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Wind Scalability and Performance in the Real World: A Performance Analysis of Recently Deployed US Wind Farms

A Performance Analysis of Recently Deployed US Wind Farms

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Abstract

Real world performance, costs, and supply chain issues determine the rate at which wind turbines can be constructed, deployed, and installed. To study this issue for the case of the USA, a sample of ~600 individual US wind farms that have come into operation as of January 2010 has been assembled and analyzed using standard statistical procedures. Results for wind farm turbine composition and overall wind energy installation rates are: (a) individual unit turbine capacity ranges from 1–5 to 3 MW, although the bulk of the installations are $\leq$2.0 MW; (b) starting in late 2012, turbines of size 2.5–3.0 MW are being installed but there are logistical transport problems that come into play on this scale; (c) as of July 1, 2014, the Horse Hollow development in Texas has the largest individual wind farm nameplate capacity of 736 MW and 10 other locations have aggregate capacity that exceed 500 MW; (d) over the period of 2006–2012, cumulative wind capacity growth was sustained at a rate of 23.7 % per annum and by January 1, 2013, total installed US wind energy was 60,000 MW; (e) if this growth rate could be sustained over a 10-year period beginning at the end of 2012, then the USA would achieve a total nameplate capacity of ~475 GW for wind, which would be approximately 40 % of the entire US electrical generating nameplate capacity; (f) due to considerable uncertainty over the future of the federal production tax credit (PTC), continued growth in 2013 did not occur and this flattening has now placed US wind energy growth on a significantly more subdued trajectory; and (g) a small extension of the PTC in 2014 allowed for an additional 4,800 MW to come on line bringing the total US installed capacity to 66,000 MW as of January 1, 2015. This is approximately 45 GW less than would have been predicted based on the previous growth rate and clearly shows the dependence of growth rate on the continuation of the PTC.

Statistical analysis of real world performance and costs shows that: (a) average state measured capacity factors (CF) have a mean of 0.31 and standard deviation of 0.05; this can be compared to the average CF for European countries of 0.245 +/− 0.04. The difference in these averages is statistically significant; (b) approximately 15 % of the sample has CF $>$ 0.4 and these sites are primarily located in Kansas, Oklahoma, and Texas; (c) recently constructed wind farms with actual published project costs indicate an average of \$2 per nameplate watt; (d) CF weighted costs average about \$7 per generated watt but there is considerable variation around this average; (e) CF weighted costs lower with increasing nameplate capacity which indicates an investment strategy; (f) considerations of supply chains and transport logistics indicate that the delivery of single turbine blades to the turbines that require blades of length $>$55 m will likely be the limiting factor that governs the rate at which new large-scale wind farms can deployed.

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Keywords

Wind energy supply chain; Wind turbine growth; Wind farm capacity factors; Growth of wind energy in the US

Introduction

The feasibility of wind power as a renewable form of electrical energy generation has been clearly borne out in the US and Europe over the last decade or so. Individual wind farms and wind farm complexes are most properly characterized by their nameplate capacity and their capacity factor (CF). Nameplate refers to the maximum power for which an individual wind turbine is rated. For instance, a 2.5 megawatt (MW) wind turbine will produce 2.5 MW if the wind is continuously blowing. Since wind is an intermittent source then, on a daily basis, the average electricity production will be less than the nameplate. CF is a measure of the percentage of time a wind farm is able to produce at its nameplate capacity. Canonical and planning values for CF are usually taken to be 1/3 (i.e., the wind blows 8 h a day). However, CF must be properly measured in the real world for a reliable evaluation of wind energy's potential contribution to the overall portfolio of electricity generation for the US.

To make these measurements, we have assembled a data base of approximately 600 US wind farms and wind farm complexes that have come online since 2010. The primary data sources used in this study are, (a) The US Energy Information Administration (EIA), (b) market reports from the American Wind Energy Association (AEWA), (c) various white paper studies do from the National Renewable Energy Laboratory (NREL), and (d) informal e-mail and telephone conversations with various wind farm operators who have responded with various levels of information giving. In addition, much pertinent information comes from local newspaper articles related to the opening or commissioning of a facility. Oftentimes, these articles contain a "fun facts" section which conveys information, e.g., total project costs that cannot be found via conventional sources as this is not a reporting requirement.

The gathering of as much real world information as possible is critical to a proper assessment of the performance and scalability of wind power in the real world as the real world is often much different than the ideal world. For instance, annual reporting of wind farm output and capacity factors for the WA state in the year 2012 are significantly compromised due to a policy decision in the real world. Spring runoff in the Pacific Northwest for 2012 was unusually high and so the hydroelectric capacity of the 31 dams on Columbia River system was fully realized. As the Columbia River System electrical grid could not handle any increased load (due to the lack of energy storage facilities), the Bonneville Power Administration ordered that the regions wind farms were to be turned off for the entirety of May 2012. Although this story was well covered via local newspapers (e.g., Sickinger 2012), this physical incident is not readily noted in the EIA databases

Data is reported to the EIA in the form of Plant Identification number and this reported data set consists of approximately 600 unique plant IDs that have come online since 2010. In the cases of large complexes or aggregates (e.g., the Altamont Pass area in CA), there can be a number of individual plant IDs. A wind farm complex is therefore defined as all aggregated individual plant IDs within the radius of 15 km from a geographic center. Approximately 40 such complexes satisfy this definition, but many of these involve

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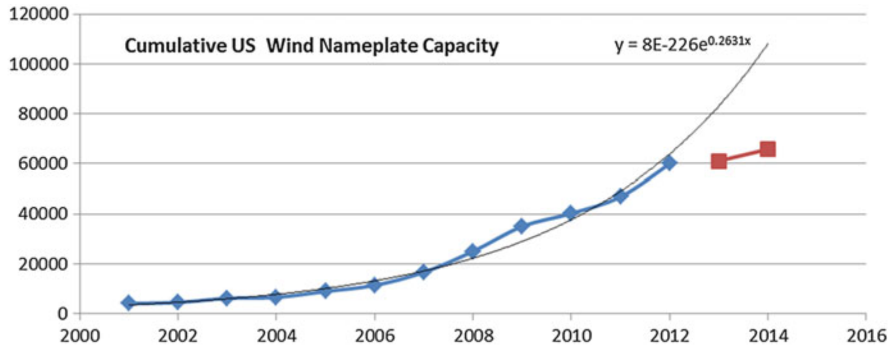

Fig. 1 Cumulative build out of wind power in the US 2001–2014; Y-axis is in units of MW

only two components. This data is then statistically analyzed using simple Gaussian procedures in order to derive basic statistics and distributions for parameters like wind farm outputs and capacity factors. The goal of this study is to combine this statistical data, with real world interrogation of some facilities, to more accurately report on the current US wind situation and to assess overall feasibility and scalability with respect to future deployment scenarios.

The Current State of Wind Energy in America

Current Growth Rates

In the USA, the three main considerations for development of wind farms at certain locations are:

(a) Land areas with reliable wind power
(b) Access to the existing transmission line infrastructure
(c) An available power purchase agreement (PPA)

The weighted combination of these three factors determines the annual rate of wind turbine installation. Currentlywithin the USA, there are now several individual wind farms or wind farm complexes that would be considered as utility scale (e.g., >500 MW nameplate power) and this is a sign of a healthy wind industry in which the combinations of a, b, and c have continuously worked together for sustainable wind deployment. As discussed below, this is no longer the case as of 2013 and the growth rate of US wind energy deployment has dramatically lowered.

