Global Aspects of Wind Energy Generation: A May 2018 Review

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Abstract

The feasibility of wind power as a form of renewable electricity generation has been well demonstrated in US and Europe since about the year 2000. The nature of wind energy and wind energy installations is also rapidly changing and the recent (less than five years) development of large scale OFF shore wind farms using large unit capacity turbines provides good evidence of such change. As such, and given the vast amount of online information that is now available about all aspects of the wind industry, it is somewhat difficult to decide which of these aspects are worth a succinct view of the current and future states of wind energy that can be accessible to the interested reader. In addition, there are many other reviews of wind energy that helped funnel into this current review [1, 2, 3, 4, 5] Here we present a focused review of topics that have large general interest and which can also be used as educational materials. Compared to other forms of renewable electricity generation, wind power has several potential advantages including a) relatively rapid deployment, b) high scalability, d) less material intensive than ocean wave energy devices, and d) the cost of wind-driven electrical power has been going down. The three principal disadvantages of wind are a) it is highly locally intermittent, b) newly constructed wind farms may require new transmission infrastructure which can greatly add to the overall cost and c) public opposition to perceived negative environmental effects of wind turbines, while overstated, nonetheless contribute to delays and in some cases, complete cancellation of proposed wind farms.

Broadly speaking, the deployment of wind energy has gained significant momentum since the year 2000. For example, over the period 2000-2017 wind energy in the US grew from 2500 MW to 90,000 MW or a smooth annual growth rate of 21%. Over the same time periods, Europe and the World grew at 25% and 20%, respectively. While these growth rates are encouraging, as will be stressed later, to support these rates requires building an increasing number of components each year, particularly turbine blades, and at some point, the wind energy supply chain [6] is unlikely to keep up with this pace. For example, in the year 2017, 52GW of wind energy was installed in the world. If the average turbine capacity per installation was 2.4 MW, then approximately 22000 turbines were installed (equivalent to ~ 60 per day) and 66,000 turbine blades were made. The average growth rates derived above are equivalent to doubling every 3 years – hence in 2020 we would need 192,000 turbine blades. The likely entire reason, that wind energy has been able to effectively scale is simply the growth in capacity in the size of the installed turbine from 1-2 MW in 2000, to 5-10 MW currently.

As of the end of 2017, nameplate capacity in Global wind was 540 Gigawatts (GW) and 188 GW of that is in China. Nameplate capacity refers to the power output of an individual wind turbine as if the wind was blowing 100% of the time. The amount of time that the wind blows over a particular wind turbine is known as the capacity factor (CF). In general, ON shore wind facilities have CFs in the range of 25-45% with most of them lying between 30-35 % [7]. The total net generation is thus nameplate power * CF. The world is currently close to 3TW of electrical power [8] so in terms of nameplate capacity Wind comprises about 1/6 of that total. But since wind has an overall capacity factor of about 1/3 then wind stands at only 5% of total electricity generation. Projecting future capacity based on past trends is quite problematic as two issues arise: a) larger capacity wind turbines have longer length blades which creates significant logistical delivery situations, some of which have been solved by the discussed novel techniques, but it is unclear if such techniques are scalable and b) we are just now starting to see the first OFF shore wind farm installations. In the US, the Block Island wind farm completed in Dec 2016, has a nameplate capacity of 30 MW using 5 6 MW turbines. In contrast, the London Array (commissioned July 2013) consists of 175 turbines at 3.6 MW each to produce 630 MW of nameplate capacity. Had that facility been built slightly later, it might have incorporated 6 MW turbines for unit capacity, thus nearly doubling is electrical output for the same infrastructure requirements

As wind farms start to reach output levels similar to those of fossil fuel plants (e.g. 1000 MW) they potentially become part of the baseload power plan for countries. In this case, the management of intermittency becomes important. To date, the country of Germany has been most affected by this. In times (minutes to hours) of low wind, rolling brownouts have occurred while in times of high wind, usually associated with the presence of storms, traditional power plants can be shutoff so that, in fact, German consumers of electricity get it for free, such as occurred on October 28, 2017 [9]. Most measurements show that a typical windfarm is subject to +/- 30-50% outputs on time scales of minutes to a couple of hours [10, 11]. This volatile situation demands investments in energy storage so as to not waste excess power when it is being produced. However, most wind farms built to date have no form of integrated energy storage associated with them.

In what follows we will give adequate consideration to the broad issues previously raised. In Section 2, we characterize some of the factors that have promoted wind energy growth in the USA and to visually show evolution in various USA wind farm complexes. In Section 3 we use the data to characterize rates of growth in different ways and directly consider the role of incentives that encourage wind energy build out. Here we also consider some of the logistics that can act as deployment barriers, particular for large capacity wind turbines that require longer length blades. At the end of this section, we use various forms of real world behavior to make forecasts of regional and world energy generation by wind in the year 2035, paying particular attention to the likely expansion in OFF shore wind facilities. In Section 4 we consider other important aspects of wind energy generation including a) issues of capacity factor (CF), b) the natural presence of intermittency and the overall need for energy storage integration into new wind farms, c) trends in the cost of wind generated electricity and the potential need for new transmission, d) possible material shortages than hinder future turbine construction and e) some of the perceived and known environmental aspects of wind turbine farms. Concluding remarks are presented in section 5.

Section 2: Conditions for Wind Energy Growth in the United States

The annual growth of wind energy is enabled or hindered by three basic conditions: a) access to available transmission infrastructure so that the electricity can be exported; b) policy incentives or dis-incentives; c) supply line support, in particular blade delivery to wind turbine towers, sometimes in remote locations. These three items, especially b) can vary on a year to multiyear timescale, and sustained build out at a constant rate is difficult to maintain. For the USA, we emphasize that its national wind growth is largely determined by the behavior of a few individual states whose investment in wind energy is largely driven by the need to meet some renewable portfolio standard (RPS) that has been mandated by the voters. In the cases of Washington and Oregon, which do not have particularly large wind resource their respective RPS measures do not include hydro and therefore they must be met with other technologies. Building out wind energy was really the only practical choice, and it has resulted in some particular management difficulties due to intermittency (see section 4.1.3). In view of this, we therefore present some wind build data for individual states in the US, as we will also do for individual countries in Europe. As the rest of the world is dominated by China, we will fully consider that case as well.

When examining the various wave forms of cumulative wind capacity, it important to note that some individual gains from year to year are occurring because a single large facility has been commissioned. This can be seen easily in the case of Europe where the 2015 gain relative to 2014 was only 3 GW while 2015 to 2016 was 22 GW. Hence, year to year fluctuations can be high and require a longer timescale to smooth over, leading to better predictions for future wind capacity. It is also important to note that what is physically growing, on an annual basis, is the number of installed turbines. Power increases are then driven by moving towards larger unit capacity turbines in these installations. This is particularly true for the case of OFF shore wind deployment. Proper estimates of future wind capacity then need to take observed growth rates and convolve them with forecast increases in average wind turbine capacity.

2.1 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 cases 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 and produced 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 scenarios in which these are the only two facilities in our scaled 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 1 shows the results obtained by this facility and the additional facility that comes ON line 5 years later. This approach is highly scalable for any growth rate given a starting condition -e.g. 2/3 of available supply.

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*	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 these results 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 and commissioned in increasingly less time. Arguably, this is the reason that the US rate of growth was strongly exponentially 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, require a significant increase in facilities. Figure 1 shows the Google Earth image of the Brighton facility indicating just how much land is required for these kinds of facilities - 1.2 x 0.8 km ~ 1 sq. km

The result of this exercise shows that infrastructure saturation and/or supply chain weaknesses can eventually limit the rate of growth of wind turbine build out. To a large extent, in terms of installed power, that growth can be better maintained by increasing turbine unit capacity, and therefore blade length. Most blade turbine facilities seem to be able to retool to assemble, up to a point, larger and larger 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. In these cases, turbines of capacity 6 and 7.5 MW have been installed with some design plans going to 10 and 12.5 MW resulting in considerable fewer blades per GW power increase. However, the logistics of blade delivery in this environment is requires some innovative solutions.

2.2. Regional Trends in US Wind Growth

As of April 2018, there were 57,636 individual turbines contained in the US Wind Turbine Database – the USWTB [12]. The total nameplate output is ~89,000 MW meaning an average turbine capacity of ~ 1.5 MW. The maximum turbine capacity at any land-based installation is likely limited by the ability to ship the appropriate size blades to the location. Thus in any given year we might expect new facilities to incorporate different size unit capacities, since, even though larger capacity turbines exist, it might be unfeasible to locate them at a particular site. This behavior can be seen in Figures 2a and 2b where we break the USA into four regions and from the USWTB we estimate annual installed blades for that region as well as increases in the average turbine capacity. This analysis indicates the following for each region:

Region 1 corresponds to the American NW in which wind farms in OR, WA and WY mostly contribute. Build out in this region started around 2005. Over the period 2006-2012 approximately 6000 new turbines were constructed and the average MW per turbine rose from 1.15 to 1.65 MW. As seen in Figure 2b, most all regions show asymptotic behavior in the evolution of average turbine capacity.

Region 2 corresponds to the American SW in which wind farms in CA and TX dominate. In the year 2000, there were already 7150 wind turbines, but most of these are the small turbine wind farms constructed in CA in the 1990s. This resulted in an average turbine capacity of only .12 MW. In hindsight, it seems clear that erecting these wind turbines that mostly consist of 40 – 200 KW wind-turbines was likely not very practical or cost effective and really got wind energy off to a bad start. Indeed, these wind turbines are fairly close to the ground and densely packed and really were a large threat to birds and other flying animals. These facilities should never have been built as the industry in CA should have waited until 1 MW wind turbines became available in the early 2000s. As detailed more below, starting in 2008 or so, the large-scale Alta Vista facility was started. By 2011 individual 3 MW turbines would be installed in some regions. From 2000 to 2012, this region built 13,000 more turbines and deployed them at the rate of 1500 per year from 2006 – 2012. Still, the average wind turbine capacity only rose to 1.35 MW by the end of 2017 indicating number dominance by many legacy smaller capacity turbines. Still, this is an order of magnitude improvement over the 2000 situation.

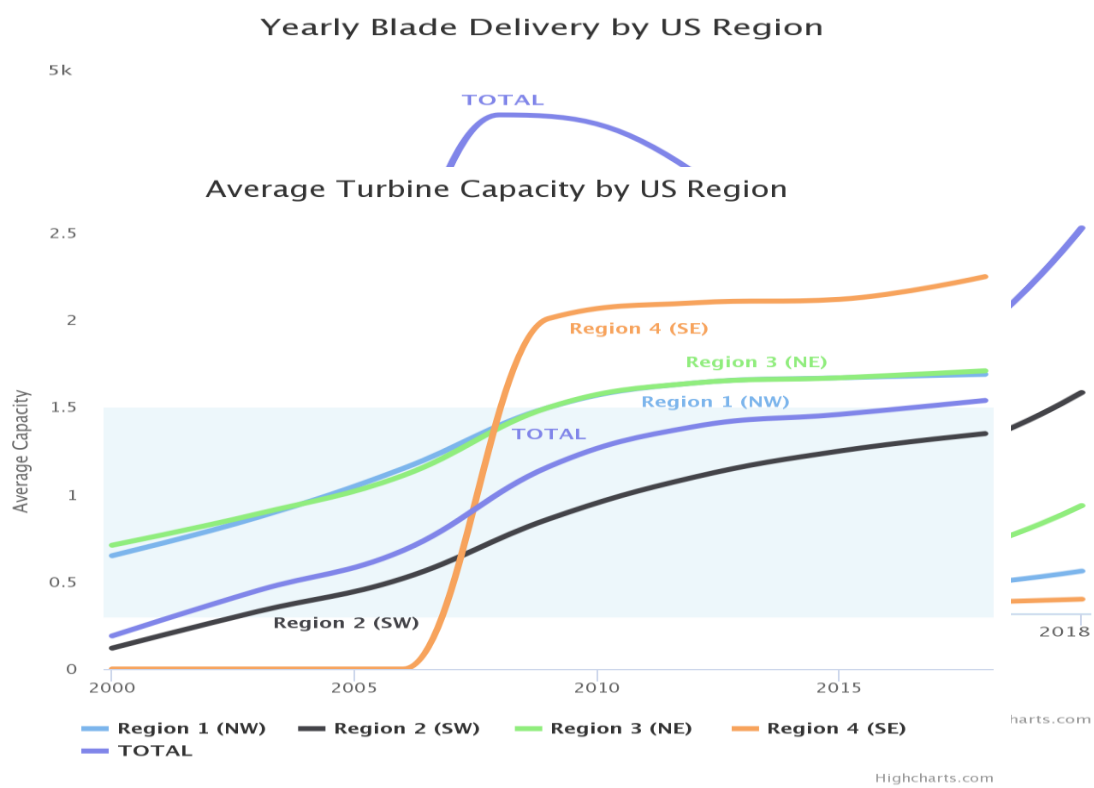
Region 3: This is the American NE. Wind development initially occurred in SW Minnesota as the first large scale wind farm. Again, over the 2006 to 2012 period, this region saw a significant ramp up of facilities with 1700 turbines per year being installed. Most of this activity occurred in the large flat areas found in Iowa, Kansas, and Oklahoma.

