

I use peer-reviewed literature and each country's energy production and consumption data to tackle this question. The paper centers on finding the best suited renewable energy source(s) for each region based on their climate, geographical location, water cycle, and solar radiation. Section 2 summarizes my data and methods for the study. Section 3 explains the results of the study, with the help of tables and graphs. Lastly, section 4 concludes the study.

Discussion/Results

In order to create a global supergrid, the world had to be split into regions based on my criteria of mostly geographical proximity (Figure 1).

North America

North America was broken into 2 regions in the supergrid, as Central America was its own region. North America produced 124.911 quadrillion BTU of energy, where 80% was fossil fuels. It consumed 115.045 quadrillion BTU of energy

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Fig. 1 A map of all the regions in the global supergrid. There are 15 regions and each is its own color.

and 79.8% was from fossil fuels. It was concluded that upper North America would be best suitable for hydro energy and wind energy, more specifically due to the climate and geography of Canada. The eastern coast of Canada experiences wind speeds from 7 to 10 m/s, which makes it a great area for wind energy [[25], Figure 3]. Not only that, Western Canada has a great potential for hydro energy, specifically to produce 100-1000 GW/h of hydro energy [[22], Figure 4] Some areas can produce over 1000 GW/h [Figure 4]. Furthermore, the United States of America has many options when it comes to renewable energy. Geothermal energy would work very well in the western US [[26], Figure 5]. Solar energy would also work especially well in the southwestern part of the country, as they have extremely high incoming solar radiation [[27], Figure 2]. Presently, the Southwestern United States' photovoltaic power output ranges from 1800-2000 kWh/kWp [Figure 2]. The east coast of the country is quite suitable for hydro power [Figure 4] and offshore wind energy [Figure 3]. The Central US (Midwest), has ideal conditions for onshore wind farms [Figure 3] and biomass energy. It is mostly plains and contains many plants, perfect for biomass. Many states in the Midwest grow corn, which is turned into ethanol and further burned, a significant biomass source in the United States[26]. This could be a great source of energy for the United States, but other renewables described above should be focused on first and foremost and only if those options can no longer meet demand should biomass be invested in[26].

Central America's environment differs from North America, which is why it's a separate region. Central America produced 6.396 quadrillion BTU of energy, where 84% came from fossil fuels and it consumed 10.444 quadrillion BTU, and 83% is from fossil fuels. Most of this region is on the equator or extremely close to it, causing it to have an extremely warm climate all year. As shown in Figure 2, solar energy would work well in the Northern part of Central America, closer to Mexico. This part of Central America has an annual photovoltaic power potential of 1753-1899 kWh/kWp [Figure 2]. This value drops to 1461 kWh/kWp the further south you move in this region [Figure 2]. Geothermal energy is also suitable for Central America as it is very tectonically active. These countries are some of the most suitable for geothermal energy, as they have a 0.8-1 probability that large geothermal power plants would be successful [Figure 5]. For example, Costa Rica lies on a subduction zone, leading to many active volcanoes. Tidal energy would also work well in Central America, as many of the countries have access to the shore of the Atlantic Ocean and/or the Caribbean Sea. Hydro power would also work very well in Central America, as storms are a common occurrence. Most countries in Central America can produce 100-1000 GW/h a year of hydro power [Figure 4] and similarly to Canada, some can produce over 1000 GW/h annually [Figure 4]. As shown in Figures 2, 3, 4 hydro, wind, and geothermal energy are not well suited for the Caribbean. Onshore wind energy is not suitable for the Caribbean islands, but the wind map does show that wind energy would work well on the Caribbean Sea. Unfortunately, the area is prone to hurricanes which can damage wind turbines. For this reason, it is recommended that the smaller countries in the Caribbean look to nuclear energy as one of their primary energy sources. This would work very well because it doesn't take up a lot of