In most cases, the PPA is driven either at the Federal level (via the production tax credit mechanism – PTC) or at the State level via the adoption of renewable portfolio standards (RPS). At the time of this writing (April 2014), in the USA there is 12,700 MW of new wind currently under construction and 3,300 MW of PPAs were signed in 2014.

Over the 7-year period, 2006–2012, installed wind capacity grew from 11,450 to 60,012 MW. This 5.25 factor of growth corresponds to an annual growth rate of 23.7 % or a doubling time of 3 years. This is an astonishing high growth rate, which, if sustained for the next 10 years (2013–2022) would yield a total name plate capacity of 475 GW for wind, which would be approximately 40 % of the entire US electrical generating nameplate capacity. It is precisely this high relative growth rate that promotes policy optimism with respect to the viability of wind energy has a significant component of America's renewable energy portfolio.

Figure 1 below shows the cumulative build out of wind power from 2000 through 2014 in units of megawatts (MW). The black exponential trend line is a fit of the 2001–2012 data (the blue points) with

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26 % annual growth. If sustained, this growth rate predicts approximately 110 GW of installed wind nameplate by the end of 2014. The two red points show the actual 2013 and 2014 data. The growth rate from 2013 to 2014 was 7.5 % or 3.5 times lower than the previously sustained rate. Thus, the USA has lost significant momentum in its cumulative wind energy install rate due mostly to uncertainty over the future of the PTC as discussed below.

The Role of the Production Tax Credit

The overall waveform shown in Fig. 1 indicates sustained growth over the period 2001 through 2012. However, sustained growth can only occur under conditions of scalability. In general, wind output growth physically means that the number of turbines built and deployed per year must increase. To support this increase, the number of turbine components built per year must also increase and each of these new turbines must have access to transmission line infrastructure. In addition, PPAs must be in place. Historically, these have been in for the form of the Federal Production Tax Credit (PTC).

In general, the federal PTC reimburses wind development at the rate of 2.3 cents per kilowatt hour (KWH). AWEA and DOE reports that in 2013, the average metered rate for wind energy in the USA was in the range 5–7 cents per KWH, so the PTC is a significant form of revenue return for wind energy providers.

However, in the early months of 2012, the US congress made noises to suggest that the PTC would expire at the end of 2012. This led to an extreme rush to complete various existing projects and indeed Q4 of 2012 witnessed an additional 8.4 GW of wind power installed and deployed. This value can be compared to the values of 4.1, 4.1, 3.3, and 3.5 for the Q4 build outs in 2008, 2009, 2010, and 2011. Thus, it is clearly standard operating procedure for the wind industry to assume that the PTC will expire at the end of any given year and there is a rush to complete projects before that expiration. This lingering uncertainty over the PTC is not helpful to maintain the waveform shown in Fig. 1 and at worst, threatens to mostly throttle the previously established momentum (see also Jenkins 2013).

This PTC uncertainty basically explains why 2013 manifests an extreme loss of momentum as only about 1 GW (1.5 % increase from 2012) of new wind energy came on line (and that was almost entirely in Q4). Using the growth rate previous established, approximately 12 GW of new wind resource should have come on line in 2013. This effect is best expressed in a press release issued by the AWEA in late 2013:

> The supply chain had slowed down during the months preceding the threatened expiration. As a result of the slowdown and the months needed to region momentum, the industry saw a 92 percent drop in installations, down from a record 13,131 MW in 2012 to just 1,087 MW in 2013.

This indicates the momentum is still very dependent on the continuation of the PTC.

As it turns out, the PTC did not, in fact, expire at the end of 2012 but has expired at the end of 2013. A complication arose in that a new provision was included in the American Taxpayer Relief Act of 2012 (enacted in January 2013) allowing eligible projects that were under construction before January 1, 2014, to qualify for the PTC. This allowed for a restart of many stalled projects which has therefore helped the 2014 build out to recover from the 2013 abyss. In late 2014, the US congress authorized a short-term extension to the PTC. However, at the time of this writing, it is not clear that the PTC will achieve a more permanent incentive status. While the industry can still survive without the PTC, its absence clearly and strongly affects overall production and deployment of this renewable resource. A simple numerical exercise shows in the year 2021 ~480 GW of nameplate capacity would have been reached under the older growth rate, where the new growth rate (7.5 %) would produce ~100 GW of nameplate capacity.

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Table 1 Growth of unit turbine capacity in US wind farms

Time frame	Unit capacity (MW)	# Needed for 10 GW	# Blades needed for 10 GW	Required daily construction rate
2000–2005	1.5	~6,700	~20,000	~18
2005–2010	1.8	~5,500	~16,500	~15
2010–2015	2.3	~4,400	~13,000	~12
2015–	3.0	~3,300	~10,000	~9

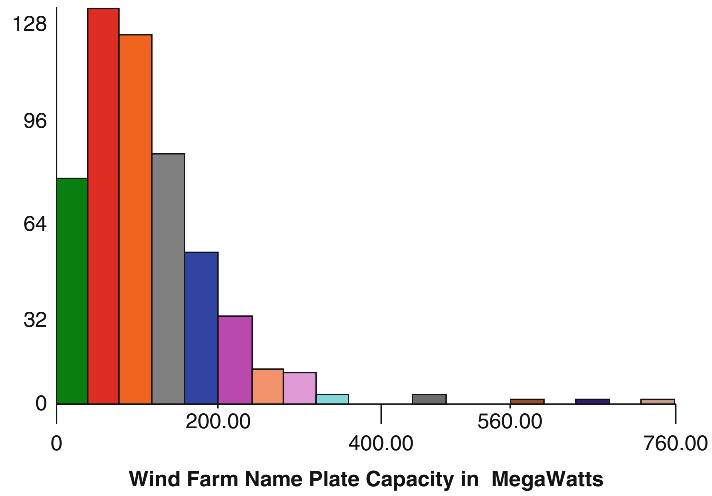

Fig. 2 Distribution of individual plant ID nameplate capacities

The Role of Increases in Individual Turbine Capacity

One of the factors that have aided the build-out of wind energy is the evolution towards larger unit capacity wind turbines. As of the end of 2014, there are approximately 48,000 individual turbines that comprise the current 66 GW of name plate capacity. This means an "average" turbine capacity of 1.38 MW. However, many projects that started in 2014 are making use of individual turbine capacities of 2.5 MW. For the year 2014, 2,500 turbines were installed at average capacity of 1.83 MW. Additionally, 80 % of these installed turbines had rotor blades larger than 50 m. Near future planned projects may move to unit capacities of 3 MW, using the Vestas V90 or V112 units.

These increases in unit capacity represent a great gain in efficiency. Independent of unit capacity, turbine installation still requires labor, cranes, and access roads. The physical process of installation is no different for a 1.5 MW turbine than a 3.0 MW turbine other than the need for more heavy lifting cranes. However, at unit capacities of 2.5–3 MW, individual turbine length is 45–55 m. This makes the delivery of blades to the wind site highly problematical as the blade length exceeds the radius of curvature of many roads and highways. Thus, shipping by rail is the only viable option. As described in detail in section "Logistical and Supply Chain Challenges," annual production and delivery of turbine blades is the likely logistical limiting factor for wind energy build-out.

