8

Silent Wind Revolution

> The pessimist complains about the wind; the optimist
> expects it to change; the realist adjusts the sails.
>
> —William Arthur Ward (1921–1994)

THERE IS A TECHNOLOGICAL REVOLUTION UNDERWAY TODAY in wind energy. However, it is not from vertical-axis wind turbines, nor from diffuser-augmented wind turbines. It's not sexy. It's not flashy. It doesn't garner headlines or breathless prose from venture capitalists looking for the next Google. It is, as French renewable energy analyst Bernard Chabot calls it, "a silent revolution."

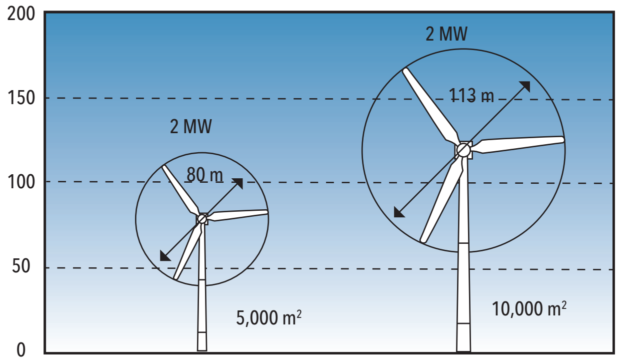
This revolution is being led by new large-diameter wind turbines with low generator ratings. To the casual observer, these wind turbines look exactly like the wind turbines that they supersede with the exception that maybe the blades are a little longer, a little more slender, and a little more flexible than previously. This is the technology that makes high penetration of wind energy more likely than ever before because it reduces the need for storage and new high-voltage transmission capacity. These are the wind turbines designed for low and moderate wind regimes, whether in central Indiana or the central highlands—the *mittelgebirge*—of Germany.

Some journalists have attempted to describe this phenomenon as a new technology that mysteriously delivers very high generator performance. It's not. We've known how to do this for decades. What's new is that wind turbine manufacturers are now delivering products that meet the need (see Figure 8-1. Silent wind power revolution).

In short, manufacturers are now offering very large diameter wind turbines with relatively low power ratings that are designed for low to moderate wind speed sites. For example, a wind turbine that would have been rated 3 MW or more a few years ago is now being offered as a 2-MW turbine, sometimes even less. These wind turbines will generate much more electricity than earlier turbines rated at 2 MW, delivering very high generator performance. In this regard, they're revolutionary.

Is this a good thing? Yes, absolutely. Here's Chabot's summary of why:

- More generation and higher penetration rates relative to installed capacity,
- Expanded opportunities through use of lower-wind sites,



Year		2000	2014
Diameter	m	80	113
Swept Area	m^2	5,000	10,000
Hub Height	m	80	130
Capacity	MW	2	2
Specific power	W/m^2	400	200
Specific area	m^2/kW	2.5	5.0
Diameter/height		1.0	1.2

Figure 8-1. Silent wind power revolution. By the late 2010s, there was a silent revolution underway in wind turbine design. Manufacturers began introducing wind turbines with very large rotors relative to their generator ratings, in some cases doubling specific area. They also were installing the turbines on increasingly taller towers relative to their rotor diameter. Together, both factors dramatically increased relative performance in terms of capacity factor and full-load hours. Under moderate wind conditions, the turbine on the right will generate twice the amount of electricity as the turbine on the left, even though they both produce the same peak power.

- Less opposition to wind as less high-wind, high-value sites are now required,
- Less demand on grid operators,
- Less demand for new transmission capacity or capacity upgrades, and
- Wind turbines with large rotors relative to their generator size will allow easier integration of wind energy into the grid, and allow us to put the wind turbines where the people are, that is, near our cities, towns, and villages.

Why this is so requires some explanation.

What Is a Wind Turbine?

In essence, a wind turbine is a rotor to capture the wind and a generator to produce electricity. Physics professor and wind energy authority Vaughan Nelson has emphasized for more than three decades that it is the area of the wind stream intercepted by a wind turbine—the swept area—that largely determines how much energy the wind turbine will capture. Obviously, the generator is a critical component, but it is not the most critical component in what makes a wind turbine—a wind turbine. It is the rotor powered by the wind that separates a wind turbine from a steam generator, for example.

Generator Ratings

Wind turbines are designed with a specific combination of rotor and generator for a specific wind resource. In *Wind Energy*, wind turbines are often described by their rotor diameter—a shorthand for their swept area. However, the media, utility engineers, and even some in the wind industry mistakenly use the generator size in kilowatts (kW) or megawatts (MW) to describe the size of a wind turbine. The wind turbine's generator will produce its "rated power" at a certain wind speed. The wind doesn't always blow at this speed, and this is where descriptions such as this complicate our understanding of what a wind turbine will produce.

Swept Area Trumps Generator Ratings

Let's consider the tale of two wind turbines on the market in the early 2000s: the V82 and the V80. Vestas's V82 is an 82-meter (270-foot) diameter wind turbine capable of generating 1.65 MW. Vestas's V80 is an 80-meter (260-foot) diameter wind turbine variously rated from 1.8 MW to 2.0 MW. Vestas's V82 is a larger—more powerful—wind turbine than the Vestas V80.