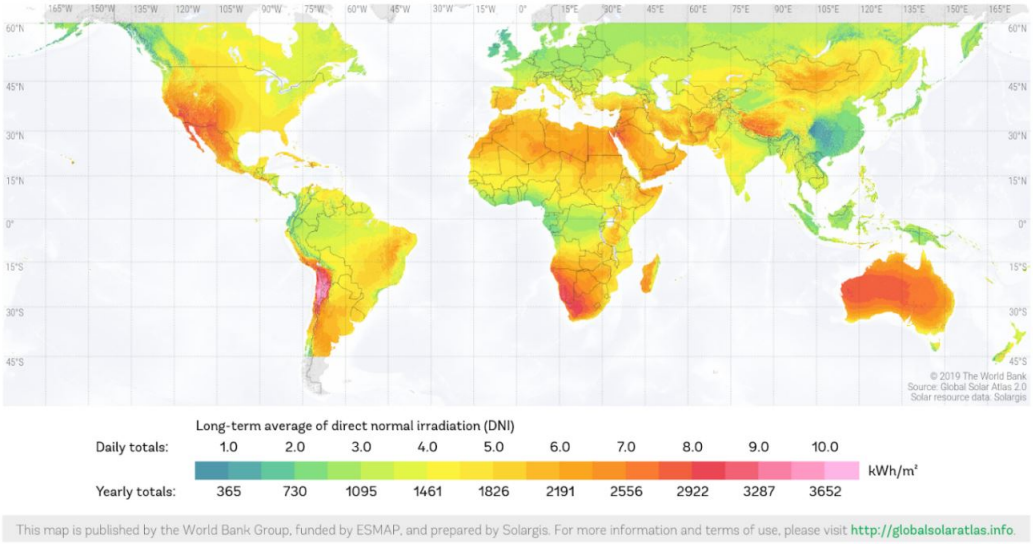

Fig. 2 This is a map of solar radiation in the world. The dark red areas get the highest solar radiation, while the blue areas receive the lowest solar radiation[22].

space and works all the time; however, much care would have to be taken to ensure the nuclear plants are able to withstand hurricanes and earthquakes, common in the area. On the other hand, the Caribbean has between 1461-1607 kwh/kwp of annual photovoltaic power potential [Figure 2], so solar energy would also work in this region.

South America

South America is the next region in the supergrid. In total, the region produced 30.615 quadrillion BTU of energy, 71.2% was from fossil fuels. It consumed 25.36 quadrillion BTU of energy, 70.8% came from fossil fuels. It is a very diverse region as far as climate goes, making it difficult to find renewables that would work for the entire region. For this reason, it was necessary to look at South America from a different perspective. Solar energy is not ideal for most of South America, except for Chile and eastern Brazil. Northern Chile has an annual photovoltaic power potential of 2337 kwh/kwp [Figure 2], one of the highest in the entire world. Southern Chile and Brazil both have 1753 kwh/kwp of potential [Figure 2], making these areas suitable for solar as well. Hydro energy would work well in the northern, western, and eastern part of the continent. The only countries where hydropower is not recommended is Uruguay, Paraguay, Argentina, and the very northern part of Chile. All the other countries have the potential to produce 100-1000 GW/h of hydro power annually [Figure 4]. Parts of Ecuador and Venezuela can produce over 1000 GW/h of hydro power annually [Figure 4]. Wind energy would work well in the southern tip of South America. Specifically, it is recommended that Paraguay, Uruguay, Argentina, and Chile should use wind energy as wind speeds range from 7 to 12 m/s [Figure 3]. Therefore, South America has many options for a 100% renewable energy system.

Europe

Europe is made up of three regions in the supergrid, the United Kingdom, Northern Europe, and Continental Europe. In total, Continental Europe produced 25.764 quadrillion BTU of energy, where 31.4% came from fossil fuels. The region consumed 43.064 quadrillion BTU of energy, where 88.4% was from fossil fuels. This region is very large, which makes it difficult to pick which renewable energy sources would be best for the entire region. Therefore, I will offer suggestions of renewable energy sources for the northern and the southern parts of this region. Solar energy is strongly recommended for the southern part of the region, as has the photovoltaic power potential of between 1300-1700 [Figure 2]. Most of this area has the potential to produce 100-1000 GWh/year using hydro power [Figure 4]. Wind energy would work great in Northern continental Europe as the region receives winds between 6-8 m/s [Figure 3]. This region in Europe is much more suitable for geothermal energy and hydropower in comparison to the United Kingdom and Northern Europe. However, those regions seem to have a better potential for wind energy.

However, it was identified that the United Kingdom should be considered a separate region from continental Europe. In total the UK produced 5.485 quadrillion BTU of energy, and 70% was from fossil fuels. It consumed 8.281 quadrillion