Table 1 summarizes the overall evolution of unit capacity increase and its associated economy of scale as it relates to the task of building out 10 GW of new capacity per year. Very likely, 3.0 MW is the limiting size that can be achieved for land-based turbines due to the difficult logistics of transporting single blades larger than 60 m in length. In addition, overall tower heights must remain less than 152 m to be in compliance with existing FAA regulations (see Cotrell et al. 2014).

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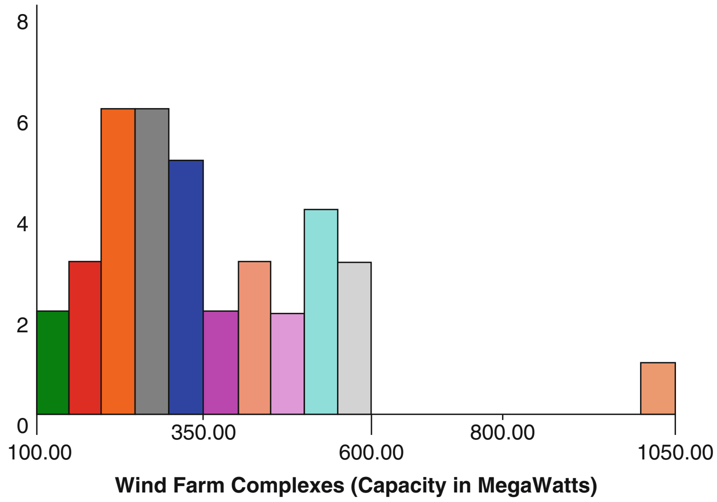

Fig. 3 Distribution of nameplate capacities for wind farm aggregates

Table 2 Listing of individual wind farm complexes with nameplate >500 MW

Complex name	#	Total capacity	State
Alta Wind Energy Center	7	1,020	CA
Horse Hollow	1	736	TX
Capricorn Ridge	1	663	TX
Fowler Ridge	1	600	IN
Sweetwater	5	586	TX
Flat Ridge	3	570	KS
Cedar Creek	2	551	CO
Buffalo Gap	3	523	TX
Majestic	2	511	TX
Shiloh Aggregated	4	504	CA
Meadow Lake	4	501	IN

Nameplate Capacities of Current US Wind Farms

Across the US, there are approximately 900 wind farms that provide the current 66 GW of US name plate capacity. This reduces to an average wind farm size of only 60–70 MW but it would be quite misleading to use this value as a "standard" wind farm capacity for the USA. Most wind farms that have been built within the last 5–10 years are individual aggregate capacities much larger than this value. Figure 2 shows the distribution of individual wind farm capacities, as defined by unique plant identification number (several different plant IDs often exist in the same geographic area that defines a large-scale wind complex) for the 608 operations that are in the analysis sample.

Clearly, given the skewed nature of this distribution, the concept of the "average wind farm" has no meaning. In this distribution, the median wind farm is of size ~120 MW and 2/3 of the distribution is less than 180 MW. Many of these individual plant ID operations can be aggregated together into one geographic wind complex (for example, the Altamont Pass area in CA). The distribution of those aggregate capacities is shown below for 37 complexes (Fig. 3).

Table 2 lists individual complexes and aggregates that are above nameplate capacity of 500 MW. In principle, these large-scale facilities are what can eventually help to replace coal and NG fired electricity.

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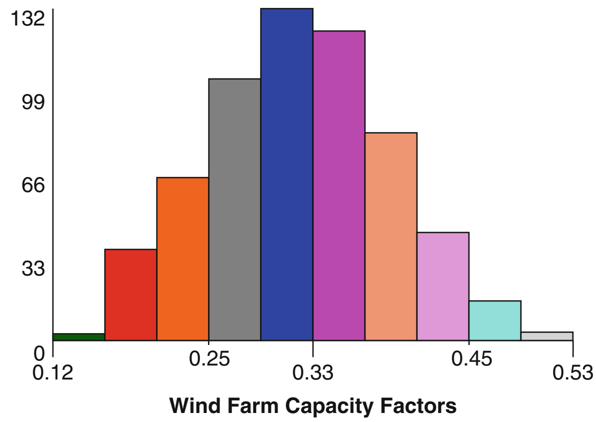

Fig. 4 Distribution of wind farm capacity factors of 2013

Real World Capacity Factors

Electrical output of wind farms is dependent on their nameplate infrastructure capacity convolved with the percentage of time that the wind blows at sufficient speeds to rotate the turbines. This percentage is known as Capacity Factor (CF). As measured in the real world, capacities factors have a very large range of values. For instance, the 21 MW Pakini Nui wind farm (in Hawaii) has an extremely high CF of 0.635 due to very reliable trade winds at that location. In contrast, the 275 MW wind farm located on Vansycle Ridge in WA experienced a CF in 2012 of only 17 % suggesting this was a poor site location for wind, at least for that year.

Figure 4 shows the distribution of CF for the year 2013 for 594 individual plant IDs that were certified to be in operation for the full year.

This distribution is well fit by a normal distribution with mean = 0.32 and standard deviation = 0.07. This real world mean is close to anecdotal value of 1/3 that is often used informally for CF. However, in this normal distribution approximately 15 % of the sample would have CF $>$ 0.4; these wind farms are generally located in the large flat areas of the Midwest. On the other hand, there are approximately 100 locations which are operating at CF $<$ 0.25 and these facilities may be suffering from the micrositing issues discussed below.

For some of the complexes and aggregates shown in Table 2 the results are quite mixed:

- The Altamont Pass area has an integrated capacity factor which is rather poor, at 0.24. Within the aggregate, individual "arrays" range from 0.195 to 0.30.
- Similarly, the Horse Hollow project (still under construction) did not perform well in 2013 with a CF of only 0.23. The Capricorn Ridge location, near the Horse Hollow project, performed much better with CF = 0.35.
- The Flat Ridge complex in KS performed extremely well with a measured CF of 0.42. This was followed by the Sweetwater TX location with CF = 0.37. Both of these locations are sited in large, flat, open country.