How can this be? The V82 intercepts ~ 5% more of the wind stream than the V80. For low and moderate wind sites, the V82 will out produce the V80. At higher wind sites where the V80's larger generator will be used more often, the V80 will generate slightly more than the V82 (see Figure 8-2. Comparison between a V82 and a V80).

To illustrate that this isn't a quirk, here's another case from the early to mid-2000s. Nordex was one of the pioneers in large-diameter turbines with relatively low power ratings. For example, Nordex offered its N80 rated at 2.5 MW while it was also offering its N90 rated at 2.3 MW. Again, the N90 is the larger, more powerful wind turbine. The N90 sweeps ~ 25% more of the wind stream than the N80 and, consequently, would generate considerably more electricity—even though it has a lower generator rating than the N80 (see Figure 8-3. Comparison between a N80 and a N90).

Here's one last example to drive home the point. GE's tried and true 1.5-MW platform was introduced in the early 2000s and has been on the market for more than a decade since. It began with a 71-meter (230-foot) diameter rotor and evolved to the 1.5-MW SL, a 77-meter (250-foot) diameter wind turbine. Though both turbines used the same generator rating, the SL used a rotor that intercepted 18% more of the wind stream. Consequently, the 77-meter turbine would generate more electricity even though it had the same generator rating as the earlier model (see Figure 8-4. GE 1.5-MW platform).

The GE example is noteworthy because GE expanded the platform even farther with its 100-meter (328-foot) diameter model rated at 1.6 MW, effectively doubling the turbine's swept area relative to its earliest model. Wind developers have installed hundreds of this turbine in central Indiana and adjoining states (see Figure 8-5. GE 1.6 MW wind turbine).

While these turbines are, for the most part, no longer on the market, they serve to conclusively illustrate that it is the rotor diameter and, hence, the swept area that determines the amount of electricity a wind turbine will produce.

Metrics of Productivity

There are two principal metrics used to describe the productivity of wind turbines: capacity factor and annual specific yield. Capacity factor is a

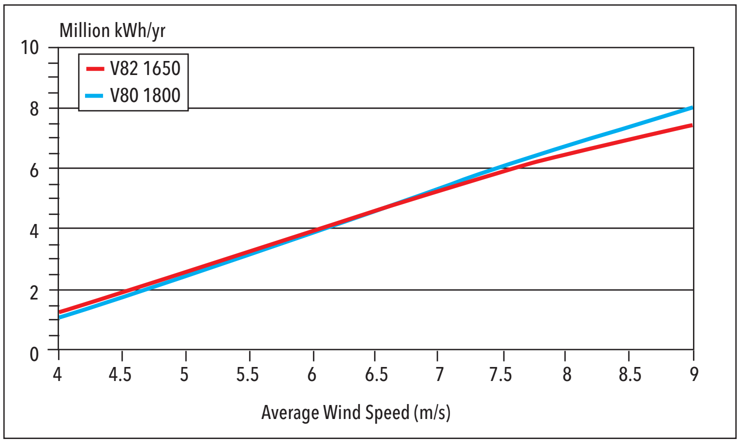


Figure 8-2. Comparison between a V82 and a V80. Vestas's 1.65-MW V82 with a rotor diameter of 82 meters will generate more electricity than Vestas's 1.8-MW V80, a wind turbine with a rotor diameter of 80 meters, at average annual wind speeds of less than 7 m/s (15.7 mph) simply because it uses a larger rotor. The V82's rotor intercepts ~ 5% more area of the wind than the V80.

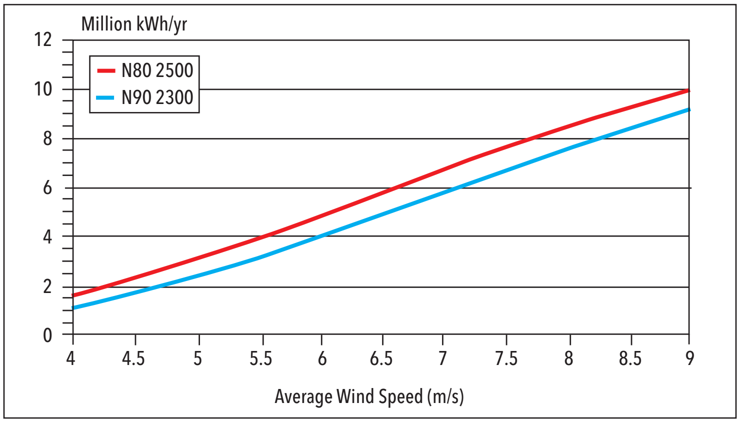


Figure 8-3. Comparison between a N80 and a N90. Nordex's 2.3-MW N90 would generate ~ 25% more electricity than its 2.5-MW N80 even though it has a lower "rated" capacity.

