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Abstract

Existing statistical data on the sources of global electricity generation show that the world has been very slow to adopt renewable sources of electricity generation to replace our over reliance on fossils for such generation. Most modeling agrees that over the next 30 years, global demand for electricity will at least double meaning there is a requirement to bring an additional 3 TW of electrical generation on line. Ideally these new forms of electricity generation should be renewable and sustainable. It is in that context where we examine the feasibility of OFF shore wind and its capability of delivering this required 3 TW. On balance, there is reason to be optimistic in this approach. This optimism is largely based on the relatively rapid deployment of OFF wind facilities, primarily lead by the UK beginning in 2013 with the completion of the London Array. In addition, OFF shore deployment in 2013 used individual 3.6 MW turbines whereas by 2023, 12 MW turbines will likely become the unit turbine per OFF shore array, This is a significant increase in the scalability of this technology and a global commitment to eventually produce and install 10,000 12 MW turbines on an annual basis will reach the target goal of 3 TW. Here, we examine various logistical and material limitations that could possibly hinder the deployment of OFF shore arrays and conclude such potential obstacles can be overcome, although innovative transport and assembly infrastructure will be needed for the 107-m long blades that comprise a 12 MW turbine. The relatively high capacity factor of OFF shore windfarms (40–50%) favors this technology over solar PV which has a much lower capacity factor. Furthermore, nuclear power has a history of relatively slow build out and it's very unlikely that this build out could be ramped up so that nuclear is a significant component of the required 3 TW; but in fact, since this can all be achieved through OFF shore wind, there is no real need for that alternative. As such, OFF shore wind production has a very bright future ahead of it and this should guide the necessary worldwide investment needed to help bring a new era of sustainability to the planet.

Off Shore Wind Power: A Promising and Scalable Future Electricity Source

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AQ1

Abstract. Existing statistical data on the sources of global electricity generation show that the world has been very slow to adopt renewable sources of electricity generation to replace our over reliance on fossils for such generation. Most modeling agrees that over the next 30 years, global demand for electricity will at least double meaning there is a requirement to bring an additional 3 TW of electrical generation on line. Ideally these new forms of electricity generation should be renewable and sustainable. It is in that context where we examine the feasibility of OFF shore wind and its capability of delivering this required 3 TW. On balance, there is reason to be optimistic in this approach. This optimism is largely based on the relatively rapid deployment of OFF wind facilities, primarily lead by the UK beginning in 2013 with the completion of the London Array. In addition, OFF shore deployment in 2013 used individual 3.6 MW turbines whereas by 2023, 12 MW turbines will likely become the unit turbine per OFF shore array, This is a significant increase in the scalability of this technology and a global commitment to eventually produce and install 10,000 12 MW turbines on an annual basis will reach the target goal of 3 TW. Here, we examine various logistical and material limitations that could possibly hinder the deployment of OFF shore arrays and conclude such potential obstacles can be overcome, although innovative transport and assembly infrastructure will be needed for the 107-m long blades that comprise a 12 MW turbine. The relatively high capacity factor of OFF shore windfarms (40–50%) favors this technology over solar PV which has a much lower capacity factor. Furthermore, nuclear power has a history of relatively slow build out and it's very unlikely that this build out could be ramped up so that nuclear is a significant component of the required 3 TW; but in fact, since this can all be achieved through OFF shore wind, there is no real need for that alternative. As such, OFF shore wind production has a very bright future ahead of it and this should guide the necessary worldwide investment needed to help bring a new era of sustainability to the planet.

AQ2

AQ3

1 Introduction

There is a great deal of momentum and interest in making both the near term and far term future operate in a much more sustainable manner that has occurred in the past. A principle way to achieve a more sustainable future lies in greater deployment of renewable electricity resources. In this contribution we outline some recent developments in OFF shore wind facilities and the promise that such facilities now offer. Recent

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examples of such development include the implementation of several OFF shore wind farms in the UK operating at scales larger than 200 MW with measured capacity factors that exceed 40%. In addition, the first small OFF shore wind facility consisting of 5 6 MW turbines has now come on line off the coast of Rhode Island and the world's first small scale floating wind turbine farm has been deployed off the coast of Scotland. The initial London Array (2013) was built with 3.6 MW turbine unit capacity. Similar offshore arrays built in the period 2015–2018 employed unit capacity of 6 MW; the recent UK Burbo Bank array is the first to use unit capacity of 8 MW and now there are firm plans to make use of the new GE Hailade 12 MW turbine in new arrays coming on line in the North Sea over the next 3–5 years.

The purpose of this paper is to highlight the quite remarkable and rapid progress made in the OFF shore wind industry over just the last 2–3 years to better emphasize the now large potential that future OFF shore wind deployment has in contributing to the world's electricity generation portfolio. Recent discussions of possible future electricity mixes tend to not include or even downplay this potential contribution [1–4]. However, this future has now been made particularly bright by the development of the 12 MW platform as unit capacity makes all the difference. For instance, approximately 50 GW of wind global wind power was added in the year 2018 through the deployment of 15–20,000 individual turbines indicating that the supply line is currently capable of supporting the building of this many turbines per year. An optimistic future suggests this supply line can continue to support the building of 12 MW turbines, at an approximate rate of 10,000 turbines per year, and that the potential logistical obstacles associated with producing and transporting the required 107-m long rotor blades will be overcome.

But, renewable electricity resources, no matter what they are (wind, solar, biomass, ocean waves, ocean currents) are confronted with a very daunting scale. Currently, human activities produce electrical power mostly from a feedstock involving the dwindling supply of fossil fuels. The current scale of planetary electricity generation is approximately 3 Terawatts (TW) (see Fig. 1). While the ambient energy that nature provides us far exceeds this value, there are significant engineering, material and logistical barriers to building enough devices to capture this ambient energy at our current scale of use, let alone future use increase. A good example of these difficulties lies in potentially capturing the tremendous wind power that is available along the Aleutian Island chain [5]. Since TWe for the planet will likely double over the next 30 years, it is imperative that scalable forms of renewable electricity devices be designed and deployed. OFF shore wind installations have rapidly experienced this scalability as 3.6 MW turbines have gone to 5 MW, 6 MW, 8 MW and now 12 MW planned for the Dogger Bank wind farm located in the North Sea.

In this paper we further explore the scalability of OFF shore wind farm development as the primary means to replace the future loss of electricity generation from dwindling fossil fuel supplies. We begin in Sect. 2 by describing the present global electricity mix and its past evolution to show that the evolution, to date, toward renewables has been quite small on the global scale. From that data we are able to show how global electricity demand has scaled with world population growth. From that scaling we present a future electricity mix that includes 1/3 renewable of "green" power. In Sect. 3, we examine the recent growth of global wind in general, and OFF shore wind specifically. We then discuss potential barriers to the sustained growth of wind electricity production. These barriers include possible supply line constraints and possible material limitations. In Sect. 3.3c we explicitly discuss the important issue of wind amplitude variability or intermittency and the possible needs for energy storage to smooth out these fluctuations. In Sect. 4 we give a very specific future forecast for global wind capacity and how it can account for most of the world's new renewable electricity generation. Concluding remarks are contained in Sect. 5 where we emphasize that among all the future possible scenarios, one thing remains crystal clear – future forms of electricity generation will not be a repeat of the past.

2 The Present Global Electricity Mix and Its Past Evolution

For future guidance it is always useful to look at past behavior as this behavior has served to produce both cultural and technological inertia that makes change difficult, even when such change is absolutely necessary. This inertia must be overcome so that our near future is not a repeat of the past. This generality easily explains why fossil fuels remain dominant, despite likely globally negative changes to the Earth's climate system. This dominance of fossil fuels can be seen below, where the information is provided by the International Energy Agency (IEA) through their publication *Key World Energy Statistics* [6]. For the year 2015, the global electricity profile was:

- Fossil Fuels 66%
- Nuclear 11%
- Hydro 16%
- Other Renewables 7%

Since it is quite unlikely that the fossil fuel contribution will grow with time, the issue comes down to what other sources are the most feasible to deploy for the world to be able to meet future electricity demand. In particular, over the 1971–2015 time period global population grew by a factor of 1.95, but global electricity production has grown by a factor of 4.5. This suggests a scaling of

$$(Electricity\ Production)\,\alpha\ Pop.Growth^{2.25}$$

Indicating that per capita use of electricity increases. It is likely that the exponent of 2.25 will remain this high in the future as result of the continuing development of much of the world. Indeed, over the time period 1950–2000, the relevant exponent for the US was 3.5. We can therefore adopt a simple future scenario where the exponent is 2.25 and the future population of the world is 10 billion by the year 2050 (2017 UN projection). Under that scenario, TWe demand will grow by

$$(10/7)^{2.25} \sim 2.23 \sim 6.7\,TWe$$

to meet the needs of 10 billion by the year 2050.