Table 3 shows State average CFs for states with at least 10 separate sites that can be measured to form a reliable average, for 2011, 2012, and 2013 (2014 data not available at the time of this writing):

These state average CFs are fairly constant from year to year with the notable exceptions of KS, MN, OK, and WY whose 2013 CFs are at least 5 % lower compared to the 2011 and 2012 performance. This might be due to some large-scale shift in wind patterns, which is one of the many potential manifestations

Table 3 Average capacity factors for the most wind farm active states

State	2011 CF	2012 CF	2013 CF
CA	0.25	0.26	0.30
CO	0.28	0.33	0.31
IA	0.32	0.34	0.31
ID	0.29	0.34	0.32
IL	0.29	0.30	0.33
KS	0.39	0.36	0.30
MN	0.33	0.35	0.24
ND	0.39	0.39	0.38
NY	0.23	0.24	0.25
OK	0.40	0.41	0.36
OR	0.29	0.26	0.27
PA	0.27	0.25	0.29
TX	0.34	0.35	0.33
WA	0.30	0.28	0.26
WI	0.25	0.26	0.29
WY	0.36	0.35	0.26

Table 4 Average capacity factors European countries

Country	2011 CF	2012 CF	2013 CF
Denmark	0.28	0.23	0.27
Finland	0.28	0.24	0.26
Germany	0.19	–	0.18[a]
Ireland	0.32	0.28	0.31
Italy	0.18	–	0.21
Netherlands	–	0.20	0.22
Portugal	0.26	0.28	0.29
Switzerland	0.20	0.20	0.20
United Kingdom	0.27	0.27	–

[a]The Fraunhofer Institute reports 2013 German wind CF was 0.166

of climate change. Averaging over the 3 year period, the best performing states (green shading) are ND, KS, and OK while the worse performing states are NY, WI, and OR (orange shading).

Comparison with European Wind Farms

Table 4 summarizes average CFs for countries in Europe that have substantial wind facilities which have reported data. These data come from the annual wind reports compiled by the International Energy Agency (IEA). Not all countries report annual values.

In general, the CFs are lower in European countries than in individual states in the USA and it is noteworthy that none of the reported data in Table 4 exceeds 0.32 whereas 18 out of the 48 entries in Table 3 (38 %) exceed this value. For the US states listed in Table 3, the average 3-year capacity factor is 0.31 +/– 0.05 while for the listed European countries the average is 0.245 +/– 0.4. Application of the statistical Z-test shows that the difference in these means is significant at 5.3 standard deviations. Thus, statistically, CF's in the US are significantly higher than those in Europe. This difference is driven mostly by the lack of large, windy, open, and flat areas in Europe as seen in the US in the form of the States of Kansas, Oklahoma, and Texas.

The case of Germany is especially noteworthy in terms of the cost effectiveness of renewable energies. A detailed study (Burger 2014) for the year 2013 showed that both wind and solar installations in

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Germany have quite low capacity factors (16.6 % and 9.5 %, respectively). These low capacity factors can aid in pushing the return on energy investment to below unity – meaning that it takes more energy to produce the infrastructure than is returned to the grid.

Micrositing Issues

Micrositing of individual wind turbines is designed to minimize the amount of disturbed air flow, either by terrain or adjacent wind turbines, to an individual wind turbine. By nature, micrositing is a constrained optimization problem due to the nonlinear nature of turbulence and its associated wake effects. Many different approaches exist to model and simulate these effects (e.g., Gaussian particle swarm – Chan et al. 2012; application of the greedy algorithm – Song et al. 2014). In general, micrositing becomes an important issue when wind farms are built in hilly or mountainous areas, or are located on ridge lines. The typical wind farm or wind farm complex in the US, however, is generally not sited in these locations.

While the actual site-specific optimization remains complicated and difficult to employ, the following guidelines are generally used in actual US installations:

- For large-scale wind farms (see Fig. 5 below), turbines should be placed 2–3 rotor diameters apart in the plane which is perpendicular to the prevailing wind and 10 rotor diameters apart in the parallel plane. The windfarms in the US Midwest and Texas all conform to this guideline and generally show the highest CFs.
- For ridgeline installations, the turbines should be set back from the edges to minimize the impacts of updrafts and other vertical components. The wind farms in OR and WA are mostly located on ridge lines and the complicated air flow caused by this terrain may be responsible for the lower CFs at these sites.
- Wind farms should not be placed on steep slopes because of enhanced turbulence as the wind flows over the terrain. Only the Altamont Pass complex in CA is guilty of being constructed in such terrain and this is likely directly responsible for the relatively low integrated CF of this complex, as noted earlier.

Figure 5 below shows a Google Earth Image of part of the Flat Ridge complex in KS. The rotor blades are approximately 50 m in length and the individual turbines are clearly well spaced with respect to that dimension. Extant data already show that these locations have the highest CFs in the USA and their relatively wide open domain facilitates the optimum deployment of individual wind turbines, making the problem of micrositing much less severe. Given the available large land area in the flat and windy Midwest, it seems quite clear that this region is optimal for growth.

Wind Farm Construction Costs

As wind farms are not required to report their capital construction costs, it is not directly possible to then know this for many wind farms. However, many times these costs are revealed through some “Fun Facts” article in a local newspaper related to the commissioning or opening of the project. Capital costs for some wind farms also appear on some State agency web sites. Reliable information was found for a small sample of wind farms of widely varying nameplate capacity. Figure 6 shows the distribution of these costs, in units of $ per Watt as shown for a sample of 29 wind farms with reported costs built from 2008 through 2012. While $N = 29$ is low, if this method of obtaining costs does represent random selection, then the derived mean and standard deviation is a good indicator for the entirety of wind farms constructed during this period.

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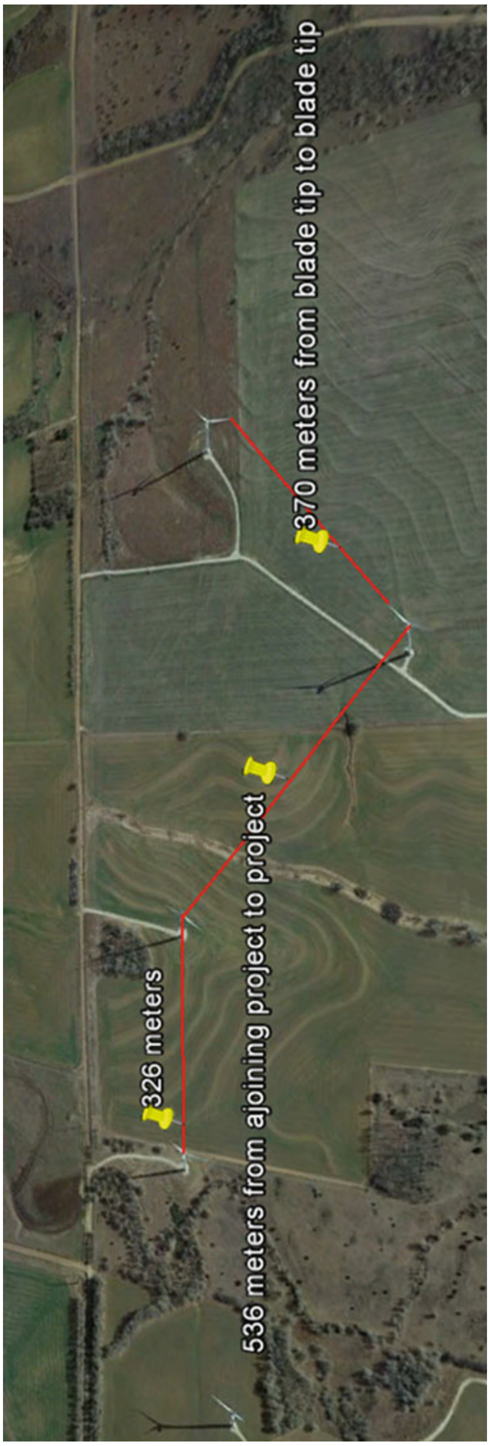