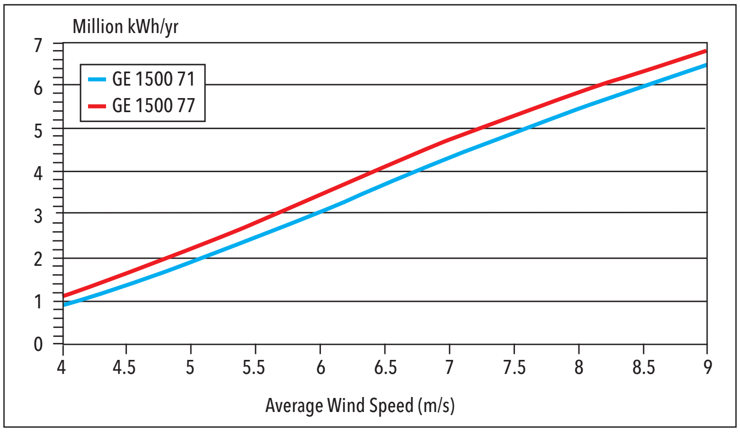


Figure 8-4. GE 1.5-MW platform. GE rated its increasingly larger wind turbines the same as its earliest model: 1.5 MW. The 77-meter diameter, 1.5-MW wind turbine would generate ~ 18% more electricity than its earlier 71-meter, 1.5-MW wind turbine because of its larger diameter and, hence, its greater swept area.

Figure 8-5. GE 1.6-MW wind turbine. German utility E.ON installed 125 of GE's 100-meter (328-foot) diameter turbines in the first phase of its Wildcat Wind Farm near Elwood, Indiana. With a specific area of 4.9 m^2/kW–about twice that of wind turbines manufactured only a decade before–GE's 1.6-MW wind turbine has been designed for areas with low to moderate wind speeds. 2013.

measure of how much electricity the wind turbine produces relative to how much it would have produced if the turbine had run all the time at full capacity. It's a common measure in the utility industry in North America, but it's often misused when applied to variable sources of generation such as wind and solar energy. Plant factor is the British expression for the same concept. Continental Europe uses full-load hours, a more direct expression than capacity factor. It is simply how many hours the turbine would have produced at full output.

Capacity factor (CF), because it can be expressed as a percentage, is often confused—sometimes deliberately—with efficiency (η). They are not the same. A wind turbine can have a very low capacity factor and yet be highly efficient at extracting the energy in the wind. Moreover, a wind turbine with a low capacity factor can be cost effective. Capacity factor is simply a measure of the generator's utilization and the effectiveness with which the wind turbine may use the grid. A much more useful measure of wind turbine performance is annual specific yield, or how many kilowatt-hours of electricity a wind turbine generates relative to the area swept by its rotor in $kWh/m^2/yr$.

To determine specific yield or capacity factor, we need actual performance—how much electricity the wind turbine generated over a specific period—or estimate it based on the expected wind resource. When a specific wind resource isn't known, we can compare wind turbines based on their relative swept area.

Measures of Relative Swept Area

There are two measures of relative swept area, that is, how much of the wind stream a wind turbine intercepts relative to its generator capacity: specific power and specific area.

Specific capacity or specific power has been traditionally used and is presented in either watts per square meter of rotor swept area, W/m^2, or kilowatts per square meter of rotor swept area, kW/m^2. The new large-diameter wind turbines have very low specific power. GE's 1.6

Table 8-1. Sample Specific Power & Specific Area

		Rotor Dia.	Swept Area	Rated Power	Specific Power	Specific Area
Manufacturer	Model	m	m^2	kW	W/m^2	m^2/kW
Nordex	N80	80	5,027	2,500	497	2.0
GE	1500	71	3,959	1,500	379	2.6
Nordex	N90	90	6,362	2,300	362	2.8
Vestas	V80	80	5,027	1,800	358	2.8
GE	1500SL	77	4,657	1,500	322	3.1
Vestas	V82	82	5,281	1,650	312	3.2
GE	100-1.6	100	7,854	1,600	204	4.9

MW, 100-meter-diameter turbine has a specific power of 204 W/m^2. Lower specific power delivers greater capacity factors—or more full-load hours—than turbines with higher specific power for the same wind conditions.

French renewable industry analyst Bernard Chabot principally uses specific area because it is simpler to interpret—a higher number offers better performance for the same wind resource. (Specific area is the inverse of specific power.) Specific area is in units of m^2/kW. GE's 1.6-MW, 100-meter-diameter turbine has a specific area of 4.9, almost double that of turbines marketed in the mid-2000s.

The design of the Vestas V80 in our earlier example was typical of its day: 358 W/m^2, or 2.8 m^2/kW. The V82, in contrast, had slightly less rotor loading than the V80, reflecting its greater intercept area. When GE introduced its 1500 in the early 2000s, it had a specific power of more than 400 W/m^2, or 2.4 m^2/kW. While this was typical of the day, GE rated their turbine more aggressively than Vestas did its V82 (see Table 8-1. Sample Specific Power & Specific Area).

Historical Abuse of Power Ratings

The problem with using measures of capacity or power in describing the size of wind turbines arises because it is easy to abuse. Technically, wind turbines can be designed with high power ratings relative to their swept area for very windy sites. Nevertheless, some manufacturers have played on ignorance of how wind turbines work and have marketed wind turbines with very large generator ratings relative to the turbine's swept area (See Table 8-2. Specific Rated Capacity of Selected Wind Turbines in the 1980s). Such abuse was particularly egregious during the California "wind rush" of the early 1980s.

Why? Because unsophisticated buyers often compared wind turbines on their installed cost relative to their installed capacity. By inflating the wind turbine's rating, the manufacturer could charge more money for its product than a competitor and still look cheaper relative to installed capacity.