Region 4: This is the American SE. In general, this region of the USA has very little wind resource. As a result, there is virtually no development until 2005 when Eastern Texas (which lies at the extreme western end of this region) began installations. However, these installations immediately took advantage of the most modern turbine technology and hence have achieved average turbine capacities higher than any of the other regions.

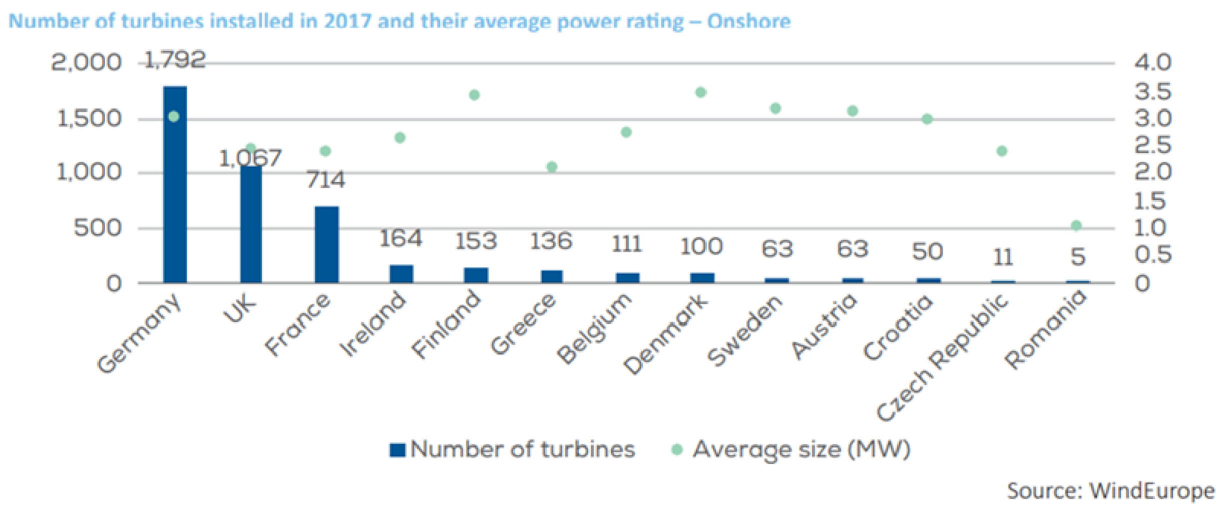
The graphical history of this regional development shown in Figures 2a and 2b show that although strong regional differences exist, aggregated for the entire US, the data indicate

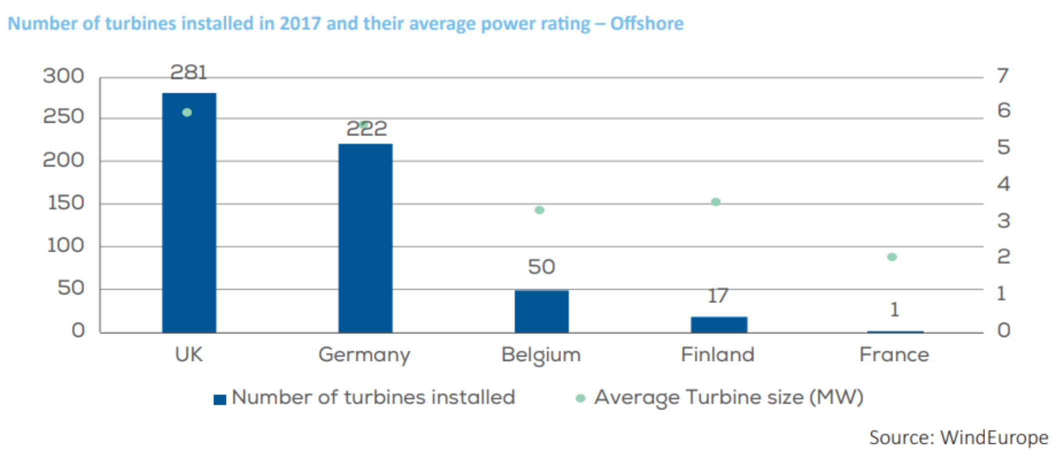
- The evolution of average turbine capacity shows strong asymptotic behavior which levels off between 1.5 and 1.6 MW. As shown further below, this situation is substantially different than in Europe which is making much more steady progress on increasing average turbine capacity.

- During the strongest period of relative growth, 2009—2012, the US was able to build 4600 turbines per year. Due to loss of momentum in 2013 (see more below) that rate has now dipped to 2750 turbines over the last 5 years.



Similar behavior regarding trends in turbine capacity can be seen from the most recent European Wind Energy report [13]. Figures 3a and 3b show the relation between the number of turbines and the average size per turbine that was installed in 2017. This data clearly shows that European installations, particularly those in Germany, have broken the 3.0 MW thresholds for average turbine nameplate power. Finland and Denmark (home of Vestas) are leading the way at 100+ turbine farms using 3.5 MW turbines. Some of these facilities are located on shore or slightly off shore. Figure3b shows that this trend for increasing turbine size is particularly true for OFF shore installations.





2.3 Time evolution of Turbine Mix in Example Wind Farm Complexes

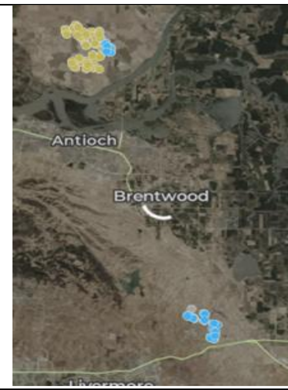
More detailed behavior can be illuminated by considering some evolutionary time snapshots of selected US windfarms which have some turbines at the maximum possible size for the technology of that time. This information is shown in Table 2 where the consistent color coding goes from low unit turbine capacity (blue < 1 MW) to high capacity (red > 3 MW). For each complex we tabulate its total power output and its total turbine count. We make this determination every 2 years from the available data in the USWTDB to illustrate overall evolution in wind turbine component mix.

Year: 2001
Location: TX
Nameplate: 680 MW
Total Turbines: 688
Average: 1 MW

107 @ 1.5 MW
214 @ 1.3 MW
242 @ 0.7 MW
125 @ 0.7 MW

Year: 2003
Location: CA
Nameplate:197 MW
Total Turbines: 142
Average: 1.4 MW

90 @ 1.8 MW
52 @ 0.7 MW



Year: 2005
Location: TX
Nameplate: 1412 MW
Total Turbines: 953
Average: 1.5MW

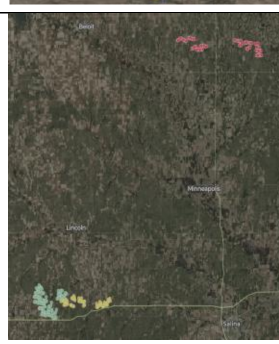
54 @ 2.3 MW
67 @ 1.8 MW
61 @ 1.6 MW
511 @ 1.5 MW
130 @ 1.4 MW
130 @ 0.9 MW

Year: 2007
Location: TX
Nameplate: 567 MW
Total Turbines: 424
Average: 1.3 MW

21 @ 3.0 MW
223 @ 1.5 MW
180 @ 1.0 MW

Year: 2009
Location: KS
Nameplate: 450 MW
Total Turbines: 222
Average: 2 MW

67 @ 3.0 MW
56 @ 1.8 MW
99 @ 1.5 MW



Year: 2011
Location: CA
Nameplate: 1678 MW
Total Turbines: 707
Average: 2.4 MW

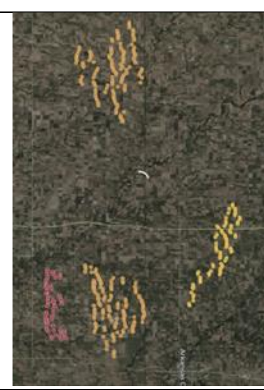
374 @ 3.0 MW
107 @ 2.0 MW
226 @ 1.5 MW

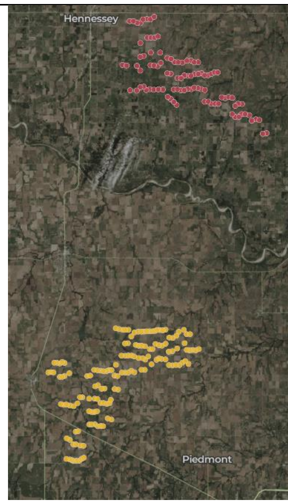
Year: 2013
Location: TX
Nameplate: 272 MW
Total Turbines: 135
Average: 2 MW

17 @ 3.6 MW
118 @ 1.8 MW

Year: 2015
Location: OK
Nameplate: 1000 MW
Total Turbines: 418
Average: 2.4 MW

56 @ 3.3 MW
27 @ 2.4 MW
260 @ 2.3 MW
75 @ 2.0 MW



Year: 2017 Location: OK Nameplate: 418 MW Total Turbines: 154 Average: 2.7 MW 95 @ 3.1 MW 59 @ 2.0 MW		Year:2017 South Plains II Nameplate: 1328 MW Total Turbines: 627 Average: 2.12 MW 91 @ 3.3 MW 84 @ 2.4 MW 200 @ 2.0 MW 81 @1.9 MW 11 @1.8 MW 150 @ 1.7 MW Panel J	

Based on the previous analysis of snapshots it is clear that a) the average turbine capacity at installations has increased and b) there is a likely asymptote between 2.4 and 2.7 MW per new complex to be installed.   For wind turbines of larger than 3 MW there are likely logistical issues that limit their large scale build out.   In general, these large turbines are located in relatively flat places in the US. One of the largest recent installations is the South Plains II project which sites 91 3.3 MW turbines and is located in a remote flat region of Texas.   The macro wind farm environment of South Plains II in shown panel J and this environment is a good example of an integrated wind farm complex that is at utility scale (e.g. 1000 MW)