Fig. 5 Microlayout of individual wind turbines Flat Ridge complex KS

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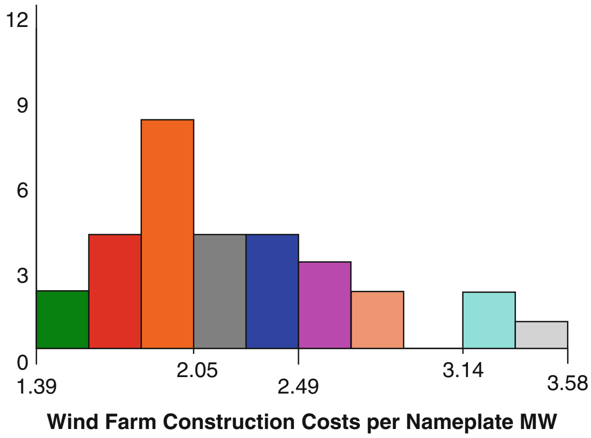

Fig. 6 Distribution of wind farm construction costs in units of $ per nameplate watt

The average of this real world derived cost is $2.2 +– 0.45 per watt. A subsample of 12 projects completed in 2012 is slightly lower at $2.06 +/– 0.33. These real world values are consistent with the 2012 DOE (Wiser and Bolinger 2013) report that cites a capacity weighted average of $1.93 per watt.

Figure 6 reveals there is a fairly large range around the average. This suggests that wind installation costs have strong local components. While the sample size is too small to convincingly demonstrate that costs are coming down with time (as claimed by the DOE report), there is some anecdotal evidence to support this.

- The Flat Ridge complex in KS shows that the 2009 cost installing 40 2.5 MW turbines was $2.82 per watt while the 2012 costs of installing 294 1.6 MW turbines was significantly lower at $1.70 per watt.
- A similar low cost is seen for the Bison Wind Energy Center in ND where 96 3 MW turbines were installed in 2012 at cost of $1.71 per watt.

- The most expensive is the 2008 Smoky Hills project in KS, where 56 1.8 MW turbines were installed at cost of $3.47.

The 2012 sample can be updated with 11 new projects completed in 2013 that have published costs. That combined sample of 23 produces a real world cost average of $2.00 +/– 0.37, again indicating that these costs are declining in the real world and has a mean value consistent with DOE expectations.

Moreover, the data do reveal an economy of scale in that cost reduction occurs when nameplate capacity increases. In general, capacity per wind farm increases due to either a greater number of turbines installed or an increase in unit turbine capacity. Since the same access roads, cranes, and labor is needed to install a 1.8 MW turbine or a 2.5 MW turbine, there is a natural expectation that the $ per watt costs should decrease in response to this. Plotting this cost against nameplate capacity for the 2012 + 2013 sample yields the following:

In this data, the average costs for the 13 facilities less than 200 MW is 2.25 +/– 0.37 $ per watt compared to 1.77 +/– 0.31 for the 7 facilities greater than 200 MW. Using the Z-test shows that the difference between these means is 3.1 standard deviations which is significant; the data are consistent with lower costs as nameplate capacity increases.

In addition, what is readily apparent in Fig. 7 is that all these large scale facilities have reported real world costs that are less than 2$ per watt. The leader is the Flat Ridge Aggregate which, as of 2013, would have production costs of $1.4 per watt. However, there is an important caveat: this computed cost index

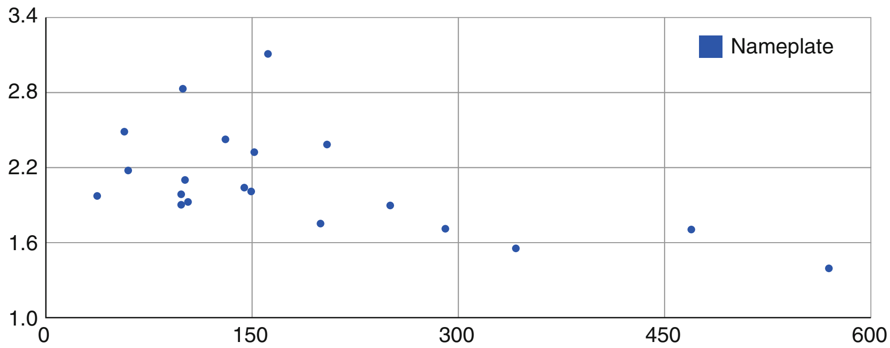

Fig. 7 Relation between construction cost ($ per watt on the Y-axis) and wind farm nameplate capacity

does not take into account any costs associated with acquiring new transmission capability. Those costs can significantly increase the overall cost of building wind turbines to produce and export electricity.

The Generation Cost Index

Utilizing the CF can produce a cost index per wind farm. This cost index simply divides the capital costs of constructing the nameplate capacity of a given wind farm by the CF for that wind farm. This creates a cost per generated watt or the generation cost index (GCI). Figure 8 shows this cost index for some example newly constructed projects to show the real world range with most projects coming in at cost index of $6–8 per generated watt. However, there are clearly examples of projects with rather large cost index, suggestion that those have turned out to be relatively poor sties for turbine siting. Owing to its high CF (see above), the Flat Ridge project in KS is clearly the most cost effective current installation.

When CF is factored into the costs, an important and reasonably linear relation appears in the expected sense that sites with higher CF are more cost effective. Figure 9 shows this trend for the 2012/3 sample. While there are some outliers, the data show a decreasing GCI as capacity factor increases. In addition, the scatter around the relation significantly narrows once CF > 0.3 is achieved. As can be seen, sites with CF > 0.4 are 2–2.5 times more cost effective than sites with CF ~ 0.25. The overall mean value of the GCI is $6.97 +/− 2.4 with most of that deviation coming for wind sites with CF < 0.3. Thus, from an investment efficiency point of view, it is much better to populate KS and OK with wind farms rather than CA and OR.

Permanent Job Creation and Wind Farm Construction

One final aspect of wind farm construction and installation which remains relevant to the real world involves the number of permanent jobs created. As might be expected, this is difficult to ascertain through any formal reporting channels so once again, the limited data set is culled from various PR based publications regarding certain wind farms. Figure 10 below shows the relation between the number of permanent jobs created and the nameplate capacity.

These data are consistent with a rubric that there is one permanent job created per 10–15 MW of nameplate capacity. Thus a 300 MW nameplate facility would be expected to create 20–30 permanent jobs.