The most notorious example was Fayette Manufacturing. Its unreliable turbines were the

Table 8-2. Specific Rated Capacity of Selected Wind Turbines in the 1980s

	Rated Capacity	Swept Area	Specific Power	Specific Area	Approx. Date of Introduction
Manufacturer Model	kW	m^2	W/m^2	m^2/kW	
Fayette 400	400	374	1,070	0.9	1985
Fayette 95	95	95	1,000	1.0	1983
FloWind 19	250	260	962	1.0	1985
Carter 300	300	332	904	1.1	1985
Fayette 75	75	85	882	1.1	1981
Carter 250	250	332	753	1.3	1984
FloWind 25	381	515	740	1.4	1986
Windmaster 200	200	373	536	1.9	1983

bane of the California wind industry during the 1980s. (Fortunately, all but one has been removed.) VAWT manufacturers also overrated their products compared to conventional wind turbines.

Suffice it to say that despite the high specific power of the Fayette wind turbines, they didn't generate any more electricity than other wind turbines with comparable swept area. Because they didn't generate any more electricity than other turbines of similar size, the Fayette wind turbines produced very low capacity factors.

Wind Turbine Design and Wind Regimes

To designate which wind regimes wind turbines are designed to withstand, the International Electrotechnical Commission (IEC) set a design standard. The standard defines what wind conditions the wind turbines must not only endure but remain ready for a return to operation. There are currently three IEC classes and a catchall category. A fifth IEC Class may be added (see Table 8-3. IEC Large Wind Turbine Classes).

IEC Class I is for the windiest sites, those with an average annual wind speed of 10 m/s (22.4 mph) at hub height. Class II is for less windy sites with an average wind speed of 8.5 m/s (19 mph) at hub height. Class III is for even lower wind sites with an average wind speed not to exceed 7.5 m/s (16.8 mph). Class IV is for very low wind speed sites with an average wind speed of 6 m/s (13.4 mph).

Not all wind turbines, then, are created equal. Some turbines are designed for exceptionally windy sites and others for less windy sites. As a result, the specific capacity and specific area will differ between the different IEC classes.

Wind turbines designed for IEC Class I conditions can be used at any site. They will typically have a high specific power and a low specific area. However, wind turbines designed for Class II or Class III sites shouldn't be used at a windy Class I site. Wind turbines intended for Class II or Class III wind regimes will have low specific power and high specific area, reflecting their relatively larger rotor diameters.

When a Class I turbine is used in a low to moderate wind regime, it will deliver a low capacity factor or fewer full-load hours than it would at a windy site because it has a relatively high specific capacity or low specific area. Consequently, specific power and specific area varies with the IEC Class the wind turbine is designed to serve.

For example, a Class I wind turbine will have a specific capacity of 400 W/m^2, or a specific area of 2.5 m^2/kW (see Table 8-4. Specific Capacity and Specific Area of Large Wind Turbines: Example IEC Class I Turbines).

Whereas Class II turbines will have specific capacities of 300 W/m^2 to 400 W/m^2, or a specific area of 2.5 m^2/kW to 3.0 m^2/kW (see Table 8-5. Specific Capacity and Specific Area of Large Wind Turbines: Example IEC Class II Turbines).

And Class III turbines will have specific power of 200 W/m^2 to 300 W/m^2, or a specific area of 3.5 m^2/kW to 5.0 m^2/kW (see Table 8-6. Specific Capacity and Specific Area of Large Wind Turbines: Example IEC Class III Turbines).

The introduction of IEC Class III wind turbines greatly expands the developable wind resource, making entire regions once considered unsuitable for wind energy now attractive.

This trend toward low wind speed turbines is expected to continue. Manufacturers were field-

Table 8-3. IEC Large Wind Turbine Classes

(Wind speed in m/s)

		I	II	III	S
Reference Wind Speed	V_{ref}	50	42.5	37.5	Values Specified by the Designer
Annual Average Wind Speed	V_{ave}	10	8.5	7.5	
High Turbulence (A)	I_{ref}	0.16			
Medium Turbulence (B)	I_{ref}	0.14			
Low Turbulence (C)	I_{ref}	0.12			

V_{ref}: 10-minute average wind speed at hub height; I_{ref}: Expected turbulence intensity at 15 m/s; IEC 61400-1, 2005.

Table 8-4. Specific Capacity and Specific Area of Large Wind Turbines: Example IEC Class I Turbines

		Rotor Dia.	Swept Area	Rated Power	Rated Wind Speed	Perf. at Rated Power	Specific Power	Specific Area	Wind
Manufacturer	Model	m	m^2	kW	m/s	%	W/m^2	m^2/kW	Class
Siemens	2.3-82 VS	82.4	5,333	2,300	13.5	0.29	431	2.3	IA
Siemens	3.6-107	107	8,992	3,600	13	0.30	400	2.5	IA
Vestas	80-2.0	80	5,027	2,000	14	0.24	398	2.5	IA
Nordex	90/2500	90	6,362	2,500	13	0.29	393	2.5	IB
Vestas	112-3.3	112	9,852	3,300	13	0.25	335	3.0	IB

Table 8-5. Specific Capacity and Specific Area of Large Wind Turbines: Example IEC Class II Turbines