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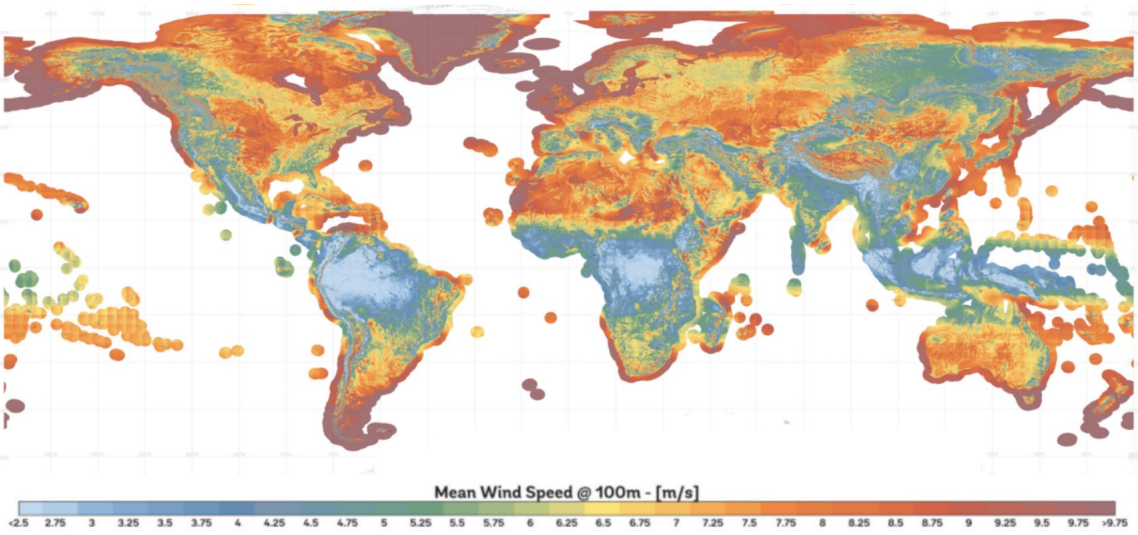

Fig. 3 This is a map of average wind speeds in each location. Dark blue are the slowest wind speeds (1 m/s), and dark red/purple are the highest (10-12 m/s)[23].

BTU of energy, and 79% was from fossil fuels. Each country in the United Kingdom has access to water, ideal conditions for tidal and hydro energy. Wales, Scotland, and Northern Ireland have a lot of potential for hydro power production and consumption. Scotland has the potential to produce between 100-1000 GWh/year [Figure 4] and Northern Ireland and Wales have the potential to produce 10-100 GW/h of hydro energy [Figure 4]. Wind energy would also be an efficient source of energy for the UK, as winds reach speeds between 7 and 9 m/s [Figure 3]. Offshore wind energy would also work very well in the United Kingdom, as wind speeds on the ocean range from 9 to 11 m/s [Figure 3]. Solar and geothermal energy are not recommended as efficient sources of energy for the UK, considering its cold climate and low incoming solar radiation.

Another region of Europe which we identified as its own region is referred to as Northern Europe, which consists of Greenland, Iceland, and Norway. This region produced 9.029 quadrillion BTU of energy, with 85% from fossil fuels. It consumed 2.121 quadrillion BTU of energy, with 32% from fossil fuels. Onshore and offshore wind energy is very efficient in the region as wind here travels between 7-12 m/s [Figure 3] onshore and between 10-12 m/s offshore [Figure 3]. Iceland has the potential to make between 10-1000 GW/h of hydro power each year [Figure 4]. Norway has the potential to produce 10-100 GW/h of hydro energy each year [Figure 4]. Solar energy is not a good fit for Iceland, Greenland, and Norway, as they only get an annual solar radiation of 1022-1168 kwh/kwp [Figure 2]. Lastly, geothermal energy would be a great energy source for Iceland [Figure 5].

Ukraine, Belarus, Mongolia, Kazakhstan, and Russia

Russia, Mongolia, Kazakhstan, Ukraine, and Belarus form another component of the global supergrid. In total, they produced 76.285 quadrillion BTU of energy, 93% from fossil fuels. They consumed 41.689 quadrillion BTU of energy, 46% from fossil fuels. Along with many of the other regions, this one is very versatile. Wind energy is a good fit for the whole region, besides Eastern Russia. These countries experience winds between 7-8 m/s [Figure 3]. Hydro energy has a lot of potential in Eastern Russia because it is estimated to produce 100-1000 GWh/year of hydro energy [Figure 4]. Mongolia is the only country in the region that would efficiently produce solar energy, especially in the Gobi Desert. It has a photovoltaic power potential of between 1753-1899 [Figure 2]. Geothermal energy does not appear as an efficient source of energy in this region. If wind and hydro power are not able to provide for all of the regions' energy demand, biomass energy and nuclear energy could be a backup option.

Middle East

The next region that was identified in the global supergrid is the Middle East. The region produced 96.376 quadrillion BTU of energy, 98% from fossil fuels. It consumed 47.68 quadrillion BTU of energy, 97% from fossil fuels. Much of the Middle East receives very little precipitation throughout the year, as it is covered in desert[28]. Solar energy would therefore work exceptionally well in the region. The region has the photovoltaic potential of 1753-2045 kwh/kwp [Figure 2]. Based on Figure 5, there is also some potential for geothermal energy

