ANALYSIS OF WIND FARM ENERGY PRODUCED IN THE UNITED STATES

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ABSTRACT

The electricity generated by wind farms in almost every state in the United States with over 10 MW of wind turbine capacity was analyzed over a five year period (2002 to 2006). The total amount of wind generated electricity in the United States for 2006 was estimated at 26.3 terawatt-hours which was 0.64% of the total electricity generated in the U.S. The average wind farm capacity factor for several states was estimated during 2006 and the highest wind farm capacity factor achieved was 41% (Nebraska and Oklahoma tied). Besides capacity factor, another way of estimating wind farm efficiency was developed by normalizing the wind farm output by wind farm rotor swept area instead of megawatt rating of wind farm. How well wind generation in different states matched utility load was also discussed. Capacity factors for the same wind turbine were determined for 15 different states which indicated which states had the best wind resource. Increasing the wind turbine rotor diameter by 8% was shown to be better at increasing wind farm output than increasing the hub height an additional 25 meters from 75 to 100 meters, at least in the state of Texas.

INTRODUCTION

The installed MW capacity of wind turbines in the United States are well publicized numbers in the popular press. The data which has received less publicity is the amount of electricity generated by wind energy. Wind generated electricity has a greater relevance than installed wind capacity since it represents the actual amount of electricity displacing fossil fuel generated electricity, and the burning of fossil fuels is thought to be the primary cause of global warming. These wind generated electricity numbers are not readily accessible, so we decided to gather these data. The Energy Information Agency of the U.S. Government (www.eia.doe.gov) keeps track of both the installed MW capacity and the energy generated by all sources of electricity (e.g. coal, natural gas, nuclear, hydro, wind, etc.). However, their latest published numbers on renewable energy generation in U.S. were for 2003. We were able to make fairly accurate estimations of the wind energy generation in most states (see Table 1) with significant wind farm capacity installed (> 10 MW) using information from the Federal Energy Regulatory Commission (FERC), the Electric Reliability Council of Texas (ERCOT), various state energy offices, and wind resource data. In Table 1 the energy generated sometimes doesn't appear to correlate well with the installed capacity, but this is because the capacity number listed represents capacity as of Dec. 31st of that year, and some of the wind farms installed at the end of year may have contributed little to the total wind energy generated that year. However, the capacity factor listed in Table 1 for 2006 took into account how long each wind farm operated during that year.

Capacity factor (CF) is the most popular way of estimating the efficiency of a wind farm (WF) and is defined below:

$$CF = \frac{\text{WFoutput (MWh)} * 100\%}{\text{Rated power output of WF (MW)} * \text{hours in time interval (h)}} \quad (1)$$

All the wind turbines installed at wind farms in the past four years are pitch controlled wind turbines (as opposed to stall controlled wind turbines), and power curves of some typical wind turbines used are shown in Fig 1. All the power curves shown in this paper assumed a turbulence intensity of 10% and a 0 degree inflow angle. Although the output of a wind turbine is dependent on the maximum MW rating it reaches, it is also very much a function of the swept area of the wind turbine. In some California energy reports, in addition to reporting capacity factor, the wind farm energy output of the wind farm is divided by the swept area of wind farm (e.g. units are kWh/m^2). The problem with this number is that its value depends on the time interval of the data reported. To make the quantity independent of time then this number can be divided by the time interval, so the units are W/m^2. The definition of this Average Wind Turbine Output Density (AWTOD) number is:

$$AWTOD = \frac{\text{WFoutput (MWh)} * 10^6 \text{ (W/MW)}}{\text{Swept Area of WF } (m^2) * \text{hours in time interval (h)}} \quad (2)$$

Since the wind farm is dependent on both the wind farm capacity (MW) and the wind farm swept area (m^2) then both numbers can be helpful in analyzing a wind farm.

Besides analyzing the energy output from the wind farms, we also analyzed the effect of increasing rotor diameter (maintaining the same MW rating) and also the effect of increasing the hub height using tall tower hourly anemometer data.