Section 3: Data Driven Growth Scenarios

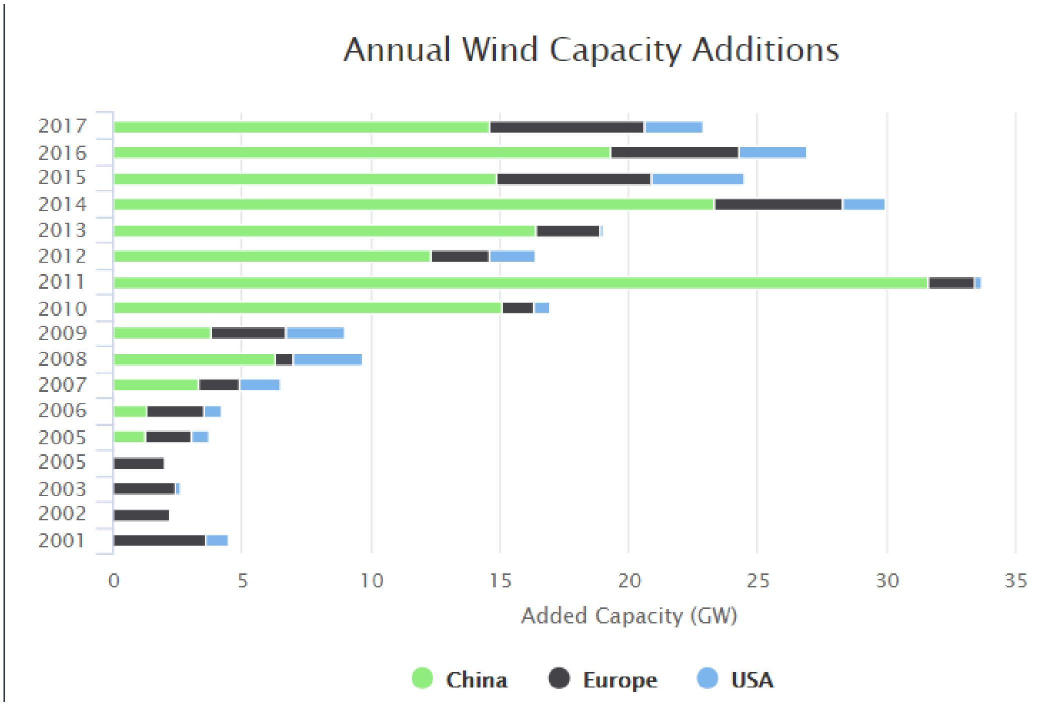
We begin all growth scenarios from the year 2000. Keep in mind that growth occurs both because the physical number of turbines is increasing and the average turbine capacity per wind farm is also increasing, albeit at a slower rate. There are features in the growth data that are important in properly producing an estimated growth rate for the future and we will discuss them presently.   For now, we simply produce projections to the end of 2017 based on simple analysis of growth rates during various time periods, for the US, Europe, and the World.   In Table 3 we present the difference between the predicted cumulative wind power and that which was actually achieved, in terms of some factor over/under, using values of 90 GW, 170 GW, and 540 GW respectively. In general, and not surprisingly, all estimates of future capacity based on time averaged exponential growth rates produce over-estimates. This is a consequence of a) at early times exponential growth can be easily supported and the supply chain can produce the requisite number of annual units – eventually that breaks down and b) various incentives and other economic conditions can make some year(s) economically unfavorable for wind development. In some cases, the over-estimate can be quite severe – for instance, based solely on the 2000-2010 period, the 2017 prediction is overestimated by a factor of 3 for the USA. The use of linear predictions is totally inappropriate for early times as that will lead to large under predictions.

However, as time goes on, linear predictions (GW per year) become closer to the on the ground reality. Indeed, the linear projections based on the first 10 years of European growth are considerably more accurate than the large over-predictions generated by the exponential scenario. The transition from exponential growth to linear growth probably occurs when various supply line limitations began to manifest.

Region	Time Period	Exp. Rate	Linear	Exp. Prediction	Linear Prediction
USA	2000-2005	25.3%	1.9	2.1x	0.27x
	2000-2010	27.5%	3.1	3.1x	0.78x
	2000-2015	22.4%	2.2	1.3x	0.87x
Europe	2000-2005	23.0%	6	3.8x	0.64x
	2000-2010	18.8 %	4	1.8x	0.68x
	2000-2015	15.5%	5	1.05x	0.97x
World	2000-2005	24.9%	8	2.2x	0.3x
	2000-2010	24.6%	14	2.1x	0.67x
	2000-2015	21.6%	24	1.25x	1.1x

3.1 Annual Capacity Additions

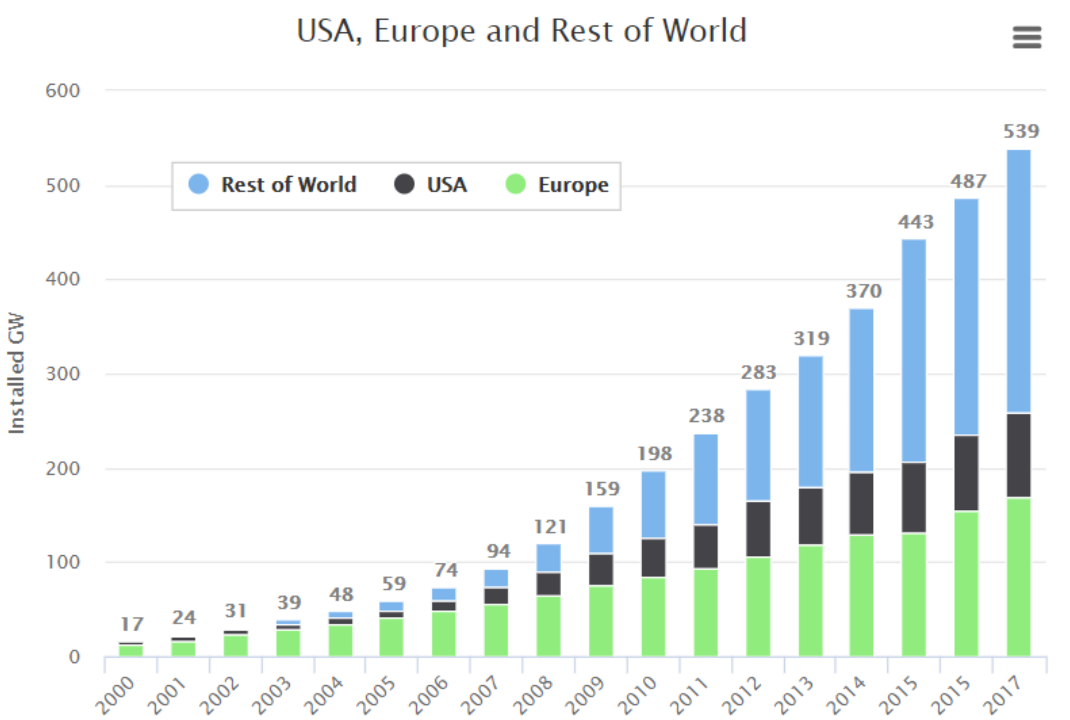
In the Figure 4 we do a similar exercise for three principal regional drivers, Texas (USA), Germany (Europe), and China (World) showing annual increments in build out. Data shown this way indicates that sometimes growth can be limited by economic conditions (e.g. the global meltdown of 2009) or enhanced by bringing on single large scale facilities. In the case of China, we begin in 2005 as there were no installations prior to that.



In Table 4 we compare average annual installs for three time periods, a) initial ramp up – 2001 to 2007, b) the global economic recession, 2008 – 2013, c) the last 4 years. The ratio of the standard deviation to the mean provides an indication of volatility or year to year instability. For example, the early ramp up period in Texas was tremendously volatile as there were years in which the capacity addition was 0. This was driven by the expiration of the production tax credit for wind, further discussed below, which acted as a policy disincentive for some years in the early 2000's as well as for the year 2013. In contrast, Germany is relatively stable, even though its output decreased during the global recession period it was still maintained year to year.

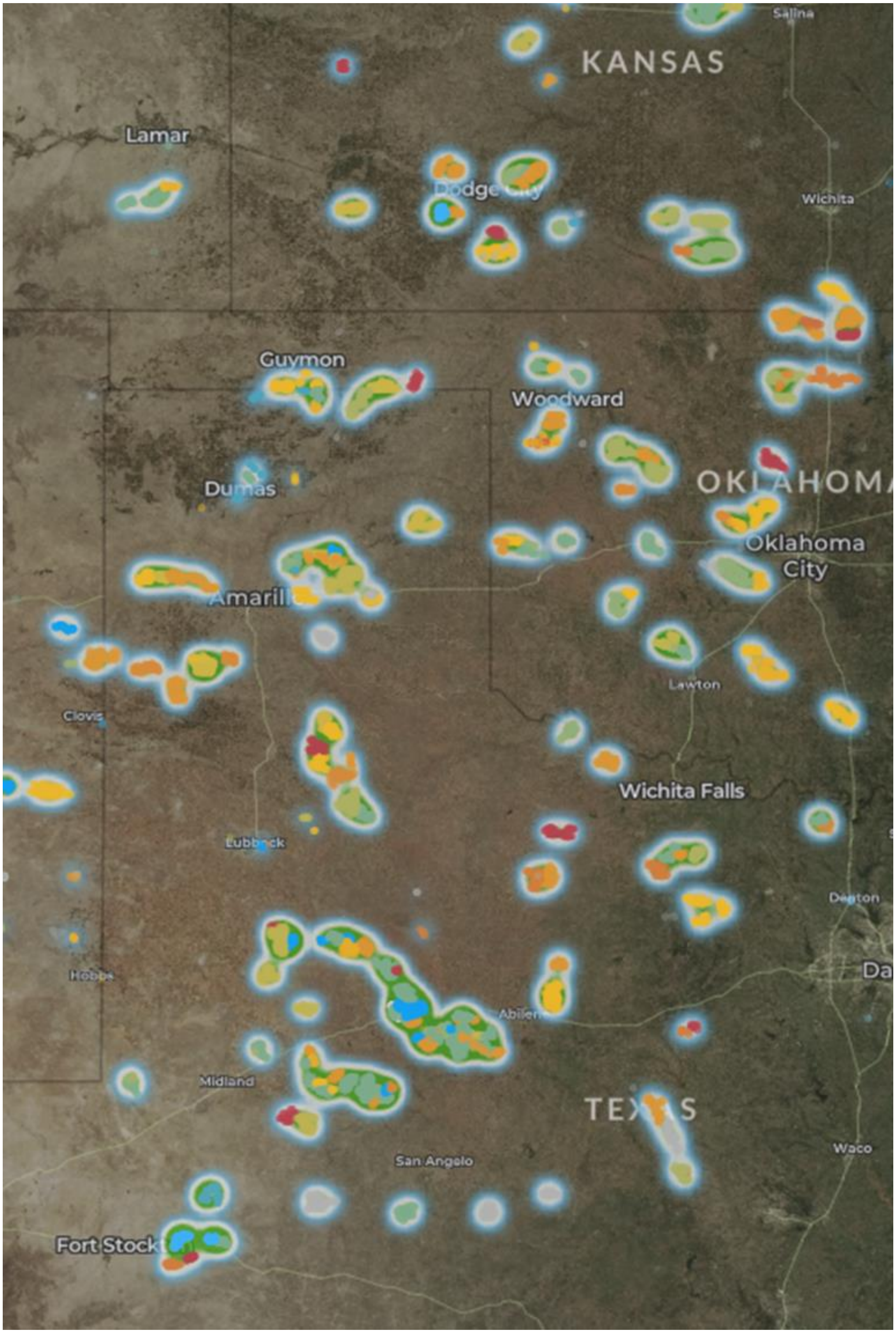
Region	Ramp Up	Recession	Recent
Texas	0.6 +/- 0.6	1.3 +/- 1.1	2.6 +/- 0.8
Germany	2.3 +/- 0.65	1.9 +/- 0.8	5.5 +/- 0.5
China	…	14.2 +/- 9.8	18.0 +/- 4.1

In Figure 5 we graphically compare the cumulative capacity curves for the USA, Europe and the World.