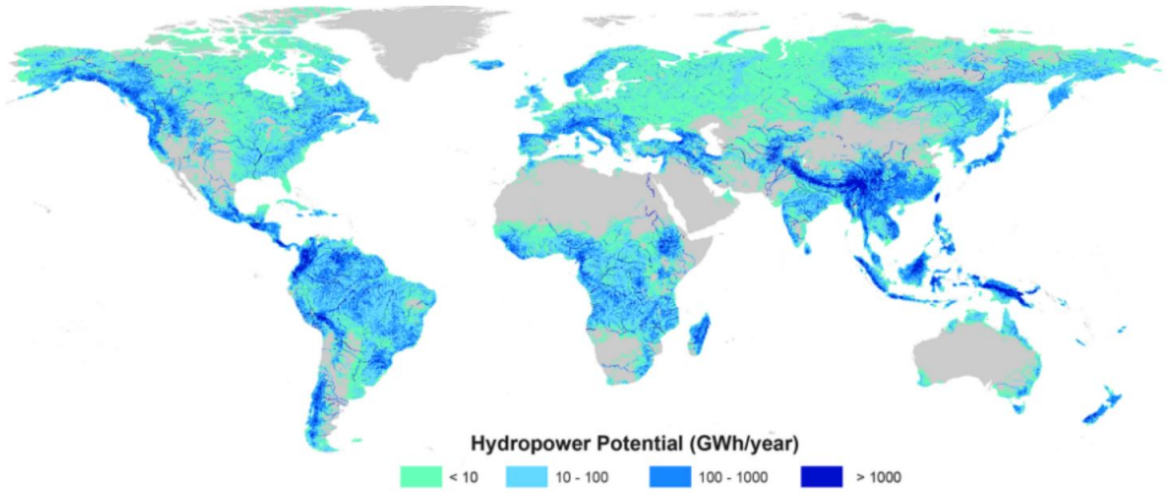

Fig. 4 This is a map of hydro power potential in the world. The darker blue regions have a greater potential to produce hydro power than the lighter blue regions[24].

in the region. The region is not very windy [Figure 3] and is scarce on plant life, eliminating most other renewable energy sources as an option. Hydro energy, however, can work very well in the northern part of the region, such as in Turkey, Georgia, and Armenia. These areas have the potential to produce 100-1000 GWh of hydro energy each year [Figure 4]. Nuclear energy could be implemented to supply the remainder of the energetic demand, as many renewables, asides solar, do not work particularly well in this region. Unless large energy storage facilities are built, it'd be difficult to meet energy demand after sunset.

Asia

The remainder of Asia was split into five different regions on the supergrid: China, India and some of its surrounding countries, Indonesia and Malaysia, Korea and Japan, and Southeast Asia. I felt this strategy would be best in order to accommodate the diverse weather conditions across the continent. Firstly, China, due to its large size, has a host of options to supply its energy from renewables, similar to the United States' situation. In total, China produced 117.798 quadrillion BTU of energy, 83% from fossil fuels. They consumed 147.57 quadrillion BTU of energy, 87% from fossil fuels. The Northern part of China is cold and windy [Figure 3]. This makes it suitable for onshore wind energy V[12]. The western and northern part of China experiences wind speeds between 7 and 10 m/s, making it the perfect place for wind energy [Figure 3]. Northeastern China is a good place for solar energy, along with the southern part of the country, as the photovoltaic power potential is approximately 1826 kwh/kwp daily [Figure 2]. Hydro power is really only suitable for a small region in the south of the country, but it has the potential to produce over 1000 GW/h yearly [Figure 4]. Geothermal energy has some potential in the southeastern part of the country [Figure 5]. China's total energy demand is large due to its population size. These renewable energy sources might not be enough to help sustain the entire country and for this reason, China should consider using biomass energy as an extra source of energy. Similar suggestions go for nuclear power.

India and its surrounding countries such as Pakistan, Bangladesh, Sri Lanka, Nepal, and Bhutan comprise the next Asian region.The region produced 20.477 quadrillion BTU of energy, where 88% was from fossil fuels. It consumed 37.164 quadrillion BTU of energy, where 90% was from fossil fuels. Overall, these countries have a warm climate with high incoming solar radiation. The entire region has the photovoltaic power potential of 1607 kwh/kwp yearly [Figure 2]. Nepal and Bhutan are well positioned for efficient geothermal energy production, as they have between 80-100% chance that they are well suited for a high performance geothermal power plant [Figure 5]. According to Figure 3, onshore wind energy is not a good option for this region, but offshore wind energy could be an efficient source of energy in India, Pakistan, and Sri Lanka, as they have access to the Indian Ocean. Offshore wind farms on the coast of all three countries would be the most beneficial, as this area experiences wind speeds between 7 and 10 m/s [Figure 3]. Hydro energy is ideal for eastern India, Nepal, and Bhutan, as each of these countries have the potential to produce between 100-1000 GWh/year [Figure 4]. Based on the data collected, none of the renewables seem to be extremely well-fitted for Pakistan. Even biomass energy is not a good option, considering less than 6 percent of the total area in Pakistan is forests[29]. Therefore, it is recommended