Logistical and Supply Chain Challenges

The logistics of transporting wind turbine components, particularly the turbine blades is one of the biggest challenges faced in the scalable deployment of new onshore wind farms. For example, the latest update to

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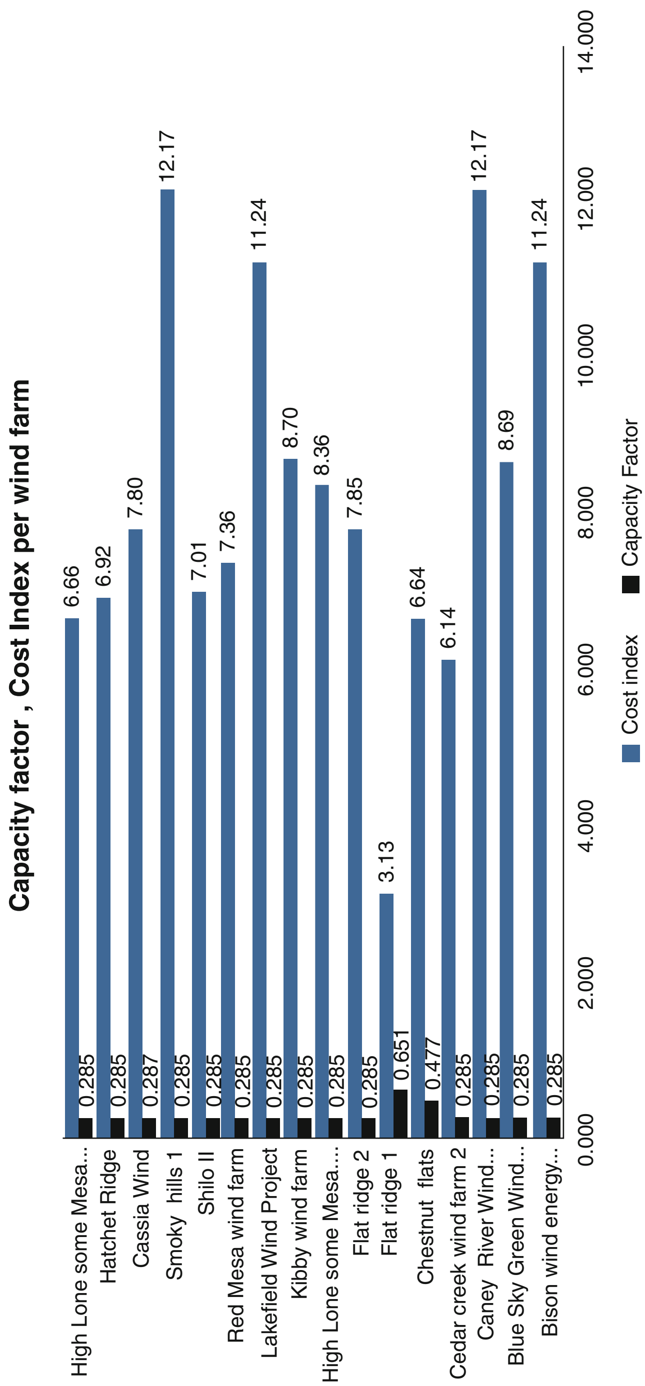

Fig. 8 Example CGI costs for some recent wind projects

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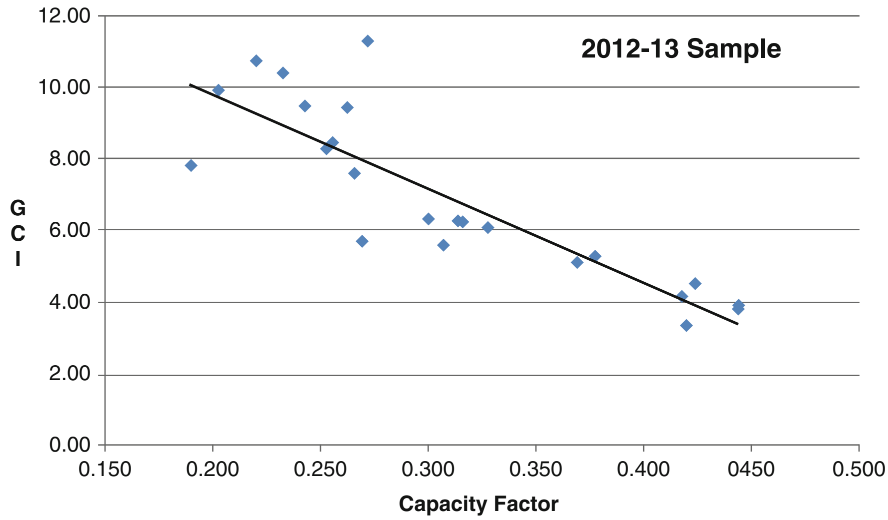

Fig. 9 Relation between generated cost index and capacity factor

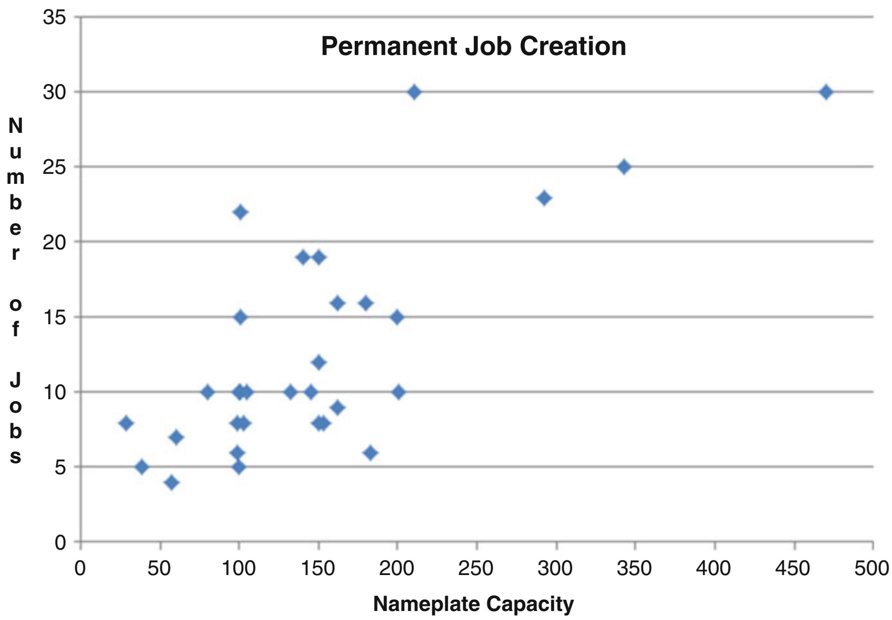

Fig. 10 Number of permanent jobs created vs nameplate capacity

the Bison Wind Farm in North Dakota, scheduled for completion in December of 2014 is utilizing individual turbines of capacity 3 MW (Siemens 3-MW D3). Individual blade lengths for that turbine are 56.5 m. It is this blade length that is likely the fundamental constraint on the maximum size wind turbine that can be deployed on land. While larger tower heights are needed for larger capacity turbines, those towers are typically composed of three sections that can be individually shipped an assembled on site. Turbine blades, on the other hand, cannot be made in sections (yet) and assembled on site; they need to be shipped as one single unit. According to Cotrell et al. (2014), the maximum length blade that can be transported given radius of curvatures on various rail routes as well as overhead obstacles is 62 m.

In addition, many wind turbine components are manufactured internationally so that port delivery is a requirement. For instance, the Port of Longview, just north of Portland, OR, has become one of the

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Table 5 Break down of major component suppliers for wind turbines

Component	#	Locations
Blades	12	CO (3), ND, SD, TX, IA, IL, AS, IN, PA, NJ
Gearboxes/mainshafts	3	OR, IL, PA
Generators	2	CO, NC
Towers	17	CA, CO(2),TX(4), NE, KS(2),OK(2), MN, IL, WI, MI, MA
Turbines/nacelles	15	CA(3), NV, CO, TX(2)KS, IA, AS, MI, FL, SC, NH

nation's top entry points for wind energy equipment made in Denmark and Germany. To maximize efficiency of port to site component transport, the port designed a specialized system to transport these components from the dock directly to railcars, eliminating the need for trucks as an intermediate transport vehicle.