The dominance of fossil fuel electrical power can clearly be seen in Fig. 1 which plots increased global electrical generation from 1971–2015. Here the Y-axis is in units

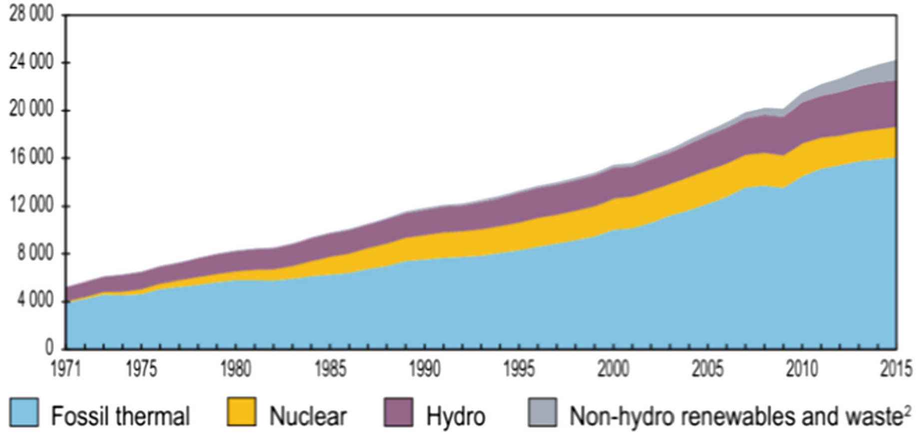


Fig. 1. Historical Sources of Electricity Generation. [1]Units of electricity generation energy are annual TW-hours. [2]This includes wind, solar and co-generation involving biomass waste and residues

of TWH per year. In 2015, 24,255 TWHs of electricity was produced which corresponds to a constant electrical power of 2.75 TW.

We can further break down the components of Fig. 1 into Table 1 which compares the global electric portfolio "evolution" between 1973 and 2015. This breakdown indicates that it took 30 years for the fossil fuel contribution to decline by a mere 10%; our future will require a much faster rate of decline than this past rate.

Table 1. Evolution of electricity feedstocks

Source	1973	2015
Coal	38%	39%
Oil	25%	4%
Natural gas	12%	23%
Total fossils	75%	66%
Nuclear	3%	11%
Hydro	21%	16%
Other	1%	7%

- The use of natural gas fired electricity has just about doubled its contribution to the world's electrical portfolio. The world has de facto chosen this path rather than the renewable electricity generation path, over this time frame with a belief that this choice does significantly decarbonize the electrical grid [7]. The overall sensibility of this path is greatly compromised by the lack of appropriate carbon and capture storage facilities [8].

- Nuclear power has almost tripled its contribution to world electricity production. However, as discussed later, it seems very unlikely that this rapid rate of growth can be sustained.
- Renewable sources of electricity generation only increased their contribution to the world's electricity portfolio by a mere 6% over this 32-year period. The lack of appropriate technology over this time frame is a contributing element to this slow growth of renewables. In particular, large unit wind turbine (>2 MW) capacity did not occur until approximately 2005.

In Table 2 we show the changes in overall fuel source for electricity production in different parts of the world again over the time period 1973–2015. These regions are (a) the 34 countries comprising the Organisation for Economic Co-operation and Development (OECD), (b) China, (c) the Middle East, and the rest of the world countries (ROW). The numbers in the table represent the per annum production in 2015 compared to 1973 for various fuel sources in these 4 principle regions. For example, China had 30 times more electrical production using hydro in 2015 compared to 1973, while the ROW used 8 times more hydro in 2015 compared to 1973. The larger the number in Table 2 the more it represents either new discovery and access to new resources in a particular region, or a new investment strategy. The smaller the number indicates that region is constrained by the kind of inertia previously discussed. Note that currently we are well removed from being a world which engages in global decision-making strategy and implementation – instead this is mostly done at the country (e.g. China) or regional level (e.g. Middle East, EU) and so it is instructive to analyze that regional behavior. AQ4

Table 2. Changes in electricity generation by fuel sources

Region	Coal	Oil	Natural gas	Hydro	Wind*
OECD	1.0	1.5	1.5	1.55	6
China	7.7	3.6	NA	30	88
Middle East	NA	1.4	22.8	NA	NA
ROW	1.67	1.5	5.1	8	9.5

Some of the main elements shown in Table 2 include:

- The OECD, aside from wind, has not shown very much growth in resources devoted to electricity use. Thus, OECD countries are increasingly reliant on net imports of electricity sources to meet increasing demand.
- China is clearly ramping up its coal production and by now (2019) is responsible for about 50% of global coal production, yet China continues to import coal (primarily from Australia). At the same time, China is the clear world leader in ramping up renewable electricity generation by way of hydro and wind. The Three Gorges Dam, completed in 2008, is the world's largest at 18,000 MW. Since then, additional turbines

and powerhouses have been added to make it a 22,500 MW facility. Future plans, yet to be realized, are to harness some 65,000 MWs of power from rivers on the Tibetan Plateau. Also, in 2015 China added more wind power than the ROW combined and has ambitious plans to continue in this direction.

- The Middle East starting discovering large pockets of natural gas (NG) in the early 1970s at a time when that resource was not immediately needed. These gas fields are generally located in or near the waters of the Persian Gulf. The country of Qatar is ideally located with respect to these offshore gas fields and was one of the first countries to export this product on a large scale. The overall large rate of growth for NG production in the Middle East has arguably been the single biggest factor in maintaining our use of fossil fuels as preference over investing in renewables.
- The ROW is discovering sources other than traditional coal and oil. Although this region has more limited ability to develop large scale facilities, their recent development of new hydro and wind resources is a bright spot for future changes in the global electricity mix.

2.1 A Future Scenario

Using the previous information as a guide, future electricity mix scenarios can be proposed. The basic challenge is whether or not sufficient new kinds of infrastructure can actually be built at the capacity to meet various target goals. An example scenario, among many that are possible, is shown in Table 3 where a doubling of electrical demand is predicted over a timescale of 30 years [9–11]. This scenario has the following baseline assumptions:

Table 3. A possible future global electricity mix

Source	Now	Now +30
Coal	39%	17%
Oil	8%	0%
Natural gas	20%	16%
Total fossils	67%	33%
Nuclear	17%	33%
Hydro	16%	10%
Solar	0	8%
Wind	0	11%
Bio + geo	0	5%
Total “green”	16%	34%

- Oil as an energy source will be exhausted in 30 years
- For wind and solar we start with 0 compared to what is needed in 30 years.

The principle features in this particular scenario are

(a) the contribution of nuclear electricity will double
(b) wind +solar will increase from 0 to 20% of the total electricity portfolio;
(c) the use of coal dramatically decreases.

This particular scenario, especially component c, would apply to a policy choice that prioritizes decarbonization of world electricity generation over the next 30 years. Under this scenario as well as others it remains to be seen if new resources can be built and implemented over this 30-year period. A major uncertainty in any future scenario is the overall role that conservation might play in determining the timescale over which electricity demand doubles from its current value. This particular scenario does not factor conservation in as there is no evidence yet that conservation has ever even occurred on a significant scale. The main difficulty is that, while the developed world may begin to practice better conservation habits, much of the world remains undeveloped and their per capita use of electricity will accelerate while countries in the developed world may decline somewhat. This doubling over 30 years scenario (a) argues that per capita increases in electricity use in the developing world far outpace any conservation strategies in the developed world and (b) requires the deployment of devices that can yield 3 TW of new electrical power.