		Rotor Dia.	Swept Area	Rated Power	Rated Wind Speed	Perf. at Rated Power	Specific Power	Specific Area	Wind
Manufacturer	Model	m	m^2	kW	m/s	%	W/m^2	m^2/kW	Class
Enercon	E82-2.3	82	5,281	2,300	13.5	0.29	436	2.3	NVN IIA
Enercon	101	101	8,012	3,000	11.5	0.40	374	2.7	NVN IIA
Gamesa	87-2000	87	5,945	2,000	15	0.16	336	3.0	IIA
Vestas	112-3.3	112	9,852	3,300	13	0.25	335	3.0	IIA
GE	1.5-77	77	4,657	1,500	14	0.19	322	3.1	IIA
Vestas	117-3.3	117	10,751	3,300	13	0.23	307	3.3	IIA
Siemens	2.3-101	101	8,012	2,300	12.5	0.24	287	3.5	IIB

Table 8-6. Specific Capacity and Specific Area of Large Wind Turbines: Example IEC Class III Turbines

		Rotor Dia.	Swept Area	Rated Power	Rated Wind Speed	Perf. at Rated Power	Specific Power	Specific Area	Wind
Manufacturer	Model	m	m^2	kW	m/s	%	W/m^2	m^2/kW	Class
Vestas	90-1.8	90	6,362	1,800	12	0.27	283	3.5	IIIA
Siemens	2.3-113	113	10,029	2,300	12.5	0.19	229	4.4	III
Vestas	100-1.8	100	7,854	1,800	12	0.22	229	4.4	IIIA
Nordex	117/2400	116.8	10,715	2,400	12.5	0.19	224	4.5	IIIA
Vestas	110-2.0	110	9,503	2,000	11.5	0.23	210	4.8	IIIA
Gamesa	114-2.0	114	10,207	2,000			196	5.1	IIIA

ing wind turbines for sites with an average annual wind speed less than 6.5 m/s (14.6 mph) in 2014. Turbines in this class have specific power of less than 160 W/m^2 to 200 W/m^2 and specific area of from 5.0 m^2/kW to more than 6.0 m^2/kW. Nearly two-thirds of the wind projects proposed in China, the world's largest market for wind turbines, in 2012 were destined for such sites.

Small and Medium-Size Turbines

Small and medium-size wind turbines are also designed to withstand specific wind conditions represented by an IEC classification similar to that for large wind turbines (see Table 8-7. IEC Small Wind Turbine Classes).

Here too a silent revolution is underway as new products are entering the market with much larger rotor diameters relative to generator size than in the past (see Table 8-8. Specific Capacity and Specific Area of Selected Small & Medium-Size Turbines). Typical wind turbines of just a decade ago, such as Bergey's Excel and Northern Power Systems' Northwind 100, had specific powers from 250 W/m^2 to 300 W/m^2, or a specific area of 3.5 m^2/kW to 4.5 m^2/kW for Class II conditions. Now Northern Power

CASE STUDY GERMANY: NEW WIND TURBINES EXPAND THE WIND RESOURCE

One of the earliest examples of how the new wind turbines entering the market are revolutionizing the wind industry is a study published in mid-2013 for Germany's Environment Agency, the Umweltbundesamt (or UBA). The study by the Fraunhofer Institute for Wind Energy in Kassel reexamined the potential of wind energy on land in Germany.

Several such studies have been done in the past, one as recently as 2010. All have concluded that even in densely populated Germany there's more than enough land area to meet the country's renewable energy targets after excluding national parks, nature reserves, and other sites where development is prohibited.

What was different this time was the scale of the wind resource that the researchers found. They discovered that nearly 14% of Germany's land area or 49,000 km^2 (~ 19,000 mi^2) was suitable for wind energy when newer low-specific power, high-specific area turbines were used. There is the potential, said researchers, to install an astonishing 1.2 million megawatts of wind generating capacity in the country. Such a fleet of wind turbines could generate 2,900 TWh of electricity per year or nearly five times Germany's current consumption (see German Wind Energy Potential on Land).

By including larger diameter turbines installed on towers up to 140 meters (430 feet) in height, researchers could expand the developable wind resource from the North German Plain to the central highlands, the *Mittelgebirge*, and the south of Germany. (Wind speeds typically decrease from north to south in Germany.) They found that the wind resource in Germany doubled when using the new wind turbines designed for low-wind sites.

What is striking is that the Kassel researchers were being conservative. They were using a hypothetical low-wind turbine with a specific power of 314 W/m^2 and a specific area of 3.2 m^2/kW. As noted in this chapter, manufacturers were selling and developers were already installing wind turbines in 2013 that far exceeded these measures, some with a specific power nearly 200 W/m^2 or nearly 5 m^2/kW. These turbines, which exist today, would expand the developable wind resource in Germany even more. That is revolutionary.

German Wind Energy Potential on Land

Region	MW	TWh/yr	%	Full-Load Hours	Capacity Factor
North	526,000	1,378	48%	2,621	30%
Central	287,000	728	25%	2,540	29%
South	375,000	791	27%	2,108	24%
	Total	2,897		2,440	29%

Source: Potenzial der Windenergie an Land, Umwetbundesamt, June 2013.

Table 8-7. IEC Small Wind Turbine Classes

(Wind speed in m/s)

		I	II	III	IV	S
Reference Wind Speed	V_{ref}	50	42.5	37.5	30	Values Specified by the Designer
Annual Average Wind Speed	V_{ave}	10	8.5	7.5	6	
Turbulence Intensity at 15 m/s	I_{15}	18%	18%	18%	18%	
Dimensionless slope parameter	a	2	2	2	2	
IEC 61400-2.						