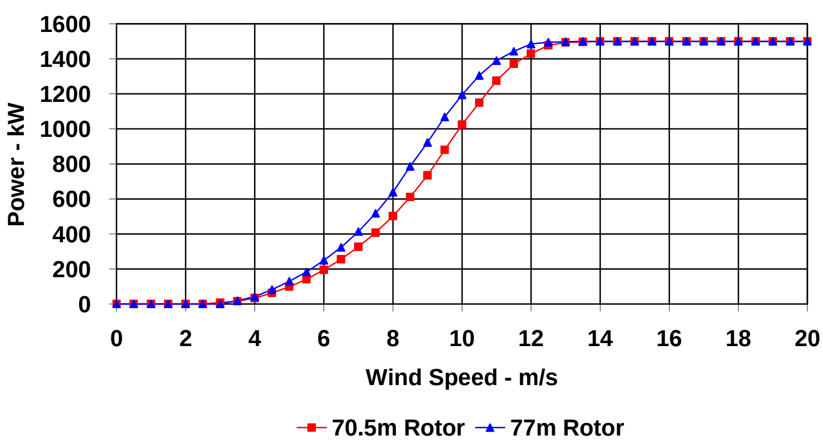


Fig 1. Power Curves of GE[1] 1.5 MW Wind Turbine with Two Different Rotors (Sea Level Standard Day).

[1] The mention of trade or commercial products in this article is solely for the purpose of providing specific information, and does not imply a recommendation or endorsement by the U.S. Department of Agriculture.

U.S. Wind Generated Electricity

Fig 2 shows the trend in installed wind farm capacity (MW) and the wind generated electricity (GWh) in the United States from 2002 to 2006. The installed capacity and energy generation for years 2002 and 2003 were obtained from the Energy Information Agency. The installed capacity for years 2004 to 2006 was obtained from published data by AWEA (www.awea.org) and the wind generated electricity for that same time period we estimated based on data we gathered from various websites including: www.ferc.gov, www.texasrenewables.com, www.energy.ca.gov, www.kansasenergy.org, www.neo.ne.gov, and www.rnp.org. Additional wind farm energy information were obtained from the state energy offices whose location can be found on the website www.eere.energy.gov, and some wind farm energy were estimated from published wind resource data. In Fig. 2 the increase in the U.S. installed wind capacity is linear, but the increase in wind energy generation is increasing at a faster rate.

Fig 3 shows the wind energy generated (GWh) over the past five years (2002-2006) for the top four wind energy production states – Texas, California, Iowa, and Minnesota. The amount of electricity generated by wind turbines in California, Iowa, and Minnesota has been increasing at about the same rate, but the amount generated in Texas has been increasing at a much steeper rate each succeeding year. Texas wind farm growth is dependent on many factors including: a well written renewable portfolio standard (RPS), good wind resource (West Texas and Texas Panhandle) combined with high electrical load nearby (east Texas), Texas folks favorable attitude toward wind farm installation (little NIMBY attitude), and good business climate.

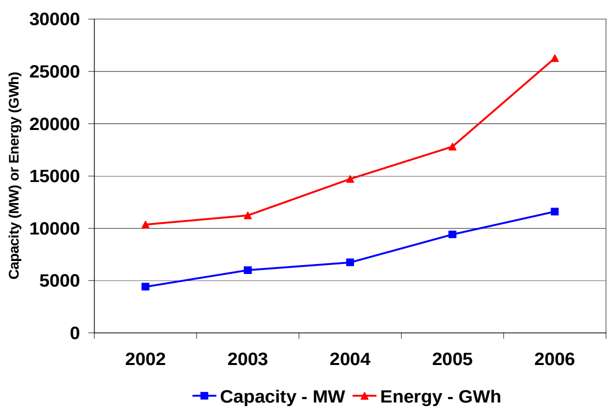


Fig 2. Wind Farm Capacity (MW) and Energy (GWh) in United States.

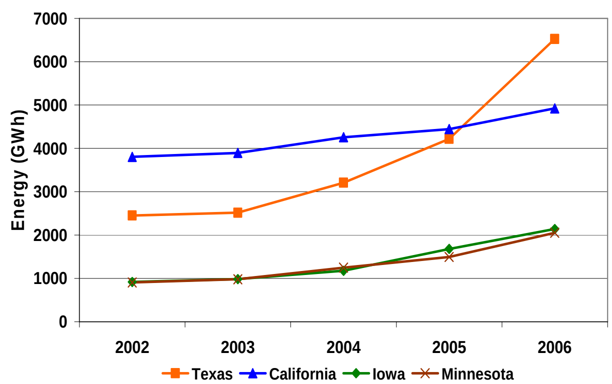


Fig 3. Wind Farm Energy for Top Four Wind Farm Production States.