In backward years from 2017, the ½ time for the USA, Europe and the World are 6.5 years, 7 years, and 4 years respectively. Using this real world data and working backwards is likely the better way to estimate the future – weight recent performance more than past performance, when the annual percentage gains are larger when the number of units to annual build is smaller. This particular lens shows that the World is catching up faster and this is almost exclusively driven by developments in China, which is now adding close to 20 GW per year of annual capacity additions. This rate is nearly 10 times the annual capacity shown by India, although India has doubled it wind capacity in 6.5 years (like the US has). As of end 2017, India had a cumulative capacity of 34 GW. But overall, this aspect of the data begs the question; can the ROW/China double its output over the next 4 years? Will the supply chain bear this kind of rate of addition?

We conclude this section with a current density of turbines representation of the various wind energy complexes in the regional section of the USA that has the greatest wind energy resource. This is shown in Figure 6. The mix of colors represents the different mix of unit turbine capacity. The integrated output of the complexes shown represents about 30,000 MW of wind power at average power of 2 MW per turbine.


Salina
KANSAS
Lamar
Wichita
Guymon
Woodward
Dumas
Oklahoma City
Lawton
Clovis
Wichita Falls
Midland
San Angelo
Waco

3.2 Incentives and Logistics as Barriers to Growth

3.2.1 The USA Production Tax Credit

In the USA, the first incentive for the development wind power occurred in 1992 as part of the Energy Policy Act. This incentive is known as the Production Tax Credit (PTC). The PTC for wind and closed-loop biomass was first enacted in 1992. At the time of this enactment, the PTC paid a 1.5-cent subsidy for every KWH of electricity that was produced by renewable energy technologies. Adjusted for inflation, the 2016 subsidy amounted to 2.3 cents per KWH. For the most part, this was devoted to the development of wind energy. Like the situation mentioned above for CA, however, this incentive comes at a time when the technology of wind was in its infancy and this lead to the construction of poorly designed wind farms. When initially passed, the PTC was meant to be temporary and to be only used to jump start the wind industry, not to maintain it. However, as time wore on, the PTC proved to be a valuable tool for helping to expand the wind industry, but also, uncertainty over whether or not the PTC would be extended will also halt some momentum in some years.

When first enacted, the PTC was scheduled to expire on July 1, 1999. Since 1999, the PTC has been extended 10 times. On several occasions, the PTC was allowed to lapse before being retroactively extended, and this created significant uncertainty. This is exactly what happened in 2013. Near the end of 2012, there was wide spread belief that the US Congress would suspend the PTC by the start of 2013, and possible terminate it. Although the PTC was not suspended at that time (but will be soon), there was sufficient uncertainty that meant only 1 GW of capacity was added to the USA for 2013. In the years following 2013, wind energy buildout in the USA is much more on a linear trajectory than an exponential one. This kind of behavior was also seen earlier. The first lapse of the credit occurred seven years later in 1999, causing a near halt in production the following year. This collapse resulted in the PTC being turned on in 2000, but then turned off the following year, and once again there was a collapse which resulted in turning the PTC on again in 2002. Since 2002, Congress still allowed the PTC to expire multiple times. This policy uncertainty resulted in boom-bust cycles of development and always made future projections highly uncertain. The data in Table 5 clearly shows that when the PTC has certainty, sustained growth can occur. In particular, the PTC had the most certain in the period 2005 to 2009 and that saw the largest exponential rates of growth. In addition, the years 2009 and 2012 saw spikes in buildout due to the perceived likely lapse of the PTC for the following year. The 2012-2013 case is particularly absurd. Here, the annual install fell from 10000 MW to 1000 MW!

Years	PTC Status	Annual Install (MW)	Total Growth in Period (MW)	Avg. MW per year
Period 1:				
1999	ON	844		
2000	OFF	71		
2001	ON	1690		
2002	OFF	411		
2003	ON	1685		
2004	OFF	396	5100	850
Period 2:				
2005	ON	2374		
2006	ON	2457		
2007	ON	5253		
2008	ON	8382		
2009	ON	10005	28500	5700
Period 3:				
2010	Lapsed	5216		
2011	ON	6820		
2012	ON	13131	25000	8400
Period 4				
2013	Lapsed	1087		
2014	ON	4854		
2015	ON	8598		
2016	ON	8203		
2017	ON	7017	30000	6000

In December of 2015 the PTC phasedown was initiated and the PTC will end after 2019. Under this phasedown, wind projects that started construction in 2015 and 2016 receive a full value PTC of 2.4 cents per kilowatt hour. For projects that begin construction in 2017, the credit is at 80 percent of full value; in 2018, 60 percent PTC; and in 2019, 40 percent PTC. Despite this phase down and eventual elimination, the wind industry was guaranteed 5 years of policy stability in which to plan. This helped to sustain the build out but 2017, the first year of the phase down, did see a reduction of 1200 MW of installed wind, compared to the previous year. For the years 2018 and 2019, there are 20-25 GWs of planned wind but it remains to be seen how much will actually be built, given the reduction in incentives.

3.2.2 European Incentives

In general, the European Union (EU) has been the most forward thinking governmental body on climate change. Their overall goal was to cut greenhouse emissions by its member countries a total of 40% from 1990 levels by 2030 (40 in 40 years). In addition, some percentages for wind contributions to the overall renewable energy mix were mandated.

Although this impressive trajectory was somewhat halted by the European austerity response to the 2009 global economic meltdown [14], steady progress towards meeting these mandated targets begin in earnest a few years later. More specifically, during the time of this period of austerity, approximately 10--12 GW of annual install occurred. In 2015 and 2017 22 and 15 GW were installed. Under the EU's 2050 roadmap [14] member countries should achieve 30% of their total electricity mix, from renewables. Some countries, like Germany are well ahead of meeting this target. The very recent development of OFF shore wind (see more below) now makes it likely that the UK will be able to meet this target. To help the various member countries meet their targets, the EU developed a range of incentives:

- Feed-in tariffs
- Tradable green certificates
- Investment subsidies
- Tax cuts

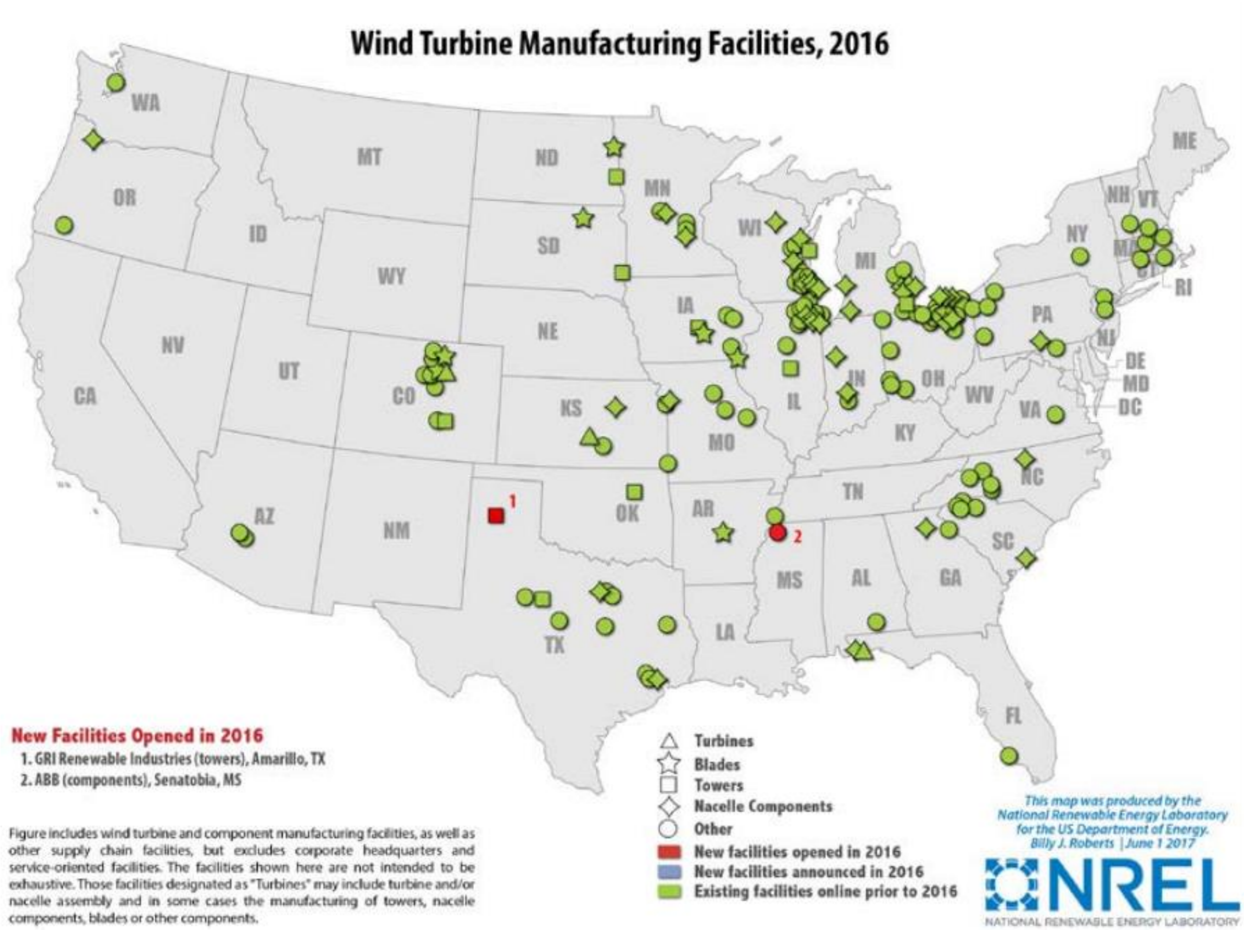
Feed-in tariffs (FITs) act like a price incentive where various grid operators are obligated to buy electricity that is produced by some renewable source. The tariff rate is regulated by regional governments and usually represents a fixed amount per produced MWh, using a renewable source. To supply certainty, this incentive framework is guaranteed as soon as the particular power source is connected to the grid. As a further incentive, FITs apply only to newly constructed facilities and will apply throughout its lifetime. Tradable Green Certificates (TGCs) obligate the producers of conventional electricity that use fossil fuels (coal, natural gas) to purchase a pre-determined number of green certificates per MWh of green energy produced. These certificates can be traded in a regulated marked so that they become TGCs. The market price of TGCs is determined by supply and demand dynamics as forced by various governmental renewable energy quotas. Hence, there is an advantage for any government to bring on new renewable sources of electricity production as soon as possible. The construction of wind farms, in general, can occur relatively quickly and as such, they provide a natural instrument for gaining a competitive advantage in the TGC market. The level of these incentives is country based, with countries like Spain and Germany being the most aggressive.

A disadvantage of this system is that the cost of both FITS and TGCs is eventually off loaded on the electricity bill of the consumer, leading to higher electricity prices. While the enlightened consumer should have no problem paying higher prices for green-based electricity, most consumers would likely prefer to pay the least for electricity. As a consequence, countries with high incentives were forced to reduce their incentives, especially during the period of austerity. A good example is the country of Italy which in 2012 stopped all incentives related to the building of new photovoltaic plants. Similar, solar build out in Spain was significantly interrupted. Overall, however, wind buildout was not strongly affected by this situation.