How can the need for 3 TW of electrical power best be met? When an electrical power device is built (e.g. a 5 MW turbine) its power output is referred to as nameplate capacity (in this case nameplate would be 5 MW). Nameplate capacity represents the power output of a device under ideal conditions. The actual power output is a convolution of the nameplate capacity and the operating efficiency, often called the capacity factor (CF). Nameplate capacity, however, is a useful concept since that represents the total investment in some technology. For example, it will cost the same to build and install a 5 MW wind turbine, independent of location. If it were installed at a place where the wind never blew, then clearly that would be a waste of money. Instead, one wants to ideally install the 5 MW turbine at a location where the wind blows the greatest percentage of time.

As an example of how CF determines overall throughput, we can compare nuclear electrical power vs solar electrical power. At the end of 2017, both solar PV and nuclear, coincidentally, had a global installed capacity of about 390 GW. Electricity generated from nuclear power in 2017 was about 2500 TWHs (11% of global generation) indicating a capacity factor of 73%. Electricity generated from solar PV was about 375 TWHS (1.6% of global generation) indicating a capacity factor of 11%. This low CF for solar PV is simple to understand. Rated (nameplate) solar power for PVs refers to peak power when the sun is directly overhead. However, fixed PV panels illuminated over the course of the day have an average power of approximately 25% of peak power. As the panels are illuminated only ½ of any 24 h period, on average, here is another factor of 2 loss leading to an overall throughput of 12%.

Under perfect conditions (CF = 100%) 1 TW of power produces 8760 TWHs of electrical energy for that year. For PV, nuclear and wind, 1 TW of new nameplate power then produces 963, 6394, and 3942 TWHs of new electricity respectively (here we assume that new wind is OFF shore with CF ~45%). What weighted combination of sources, given their respective CFs, can produce 3 TW per year (~26,000 TW hours/year)? One example target could be a combination of 50% wind, 30% nuclear and 20% solar PV. This would require about 5.5 TW of new solar nameplate, 1.25 TW of new nuclear nameplate, and 3.3 TW of new wind. Are any of these nameplate targets remotely possible to achieve over the next 30 years?

For solar growth (mostly solar PV), the last few years has been rather extraordinary due to large scale Chinese manufacturing of panels that has brought costs down on a worldwide basis. At the end of 2013 there were 137 GW of global capacity and by the end of 2017 there was ~400 GW, with 81 GW installed in 2017 alone. In 2014 there was only 40 GW installed. Thus, production doubled in 3 years. But exponential scaling at high rates can never occur over many doubling times as at some point, the amount of new facilities one needs to build to make twice as many turbine blades, or twice as many PV panels as the prior 3-year period becomes physically challenging (see example below). Going from the 2017 value of 400 GW and scaling that to the 30-year requirement of 5.5. TW would require a sustained annual growth of production of ~9% or a doubling time of 7.7 years. While difficult, this does suggest that continued production and growth in the PV industry could meet this 30-year goal.

For nuclear power, the current installed capacity of 392 GW is met by 450 nuclear power plants indicating an average capacity of 0.87 GWs. Recently constructed plants are at nameplate capacity of 2 GW. In the United States the average time it takes for a new nuclear plant to come on line, from design through approval, building, and inspection, is about 17 years [12]. The process is quicker in other parts of the world but still occurs over many years' timescale. If each new plant is rated at 2 GW then 600 new nuclear plants will have to be built and come on line over the next 30 years; this equates to 20 new nuclear power plants per year. In addition, it is likely that some older nuclear power plants will be decommissioned over this time frame which will then require more than 600 new plants be built. Hence, the construction of new nuclear facilities is unlikely to occur at a sufficiently high rate to reach this 30-year goal.

The situation for Wind is much more favorable due to the emergence of off shore wind power in the UK and Germany as a proven viable technology including the world's first floating OFF shore wind farm off the coast of Scotland. OFF shore wind also has higher CF than onshore with values in the range of 40–50%. At the end of 2017 there was approximately 540 GW of installed wind capacity, with an average of 56 GW added per year over recent years. Recent world data suggests a doubling time for cumulative global wind power of ~5 years (see below). These considerations show that 3.3 TW of new wind generation could be produced in less than 20 years! Thus, wind power, and particularly OFF shore wind power should be regarded as a promising choice for increasing the world's share of renewable electricity generation as it can be built out at a much larger rate than nuclear power and has much more favorable CFs than solar power. We now give full consideration to this potential.

3 The Near Future Promise of OFF Shore Wind

In the previous section(s) we have presented the data view of current and future world electricity mixes and have established the following trends and concepts:

(a) Globally we have not yet taken the implementation of renewable electricity sources at scale very seriously. We continue to overly rely on fossil electricity generation and most of that is now from the use of natural gas. At the moment, especially in the US, the use of natural gas is being treated like the initial use of oil – natural gas reserves are being regarded as essentially infinite.
(b) Since electricity growth is larger than population growth it is reasonable to expect that global demand for electricity will increase on a 30-year timescale and we adopt that timescale as the doubling time for electricity demand.
(c) Over the representative period from 1970–2015 the data show very little increase in the contribution of renewable sources to the global electricity generation portfolio and overall exhibit a decrease of only 10% in the fossil contribution.
(d) Fossil resources are dwindling and all future electricity generation schemes should not rely on fossils as an increasing feedstock.
(e) A future new electricity mix must use growth in wind, solar and nuclear facilities as the primary means of generating more electricity. Of these alternatives, wind seems, by far, to be the most feasible choice.

It is in this context that we now examine recent behavior in the global wind industry, particularly recent developments in OFF shore facilities, discuss some possible limitations to sustained growth, and evaluate the overall ability for OFF shore wind facilities to become a major source of electrical generation on the planet.

3.1 Global Growth of Wind

We begin by examining the global growth in wind power production as shown below in Fig. 2, which show both cumulative installed growth and annual capacity additions: AQ5

Overall the data portrayed in Figs. 2 and 3 show three central trends:

(a) From 2000–2017 global wind growth is strongly exponential indicating an average annual growth rate of ~20% and this growth rate has been able to be maintained, primarily because the unit capacity turbines have increased by a factor of 2–3 over this time period. This kind of unit capacity scaling is the major advantage that wind deployment has over other alternative approaches.
(b) If the growth rate can somehow be maintained, then on just the 10-year time-scale we will have reached a capacity of .540 * exp (.2 * 30) = 4 TW. At average CF of .33, this equates to 1.33 TW of generated electricity. Thus, we are on a path where 1TW of electrical power from wind is in our near future.
(c) China is completely outpacing the rest of the world in terms of capacity additions having added 150 GW of wind power over the period 2010–2017 compared to 60 GW for the ROW. Whether this continues is very hard to say.