Wind Farm Efficiency Analysis (Capacity Factor)

Historically wind farm efficiency has been determined by calculating the monthly, quarterly, and/or annual capacity factor. Fig 4 shows the quarterly and annual capacity factors for three wind farms with the same wind turbine at three different locations in U.S. (West Coast, Midwest, East Coast). The quarterly data shows that in the winter (1st quarter) the East Coast has its highest wind energy production, and West Coast is always lowest. In the spring (2nd quarter) the Midwest data is always highest, and the East Coast is always lowest. In summer (3rd quarter) the west coast is always highest and East Coast is always lowest. In the fall (4th quarter) the Midwest and East Coast wind energy generation are about the same and the West Coast is always lowest. Over the whole year the average annual capacity factor is always highest in the Midwest while the average annual capacity factor on the East and West Coast is approximately the same.

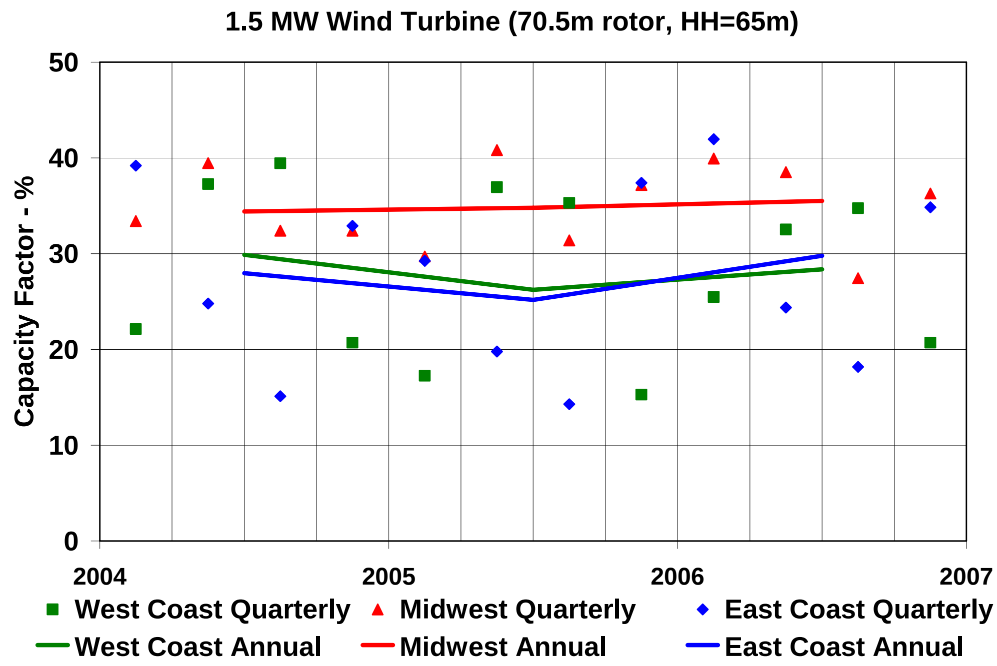


Fig 4. Wind Farm Quarterly and Annual Capacity Factors for 3 Regions in U.S.

Fig 5 shows the monthly variation in capacity factor for the same 3 wind farms, but just for the year 2006. The peak wind energy month for West Coast is July while its lowest wind energy month is December. The peak electrical loading for all three locations is in the summer, and the wind farm on the West Coast helps the utility the most with its peak load.

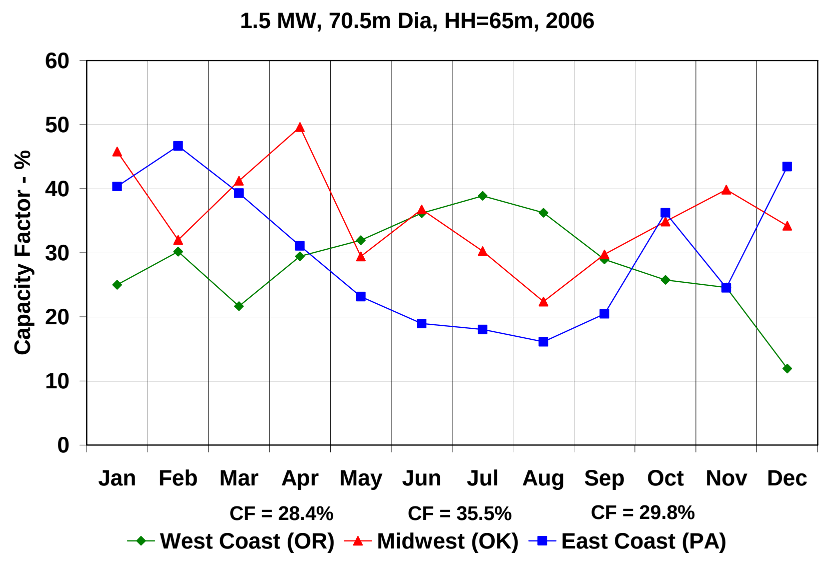


Fig 5. Monthly Variation in Wind Farm Capacity Factor for 3 Regions in U.S.