While OFF shore wind farm development will be immediately discussed below, it is worth noting that even though the UK has established world leadership in this regard, there is currently a threat to expire the subsidy for future OFF shore development. At the time of this writing (June 2018), the expiration is set for October of 2018. Currently there are several OFF shore wind farms in a construction phase around the UK but all of these farms use "conventional" wind turbines that are fixed to the seabed floor. Therefore, like the London Array, such facilities need to be located near the shore, where the water is sufficiently shallow for the tower to be anchored to the seafloor. 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 [16]. The 30 MW Hywind project commissioned in Oct 2017 is the world's first floating wind farm. While this technology is just in its infancy its future is now being threatened is this subsidy ends. Three more additional floating wind farms are being planned or are under various phases of construction but none will be operational by October 2018 and they will not qualify for a subsidy unless this deadline is extended. This situation seems identical to what the USA has already proven to be a highly flawed strategy. At the infancy of ON shore wind farms, the USA allowed development in a very uncertain policy world. The exact same thing seems to be occurring in the case of UK-based off shore wind farms [17]. The industry needs to learn from past periods of failure and to note reproduce them so as to limit the evolution of promising new technologies.

3.3 Some logistical Concerns

There is a large body of literature and reports on the state of the wind energy supply chain through time [18, 19, 20]. 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 players which needs overall coordination. The situation in the USA as of 2016 is shown in Figure 7.



Many of the turbine component manufactures are located in the upper Midwest as various facilities of the automotive industry have been retooled, particularly to make turbine generators. For the USA, prior to 2014 it is clear that what limited the wind energy build out was not supply chain limitations, but rather policy incentive uncertainty. Scaling up wind turbine size has two principle logistical issues, a) the sheer weight of the components and b) the length of an individual turbine blade. Currently there are tens of thousands of blades produced annually at lengths up to 80 meters and weighing approximately 25-35 tons. As an example of a logistical challenge a single wind turbine can require up to eight deliveries -- the nacelle, three blades and three to four tower sections. A hundred turbine wind form would therefore involve 800 deliveries over the course of construction after the components have been delivered, usually by rail, to some distribution site. While this has proven to be manageable to date in the US, there is a future need to have better waterway distribution for the larger tower sections. 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 blades to maneuver around corners [21]. Such rail deliveries are generally restricted to the relatively flat areas of Texas, Kansas and Oklahoma. Indeed, the only occurrence of 3.6 MW is the 17 unit instillation Cirrus Project in a very flat area of West TX. In fact, blades made at the Colorado facilities discussed previously, in theory, can be shipped via rail as its quite flat from that location to the West TX location

For OFF shore installations, initially, the 3.6 MW turbine was preferred. The blade length for the Block Island wind farm turbines are about 75 m and current and near future generations of the 8 MW turbine have blade lengths of 80 and 88.5 meters. 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 (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 [22, 23] of OFF wind logistics has suggested an optimum strategy of minimizing the number of components needed for installation on site and the maximum number of turbines that could be loaded on a given vessel. This strategy becomes particularly important if for the potential case of floating windfarms that might be position 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 installation is only possible for about 120 days a year [24,25] as the large components that needed to be installed are subject to large wind loads, which could prove catastrophic. The situation in the Aleutian Island, where there is some 50 Terrawatts of wind resource [26], represents an even more extreme environment where installations might only be able to be done 60-90 days a year.

Another specialized site would be mountain ridges. In general, mountain ridges have more wind resource available than surface conditions provide and they have larger capacity factors. Obviously, the delivery of blades on the usually narrow and winding roads that reach mountain ridges are a particular concern. China has developed some novel new kinds of trucks to meet this requirement [27], but each truck can only deliver one turbine blade a day to some mountain site and only a dozen or so of these trucks currently exists. Since such trucks are highly specialized they can add cost to the development of wind energy sites on remote mountain ridges since the trucks cannot easily be re-purposed. Because of this concern, there is now a concerted effort to develop airships as the means for mountain delivery of blades. Because of the vertical landing and take-off capabilities, airships can in principle delivery components to places where there are no roads. In a review of potential capability [28] of existing airships, one was thought to be suitable. The Aeroscraft ML868 is 235 meters long, and 90 meters wide – fully capable of housing several turbine blades per delivery. Like the Fred Olsen Company, we envision another innovative company will be able to deliver on this promise.

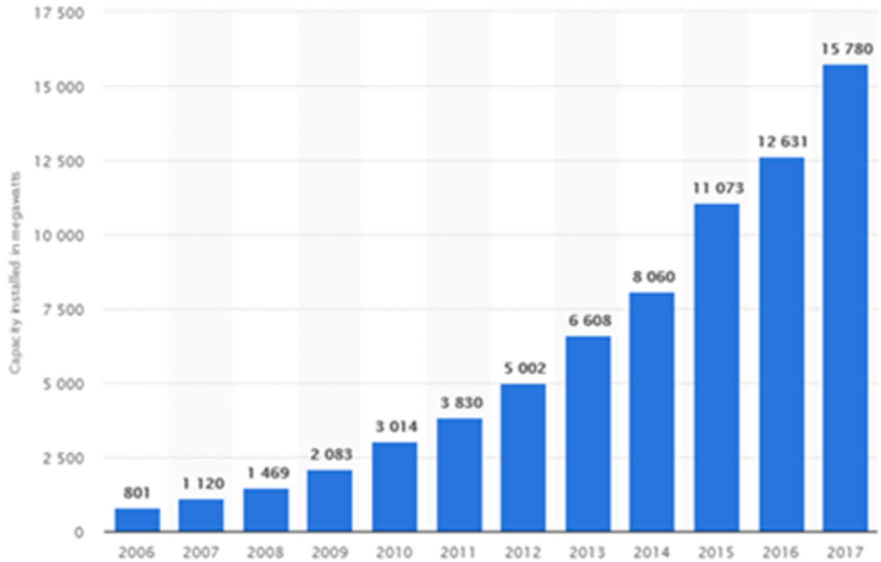
The above considerations indicate that blade transportation may become a growing source of costs which will negatively affect the future cost of wind energy. As a result, there is now renewed interest in the concept of the segmented blade, where the individual segments can be more easily transported 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 [29] 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-meter long blades. If we are to move to still large turbine capacities, segmented blade design requires careful consideration.

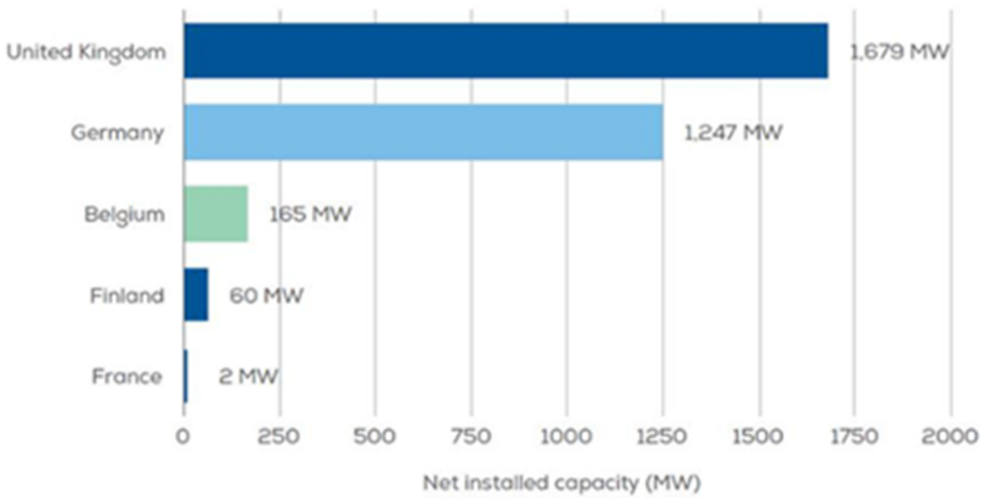
3.4 The Emergence of OFF Shore Wind

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. For example, the Block Island facility recently commissioned in the USA, generates 30 MW of nameplate power using 5 6 MW turbines. The facility, like others, is quite modular so additional 6 MW turbines can be added. 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 larger than ON shore facilities. In addition, both of these projects were strongly aided by the FITs incentives. 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 on just off shore from the Northern Wales, Western England boundary. The largest scale OFF shore facility built to date is that of the London Array (see Figure 8). This currently consists of 175 3.6 MW turbines located 20 km off short at maximum water depth 25 m. A planned doubling of the capacity for this array is temporarily on hold due to the kind of potential environmental impact that we discuss in Section 4.5. The nameplate capacity of the London Array is 630 MW and, as discussed in Section 3, OFF shore arrays tend to have considerably higher wind reliability than those ON shore.

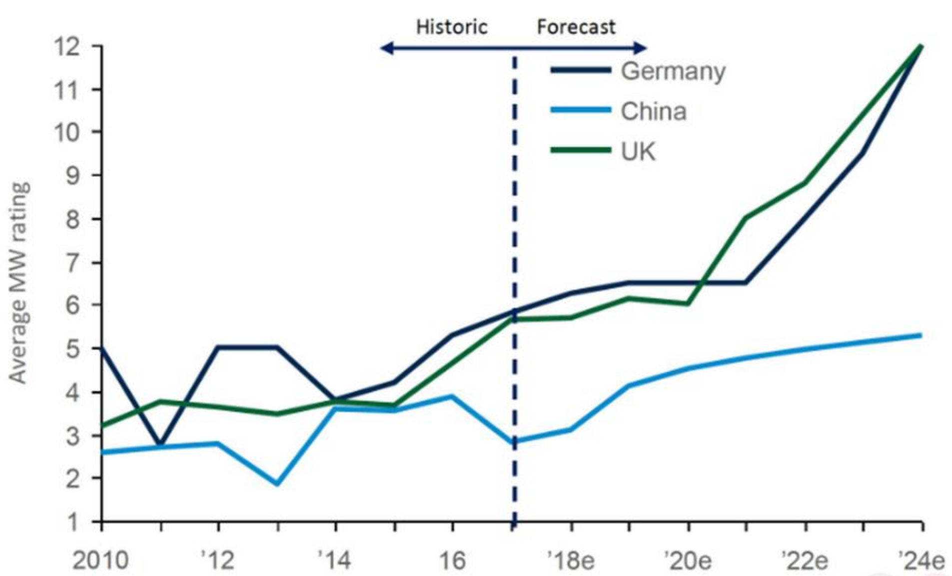
The overall growth of European OFF shore wind industry is well described by exponential growth at 27% per year. This of course mimics the growth rate of ON shore wind in the USA in its infancy. Given some of the logistical complications in making OFF shore wind farms this astounding rate of growth is certainly not likely to be maintained, but for future wind energy forecasting, it is now clear the potential future OFF shore facilities have to be included. Indeed, this is likely the most significant change in the future of wind energy development that we have seen. 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 the Figures 9a, 9b and 9c.



Capacity installed in megawatts
801
1 120
1 469
2 083
3 014
3 830
5 002
6 608
8 060
11 073
12 631
15 780
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017



United Kingdom
1,679 MW
Germany
1,247 MW
Belgium
165 MW
Finland
60 MW
France
2 MW
Net installed capacity (MW)



Historic
Forecast
Germany
China
UK
Average MW rating
2010
'12
'14
16
'18e
'20e
'22e
'24e

In October 2017, the world's first floating windfarm was inaugurated 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 meters. While this Hywind facility 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 (see section 4.3). Hence, without strong subsidies it may not be cost effective to build these promising new facilities.

3.5 Forecasts for future capacity

Here we make use of the data discussed previously and various assumptions regarding turbine growth to make estimates of the future wind capacity for the USA, Europe and the world out to the year 2035. Recall that we have already established that the use of exponential growth rates over predicts future build out because, at some point, various saturation effects in the supply chain begin to manifest. For the USA, that seems to be happening as the last few years has seen linear buildout. We have also shown that in the real-world, growths in wind energy is strongly driven by the growth in turbine size. For the case of ON shore facilities, we believe the maximum turbine size is 3.6 MW and the more feasible size is 3-3.2 MW, where this feasibility statement comes from the constraints imposed by blade delivery. For the case of OFF shore farms, we believe that new farms will start with turbines in the 6-8 MW range. Although a transition to 10-12 MW is possible in the near future, we do not consider that in our forecasts. In addition, policy uncertainty and the potential removable of subsidies strongly affects future development. In general, our estimates will more strongly weight the most recent years as opposed to overall performance from 2000.