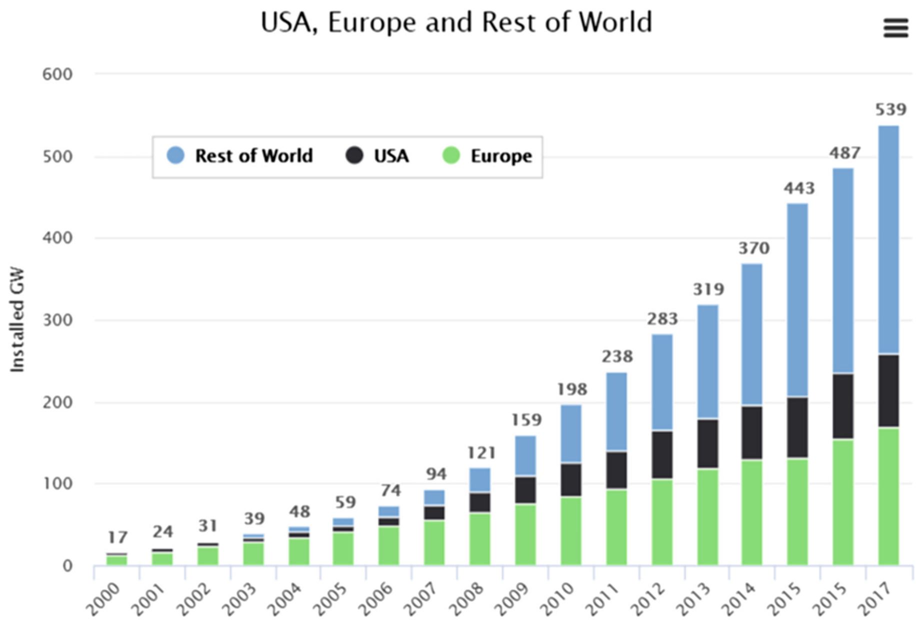


Fig. 2. Cumulative growth of global wind power

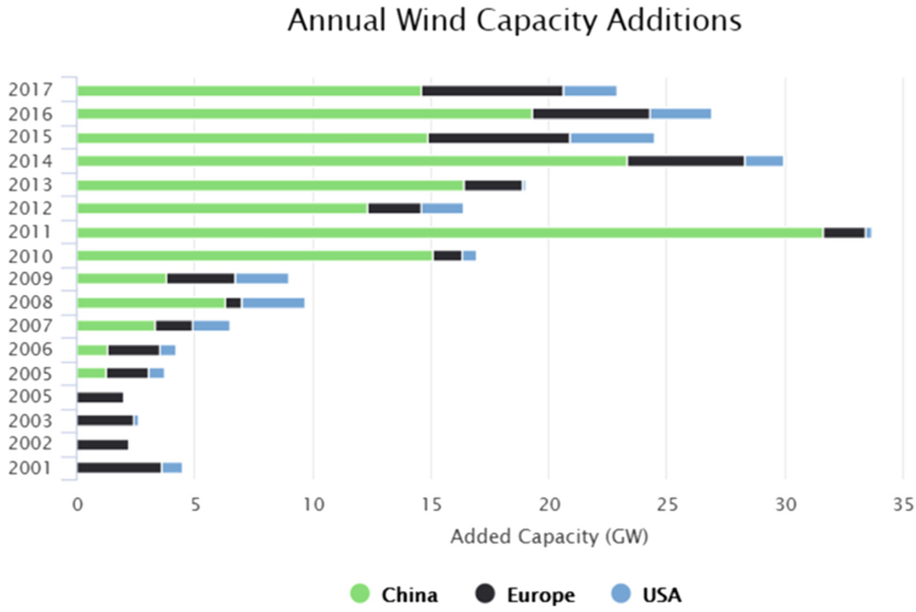


Fig. 3. Annual capacity additions to global wind

3.2 The Recent Emergence of OFF Shore Wind

By far the most important recent development in the deployment of wind power lies in the operational development of OFF shore arrays which are able to better utilize large unit capacity turbines. The era of large unit capacity OFF shore wind turbines likely started in 2013 with the commissioning of the Arnholt Wind Farm in Denmark. This 400 MW facility uses 111 3.6 MW turbines placed at a distance of 21 km from shore in water depth of ~15 m. This was followed up with the May 2015 commissioning of the Westernmost Rough wind farm that uses 35 6 MW turbines. Both of these windfarms took 5–6 years to go from planning to operational status, indicating the logistics associated with OFF shore wind farm construction is significantly longer than ON shore facilities. In addition, both of these projects were strongly aided by the feed in tariff policies of the European Union that were operational at this time (note: it is beyond the scope of this contribution to discuss the recent volatility in EU subsidies regarding wind power, even though OFF shore wind has proven to be enormously successful).

Most recently, as of April 2017, 32 8 MW turbines were added to the existing 25 3.6 MW turbines located at Burbo Bank located just off shore from the Northern Wales, Western England boundary. Hence, we have now entered the 8 MW turbine era and GE is designing a 12 MW turbine (The Haliade-X) that is 833 feet tall with rotor blades of length 107-m. While not deployed yet, these turbines have been built for the European Union OFF shore wind market. This is the kind of scalability advantage that wind power has over other devices and it is the OFF-shore environment that can best leverage this scalability. The largest scale OFF shore facility built to date is that of the London Array. This currently consists of 175 3.6 MW turbines located 20 km off shore in maximum water depth 25 m. Figure 4 displays a portion of this array.

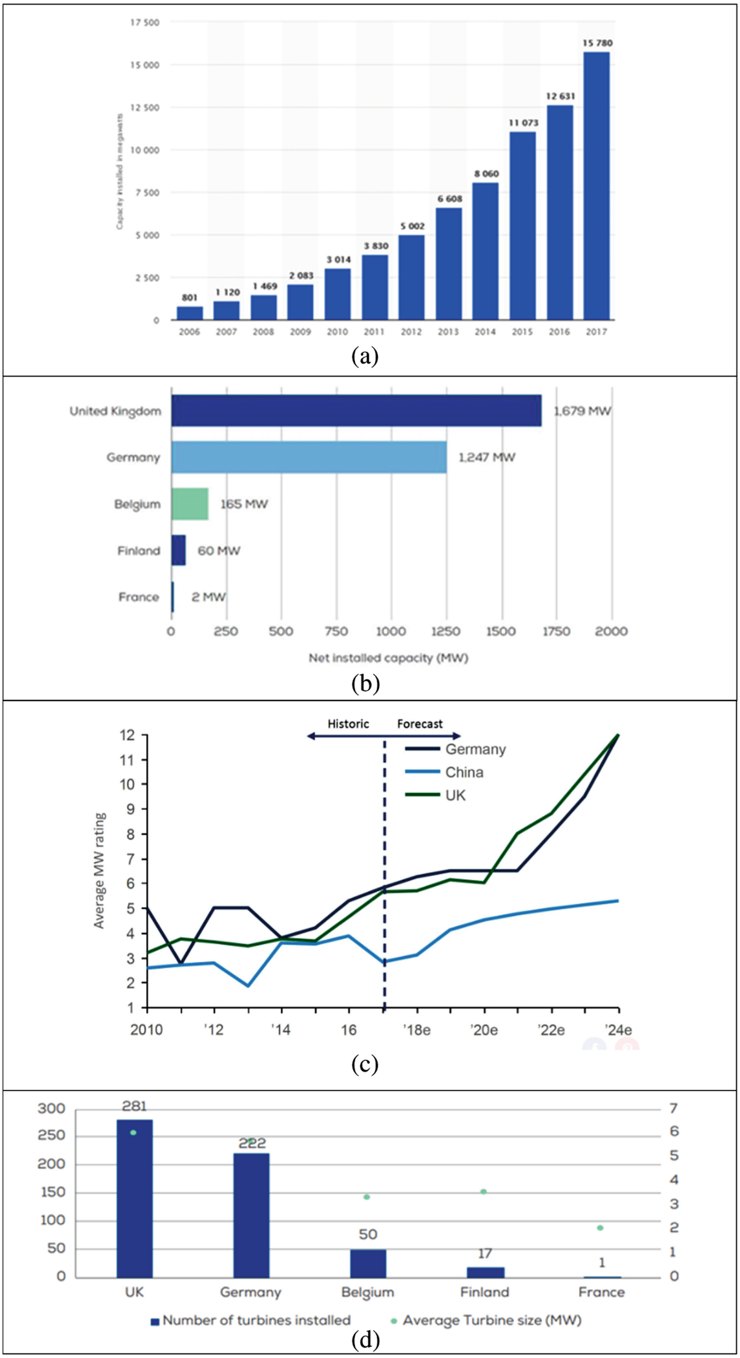
Fig. 4. Aerial view of 20% of the London Array. Here we see 5 legs each with 9 turbines along their length.

The overall growth of the European OFF shore wind industry is well described by exponential growth at 27% per year. This of course mimics the growth rate of ON shore wind in the USA in its infancy. Given some of the logistical complications in making OFF shore wind farms this astounding rate of growth is certainly not likely to be maintained. For future global wind forecasting, it is now clear that future OFF shore facilities have to be included. Current annual growth of OFF shore wind is at about 1.5–3 GW per year. In the case of Europe, this growth is dominated by the UK and Germany, both of which have good access to large regions of low water depth. However, most promising in OFF shore wind is the move towards larger and larger unit capacities. While 8 MW turbines have been installed, there is a plan to move towards 12 MW turbines as of 2024. These various aspects of the development of OFF shore wind are summarized in Figs. 5a-d below.