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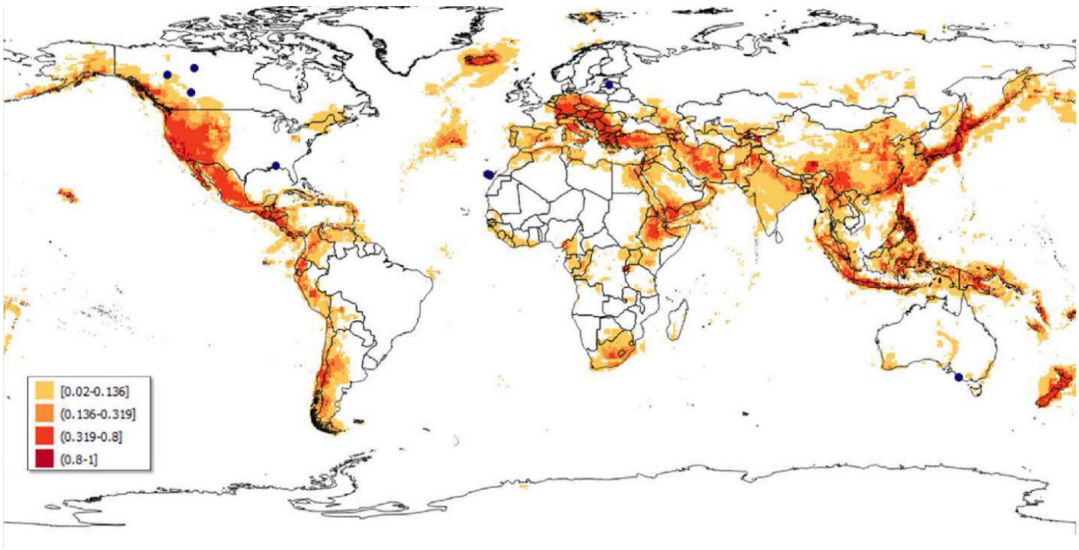

Fig. 5 This map shows the best suited places for geothermal energy. The map shows a scale of 0 (white) to 1 (dark red) of probability that the area is suitable for a high performance geothermal power plant. Based on the color each region is shaded, I can estimate how efficient geothermal energy production would be [19].

that Pakistan considers nuclear energy as one of their primary energy sources. Additionally, large parts of India are heavily forested. These conditions make biomass energy a potential source of energy. Biomass energy can supply energy to towns nearby these forests. However, biomass should always be a last resort option to meet energy demand and should be done in a sustainable way. Even though some countries in this region, such as Pakistan, are less suitable for renewable energy than other regions, such as Southeast Asia- which has amazing potential for producing large amounts of geothermal energy and hydropower- the supergrid should be able to support the nation in meeting its energy demands. Excess energy from other regions can be transported to Pakistan to help it meet its energy requirements and prevent an energy blackout.

Next, we look to Southeast Asia. In total, the region produced 7.325 quadrillion BTU, and 73% came from fossil fuels. They consumed 15.125 quadrillion BTU of energy, and 88% came from fossil fuels. Onshore wind energy is not an ideal energy source for this region, as they only experience winds with speeds up to 5 m/s. On the other hand, many countries in this region border the Indian Ocean or the South China Sea, which both have wind speeds from 6 to 10 m/s [Figure 3], great for offshore wind farms. Additionally, Southeast Asia is one of the best places in the world for hydro power. The entire region has the ability to produce 100-1000 GWh/year of hydro power [Figure 4], and many have the potential to produce over 1000 GW/h annually [Figure 4]. Solar energy isn't the best option either for this region, considering that this region has yearly monsoons. Solar farms can be made in Southeast Asia to meet energy demands, but they might not be necessary. Similarly, geothermal energy would not be ideal for this region, but can be used if necessary. As presented in Figure 5, the chances that a high performance geothermal power plant could thrive are not 0, but the chances are not very high. They are between 0.02-0.316 [Figure 5].

To provide energy for the region identified encompassing Indonesia and Malaysia, geothermal energy would offer itself as a good source of energy to meet their electricity demands. It produced 21.224 quadrillion BTU of energy, 95% from fossil fuels. It consumed 13.699 quadrillion BTU of energy, 93% from fossil fuels. This region is tectonically very active, prone to earthquakes and filled with volcanoes [30]. Indonesia currently produces 40% of the world's geothermal energy supply [8]. An energy mix consisting of mostly geothermal energy, but also hydro and tidal would be the most ideal for this region. Indonesia and Malaysia have the potential to produce over 1000 GWh/year of hydro power. Tidal energy would also work well in this region because they are surrounded by water on 3 or more sides. In regards to wind and solar energy, both are not good fits for Indonesia and Malaysia. On average, the countries have an annual photovoltaic power potential of 1607 [Figure 2] and winds at a speed of 4 m/s [Figure 3]. These renewables can be used if the others are not enough to provide Indonesia and Malaysia with the energy they need.