As one example of scale, for a 150 MW wind farm (using 2 MW turbines) it is estimated by Freight Rail Works that approximately 700 trucks and 150 railcars are required for full turbine component delivery that required eight port deliveries. Based on this scale, the required logistics to support, for example, 10,000 MW of annual installation would be ~45,000 trucks (125 trucks per day) and 10,000 railcars distributing component parts from 600 port deliveries. Hence, at some level, annual installation will be limited by logistics even if the component manufacturing supply chain can keep up with the demand rate. For example, an aspirational goal set by the DOE is that by 2030, 20 % of America's electricity could come from wind power alone. Reaching that level would require installation of at least 7,000 new turbines which requires more than 50,000 shipments of turbine components by rail annually by 2018.

As of 2013, there are 550 separate manufacturing bases that sell to the US wind industry. Most of these are minor players, but there are approximately 50 Tier 1 facilities. These Tier 1 facilities are devoted to individual major components, such as blades or towers. Table 5 shows the breakdown of these facilities as laid out in a 2013 NREL report (James and Goodrich 2014).

In 2012, tower production equated to 7.4 GW of power, Blade production 8.1 GW, and Nacelle production 13.1 GW. This indicates that the component supply chain is not in equilibrium and has weak link production points. In 2012, that weak link would have been tower production. In 2012, the 12 blade production plants combined production was 12,500 individual blades (AWEA 2013, 2014). This production is consistent with building 4,200 2 MW wind turbines (whose combined annual nameplate would be 8.4 GW).

A useful footprint of blade production is supplied by the Vestas plant in Windsor CO. This is a 400,000 square foot facility that produces 1,800 blades per year requiring 650 workers. Hence, to reach an annual install goal of 10,000 MW with 2 MW turbines would require the production of 15,000 blades per year or the equivalent of 8 Windsor plants. To therefore reach these kinds of goals, the US public–private partnership would have to make a major investment in new production line facilities to avoid blade production being the limiting factor in wind energy build out.

The production plant in Brighton CO is dedicated to producing the 57.5-m blades for the new Vestas 117 3.3 MW wind turbine to be deployed in Denmark. These blades are then transported by rail from Colorado south to the Gulf ports (no mountains are encountered along this path) for direct shipment to Denmark. The current production capacity of this factory is 1 blade per day (or 120 turbines per year).

These issues illustrate a tension that is emerging in the construction of future wind farms. On the one hand, it is clear that an economy of scale is reached when that future wind farm utilizes turbines of capacity 2.5–3.0 MW. On the other hand, delivery of turbine blades may significantly slow down the overall construction of the plant such that an equivalent nameplate capacity plant consisting of say 1.6 MW turbines may be easier and quicker to build as blade delivery is less complicated. In any case, supply chain and transport logistics must evolve to be a strong component of future wind farm siting.

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Fig. 11 Rail transport of 55 m blades using custom railcars

Although transportation logistical difficulties most definitely exist, they can be overcome, but likely not at a scalable rate. Here are two example success stories:

(a) In Gloucester MA, the Blackburn Industrial Park has now installed 3 2.5 MW wind turbines each with blade length of 49 m. The blades were shipped to Gloucester Harbor. The final mile of transport to the site was done with trucks navigating surface streets to reach the site, thus indicating that it is indeed possible to maneuver a 160 ft long item via surface streets. Obviously this was a slow process that required partial street closures and police directing traffic. But this had to be done only nine times, to populate the three turbines. However, clearly this scenario wouldn't sale if there were 300 turbines that were located at that site.
(b) In July of 2012, Transportation Technology Services (TTS) were challenged with shipping a 55 m blade from the Windsor plant in Colorado to a new wind energy project in New England, some 1,800 miles away. To meet this challenge, TTS had to design, build, and test a custom railcar loading mechanism as well as new support pivoting structures that would allow the blade to negotiate curves without being stressed. The image below shows this unique design in action (Fig. 11).

As of late 2014, it appears that the most common turbine being installed is one with unit capacity of 2.5 MW which require blades that are 50 m (164 ft) long. Hence, logistical problems are here and in some cases have required the construction of new, temporary roads, so the blades can be delivered. This, of course, adds to the total project costs.

In addition, some newly planned wind farms (e.g., the potential Steens Mountain Oregon facility) are to be sited at altitude which makes the delivery of 50 m blades by rail impossible and by truck quite problematical. As a result of this challenge, novel new transport systems are being developed. For instance, Goldhofer (a German transportation company) has designed a flatbed combination trailer than can transport a turbine blade up to length 62 m on standard European highways. Aeroscraft is designing a unique Hydrogen dirigible (airship) that would lift and deliver individual blades to remote locations at a cost which would be less than current Helicopter rates, particularly for delivery at high altitude.

Summary: Realizing the Potential of Wind

As previously discussed, there are three basic factors that need to come together in some optimal way to support sustained growth in wind farm deployment.

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- A favorable incentive/PPA climate
- Access to transmission line infrastructure at windy locations
- A robust supply and transport chain that can continue to deliver components to various remote sites

Clearly the last 2 years have dramatically showed the effect of the PTC as an incentive for wind energy build out. The future of the PTC is currently unknown and is the subject of much speculation. For instance, in the longer term, Bloomberg New Energy Finance projects that the US wind market may be able to sustain approximately 6,200 MW per year of new wind capacity from 2017 onwards. This rate is significantly below that which is illustrated in Figure 1 and indicates that while the wind industry can survive the permanent expiration of the PTC, it is not likely to thrive and therefore not likely to meet various aspirational goals. Moreover, the current “Shale Boom” in the USA has most definitely impacted investments in wind energy, as without the PTC, wind energy generation and natural gas generation have similar costs (see Trembath and Jenkins 2012).

Momentum is also highly dependent on continued build out of new transmission. AWEA estimates that 10,000 MW of new transmission capability was completed in 2013, but that new capability is not dedicated to just wind, but to all potential sources. Annual build out of new transmission must be considerably larger than this value to help foster the build out of wind energy. For example, the commitment and forward thinking by the State of Texas to simultaneously develop 18,500 MW of new transmission line infrastructure while building out large-scale wind farm projects (e.g., Horse Hollow, Capricorn Ridge) has allowed them to be the clear leader in wind-based electrical power in the nation. As of July 1, 2014, TX had a combined capacity of 12.75 GW more than twice the leading competitor of CA at 5.38 GW. In fact, this capacity in TX exceeds the combined capacities of OR, WA, CO, KS, OK, and ND (the state with highest wind energy density) despite continuing build out in those six states. This is entirely because of the commitment to transmission lines, largely financed through public bonding in TX. In contrast, ND with a significantly lower population and much lower infrastructure has had a very difficult time exporting its abundant wind energy due to transmission line limitations.