In October 2017, the world's first floating windfarm, the Hywind Project, was commissioned 22 km off the coast of Scotland. This wind farm consists 5 6 MW turbines that are encased in a floating ballast that is anchored to three moorings on the ocean floor. Thus, the turbines above the surface water are floating and drift slightly in their positions. These kinds of structures can be placed in waters as deep as 700 m. While Hywind does offer proof of concept, it remains to be seen how well this kind of infrastructure can be scaled up. At the moment, there seem to be two principal limitations: (a) the current Hywind facility remains relatively close to a mainland so that a 22 km electrical cable can be run between the array and the mainland; clearly in deeper waters more remote from a mainland, the more problematic it will be to export electricity via cable and (b) this project was very expensive in comparison with the ON shore price of wind. Specifically, the Hywind floating array had a capital cost of $235 million for 30 MW of production, or 8400 dollars/kW. For comparison, a typical ON shore wind farm cost in the US is 1750 dollars/kW [13] and the London Array of 630 MW had a capital cost of 2.4 billion dollars or 3800 dollars/kW. Hence, without strong subsidies it may not be cost effective to build these promising new facilities.

3.3 Possible Barriers to Continued Growth of Wind

There is a large body of literature and reports on the state of the wind turbine supply chain through time [14–16]. The overall logistical challenge includes the selection of a turbine site; the appropriate turbine design that can be placed at that site; acquiring all of the materials needed for production and fabrication; manufacturing each component; transporting sizeable components to installation sites; installing turbine components; connecting the turbine to the appropriate electrical grid; and maintaining each component throughout the lifetime of the turbine. That involves a wide variety of vendors which need overall coordination. As an example of a logistical challenge in the case of an ON-shore facility, a single wind turbine can require up to eight deliveries – the nacelle, three blades and three to four tower sections. A hundred turbine wind farm would therefore involve 800 deliveries over the course of construction after the components have been delivered, usually by rail, to some distribution site. Furthermore, the components needed for turbines of capacity beyond 3 MW generally exceed the height and weight restrictions for transport on US roads. To overcome this, blade lengths for 3.0+ MW turbines have to be delivered by rail shipment, on specially designed railroad cars for the longer length



(a)

(b)

(c)

(d)

Fig. 5. a. Cumulative growth in OFF shore wind capacity in Europe. b. 2017 OFF shore wind installations by country. c. Predicted increase in OFF shore turbine capacity. The most recent instillations have utilized turbine sizes of 6 and 8 MW. d. Number of OFF Shore turbines installed in 2017 and their average power

blades to maneuver around corners [17]. In the US, such rail deliveries are generally restricted to the relatively flat areas of Texas, Kansas and Oklahoma. Indeed, the only occurrence of 3.6 MW turbines is the 17-unit instillation Cirrus Project in a very flat area of West TX. For ON shore installations there was no incentive for turbine manufactures to really construct larger turbines, hence, during the initial build period of the London Array, these were the largest available turbines. Six year later, that limitation has now completely changed.

The recently completed Block Island wind farm off the coast of Rhode Island used 6 MW turbines which have blade lengths of approximately 75 m. The recently installed 8 MW turbines at Burbo Banks have blade lengths of 88.5 m and the blade length for the 12 MW turbines under design is 107 m. Single blades this long can only be manufactured at coastal locations where the blades can then be delivered by specially designed boats. For the case of the UK installations, it was the Fred Olsen company that solved the logistics of blade delivery through the innovative design of vessels (e.g. the Brave Tern vessel) that not only allows for blade transportation but an adjustable platform that allowed workers to assemble the blades at the tower site. Studies [18, 19] of OFF shore wind farm logistics suggest an optimum strategy of minimizing the number of components needed for installation on site and maximizing the number of turbines that could be loaded on a given vessel. This strategy becomes particularly important for the potential case of floating windfarms positioned more than 100 km offshore. In addition, consideration of real weather is important. For example, while the North Sea region has a large wind resource, it has been estimated that installation is only possible for about 120 days a year [20, 21] as the large components that need to be installed are subject to large wind loads, which could prove catastrophic. The situation in the Aleutian Island, where there are terawatts of wind resource [5], represents an even more extreme environment where installations might only be able to be done 60–90 days a year.

The above considerations indicate that blade transportation may become a growing source of logistical complications which will negatively affect the future growth of wind deployment. As a result, there is now renewed interest in the concept of the segmented blade, where the individual segments can be more easily transported for onsite assembly and mounting to the nacelle. Currently, only the company Enercon makes and installs segmented blades using their own proprietary technology. This unique blade design makes it then possible to install the Enercon 6.2 MW turbine in ON shore locations, though typically near a coastline such as a few single turbines in the Netherlands. A recent review [22] of the promise of future segmented blades strongly suggests that this overall approach is needed to facilitate the swifter construction of OFF shore wind farms as well as lowering the overall cost. Currently the largest wind turbine being considered comes in at 9.4 MW and has 90-m long blades. If we are to move to still large turbine capacities, segmented blade design requires careful consideration.

3.3.1 An Example Supply Line Constraint

To show the potential supply line constraints that could limit the scalable deployment of wind turbines we offer a simple model to illustrate the problem. This model is anchored in the real-world case of the Vestas blade manufacturing facilities in Colorado. In March 2008, Vestas opened its first US blade construction facility in Windsor Colorado. That operation required about 400,000 square feet of manufacturing space to produce 1200 blades per year for 1.6–1.8 MW turbines. Approximately 5 years later, a second facility was opened in Brighton Colorado that produces longer blades for use on turbines of 2–3 MW capacity. That facility can produce 1800 blades per year. Now let's consider a scenario in which these are the only two facilities in our wind turbine construction pipeline and in year 1, 2/3 of infrastructure capacity is used – that means 800 blades for 267 turbines, leaving 400 excess blades in storage to be available for the following year along with 1200 new blades. Using these facilities, we then try to sustain a 23% annual build out rate (i.e. we double production every 3 years). Table 4 shows the results obtained under this scenario. This approach is highly scalable for any growth rate given a starting condition -e.g. 2/3 of available supply.

Table 4. Example of blade production shortfall with respect to facility buildout

Year	Available blades	Turbines	Blades required	Blades left
1	1200	267	800	400
2	1600	328	984	616
3	1816	403	1210	606
4	1806	496	1489	317
5* (2nd facility)	1517	610	1831	−314
6	2686	751	2252	434
7	3434	923	2770	663
8	3663	1136	3407	256
9	3256	1397	4191	−935

From this example we quickly see the law of diminishing returns where, even if new facilities come ON line, sustaining a given growth rate requires that similar facilities be built in increasingly less time. Arguably, this is the reason that the US rate of growth was initially exponential (up until 2012) but then transitioned to a more linear trend. For any scheme a point is eventually reached that the number of annual units that need to be built to sustain a given growth rate, requires a significant increase in facilities relatively quickly. To a large extent, in terms of installed power, growth can be better maintained by increasing turbine unit capacity, and therefore blade length. Most blade turbine facilities are able to retool to assemble, up to a point, longer length blades to be placed on larger unit capacity turbines. Note that this possible kind of supply chain limitation is the biggest potential advantage to OFF shore facilities as fewer blades per generated GW need to be built. However, the logistics of blade delivery in this environment requires some innovative solutions, like that of the special vessels for turbine deployment in the London Array.

3.3.2 Possible Material Limitations

To date, there have been numerous studies on the issue of whether or not renewable electricity device build out is limited by remaining Earth materials [23–29]; with far ranging conclusions from there being severe limitations to there being essentially none. Material shortages for the construction of wind farms come in two forms, (a) the need for steel, aluminum and copper to build large towers and the nacelle components and (b) the need for neodymium and dysprosium to power high efficiency magnetic motors. Since blades are made out of various kinds of composite materials, there doesn't seem to be much of a limitation there. Note that the future supplies of neodymium and dysprosium are the most crucial as there is strong competition with electric vehicles (EV) for this supply. In addition, for most of these critical metals, new production is consistently falling short of increased demand. This means that even if a resource is not physically exhausted, its price may sky rocket to the point that future projects may no longer be cost effective. From the available data [24], Table 5 summarizes the current situation with respect to the key resources needed for future wind deployment compared to its main resource competitor in the development of 1 million EVs.