Japan, North Korea, and South Korea compose the final supergrid region in Asia. The region produced 5.026 quadrillion BTU of energy, 12% from fossil fuels. It consumed 31.809 quadrillion BTU of energy, 87% from fossil fuels. With onshore wind speeds ranging between 3 and 4 m/s in the area and offshore wind speeds between 8 and 10 m/s, the latter offers it-

Table 1 Summary of each supergrid region's total energy production and consumption values, along with each main category, in terawatts per hour. The table is organized by the 15 regions of the supergrid. The total production and consumption of each region is broken into 3 categories: Fossil Fuels, Nuclear Power, and Renewable Energy. The regions highlighted in red currently produce less energy than they consume, an issue for the supergrid because they are dependent on other nations for energy. It will be harder to make the transition to a 100% renewable based system for these regions [13,22]

	Total Production	Fossil Fuels	Nuclear Power	Renewable energy and other	Total Consumption	Fossil Fuels	Nuclear Power	Renewable energy and other
North America	36,608.09	29,315.90	2791.5	4500.69	33,716.36	26,917.11	2791.5	4007.75
Central America	1873.9	1576.43	32.24	265.23	3213.23	2719.99	32.24	461
South America	8573.5	5987.44	68.29	2517.77	7294.54	5125.23	69.46	2099.85
Northern Europe	2628.26	2237.6	0	390.66	621.6	196.65	0	424.95
Europe	7550.68	2367.72	2363.33	2819.64	9606.58	8139.17	73.85	1393.55
Africa	9525.4	9127.11	31.07	367.22	4664.23	4279.72	31.07	353.44
Ukraine, Belarus, Mongolia, Kazakhstan, and Russia	22,356.93	20,900.07	873.94	582.92	17,452.09	10,850.66	6047.81	553.61
China	34,523.19	28,784.85	816.79	4921.54	43,248.79	37,628.27	816.79	4803.73
Koreas & Japan	1472.98	179.36	587.61	706.01	9231.45	7994.98	538.96	697.51
India +	5993.6	4900.15	153.86	939.59	10,920.12	9796.49	153.86	969.77
Oceania	5037.89	4913.92	0	123.97	1800.92	1681.35	0	119.57
Southeast Asia	2146.75	1575.26	91.73	479.76	4437.98	3909.86	77.66	450.45
Indonesia +	6539.29	6201.68	0	337.62	4139.92	3869.12	0	270.8
Middle East	28,451.34	27,925.28	25.2	500.86	14,176.73	13,702.83	25.5	448.4
United Kingdom	1607.49	1134.48	156.5	316.52	2426.63	1934.86	156.5	335.27

self as a more efficient energy source. In North and South Korea, most of the region can produce 100-1000 GW/h annually of hydro energy [Figure 4]. Similarly, most of Japan can produce between 100-1000 GW/h yearly of hydro energy [Figure 4] and some areas are even predicted to be able to produce over 1000 GWh/year of hydro energy [Figure 4]. Solar energy is not suitable for this region as it only has a photovoltaic power potential of about 1022-1314 kwh/kwp [Figure 2], so this area would not be a good place for solar photovoltaic power. On the other hand, geothermal energy would be an amazing energy source for Japan, North Korea, and South Korea, because they have an 80-100% chance of the area being suitable for a high performance geothermal power plant [Figure 5]. This region in Asia is much more suitable for wind and hydropower in comparison to China because it has easy access to water on many sides. This increases the hydropower potential and wind speeds offshore, which can be taken advantage of by offshore wind mills.

Oceania

Oceania forms its own distinct supergrid region. It produced 17.187 quadrillion BTU of energy, 98% from fossil fuels. 6.096 quadrillion BTU of energy was consumed, 93% from fossil fuels. Australia has the highest solar radiation per square meter over any continent in the entire world [19]. For this reason, it is necessary to improve solar energy and to utilize it more in Australia, as it will help accommodate its electricity and grid needs. Australia has increased their use of solar energy each year [19]. Australia has an annual photovoltaic potential of between 1753-1972 kwh/kwp [Figure 2]. New Zealand and the other islands that make up Oceania are prone to storms, and only have a solar radiation of 3.6 kwh/kwp [Figure 2]. These islands and Australia are surrounded by water causing it to be very windy. The continent has wind speeds ranging from 6 to 12 m/s [Figure 3]. Hydro energy is a good fit for most of the region, such as in New Zealand, Papua New Guinea, Fiji, and the outer parts of Australia. These areas have the potential to produce over 1000 GWh/year of hydro energy [Figure 4]. Geothermal energy would work well in New Zealand, as it has between an 80-100% chance that the area is suitable for a high performance power plant [Figure 5].