Table 8-8. Specific Capacity and Specific Area of Selected Small & Medium-Size Turbines

		Rotor Dia.	Swept Area	Rated Power	Rated Wind Speed	Perf. at Rated Power	Specific Power	Specific Area	Wind
Manufacturer	Model	m	m^2	kW	m/s	%	W/m^2	m^2/kW	Class
Northern Power Systems	100	21	346	100	15	0.14	289	3.5	IIA
Bergey Windpower	Excel 10	7	38	8.9	11	0.28	231	4.3	II
Northern Power Systems	95	24	452	95	14	0.12	210	4.8	III/S
Evance	R9000	5.5	24	4.7	11	0.24	198	5.1	II
Endurance	3120	19.2	290	50	9.5	0.33	173	5.8	IIIA
Gaia	133-11	13	133	11	9.5	0.16	83	12.1	IIIB

offers a 24-meter (79-foot) diameter version of its turbine for IEC class III sites.

Endurance's E3120 raised the bar further with its 19.2-meter (63-foot) diameter rotor rated at only 50 kW. The specific power for Endurance's turbine is well below 200 W/m² with a specific area of nearly 6 m²/kW. When the turbine was introduced, Nova Scotia regulators were so unaccustomed to such a large rotor on a 50-kW turbine that they excluded it from a program designed specifically for wind turbines up to 50 kW. While the design was being lauded by wind industry analysts for its emphasis on swept area and not its generator rating, Nova Scotia regulators—out of ignorance of what makes a wind turbine work—discriminated against Endurance, who, they thought, was misrepresenting the product.

Scottish manufacturer Gaia takes a large diameter rotor coupled with a small generator to a whole other level. The 13-meter (43-foot) diameter rotor drives an 11-kW induction generator. Before Gaia, this was unheard of in small wind turbines, where many newcomers inflate generator ratings to win attention from the media—and customers. Gaia's two-blade, teetered rotor has a specific power of less than 100 W/m² and a specific area of 12 m²/kW.

While Gaia's large rotor relative to its small generator puts it outside the mainstream of today's wind turbines, the design has good company. In 1958 Ulrich Hütter, the father of German wind turbine design, developed a two-blade, downwind, teetering rotor. At a United Nations Conference on new sources of energy in 1961, one of Hütter's colleagues, Sepp Armbrust, explained why they used such a large 34-meter (112-foot) diameter rotor on their 100-kW turbine.

"The specific power loading of the circular area swept by the wing blades was kept to a low level in order to assure an almost uniform energy output in places with relatively low mean wind speeds. Therefore, contrary to teams in France, Denmark, England, United States, etc., we intentionally chose a design output of only 110 W/m² swept wheel area instead of the usual 300 to 400 W/m²."

Hütter's design represented a specific area of 9.1 m²/kW, or twice that of the Bergey Excel and nearly three times that of the Northwind 100, as well as most of the large wind turbines designed for IEC Class I and Class II sites. The wind industry has now come full circle by building wind turbines that emphasize swept area and not generator size, as Hütter had recommended in the 1960s.

Specific Power and Capacity Factor (Full-Load Hours)

For similar wind conditions, a wind turbine with a low specific capacity or a high specific area will produce a higher capacity factor or more full-load hours because it will simply generate more electricity (see Figure 8-6. Equivalent capacity factor for specific power). In other words, a larger rotor will capture more wind energy than a smaller rotor.

As noted above, this relationship doesn't hold across all wind regimes because some wind turbines are not suitable for all sites. Low wind IEC Class III turbines are not suited for IEC Class I or Class II conditions. Nevertheless, this relationship between capacity factor and specific capacity or specific area explains why manufacturers can advertise high-capacity factors and—

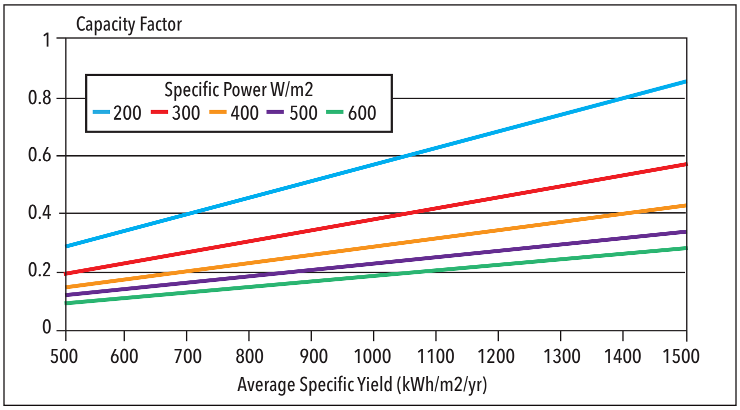


Figure 8-6. Equivalent capacity factor for specific power. There is a direct relationship between specific power (or capacity) and capacity factor relative to the yield of wind turbine at a specific site. For example, a wind turbine with a specific power of 200 W/m², or conversely a specific area of 5.0 m²/kW, at a site with an annual specific yield of 1,100 kWh/m²/yr will produce a capacity factor of more than 60%. Although we've known how to do this for many decades, it is revolutionary that manufacturers are now delivering wind turbines with such low specific power or high specific area to make it possible.