Table 5. Assessing the vulnerability of attaining 2 TW of wind power using the indicated materials

Material (1)	Wind (2)	EV (3)	$/ton (4)	Availability (5)	Wind (6)	EVs (7)	Vulnerability (8)	Costs (9)
Steel	103000	1E6	81	230.E9	2.E8	1.E8	1.E-3	33
Aluminum	1060	70000	1940	55.E9	2.E6	7.E6	1.5E-4	8
Copper	3000	25000	5660	3.5E9	6.E6	2.5E6	2.5E-3	68
Dysprosium	28	90	240000	2.E6	5.5E4	9.E3	3.E-2	27
Neodymium	198	750	42000	2.5E7	4.E5	7.5E4	2E-2	33

Column 1 is the metal; Column 2 is the number of tons needed for 1 GW of wind power
Column 3 is the number of tons needed to produce 1 million electric vehicles (EV).
Column 4 is the 2015 price in US dollars per ton; Column 5 is the estimated available resource in tons
Column 6 is the amount of resource (tons) needed to build 2 TW of new wind generation
Column 7 is the amount of resource(tons) needed to build 100 million new EVs.
Column 8 is the ratio of these build resources to estimated availability; Column 9 is total cost in $billions

The overall vulnerability to resource depletion is represented by the ratio numbers in column 8. To first order, using this simple methodology, there seems to be no concern for these 5 resources as none of them even approach the 10% level of remaining resource. Not surprisingly, the two items which have the most resource concerns about future availability are neodymium and dysprosium. For the other components, there seems to be no basis for concern. In terms of future costs, we note that they are quite similar for steel, neodymium and dysprosium material though we suspect that the price escalation of the latter two will become considerably higher. The use of copper to support 2 TW of new wind development is the most expensive resource item. Overall, however, it seems we easily have the physical resources required to build 2 TW of new wind electricity production.

3.3.3 The Intermittency of Wind

There are three forms of "intermittency" that an be used to describe the erratic behavior of wind. Often times these terms are used interchangeably but they really refer to variability over different timescales:

Variability: this refers to the amplitude change of wind power per turbine on the timescales of minutes and is not the kind of intermittency we are addressing in this section.

Intermittency: This refers to a 24-h period which may see several hours of reduced power output from a particular array. Various energy storage schemes (described more below) are now being considered as a mechanism to smooth out these variations over this 24-h period.

Capacity Factor: This refers to the percentage of time, over any given year, in which a facility generates power at its nameplate capacity. These capacity factors can vary a bit from year to year [13] due to seasonal fluctuations within a given year or as a consequence of shifting winds possible related to climate change [30].

The intermittent nature of wind power generation is a well-studied operational issue [31] since grid operators need reliable forecasts for future availability to the grid, especially when wind is used as part of the baseload generation profile. A variety of approaches and sophisticated computer models are now available and being put into use [32]. Since this intermittency is intrinsic to the nature of wind, it cannot be engineered away by different kinds of turbines or wind farm designs. About the only thing that can be practically done would be for large arrays of wind turbines (order 1000 turbines per array) over a large area (like the American Midwest) so that it raises the probability that the wind is blowing over at least part of the array structure all of the time. This large array approach, while currently only operational for the London Array, is quite conducive for OFF shore facilities.

Ideally, as an intermittent source of electricity production, wind should not be relied upon to contribute to baseload power generation. Instead it should be viewed as an auxiliary source of power that can be used in times of peak power to charge up some kind of energy storage system. When wind becomes part of the baseload, then grid management problems inevitably occur. Germany has seen instances where reduced winds, on an hourly basis, over the whole country has resulted in rolling brownouts as the grid response to managing that electricity deficit. There have been other occasions, where the wind has caused a temporary over production of electricity, relative to demand, and therefore some turbines must simply be turned off. This situation demands that the excess power in these times be re-routed to an off-line energy storage system. As discussed below, such facilities are now being incorporated in to the latest generation of German wind farms. This intermittent behavior is universally seen and Fig. 6 shows an example for Ireland where a total variation of 500 MW is observed over a particular 24-h period and there is only about a 6-h period in which the output is relatively constant. To compensate for these fluctuations, it would seem desirable that Ireland would have a 200–400 MW storage system.

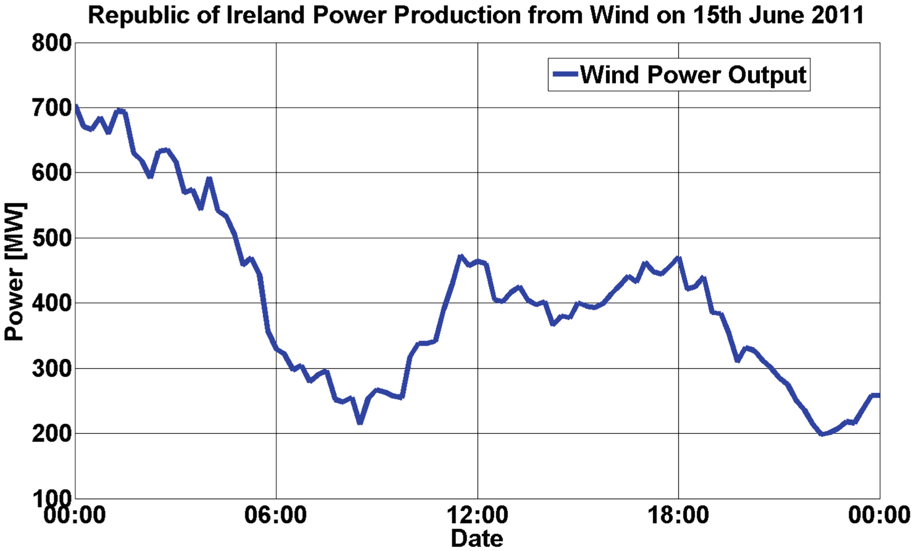


Fig. 6. Example of intermittency of wind generated electrical power over a 24-h period

To date most wind farms do not have energy storage integrated into them, with the exception of two cases that can serve as a future model. Germany has recently come ON line with an experimental 4 turbine project that will pump water to an eventual height 90 m that is stored inside the lower part of the turbine structure itself. That wind farm, located in the Swabian-Franconian forest, uses 3.4 MW turbines. The additional height needed to accommodate this water battery makes these turbines the tallest in the world, at 246 m. The total fluid reservoir is about 9 million gallons and at its stored height will produce 16 MW as it is released. This is slightly larger than the combined 13.6 MW from the 4 wind turbines so effectively, the output per turbine structure has been doubled. This is certainly a viable option for turbines "mounted" in ocean waters.

Another important development occurred in Nov 2017 when Tesla delivered the world's largest lithium-ion battery farm of 100 MW to the Hornsdale wind farm in South Australia. This wind farm is comprised of 99 3.1 MW turbines for a nameplate capacity of 315 MW, so in principle there can be excess power that can power up the 100 MW battery farm. Note that the total energy capacity of the battery farm is 129 MWhr's. This means that after being powered up, a typical battery discharges that power in 1.29 h (75 min). Hence only sections of the battery farm can really be used to help establish grid reliability, On the heels of this success, on December 15, 2017 Vestas announced [33] a new set of partnerships aimed at reducing the costs of battery energy storage to facilitate the better integration of battery farms into new wind projects.

3.4 Measured Capacity Factors for Existing oFF Shore Facilities

While the data is only preliminary, the current results for CFs are encouraging for OFF shore facilities. As of December 2017, the average measured CF for all UK + Denmark OFF shore facilities is now available [34]. For our purposes we cull from this list, those facilities greater than 200 MW for which at least 2.5 years of data exists. These facilities are listed in Table 6. The lowest CF is for the oldest installation, Thanet, which when first commissioned was the world's largest OFF shore facility. But this facility sits only slight off shore and is somewhat in the wind shadow of the nearby land masses, compared to the other facilities that are located in the more open ocean environment.

Table 6. Measured capacity factors for OFF shore facilities as monitored over the indicated number of years.

Facility	Capacity	Years	CF
London Array	639	4.7	40.8%
Greater Gabbard	504	4.4	42.1%
Duddon Sands	389	3.2	45.4
Sheringham Shoal	317	4.3	40.7
Thanet*	300	7.3	32.6
Lincs	270	4.3	42.3
Humber Gateway	219	2.6	42.9
Westernmost Rough	210	2.6	45.5
Arnholt (Denmark)	400	4.9	49.4

The CFs listed here are those that have been determined over the lifetime of the facility. CFs measured on a monthly timescale show a 7–8% difference between maximum and minimum indicating that wind patterns are fairly seasonal. Nevertheless, with the exception of Thanet, these OFF shore wind farm CFs are quite favorable, approaching 50% in one case.