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Africa

The last region of the global supergrid is continental Africa. It produced 32.936 quadrillion BTU of energy, 96% from fossil fuels. It consumed 18.846 quadrillion BTU of energy, 93% from fossil fuels. Onshore wind energy is a good fit for the northern region and the southern part of the continent; in North Africa, the wind speeds range between 8 and 11 m/s [Figure 3]. It would also work well in the most Southern countries of Africa such as Namibia, Botswana, and South Africa, where wind travels between 6-8 m/s [Figure 3]. Besides that, offshore wind energy would also work well off the coast of South Africa, as the wind speeds range between 7 and 11 m/s [Figure 3]. Central Africa is well suited for hydro power, as most of the region has the potential to produce between 100-1000 GWh/year [Figure 4]. Most of the region is a good place for solar energy, except for a small strip in the middle of the continent. The northern part of the continent has the photovoltaic power potential of 1899-2045 kwh/kwp [Figure 2] while the southern has the photovoltaic power potential of 1753-2045 kwh/kwp [Figure 2]. Lastly, the divergent plate boundary in Eastern Africa makes it a suitable spot for geothermal energy [Figure 5]. When compared to its neighbors in the Middle East, Africa is not very suitable for geothermal energy. However, hydro, wind, and solar power should be more than enough energy to supply the continent.

Challenges of the supergrid

Despite the many benefits, there are also some challenges to establishing a global supergrid. First off, each region is in a different place in regards to how much renewable energy they are currently using. This means that it will be easier for some countries to switch to a 100% renewable energy system in comparison to others. For example, as of 2021, 98% of the energy the Middle East produced and consumed was fossil fuels, less than 2% came from renewable and nuclear energy [Table 1]. On the other hand, 30% of the energy produced and 20% of the energy consumed by the United Kingdom was renewable or nuclear [Table 1]. This demonstrates the discrepancy between the regions in the supergrid and that each region will need to work together in order to reach a 100% renewable system.

Secondly, it will be a challenge for some regions to produce the same amount of energy as they consume. Even though the purpose of the supergrid is to prevent blackouts and allow energy to be transported to different regions, each region will need to attempt to make as much energy as they consume. The region comprising the Koreas and Japan produces only 16% of the amount of energy it consumes [Table 1]. Similarly, Southeast Asia produces less than 50% of the amount of energy it consumes [Table 1]. These two regions provide examples of regions that may struggle to match the amount of energy they produce and consume. However, many regions such as North and South America, Northern Europe, and the Middle East produce much more energy than they consume. This excess energy will be able to help regions to transition to closing the gap between their energy production and consumption.

Another challenge to establishing a global supergrid is connecting the dozens of regional grids around the world today. In order to connect these grids, we would need to build power lines that span thousands of miles across Earth's oceans[17]. Not only that, but while electricity is traveling from continent to continent, some may dissipate as heat, resulting in lost money[21]. A potential solution to this problem would be using high voltage direct current transmission lines. However, it would be extremely expensive to bury these lines under the ocean[21]. Another option for transporting electricity through the grid is by using the already existing undersea gas pipelines. The renewable energy would have to be converted into gas hydrogen, potentially using Proton exchange membranes, and once it reaches land, the gas would be converted back into electricity. This way, there aren't major costs in constructing new pipelines for the supergrid, however, it's inconvenient to convert the electricity to gas and back to electricity. Additionally, interconnector cables can be used to transport electricity over land, over short distances, such as neighboring countries[31].

Balance of the supergrid could easily be disturbed. For example, if climate change accelerates rivers could dry up, affecting areas that are supplied by hydropower. For this reason, it's critical to understand that the renewables supplying each region in the supergrid will need to be changed as time goes on. Additionally, the supergrid will need to be maintained, as wind and solar farms need to be replaced every few decades, which is another expense of the grid[21]. A potential solution to this is using more nuclear energy, which does not require as much maintenance and its waste can be contained.

These challenges only further prove that the need for a global system is necessary in order to make the transition to clean energy. Regions that are in a better place to make the transition to the 100% renewable supergrid will be able to help regions where there is more work needed. On the other hand, getting nations to produce extra energy for other nations is another obstacle. However, a global supergrid entails global cooperation and collaboration, countries helping each other, and without this the global supergrid won't be successful. It's going to be difficult to get every country to agree on the global supergrid, but if done, it could be the next step to reducing the effects of climate change.