This demonstrates the important of extant or new transmission line infrastructure and the continual build-out of wind energy capacity additions. The wind energy projects in TX, for instance, clearly would have not been possible if there were not a parallel effort to increase transmission capability. Similarly, a private industry project is underway in Michigan to increase infrastructure in the “thumb” region to support more wind farm development. This project involves 140 miles of new 345 kV lines with total capacity of 5,000 MW. This incentive for this project comes from the 2008 renewable energy standard enacted by Michigan that requires utilities to get 10 % of their power from renewable sources by 2015.

Overall, the performance of recently constructed wind farms in the USA is generally favorable and there are a few large sites that have experienced real world capacity factors larger than 40 %. This suggests a national strategy to continue to invest in those locations that exhibit high real world CF. However, national strategies and individual State’s RPS may be in conflict or even compete against one another. One example of this is provided by both OR and WA in that each State has aggressive RPSs and even though they share the Columbia River hydroelectric resource, this is excluded from their RPSs. This has led to a significant effort at wind farm construction that turns out to be sited at locations with relatively low CF.

Given the previously discussed logistical transport issues it is unclear what unit capacity wind turbine leads to the best build out scenarios. Obviously it makes little sense to plan a wind farm at a windy location if you can’t easily transport the turbine blade to that location. Currently there are many obstacles. These obstacles include FAA blade tip height restrictions, trucking of large diameter towers, hoisting larger nacelles onto increasingly taller towers, and trucking longer and larger blades. And overall weight issues for trucking the components.

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More specifically, the FAA height barrier is currently 152 m high. Planned wind farms from 100 to 140 m in height would need this restriction lifted in order to operate with less risk. Any structure over the 152 m height triggers FAA lighting requirements and a review process that could prevent construction either entirely or cause expensive delays. The FAA restrictions impact blade manufacturing from considering production of any wind turbine exceeding 152 m. This restriction also excludes 320,000 km^2 or roughly 1,000 GW of deployable land in areas where smaller wind turbines will not work due to lower wind speeds. One fifty two meter or larger wind towers are needed to effectively operate in these regions.

Nacelle hoisting is another barrier to be addressed. Currently, single crane picks are extremely large in order to carry out the task of raising hubs to larger and larger towers. There is a risk of crane shortages as there is approximately less than 20 cranes nationwide capable of working with 152 m and greater wind turbines projects involving 3 and 5 MW nacelles, the latter size needed for offshore facilities. These massive cranes also encounter logistical challenges due to limited access to complex terrain and a need for wider access roads due to weight and size. As a result of these concerns, smaller, less efficient, wind turbines, and shorter towers are used more frequently. For instance, there is a fleet of approximately 90 smaller cranes capable of working with 140 m wind turbines that are being used for current wind projects. Hypothetically, if this issue of crane size and availability is addressed, it will nearly double the deployable land available to 614,000 km^2 or approximately 200,000 new MW of available wind power achieved by increasing hub height from 96 to 140 m. In so doing, states which have lower average wind speeds now become viable for wind power production with infrastructure improvements and readily available cranes for these higher hub installations.

Overall wind energy build out in the USA has enjoyed a very successful growth curve up until 2012 but now faces a very uncertain future. What was once a promising component of the national renewable electricity generation portfolio is now being complicated by real world national politics and real world logistical issues. The overall potential in wind power blowing across the US is enormous and it is easy to construct hypothetical scenarios that could build as much as 1 TW of nameplate capacity in on- and offshore US wind. To realize this future, however, investments need to be made in component production and component delivery transport systems. Without these investments, current wind farms may end up, in 20 years, as rusted vertical monuments, testifying to the inability to deploy a scalable solution.

Conclusion

The generation of electricity by wind remains a viable endeavor for the USA. The US aspirational goal of 30 % wind by the year 2030 would result in about 350,000 MW of wind name capacity. As, of the end of 2014, the US stands at 66,000 MW – 20 % of what is needed. Given the significant loss of wind energy build out momentum in 2013/14, it will make achieving this aspirational goal quite problematic. Indeed, to achieve this would now require annual capacity additions of 17,500 MW – much larger than any year to date. Moreover, the scalability of wind build out is now being challenged by the following two main issues:

1. The production tax credit – this has expired at the end of 2013. Projects that were not under construction prior to January 1, 2014, are ineligible for this credit. As a result, 2014 will likely see little added wind production. Indeed, as of July 1, 2014, 4,350 MW of new utility-scale generating capacity was brought on line but more than ½ of that was in the form of new natural gas fired electricity. Only 675 MW of new wind generation occurred during this first half of 2014 and most all of that occurred in Texas

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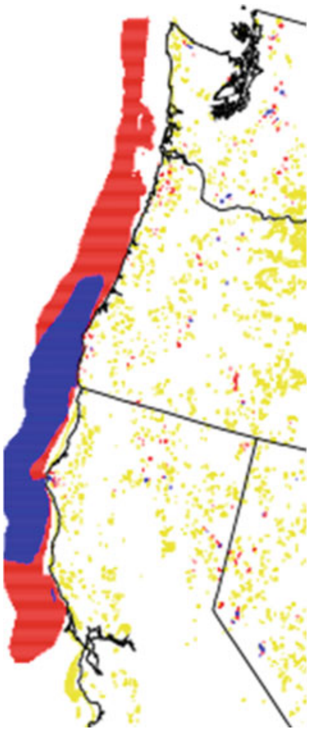

Fig. 12 Offshore wind resource potential for NW US Coast

2. Supply chain logistics – while it's clear from the data that large unit wind turbine capacity leads to more cost effective wind farms, this is balanced by the logistical problems associated with the delivery of individual turbine blades. For instance, if one were to build a 900 MW wind farm, it is very likely in the real world that such a farm could be built significantly faster by installing 600 1.5 MW wind turbines rather than 300 3 MW wind turbines

On the bright side, the potential in offshore wind for the USA is large and tapping that resource now seems like the most likely pathway to reach the US aspirational goal. For the UK, the measured average CF for OFF shore wind from 2011 to 2013 is 37 %, significantly larger than the UK onshore CF of 27 %. Similarly, the USA has several large-scale offshore wind sites that would have CF's in the range of 40–45 %. These promising sites include the North–south axis of Lake Michigan, the East–west axis of Lake Superior, and, most importantly, the nearshore coastlines of WA, OR, and Northern CA. The west coast of the USA is not subject to large-scale cyclonic disturbances, unlike the US Southeast coast and so there is little concern for large-scale damage of an offshore complex. Figure 12 below shows the most current NREL wind resource map for this region. The red areas indicate incident power density at 50 m height of 600–800 W per square meter and the blue areas correspond to 800–1,600 W per square meter.

Opening up this resource, at individual wind turbine capacity of 5–8 MW, is likely the only way that the USA can reach the 30 % by 2030 aspirational goal.

The build out of wind energy in the USA has clearly lost momentum in recent years. Much of this momentum loss can be attributed to continued investment in natural gas, via hydraulic fracking, as de facto US energy policy. During the period 2002–2012, wind energy was growing at a substantial rate and continued investment, especially keeping the PTC, turned on, allowed for a very bright future in wind energy. Now that future is in peril. Given the proven cost effectiveness of wind as a viable alternative to fossil fuel-based generation of electricity, the USA soon needs to make a more informed decision,

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balancing the need for capacity additions with the need for total greenhouse gas reductions, in order to sensibly more forward.

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