4 Forecasts for Future Capacity

The development of OFF shore wind is very much in its infancy with the UK having the most experience and most success. Most OFF-shore wind farms currently use "conventional" wind turbines that are fixed to the seabed floor like the near shore London Array that sits in shallow water. The construction of the wind farm will necessarily use the most available and convenient turbine of the time – this results in the 2013 London Array using turbines of size 3.6 MW. If built now, that array might very well use 8 MW turbines thus increasing its net output by a factor of 2.5. Indeed, the planned Dogger Bank wind farm located in the North Sea about 200 km off the English coast is planned to consists of 4 platforms of turbines each rated at 1.2 GW for a total of 4.8 GW; the largest wind farm in the world. To fully realize OFF shore wind resource would require the installation of floating wind farms that can be located in deeper waters where it is generally windier, particularly in the North Sea [35] and Dogger Bank is the first step in this realization.

When considering forecasts for the world, the uncertain role of China looms large. China's wind resources are not uniformly distributed but are highly concentrated in its northern and northeastern regions [36] and these are located somewhat distant from manufacturing capability in large urban centers. Current wind turbine installation involves blades of 68.5-m length and not many routes are suitable for road transport from the port point of entry for these blades so logistical obstacles will also be a problem for future wind growth in China. In 2001, China's cumulative installed capacity was only a little over 400 MW. By 2012, it had risen to 75,000 MW. This factor of 180 rise is certainly not going to be repeated in the future. By the end of 2017 installed capacity was 164 GW (similar to Europe) and that's still double the amount in 2012, 5 years ago. The single biggest installation year came in 2016 where 20,000 MW of wind was installed. However, measurements over the 2014–2016 time period indicate CF for China wind farms to be just 16.5%. This has been attributed to poor siting of wind farms along with sub-optimal turbine design [37, 38]. Thus, like Germany, the future of wind in China may indeed be OFF shore. Currently China has just 1.3 GW of OFF shore nameplate but has a 2020 target of 5 GW. In 2011, the International Energy Agency estimated 200 GW of OFF-shore wind potential in waters <25 m deep of the east coast of China [39].

We conclude with a simple and optimistic plan for the future to be implemented over the next 30 years to provide twice the electrical demand that currently exists. We assume that our choice for device will be the 12 MW turbine and these turbines will be placed in locations that have CF of 50%. The overall construction of wind turbines requires a manufacturing supply line, similar to that of the auto industry, to support the construction of so many units per year. In the US, for turbines of size 2–3 MW, and average of 3000 per year have been constructed since 2005. Figure 5d shows that the UK + Germany was able to install 500 turbines of size 5–6 MW for OFF-shore deployment in the single year of 2017. China's largest OFF shore wind farm, Huaneng Rudong, took about 3 years to install and uses a total of 70 turbines of size 4, 4.2 and 5 MW. One can imagine if the 12 MW turbine were available at the time, the installation time would still be about the same.

Securing a future requires a sensible vision and a commitment to honoring that vision. This, of course, is precisely how the US was able to get to the moon 50 years ago, in one decade. Building renewable devices at the scale needed to meet global consumer demand requires a similar "going to the moon" commitment. Given the very positive developments in OFF shore wind turbine deployment, we will measure our commitment to sustaining this trajectory to be the construction of 10,000 12 MW wind turbines per year, once the economies of scale become established. By comparison, according to the World Wind Energy Association, 50 GW of new wind capacity was globally added. That would have taken 20000 installs of 2.5 MW turbines and certainly we are not yet at the point where 5 MW (10000 installs) are common place. Thus, annual deployment of 10,000 12 MW turbines does not seem crazy. If this could be established, then the 30-year production timescale would produce 3.3 TW of renewable electrical production at the end of those 30 years. This is exactly what the world needs and this could become a reality if this commitment can be made.

5 Summary Remarks

In this contribution we have established that OFF shore wind production facilities, as specifically escalated by the coming availability of 12 MW Turbines, offers considerable promise for a future source of electricity generation as the primary means to effectively replace the generation that will be lost from the shrinking supply of fossil fuels. We have also placed increasing use of renewable electricity generating technologies in the context of our past behavior. Examination of that past behavior leads to two clear results: (a) the rate at which we are building out renewable electricity sources has been extremely low at approximately .2% per year. Sometime in the very near future, this build out rate must increase by at least a factor of 10; (b) the low rate of renewable build out means that we are both physically and symbolically retaining an overly strong dependence on fossil fuels; specifically we have only reduced the fossil contribution to world electricity generation by about .3% per year. If these rates were to continue, the global fossil reserves would be easily exhausted and we would not have built up the renewable infrastructure required to replace that eventuality. We must therefore globally act with wisdom and sensibility so as to invest in alternative electricity choices which can effectively replace global fossil generation of electricity as quickly as possible. Here, we have advocated that continual investment and buildout of OFF shore wind facilities would manifest that wisdom.

On balance, the future of wind as the main source of renewable electricity production is quite promising. This promise has been manifested primarily by the UK and Germany and their construction of OFF shore turbine arrays using 5, 6 and 8 MW turbines with 12 MW turbine installations planned within the next 5 years. The early (2013) building out of the London Array, using 3.6 MW, will have evolved in just a 10-year period so that next generation arrays (like the coming Dogger Bank facility) will most likely employ 12 MW turbines. Despite possible logistical and material obstacles, the OFF-shore wind industry is now in a period of explosive growth. We have demonstrated that a sustained planetary commitment of deploying 10,000 12 MW turbines on an annual basis over the next 30 years will result in the required doubling of electricity production to meet the increasing global demand. The use of spinning wind turbines to produce electricity represents a much more harmonious balance with nature than incessantly digging up the ground for more and more fossil fuels which eventually leads to the current climate change situation that threatens the livelihood of most species on the planet. Ultimately the use of electricity in the context of ever-increasing demand, requires a balanced value judgement on which technologies to use. The recent global development and success in OFF shore wind power arrays strongly suggests that this is the technology that represents the best-balanced judgement.

References

1. Goh, T., Ang, B., Su, B., Wang, H.: Drivers of stagnating global carbon intensity of electricity and the way forward. Energy Policy **113**, 149–156 (2018)
2. Laurent, A., Espinosa, N.: Environmental impacts of electricity generation at global, regional and national scales in 1980–2011: what can we learn for future energy planning? Energy Environ. Sci. **8**, 689–701 (2015)