RELATIONSHIP BETWEEN CAPACITY FACTOR, YIELD, AND FULL-LOAD HOURS

We can use the characteristics of the hypothetical turbines in Figure 8-1 to illustrate the relationships between capacity factor, full-load hours, specific power, specific area, and annual specific yield. We'll use the naming conventions of French engineer Bernard Chabot who has done much to popularize this topic.

Capacity Factor

The average annual capacity factor (CF) equals the annual energy production (Ey) divided by the product of a turbine's rated power times the number of hours in a year. It's often presented as a percentage, but it can also appear as a decimal.

$$CF = Ey/(8{,}760 * Ps)$$

For example, an 80-meter-diameter wind turbine rated at 2 MW that generates 5 million kWh per year will have a capacity factor of

$$CF = (5{,}000{,}000 \text{ kWh/yr})/(8{,}760 \text{ hrs/yr} * 2{,}000 \text{ kW}) = 28.5\%, \text{ or } 0.285.$$

Or consider a 113-meter-diameter wind turbine also rated at 2 MW. If this much larger turbine generates 10 million kWh per year, it will have a capacity factor of

$$CF = (10{,}000{,}000 \text{ kWh/yr})/(8{,}760 \text{ hrs/yr} * 2{,}000 \text{ kW}) = 57\%, \text{ or } 0.57.$$

Full-Load Hours

Full-load hours (Nh) is another way to express the same idea as capacity factor. Annual full-load hours (Nh) is simply the annual generation divided by a wind turbine's rated power.

$$Nh = Ey/Ps$$

In our first example, the 80-meter-diameter, 2 MW turbine generating 5 million kWh per year will deliver

$$Nh = (5{,}000{,}000 \text{ kWh/yr})/2{,}000 \text{ kW} = 2{,}500 \text{ full-load hours.}$$

The larger turbine will produce twice the full-load hours as with capacity factor.

Capacity factor and full-load hours are related by the number of hours in a year.

$$CF = Nh/8{,}760$$

For example the capacity factor of a turbine with 2,500 full-load hours is

$$CF = 2{,}500 \text{ hrs}/8{,}760 \text{ hrs} = 28.5\%.$$

Annual Specific Yield

Another metric of performance, annual specific yield (Eys), is independent of generator size or generator rating. It's solely a function of annual generation (Ey) and the swept area (S) of the wind turbine in m^2.

In our example of the 80-meter turbine, annual specific yield is found by dividing annual generation by the rotor swept area.

$$Eys = Ey/S$$

$$Eys = (5{,}000{,}000 \text{ kWh/yr})/5{,}000 \text{ m}^2 = 1{,}000 \text{ kWh/m}^2\text{/yr}$$

Since the large turbine is double the area of the smaller turbine and generates twice the amount of electricity in our example, the annual specific yield of both turbines is the same.

If the conversion efficiency of a class of wind turbines is assumed to be equivalent, then the annual specific yield is a surrogate for the wind resource or annual average wind speed.

Specific Power

Specific power (Ps) in W/m^2 is found by dividing the swept area (S) of a wind turbine by the turbine's rated power (P). Specific power is one widely used measure of rotor loading.

$$Ps = P/S$$

Our 80-meter, 2-MW wind turbine sweeps 5,000 m^2, therefore the specific power is

$$Ps = 2{,}000 \text{ kW}/5{,}000 \text{ m}^2 * 1{,}000 \text{ W/kW} = 400 \text{ W/m}^2.$$

Specific Area

Specific area (Su) in m^2/kW is simply the wind turbine's swept area divided by the turbine's rated power.

$$Su = S/P$$

Again, using our example of the 80-meter wind turbine rated at 2 MW, the specific area is

$$Su = 5{,}000 \text{ m}^2/2{,}000 \text{ kW} = 2.5 \text{ m}^2\text{/kW}.$$

Specific area is the inverse of specific power.

$$Su = 1/Ps * 1000 = (1/400 \text{ W/m}^2) * 1{,}000 \text{ W/kW} = 2.5 \text{ m}^2\text{/kW}$$

Relationship Between Capacity Factor and Specific Yield

There is a direct relationship between capacity factor (CF) and annual specific yield (Eys) as a function of specific power (Ps).

$$CF = Eys/(Ps * 8{,}760 \text{ hrs/yr} * 1{,}000 \text{ W/kW})$$

At a site where a wind turbine with a specific power of 200 W/m^2 yields 1,000 kWh/m^2/yr, the capacity factor is

$$CF = (1{,}000 \text{ kWh/m}^2\text{/yr})/(200 \text{ W/m}^2 * 8{,}760 \text{ hrs/yr} * 1 \text{ kW}/1000 \text{ W}) = 0.57 \text{ or } 57\%.$$

There is a similar relationship with full-load hours and annual specific yield.

$$Nh = Eys/Ps = (1000 \text{ kWh/m}^2\text{/yr})/(200 \text{ W/m}^2 * 1 \text{ kW}/1000 \text{ W}) = 5{,}000 \text{ hours.}$$

more importantly—deliver high-capacity factors in the field.

Why All This Is Important

What is revolutionary about the new low-specific power, high-specific area turbines is not that they exist—there have always been such turbines—it is that the manufacturers and wind developers have finally embraced them. In the United States, for example, Lawrence Berkeley's Ryan Wiser reported that the average specific power of newly installed wind turbines has dramatically fallen from 400 W/m^2 in 1998 to 283 W/m^2 in 2012—a change of 40%.