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 [30] and these are located somewhat distant from manufacturing capability in large urban centers. Current wind turbine installation involves blades of 68.5-meter 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 energy 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 [31, 32]. 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 offshore wind potential in waters <25 m deep of the east coast of China [33].

In Table 6 we now present some assumptions, as describe in the above set of limiting factors, and the forecast based on those assumptions for global wind power the year 2035. By the year 2035, electrical production and consumption is forecast to double, so the planet will be at 6 TWe.

Region	Assumptions	2017 (GW)	2035 (GW)
USA	Linear growth at 3000-4000 turbines per year @3 MW per new turbine; Negative effects of the loss of the PTC; Limited and discrete OFF shore facilities	90	280 ON Shore 10 OFF shore 290 Total
Europe	Continued exponential growth at 15% until 2025 for OFF shore then linear at 8GW per year. Incentive driven annual linear increments for other EU countries @ 5 GW per year.	170	275 ON Shore 150 OFF Shore 425 Total
China	50 GW OFF shore power. ON shore to grow at 215 a year in 3 MW turbines until 2025 and then linear @20 GW per year	165	700 ON Shore 50 OFF Shore 750 Total
World	Limited development in areas outside of China at linear rate of 10-12 GW per year ON shore addition to USA, Europe and China	540	1490 ON shore 219 OFF shore 1700 GW

Even though the final numbers in Table 6 appear to be large, this growth rate still does not represent a significant penetration of wind energy into the global market. As of now we are at 540/3000 (18%) in nameplate ratio and our forecasts bring this up to 1700/6000 (28%). However, especially given the addition of OFF shore wind, the global CF for wind is likely to about 10% higher than it is currently meaning a proportionally larger gain in net electricity generation. While these forecasts are likely no better than other approaches they are founded more upon real world measurements and less on theoretical expectations and therefore are likely to be a bit more conservative. Still there are several required caveats:

- The cited individual regions need to maintain continuous momentum in build out and not suffer any year to year deficits such as occurred in the 2012-2013 time in the USA due to the discussed policy uncertainty.

- It is extremely unlikely that we will return to the high periods of exponential growth, about 25% per year, in the USA and Europe.

- China is the only region that is capable of sustaining large scale projects and so the most uncertainty lies there. Still, even at a lower exponential growth rate china is predicted to have more ON shore wind production by 2035 than the USA and Europe combined.

- For OFF shore development, the forecasts are strongly dependent on turbine size deployment. If by the mid-2020s, turbine installation involves 10-15 MW platforms, then our estimates for OFF shore wind development will be understated. The future of such development looks quite promising in Europe, but so far, the USA lags greatly behind and we don't foresee this changing much over the next 18 years.

Section 4: Miscellaneous Issues

4.1 Capacity Factors

A previous treatment [7] focusing mostly on recent US facilities, showed that over the period 2010-2014, most US wind farms, were in fact, performing fairly close to expectations. For the cases of wind farms built in the flat plains of Kansas, capacity factors, as averaged over a 3 year period, were as large as 45%. CF is a very important consideration when making future forecasts. For instance, some facility with 150 4 MW turbines = 600 MW nameplate which operates at 30% CF is only a 180 MW generating facility. If that same facility were placed at a location with CF =.45, then 270 MW would be output, which is the equivalent of building about 22 more turbines. That would represent cost savings simply by locating the wind farm at a good site. Given the vagaries of regional wind patterns, it usually takes some time for reliable CFs to be determined from on the ground performance. In addition, there is some evidence that large scale wind patterns are subject to modification by climate change [34]. In general, CFs are larger for areas that are subject to stable, large scale wind patterns. This is particularly true for wind farms in the flat plains of the USA and for OFF shore facilities.

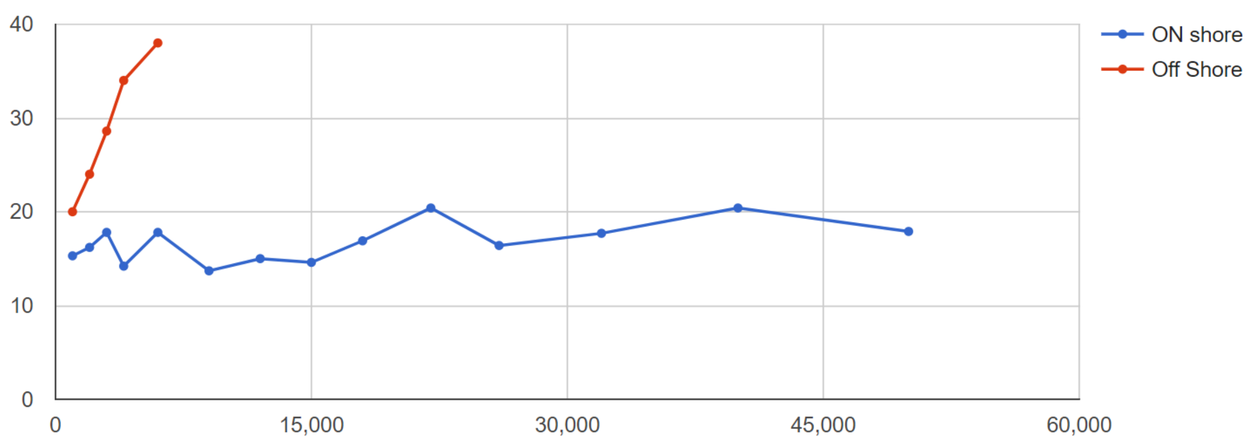
While the data can only be preliminary, the current results for CFs are encouraging for OFF shore facilities. As of December 2017, the average measured CF for all UK + Denmark OFF shore facilities is now available [35]. For our purposes we cull from this list, those facilities greater than 200 MW for which at least 2.5 years of data exists. These facilities are listed in Table 7. The lowest CF is for the oldest installation, Thanet, which when first commissioned was the worlds 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 more located in an open ocean environment.

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.

The situation in Germany is fairly unique and leaves one to wonder why there was any ON shore wind development to begin with. In general, CFs are remarkably low yet Germany continues to ramp up ON shore wind development, although it now looks as if German wind is making a transition to OFF shore to gain considerably higher CFs. This situation is summarized in Figure 10 where we plot CFs as a function of cumulative capacity for ON shore facilities and the limited, to date, OFF shore wind farms. ON shore CFS are fairly dismal, averaging around 16% and rarely were their times when CF exceed 20%, despite the fairly wide spread geographic distribution of these wind farms. One might suspect that the more wind turbines that are placed in a location, the more it would better sample the regional wind conditions and that there might be a small correlation between installed wind capacity and CF. No such correlation exists when CF is plotted against installed MWs for Germany [36]. For the US, CFs have only been measured reliably on a national level since 2013. Those numbers range from 32-37% [37]- or about twice as good as Germany. In the US, CF varies considerably from region to region; CFs for the west coast (CA, OR, WA) range from 27-30% while those in the great plains (NE, KS, northern TX) range from 40-43%. Indeed, as wind farms became more steadily deployed into the great planes, national CF did rise by about 5%, indicating the suspected correlation between more wind turbines and better sampling of the regional wind conditions.



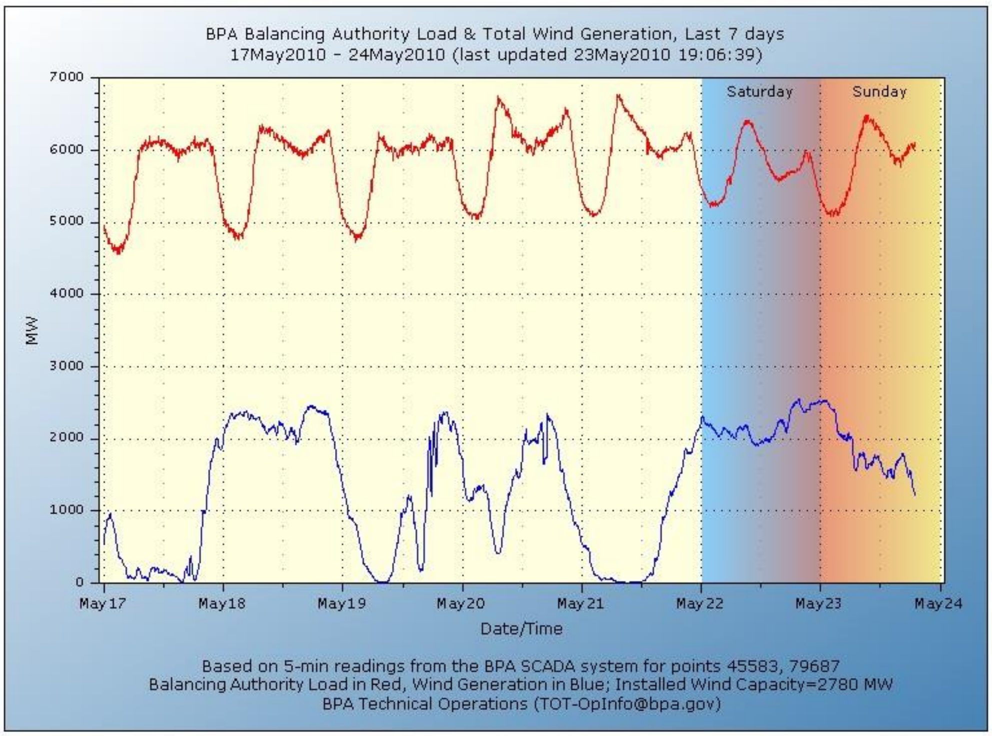
Consideration of CF variations for a countries regional wind should become an important factor in future planning. For instance, the 6000 MW of OFF shore nameplate for Germany at CF = 38% would be equivalent to 14250 MW of ON shore power given the average ON shore CF. So even if the cost is twice as high for OFF shore, Germany would still come out ahead by building all of its future facilities OFF shore. A similar situation exists in the USA as there is a large-scale geographical area that has CFs nearly as high as those found OFF shore. The wisest investment for the US to make is to continue deployment in these high CF areas as that will translate directly into larger net generation capacities. Indeed, in 2017 the state of Kansas generated 36% of its total electrical use by wind. The state of Oklahoma now has 3717 terms with nameplate of 7495 or an average of 2 MW per turbine while California has an average of only 0.8 MW per turbine. This combined with CF for OK (~43%) and CA (~28%) means that the net electrical energy generated per turbine is about 4 times more for the case of OK. This indicates as a national policy, it was likely to a mistake to build the many small turbines in CA, with relatively low CF first, as opposed to waiting until larger capacity turbines became available for deployment in OK. While it is beyond the scope of this review to properly investigate, this decision was likely motivated by the State of CA having much higher incentives available to local industry than OK. Indeed, in stark contrast to the EU, the deployment of renewable energy resources in the USA is strongly driven by individual states that effectively build a national policy from the bottom-up. This is unlikely to be an efficient process and can help explain why the European Union has made stronger gains in wind energy despite its lower available wind resources and ON shore CFs.