Future Suggestions

This study offers a suggestion of a clean, ideal global supergrid. To establish this, it is essential that each nation

adopts a 100% renewable system, instead of using a fossil-fuel based system. I have made recommendations for each country/region on what type of renewable energy sources would work best in that area based on geographical location, climate, water cycle, and incoming solar radiation. I recommend 12 regions invest in solar energy, every region excluding Northern Europe, Japan and the Koreas, and Indonesia+. I further recommend 14 regions to invest in wind energy, and that all 15 regions invest in hydropower. Lastly, 13 regions should pursue geothermal energy, excluding the United Kingdom and Russia, Mongolia, Kazakhstan, Belarus, and Ukraine. Nuclear and biomass energy should be used to fill any additional energy demands and keep the grid stable and reliable. Other manuscripts such as [12,13,19,30] have had similar findings for individual regions within my global supergrid. They have used similar techniques, such as looking at a region's geographical location and climate to construct a plan for which renewables would be most suitable for the region.

Data and Methodology

It is essential to understand the current energy consumption and production for countries around the world. This information shows how much energy needs to be replaced by renewable energy sources to create a 100% renewable, carbon-free electricity grid. This data can be gathered from the EIA (Energy Information Administration)[23]. I was able to access the production and consumption values of each country from this website, and get the amount of solid fossil fuels, natural gas, petroleum, nuclear energy, and renewable energy that were being produced and consumed in each country. To access this information, I visited the homepage of the EIA website, went to the geography subpage, and then the international energy statistics. From there, I chose to look at the total energy production and consumption of each country, which split it up into categories based on different types of energy sources. After gathering this data, I split up the countries into larger regions that would ultimately create the regions in the supergrid. Countries were grouped into regions based on geographical location, water cycle, incoming solar radiation, and climate. My thought process in creating the regions was keeping the regions simple, while making sure the countries in each region experienced similar climate conditions. I focused on grouping countries together in a continental based system, and then splitting up some of the larger continents. For example, I split up Northern and Southern Asia, with the mountainous countries in one region and the desert and warmer nations in another region.

Secondly, it was imperative that I became familiar with each region to make an appropriate suggestion on what type of renewable energy would be the most efficient to produce in the given region. I looked at sources that focused on one type of renewable energy source in one region[19] and others that focused on a smaller-based supergrid[12], but still focused on the ideal mix of energy sources. From this data, I was able to better understand what countries had already done to implement renewable energy into their energy system, and what types of renewable energy sources were the most efficient and used the most in that place.

Lastly, I used maps of photovoltaic power potential[24], wind speeds[32], hydro power potential[27] and geothermal energy[25] to make informed decisions on what specific energy types regions should be focusing on. These maps (Figures 2, 3, 4, 5) were available under a Creative Commons Attribution License and were all accessed in July of 2021. I accessed the data in Figure 3 by the Global WInd Atlas, which provided each area's wind speeds[32]. I was able to obtain the data used in Figure 4 from its paper[27]. The authors of this paper were able to systematically survey all rivers and their discharge to estimate the average annual discharge of each location[27]. They were also able to calculate the gross capacity of a hydropower plant with the equation P= p * g * H * Q, where P is the hydropower capacity, p is the density of water, g is the gravitational acceleration, H is the head, and Q is the discharge[27]. The data in Figure 5 was obtained from another paper, where the author used a number of environmental parameters from global datasets in order to assess an area's suitability for a geothermal power plant installation[25]. I was able to get the data in Figure 2 by the Global Solar Atlas, which gave each area's photovoltaic capacity[24].

All this data was in the form of statistics and images found from the Energy Information Administration or other manuscripts listed above. Additionally, this data was accessed in July of 2021.

Conclusion

I have found that hydropower and wind energy should be used after sundown and stored during the day, while solar energy predominantly powers the regions during the day. This would allow the grid to be operated on a 24 hour cycle. Solar power does not have to be the only renewable energy providing energy during the day, but it is important to recognize that consuming all renewables equally throughout the entire day is impractical and not ideal to achieve the supergrid's maximum potential.

Furthermore, some countries, such as Pakistan, don't have renewable energy that is extremely suitable for the nation, which calls for other sources of energy. To keep the system as renewable as possible, it is recommended that these nations look to biomass and nuclear power as sources of energy and receive the rest of their energy supply through other region's extra energy, which can be transported through the grid.

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I have also found that some regions currently produce significantly less energy than they consume. In order for the supergrid to function well, each region's total production and consumption values need to be extremely close in order to prevent energy blackouts. In fact, the goal of the supergrid is that some regions create extra energy depending on the day, and this energy can be transferred to regions who were not able to meet their energy demands, as renewables are based on climate, which can be unreliable.

Overall, this study has found that almost every country is suitable for a healthy balance of different types of renewable energy to power the 100% renewable energy based super grid. This study proves that the global super grid has the potential to replace fossil fuels in the near future and make another step towards clean energy and reducing the effects of climate change.

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