3. Gaete-Morales, C., Gallego-Schmid, A., Stamford, L., Azapagic, A.: A novel framework for development and optimisation of future electricity scenarios with high penetration of renewables and storage. Appl. Energy **250**, 1657–1672 (2019)
4. Wendling, Z.: Bridges beyond renewable energy: decarbonizing the global electricity sector under uncertainty. Energy Res. Soc. Sci. **48**, 235–245 (2019)
5. Doubrawa, P., Scott, G., Musial, W., Kilcher, L., Draxl, C., Lantz, E.: Offshore Wind Energy Resource Assessment for Alaska. National Renewable Energy Laboratory, Golden (2017). NREL/TP5000-70553. https://www.nrel.gov/docs/fy18osti/70553.pdf
6. IEA: Key World Energy Statistics (2018). https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf
7. Cole, W., Beppler, R., Zinaman, O., Logan, J.: Considering the role of natural gas in the deep decarbonization of the U.S. electricity sector. The Joint Institute for Strategic Energy Analysis, National Renewable Energy Laboratory (2016). http://www.nrel.gov/docs/fy16osti/64654.pdf. Accessed 15 Oct 2019
8. Babaee, S., Loughlin, D.: Exploring the role of natural gas power plants with carbon capture and storage as a bridge to a low-carbon future. Clean Technol. Environ. Policy **20**, 379–391 (2018)
9. Leimbachm, M., Kriegler, E., Roming, N., Schwanitz, J.: Future growth patterns of world regions – a GDP scenario approach. Global Environ. Change **42**, 215–225 (2017). https://doi.org/10.1016/j.gloenvcha.2015.02.005
10. Abas, N., Kalair, N., Khan, N.: Review of fossil fuels and future energy technologies. Futures **69**, 31–49 (2015). https://doi.org/10.1016/j.futures.2015.03.003
11. Moriarty, P., Honnery, D.: Can renewable energy power the future? Energy Policy **93**, 3 (2016). https://doi.org/10.1016/j.enpol.2016.02.051
12. Lovering, J., Yip, A., Nordhaus, T.: Historical construction costs of global nuclear power reactors. Energy Policy **91**, 371–382 (2016). https://doi.org/10.1016/j.enpol.2016.01.011
13. Bothun, G., Bekker, B.: Wind scalability and performance in the real world: a performance analysis of recently deployed us wind farms. In: Leal Filho, W. (ed.) Handbook of Renewable Energy. Springer, Heidelberg (2015)
14. Fullenkamp, P.: U.S. Wind Energy Manufacturing and Supply Chain: A Competitiveness Analysis. Prepared for: U.S. Department of Energy (2014). https://www.energy.gov/sites/prod/files/2014/09/f18/U.S.WindEnergyManufacturingandSupplyChainCompetitivenessAnalysis_0.pdf
15. de Vries, E.: The challenge of growth: supply chain and wind turbine upscaling challenges (2008). https://www.renewableenergyworld.com/articles/print/volume-11/issue-3/wind-power/the-challenge-of-growth-supply-chain-and-wind-turbine-upscaling-challenges-52689.html
16. D'Amico, F., Mogre, R., Clarke, S., Lindgreen, A., Hingley, M.: How purchasing and supply management practices affect key success factors: the case of the offshore-wind supply chain. J. Bus.Ind. Mark. **32**(2), 218–226 (2017). https://doi.org/10.1108/JBIM-10-2014-0210
17. Astroza, S., Patil, P., Smith, K., Bhar, C.: Transportation planning to accommodate needs of wind energy projects. Transp. Res. Rec. J. Transp. Res. Board **2669**, 10–18 (2017). https://doi.org/10.3141/2669-02
18. Poulsen, T., Lema, R.: Is the supply chain ready for the green transformation? The case of offshore wind logistics. Renew. Sustain. Energy Rev. **73**, 758–771 (2017). https://doi.org/10.1016/j.rser.2017.01.181
19. Vis, F., Ursaves, E.: Assessment approaches to logistics for offshore wind energy installation. Sustain. Energy Technol. Assessments **14**, 80–91 (2016). https://doi.org/10.1016/j.seta.2016.02.001

20. Martini, M., Guanche, R., Losada-Campa, I., Losada, I.J.: The impact of downtime over the long-term energy yield of a floating wind farm. Renew. Energy **117**, 1 (2018). https://doi.org/10.1016/j.renene.2017.10.032
21. Kalverla, P., Steeneveld, G., Ronda, R.J., Holtslag, A.: An observational climatology of anomalous wind events at offshore meteomast IJmuiden (North Sea). J. Wind Eng. Ind. Aerodyn. **165**, 86 (2017). https://doi.org/10.1016/j.jweia.2017.03.008
22. Mathijs M., Santo, G., Degroote, J., Van Paepegem, W., Blaabjerg, F.: The concept of segmented wind turbine blades: a review (2017). http://www.mdpi.com/1996-1073/10/8/1112/pdf
23. Viebahm, P., et al.: Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. Renew. Sustain. Energy Rev. **49**, 655–671 (2015). https://doi.org/10.1016/j.rser.2015.04.070
24. Watari, T., McLellan, B., Ogata, S., Teuka, T.: Analysis of potential for critical metal resource constraints in the international energy agency's long-term low-carbon energy scenarios. Minerals **8**(4), 156 (2018)
25. Brumme, A.: Masters thesis: critical materials for wind power: the relevance of rare earth elements for wind turbines (2011). http://www.qucosa.de/fileadmin/data/qucosa/documents/9970/Masterarbeit_Anja_Brumme.pdf
26. Pavel, C., et al.: Substitution strategies for reducing the use of rare earths in wind turbines. Res. Policy **52**, 349 (2017). https://doi.org/10.1016/j.resourpol.2017.04.010
27. Zimmermann, T., Rehberger, M., Gooling-Reisemann, S.: Material flows resulting from large scale deployment of wind energy in Germany. Resources **2**, 303–334 (2013). https://doi.org/10.3390/resources2030303
28. WWF Report: Critical Materials for the transition to a 100% sustainable energy future (2014). http://awsassets.panda.org/downloads/critical_materials_report___jan_2014_lr.pdf
29. Zhang, Y.: Peak Neodymium- Material Constraints for Future Wind Power Development. Master thesis in Sustainable Development at Uppsala University, No. 149 (2013). 41 pp, 30 ECTS/hp. https://www.diva-portal.org/smash/get/diva2:668091/FULLTEXT01.pdf
30. Karnauskas, K., Lundquist, J., Zhang, L.: Southward shift of the global wind energy resource under high carbon dioxide emissions. Nat. Geosci. **11**, 38–43 (2018)
31. Jacobson, M., Delucchi, M. Cameron, M., Frew, V.B.: Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes PNAS 112 m, pp. 15060–15065 (2015). https://doi.org/10.1073/pnas.1510028112
32. Su, W., Wang, J., Roh, J.: Stochastic energy scheduling in microgrids with intermittent renewable energy resources. IEEE Trans. Smart Grid **5**, 1876–1883 (2014)
33. Froese, M.: Vestas to integrate energy storage with wind power (2017). https://www.windpowerengineering.com/electrical/power-storage/vestas-integrate-energy-storage-wind/
34. Energy Numbers: UK offshore wind capacity factors (2018). http://energynumbers.info/uk-offshore-wind-capacity-factors
35. Andersen, P., Clausen, N., Cronin, T., Pirainen, K.: The North Sea Offshore Wind Service Industry: status, perspectives and a joint action plan. Renew. Sustain. Energy Rev. **81**, 2672–2683 (2018). https://doi.org/10.1016/j.rser.2017.06.073
36. He, G., Kammen, D.: Where, when and how much wind is available? A provincial-scale wind resource assessment for China. Energy Policy **74**, 116–122 (2014). https://doi.org/10.1016/j.enpol.2014.07.003
37. Huenteler, J., Tang, T., Chan, G., Diaz-Anadon, L.: Why is China's wind power generation not living up to its potential? Environ. Res. Lett. **13**, 044001 (2018). https://doi.org/10.1088/1748-9326/aaadeb

38. Lam, L., Branstetter, L., Azevedo, I.: China's wind industry: leading in deployment, lagging in innovation. Energy Policy **106**, 558–599 (2017). https://doi.org/10.1016/j.enpol.2017.03.023
39. Da, A., Xilang, Z., Jiankun, G., Qimin, C.: Offshore wind energy development in China: current status and future perspective. Renew. Sustain. Energy Rev. **15**, 4673–4684 (2011). https://doi.org/10.1016/j.rser.2011.07.084

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Delete	/ through single character, rule or underline or ├──┤ through all characters to be deleted	♂ or ♂ⓧ②
Substitute character or substitute part of one or more word(s)	/ through letter or ├──┤ through characters	new character / or new characters /
Change to italics	— under matter to be changed	⌙
Change to capitals	≡ under matter to be changed	≡
Change to small capitals	= under matter to be changed	=
Change to bold type	∼ under matter to be changed	∼
Change to bold italic	≂ under matter to be changed	≂
Change to lower case	Encircle matter to be changed	⧺
Change italic to upright type	(As above)	⊥
Change bold to non-bold type	(As above)	∔
Insert ‘superior’ character	/ through character or ⋏ where required	⋎ or ⋏ under character e.g. ⋎ or ⋏
Insert ‘inferior’ character	(As above)	⋏ over character e.g. ⋏
Insert full stop	(As above)	⊙
Insert comma	(As above)	,
Insert single quotation marks	(As above)	⋎ or ⋏ and/or ⋎ or ⋏
Insert double quotation marks	(As above)	⋎ or ⋏ and/or ⋎ or ⋏
Insert hyphen	(As above)	├═┤
Start new paragraph	⌐	⌐
No new paragraph	↩	↩
Transpose	⊔⊓	⊔⊓
Close up	linking ⁀‿ characters	⁀‿
Insert or substitute space between characters or words	/ through character or ⋏ where required	⋎
Reduce space between characters or words	| between characters or words affected	⊤