4.2 Energy Storage and the Intermittency Problem

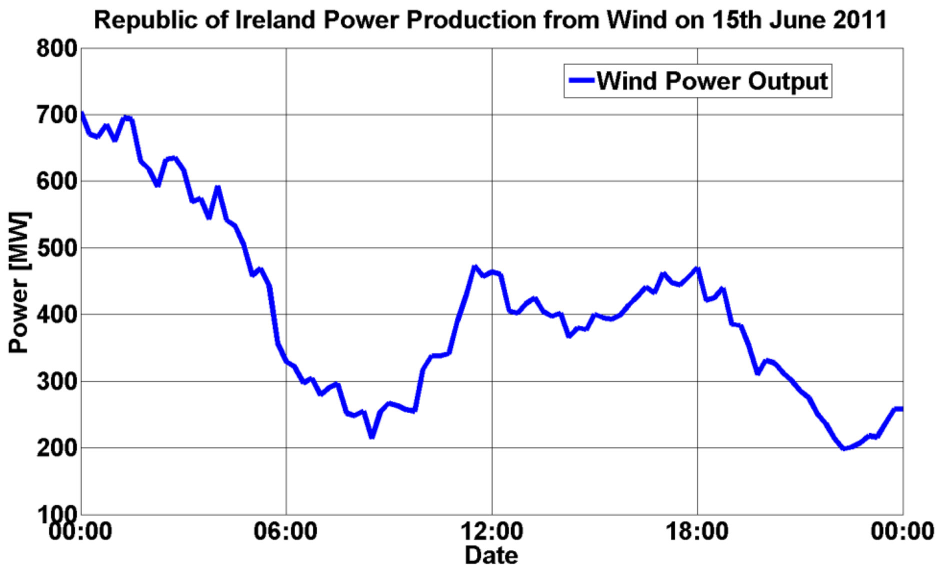
The intermittent nature of wind energy generation is a well-studied operational issue [38] since grid operators need reliable forecasts for future availability to the grid. A variety of approaches and sophisticated computer models are now available and being put into use [39]. Since this intermittency 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 large arrays of wind turbines (order 1000 per array element) 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.

Ideally, as an intermittent source of electricity production, wind energy 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 depend, 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.

A similar situation exists in the Pacific Northwest region of the USA. This region is currently undergoing a long-term drought [40] which has significantly reduced the flow in the Columbia River that powers 11 major hydroelectric dams for regional electricity generation. As a result of this overall reduced streamflow, the region has lost some 5000 MW of steady hydroelectric flow and has de facto replaced that with the variable electricity source of wind. Since wind variations are highly erratic in nature they generally will not coincide with any load cycle as shown in Figure 11. Therefore, when wind is used as a baseload power source devoted exclusively to customer demand, load balancing becomes a major management issue [41].



This intermittent behavior is universally seen and Figure 12 shows an example for Ireland where a total variation of 500 MW is observed over a particular 24-hour period and there is only about a 6-hour period in which the output is relatively constant. Thus wind farms have a pressing need to establish energy storage. For instance, suppose that baseload power expectation for Ireland wind is 400 MW. Figure 12 shows that for the first 6 hours of that day, the wind was well in excess of that amount and that excess power could have been stored, if a storage system was available.

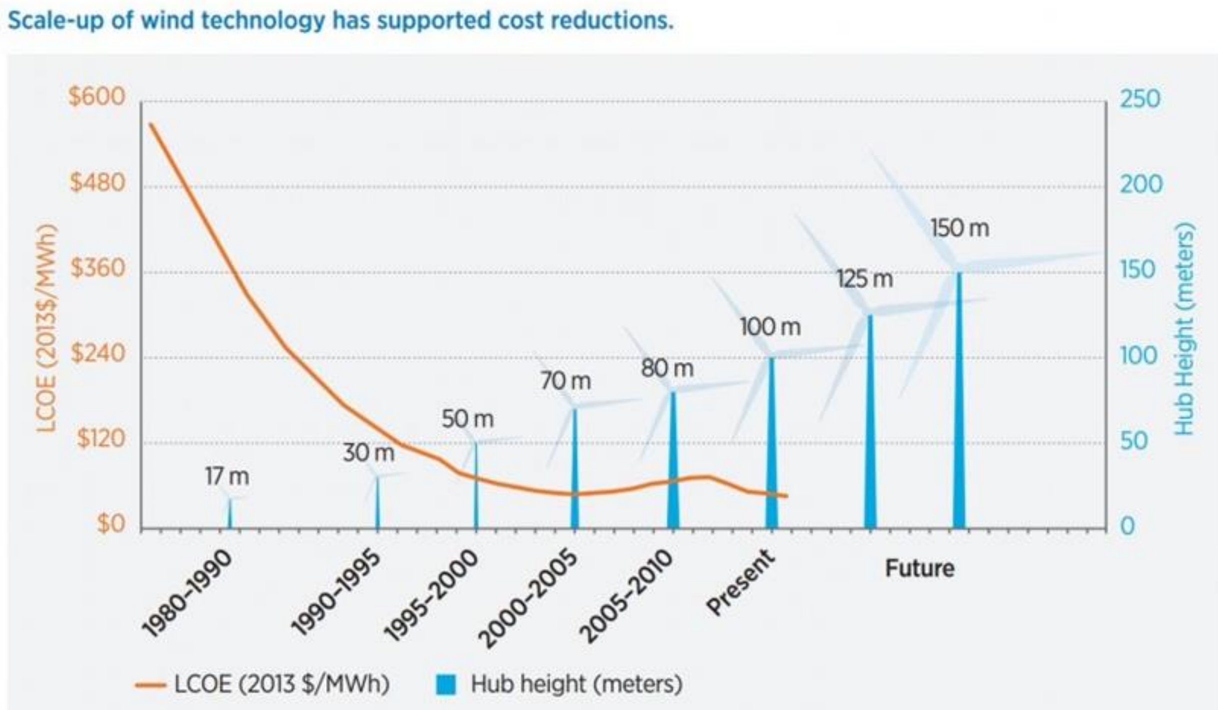


There two basic storage options for wind farms, batteries or pumped hydro. In the case cited above for the Columbia River, one storage option has always been to use excess wind energy to pump water backup hill to the dam reservoir. To date, this has not yet been put in place. However, this solution is now being tried in Germany with an experimental 4 turbine project that will pump water about 30 meters up inside the lower part of the turbine structure itself. The wind farm, located in the Swabian-Franconian forest, uses 3.4 MW turbines. The additional height needed to accommodate what is essentially a water battery makes these turbines the tallest in the world, at 246 meters. 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.

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 batteries. Note that the total energy capacity of the battery farm is 129 Mwhrs. This means that after being powered up, a typical battery discharges that power in 1.29 hours (75 minutes). 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 [42] a new set of partnerships aimed at reducing the costs of batter energy storage to facilitate the better integration of battery forms into new wind energy projects. There is also research on the efficacy of using flow batteries for wind farm electricity storage [43] as they potentially offer more flexible advantages over solid state batteries

4.3 Trends in the Cost of Wind Energy

The overall cost of electricity (COE) associated with wind farms has gone steadily down over time [44]. This reduction is primarily due to the economy of scale associated with building increasingly large wind turbines as revealed in Figure 13 which plots COE vs. turbine size.



The reason for this decline is simple to understand. To install an ON-shore wind turbine one needs road access to the wind site, a crane to erect the tower and components, and a work crew. The same infrastructure necessary to install a 50 m tower is required to install a 100-meter tower. Thus, the installation costs do not necessary increase as the turbine capacity increases. An additional component of COE reduction occurs when CF increases. Thus, wind farm electricity generation in CA will have higher costs than wind farm electricity generation in OK In terms of capital costs, over the period of 2010-2014 those were shown to be around $2,000 per kw for newly constructed wind farms in the USA [7]. A more recent study [45] found an average cost of $1600 per kw – down by about 20% from the former value. Whether capital costs go down in the future by similar amount remains to be seen. In principle, one might expect more decline as wind turbine capacity goes up but the overall transportation costs associated with the delivery of large components now can be as high as 15% of the total wind farm cost [46].

The COE for OFF shore wind energy are not yet well determined but generally are forecast to be at least twice as high as ON shore equivalents [47,48]. A significant component of this extra cost is related to various logistical barriers faced by open ocean turbine install and real world figures bear this out. For the London Array, the capital costs were approximately 2.4 billion dollars to achieve a nameplate capacity of 630 MW or 3800 dollars/kw. The Hywind floating array is higher still with a capital cost of $253 million for 30 MW of production or 8400 dollars/kw. The higher cost here is probably spurious because of the low capacity. For instance, if doubling the number of turbines caused a 33% increase in capital costs, then the final figure would lower to 5600 dollars/kw.

4.3.1 Transmission Line Limitations

COE for wind is generally estimated without the need for new transmission line infrastructure. Estimates for the costs of new transmission depend on both the total length of the new transmission lines and their rated voltages. The cost of a 69KEV line, for instance, is about 3 times lower than that for transmission at 345 KEV. In addition, the costs of buried transmission are about 3 times higher, at any voltage. Estimates for costs of new transmission line installation are highly varied and operate under different assumptions [49, 50]. Since most USA wind farms have been built without the need for new transmission, there is little basis for using real world values for an estimate. From the various studies, however, it seems reasonable that if new transmission lines are required to export the electricity then the total capital costs will be 2-3 times higher.. This significant extra cost for ON shore facilities is the main reason that the USA is not strongly developing the tremendous wind resource of the state of North Dakota (ND). ND is sparsely populated and has few large highways and other kinds of infrastructure that can assist with transmission line development. In general, this significant costs increase likely explains why newly constructed wind farms are constrained to use existing transmission lines.

For the case of the PNW, this constraint has led to a current dilemma. Existing line infrastructure in this region largely dates from the 1935-1975 period of dam construction on the Columbia River. As a consequence all wind farms in WA and OR have been built in relative proximity to these lines meaning that renewable electricity from hydro and from wind, flow over the same lines. This has led to cases where during times of high spring runoff (which are becoming rarer due to climate change), too much hydroelectricity is being generated to accommodate the extra electricity being produced by the regional wind farms. In this case, since there is no energy storage system, the wind farms are turned off [51]. This situation illuminates the larger issue that outdated power line infrastructure is a barrier to building more and more renewable sources of electricity generation.

A notable exception to these kinds of transmission line constraints is provided by the State of Texas. As part of their large scale expansion into wind energy, TX also included a $5 billion transmission line expansion plan to construct 3700 km of new lines. The first phase of that was completed in 2009 where a 375 km 345 KEV transmission line was installed in a period of just 10 months. That line crossed about 200 pieces of privately owned land, all of which needed negotiations with the land owner prior to installation or using the eminent domain mechanism that allowed the state government to take over some private land. While the costs have never been revealed, estimates suggest a total project cost of $200 million or $650 thousand per mile. The end result is the ability to deliver 735 MW of newly developed wind power from phase I of the Horse Hollow wind farm. Phase I was commissioned in late 2006 making it the largest single wind farm complex in the USA at that time. Although the total capital costs for the Horse Hollow project have not been revealed, we can make an estimate from other facilities built around the same time. The 845 MW Shepherds Flat Wind Farm stared in 2009 with $2 billion of capital financing. This equates to $2250/kw. Since Horse Hollow is unlikely to be lower, we apply that estimate to derive a total project cost of $1.65 Bn. The additional $200 million for new transmission then only represents an additional 15% to the total project costs which seems will worth the investment. However, if something like Horse Hollow were very remote so that 1000 km of new transmission was needed, that would increase the project cost by about 40% which probably means that particular remote wind farm would have never been built.

4.4 Critical Metals Depletion and the Future of Wind

To date, there have been numerous studies on this issue [52, 53, 54, 55, 56, 57, 58, 59] with far ranging conclusions from there being severe limitations to there being essentially none. Obviously the truth lies somewhere between these extremes. 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 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 [53], we summarize the current situation with respect to the key resources needed for future wind deployment.