For many years those who wanted to use wind turbines in lower wind regimes, typically near where people live, were forced to use wind turbines that were designed for high wind sites. While such turbines were adequate for the task, they produced very low capacity factors. This was acceptable as long as wind energy was a small part of the generating mix and there was more than sufficient capacity on the wires and electrical infrastructure to absorb peak power on those occasions when it occurred.

Manufacturers, meanwhile, were selling to commercial wind developers who pick the windiest sites possible to maximize their profits. This was the traditional model of power plant development since the 1940s: power plants were installed where the resource was most abundant often quite distant to where the electricity would be used. It wasn't always so. In the early days of electricity, power plants were built in the cities where the demand was.

All this began to change as more and more of the high-wind sites were developed and the bottlenecks to long-distance transmission of electricity became more problematic.

Countries such as Germany and France went so far as to implement policies—feed-in tariffs differentiated by wind resource—that would enable development at lower wind speed sites. They reasoned that it would be better for the nation if wind development was not solely concentrated on the windiest coastlines or windiest mountaintops but distributed across the breadth of the country. Not only would this simplify integration of wind energy with the transmission and distribution system, it would reduce social conflict by those opposed to wind turbines in scenic, but windy, locales while at the same time spreading economic opportunity to all regions.

Quebec engineer Bernard Saulnier believes the new IEC Class III turbines are not only revolutionary because they allow deploying new wind generating capacity in lower wind speed regions but also because–whether they realize it or not–the manufacturers have declared war on the centralized generation model and the long transmission lines that are an essential part of that model.

France and Germany have been successful in this regard. Wind development is geographically dispersed in both countries. In Germany it's not uncommon to see wind turbines near the great urban agglomerations. For example, numerous wind turbines are visible from the inland harbor of Hamburg and even from the scenic city of Freiburg in southern Germany's Schwarzwald or Black Forest.

Like his French colleague Chabot, Quebec engineer Bernard Saulnier believes the new IEC Class III turbines are not only revolutionary because they allow deploying new wind generating capacity in lower wind speed regions but also because—whether they realize it or not—the manufacturers have declared war on the centralized generation model and the long transmission lines that are an essential part of that model.

This is good news to many environmentalists who have objected to the long-distance transport of electricity. Many environmentalists prefer that generating capacity should be "distributed" among the users of electricity so that new transmission lines are not needed. Distributed generation implies putting wind turbines and solar panels in or near urban areas where consumption is greatest.

German wind engineer Jens-Peter Molly also points out that low-specific power, high-specific area turbines use the existing network so much more effectively that it drastically reduces the need for storage of a variable resource like wind energy. Thus, argues Molly, we can rethink how best to integrate the high penetration of wind energy into the grid. Incorporating these new wind turbines in the transmission and distribution system will be much more cost effective than adding expensive storage facilities, or expanding transmission capacity with thicker cables on existing lines, or installing controversial new power lines.

Molly explains it this way.

If a wind turbine with a 100-meter-diameter rotor were equipped with a generator of only 1-kW size, it should be clear to everyone that this wind turbine could run throughout the whole year at rated power without requiring expensive storage facilities or overdimensioned grid connections because the capacity factor or the guaranteed power capacity would be almost 100%. The payment for each kilowatt hour generated in this way, however, would have to be very high because with only 8,760 kWh generated, the expenditure for the large rotor, nacelle, tower, foundations, and so on would be spread over so few kilowatt-hours.

On the other hand, the same rotor diameter could be coupled with a 10-MW generator. In this case, the wind turbine would generate the rated power only for a few hours a year, in other words, enormous costs for the mechanical and structural components of the turbine, which are out of all proportion to the increased yield of the wind turbine. The cross sections of the transmission lines would have to be sized to be able to transmit the rated power generated by this turbine during only a few hours per year when it reached its rated capacity. These power lines would then be greatly underutilized and, therefore, much too expensive for the electricity generated.

Obviously, between these two extremes there must be an optimum, says Molly. And that is why there is now a range of wind turbine designs for different wind resources.

IEC Class III turbines are not robust enough for high-wind sites, says Molly, but they are well suited for large areas of countries, such as Germany, where the majority of people live and work—where the load is. He argues that it is much cheaper to pay a little extra for the generation from such a wind turbine than to either pay for storage or increased transmission capacity. Fortunately for Germany, the country's differentiated wind tariffs are easily adapted to this requirement.

Low-specific capacity, high-specific area turbines increase the average power they can deliver for a longer period of time, improving both the predictability of wind energy to grid operators and improving the ability of wind turbines to provide reserve generating capacity for emergencies, such as when a nuclear plant trips off-line. And because the difference between average power and rated power is smaller, there is a much-reduced need for greater transmission capacity.

French engineer Chabot makes a similar observation; wind turbines with low-specific power and high-specific area "represent a strategic advantage for the large-scale integration of wind energy" in the electricity system. Much greater amounts of electricity can now be generated with a lower total installed capacity, he says. And this capacity can be placed nearer the centers of consumption than otherwise, reducing the cost of electrical transmission and distribution. This is a huge advantage, says Chabot, for adapting our existing infrastructure, which was built at such a high cost, to the high penetration of renewables that is coming.

These long-awaited turbines of low-specific capacity and high-specific area are the kind of technology needed to make wind energy an essential low-cost component of supplying 100% of society's electricity with renewable energy. That's revolutionary.