- Column 1 is the metal
- Column 2 it 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 builds resources to estimated availability
- Column 9 is the total cost, in billions of dollars, assuming a factor 2 of inflation over time

Metal (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

The 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. This is in agreement with other, more detailed studies. These studies tend to be more recent and are considerably more optimistic about the future compared to previous studies. Most of this has occurred due to improved estimates of available resource. However, economic corrections to this optimism could be severe [60] making the future, of course, harder to predict.

In our context, column 8 should be regarded as an indication of relative vulnerability. In that case, resource concerns about the future availability of neodymium and dysprosium are of the most concern. We also note here that the material intensity for wind is quite favorable particularly compared to all wave energy devices. This is direct consequence that the inertial forces of moving air are considerably less than those of a denser moving fluid, like the oceans. For comparison, the material weight of a 3.6 MW wind turbine is 435 tons or 120 tons per MW. In contrast ocean wave devices like the free floating Pelamus device weighs 750 tons to produce 750 KW of power , or 1000 tons per MW. Tidal turbines can be anchored to the sea bed for better inertial resistance to the moving water but still have material intensity ratio 2-3 times that for wind. This all indicates that if material resources are running out, they are much better used in wind turbines than in ocean wave energy devices. 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 energy is the most expensive resource item. Overall, however, it seems we do have the physical resources required to build 2 TW of new wind energy, either ON shore or OFF shore.

4.5 Some Environmental Impact of Wind Turbine Farms

Seen through the myopic lens of local reactions, wind turbines have long been viewed as environmentally negative via threats to bird populations. In addition, many owners of the myopic lens believe that their local visual view of the world is privileged and should not be disturbed through visual pollution. These reactions are partially culturally based as visual pollution has been more of an object raised by citizens of the USA compared to those in Europe. Of course, the important lens is the one of decarbonizing the future grid so as to slow down the current rate of climate change [61] to make the Earth more livable in the future for ALL species.

On the human scale, that lens is often forgotten. Still, the local environmental lens has terminated some fairly ambitious wind projects. The most notable is the cancellation of Phase 2 of the London Array that would have added 240 MW (approximately 70 more wind turbines). While much of the reason for the cancellation is related to economics, threats to bird populations, specifically the red-throated diver birds that have an enhanced habit where the London Array was placed, did play a significant role.

In the USA, the cancellation of a small scale 7 turbine wind farm occurred because a local town arbitrarily placed a moratorium on the construction of wind turbines that were in sight of the town. While such a moratorium could be over turned, it delayed the project long enough that various investors pulled out. This tactic of delaying projects based on potential, but unproven, environmental impact often leads to project cancellation. The ambitious Cape Wind 468 MW project, located just off shore from Cape Cod had strong opposition based on visual pollution concerns and the possible disruption of fishing grounds. This successfully delayed project implementation until all the investors pulled out. The project was officially cancelled on Dec 1, 2017 [62], 16 years after plans were initially developed and 7 years after the main developer received the proper lease from the US Bureau of Ocean Management. Instead we now have the Block Island 30 MW farm so that the remaining 438 MW of electrical power in this region is still coming from fossil fuels. Even after a wind farm is built it can still be shut down by citizen law suits. This is currently the case for the 16 turbine Fourmile Ridge project in Maryland where local citizens are suing for closure and turbine removal on the claim that the 492-foot-tall turbines are disrupting their tranquility. Note finally that citizen objections don't always lead to project cancellation. For example, there was much citizen objection to placing wind turbines on Amherst Island in Lake Ontario because it is the home of several native birds. That opposition did not the stop the Amherst Island wind project which began in Dec 2016 and has been permitted to install 27 3.2 MW turbines.

To be sure there are some documented adverse effects of wind terms on local biological populations. For birds, it is the larger species like raptors and vultures that have been mostly studied [63]. For birds, the primary cause of death is direct collision with the wind turbine structure and not necessarily an adverse interaction with the rotating blades. Most turbine turbines use variable pitch technology with rpms of 15-20, meaning that moving birds can fly through the rotor diameter without experiencing a collision. One large scale study [64] conducted over a 10-year period around 617 turbines in Germany used 7428 search operations for detected bird carcasses and found 450 cases. The large ratio of null searches to detected bird carcasses suggests that most interactions with that environment do not result in bird deaths. If these turbines are in motion 25% of the time (remember the CF in Germany is lower) then over the course of the 10-year study there are 3.3E-05 bird deaths per hour per turbine or about 3.5 bird deaths per year integrated over all turbines.

To date, the largest impact of wind turbine farms is on migratory bats [65 ,66]. In North America the population growth rate for bats is now quite low so that further wind development is likely to be a factor for declining populations. Much of this decline is related to habitat loss and there is good evidence for large geographic variations between wind farms and the fatality of migratory bats [67]. Turbine height also plays a role as the larger the standing obstacle, the higher the probability of a collision with a bat. A study for wind turbines in NW Europe showed an annual bat mortality of approximately 5 per year [68]. That same study also indicates that bats which fly low to the ground are relatively unaffected by large turbines whose lowest point of rotor height is still generally above the low altitude flight path of many bats.

On balance, the available data indicate relatively low bird and bat mortality rates – certainly much lower than public perception and significantly lower than the annual loss of species due to climate change [69 ,70]. Thus, whether or not wind turbines are a net good or a net evil depends entirely on the lens used to examine that balance. Here we have presented the case that future deployment of wind terms can greatly help shift the planet away from continued use of fossil fuels for electricity generation which can help mitigate climate change. Clearly the behavior of the European Community reflects this.

Section 5: Concluding remarks

In this review we have focused on various issues associated with increasing the build out of wind energy generation as a green alternative to the continued use of fossil fuels. Wherever possible we have tried to use numerical figures based on the cost and performance of real world facilities. In addition, we have focused some attention on real world obstacles that can limit future growth such as a) possible materials shortages, b) policy changes that are detrimental to the wind industry, and c) the various logistical issues associated with the transportation and delivery of what now have become very large machine components. The most significant change in the wind energy future has emerged as the result of the recent wave of successful large scale OFF shore wind facilities installed primarily by the UK and Germany. Taken altogether, this review delivers
an optimistic viewpoint that most of these threatening issues will continue to be overcome and that the near-term future of wind energy build-out is quite promising. Indeed, we estimate that by 2035 there will be at least 1.7 TW of wind power and this will represent about 30% of the total world electricity portfolio in terms of nameplate capacity.

The most significant of our findings, as presented in order of appearance in this document are the following:

1. Wind growth is fundamentally done via the physical construction of wind turbines. For the USA, the newly released United States Wind Turbine Data Base has record the time evolution of all wind turbine construction. Currently there are about 57,000 individual turbines in the USA whose average capacity is 1.5 MW. A regional analysis of turbine growth shoes that wind power growth is highly enabled as the unit capacity turbine increases its size. Recently built wind complexes achieve average turbine capacities between 2 and 2.7 MW compared to older installations that average 1 – 1.5 MW.

2. In the USA there are now several regional complexes that now approach 1000 MW of nameplate power. These facilities have typically been built out in several phases, with the most recent phase usually utilizing larger turbines. Most of these facilities are in the large flat areas of Northern Texas, Oklahoma and Kansas. Only one facility to date has turbines as large as 3.6 MW which we take as the practical upper limit due to various obstacles associated with the delivery of very long blades necessary for that capacity. Most newly constructed wind farms in the USA are using 3 MW turbines.

3. In the early stages when supply chain limitations are not a concern, the growth of wind energy has been characterized by an exponential doubling time of about 3 years. However, extrapolation of that trend out to many future doubling times always produces an overestimate for future wind capacity. For instance, an extrapolation of the 2000-2010 rate for the US overpredicts the actual 2017 capacity by a factor of 3. Exponential growth rates simple can not be maintained once the required number of annual units needed for installation exceeds the current production capacity.

4. Over the past 4 years, China leads the world in annual wind power installs, averaging about 20 GW per year. The USA averages about 7.5 GW and Europe about 15. In the USA, the highest installs are occurring in Texas and Oklahoma. Texas alone is likely to have 30 GW of wind energy by 2020.

5. Continue build out in the USA and Europe is now somewhat threatened by policy changes. In the USA it is now definite that the Production Tax Credit will cease after 2019. We have shown that annual installed capacity is a strong function of whether or not the PTC is active in a given year, as it has had a history of being turned on and then off again. The data clearly show that an active PTC is a strong incentive and therefore it seems unwise to terminate it. Similar, the UK is threatening to end subsidies for OFF shore wind development in October, 2018. This is equally unwise as that industry is just starting to flourish precisely because of the existence of subsidies.

6. As turbine blades get longer and longer delivery becomes increasingly difficult and new innovative forms or trucks and railroad cars have been fashioned. For UK OFF shore facilities, specialized delivery and install vessels were constructed (by the Fred Olsen Company) that greatly improved the ability to make on-site installation of turbine blades. In the case of wind farms located in mountains areas, where it is likely to be windier, the industry is seriously started to consider specialized airships as an alternative delivery mechanism compared to trucks driving gingerly on narrow mountain roads. Ultimately, blade manufactures need to serious look towards the manufacturing of segmented blades (like Enercon currently does) to alleviate some of the difficulties associated with long blade delivery.

7. Large scale OFF shore windfarms such as the London Array (630 MW) and Arnholt Island (400 MW) have now had several successful years of operation thus proving the feasibility of such installations. Both are located in shallow depth waters (< 20m) and within 20 km of a coast line. This means that the turbines can be a) anchored to the sea bed and b) have relatively short distance of electricity output via undersea cable. More wind resource, and more challenges, arise when trying to locate OFF shore facilities in deeper waters where the wind resource is generally higher. In October 2017, the world's first floating wind farm (Hywind) consisting of 5 6MW turbines was located off the coast of Scotland. While this particular wind farm had very high capital costs, it likely does serve as a small-scale model for future, much larger, versions of this technology.

8. After many years of operation, a reliable capacity factor (CF) can be determined for a particular region. For the USA, CFs range from about 28% in the American West to near 45% in some parts of Kansas. In 2017, the USA had an overall CF of 37% when integrated over all facilities. The limited data for OFF shore facilities reveals CFs of about 45%. Germany and China, however, continue to have low ON shore CFs of 16% and 15%. These historically low CFs will likely motivate both countries to develop more OFF-shore wind resource.

9. The intermittent nature of wind remains a load balancing issue particular when wind energy is assumed to be part of baseload power. Both Germany and the American West have experience electricity management issues as a result of this intermittency. To date, most wind farms have been built without integrated energy storage that could help manage this intermittency. Recently, however, a 100 MW battery farm has been integrated into a wind farm in South Australia and new turbine towers that can accommodate lifting water to a height of 90 m, hence serving as a pumped hydro energy storage system, have just been installed in Germany. The use of these water battery has essentially doubled the power output per turbine.

10. The COE for wind power has been steadily declining. This is a direct reflection of an economy of scale associate with larger and larger wind turbines; e.g. the production and installation costs of a 3 MW turbine are a lot less than twice those of a 1.5 MW turbine. Real world data for the USA shows that the capital costs have declined from about $2000 - $2500 per kw in 2010 to $1600 per kw in 2016. The capital costs of OFF shore wind remain 2-3 times higher has no similar economy of scale has yet been reached. OFF shore wind will always have higher capital costs due to the delivery and install costs of the very large blades needed. For example, the London Array comes in at a capital cost of $3800 per kw.

On balance, the future of wind energy is quite promising. Our quick analysis of possible material shortage limitations did not reveal any. In addition, although there are environmental effects of wind turbines, the most notable being the increased fatality rate of migrating bats, 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 lead 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. Wind driven electricity has now proven to be quite viable with a relatively low ecological footprint on the planet and we predict that a sustained commitment to future wind development, particularly OFF shore, will allow the world to reach ~ 2 TW of wind power by 2035.

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