Fig 6 shows a comparison of capacity factor for wind farms in California and Texas during the month of July for years 2005 and 2006. During the month of July the average capacity factor for the California wind farm is approximately double that of the one in Texas at all times of day. However, the peak utility electrical loading usually occurs in the 4 to 6pm time period, and during this period both wind farms have about half the capacity factor as when their peak capacity factor occurs (peak capacity factor occurs in early morning hours when the utility loading is lowest). Obviously if only wind is added to a utility's load electrical generation mix then due to wind generated electricity /utility load mismatch in both Texas and California, it is challenging for a utility to add a large percentage of renewable energy to their generation. However, the renewable energy generation/utility load mismatch would be significantly improved in Texas if concentrating solar thermal power plants (CSP) were added to wind farms (Vick, 2004 and Vick, 2006) which would result in a much larger percentage of the utility load being met by renewable energy. Similar improvements in the match of renewable energy generation and utility load are likely for California if CSP were combined with wind farms. Utilities in California appear to be aware of benefit of adding CSP since they currently plan to add 2250 MW of CSP (Cohen, 2007).

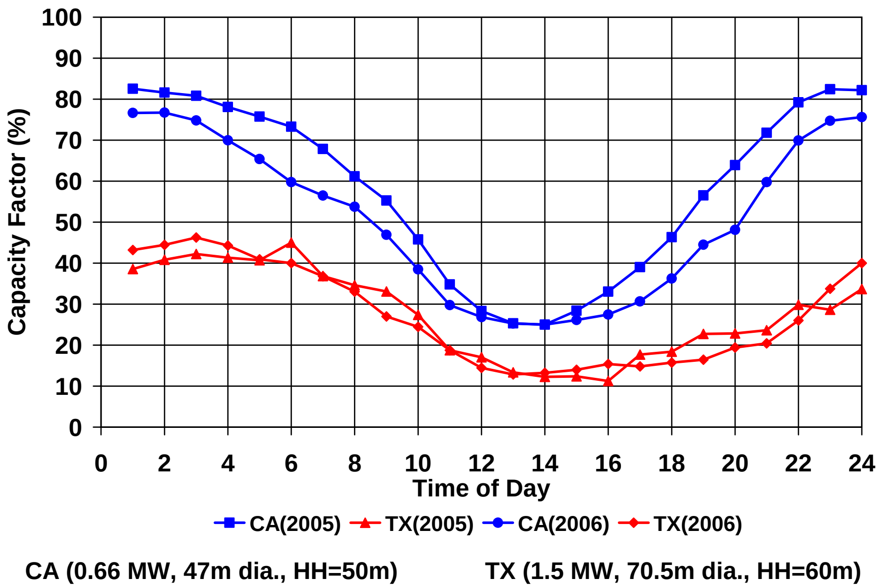


Fig 6. Capacity Factors of Wind Farms in California and Texas during July.

<u>Wind Farm Efficiency Analysis (AWTOD Number)</u>

Another way to analyze wind farm efficiency besides capacity factor is to calculate the Average Wind Turbine Output Density (AWTOD) number of the wind farm. Essentially, instead of dividing the wind farm generated output (MWh) by the MW rating of the wind farm and the time interval in hours, the wind farm output is divided by the wind turbine rotor swept area (m^2) of the entire wind farm and the time interval in hours. Capacity factor is in dimensionless units but usually expressed as a percentage, and AWTOD is best expressed in units of W/m^2. Initially we divided the energy output of the wind farm by the swept area of the wind farm, but didn't also divide by the time interval (e.g. MWh/m^2). The problem with doing this is the value gets larger for bigger time intervals (e.g. annual is larger than quarterly which is larger than monthly). By also dividing by time then the number is not dependent on the time interval. Since MW/m^2 is a small number we also converted MW into W giving the units W/m^2 – same units as wind power density which is a popular number used in assessing a wind resource.

Fig 7 shows the AWTOD numbers calculated for the same three wind farms in which capacity factor was calculated in Fig 4. Except for units, Fig 4 and Fig 7 are identical, which they should be because the wind turbines at all three locations are the same (e.g. each wind turbine is the same rated MW and the same rotor swept area). So how about wind farms with two different wind turbine power ratings and swept areas?

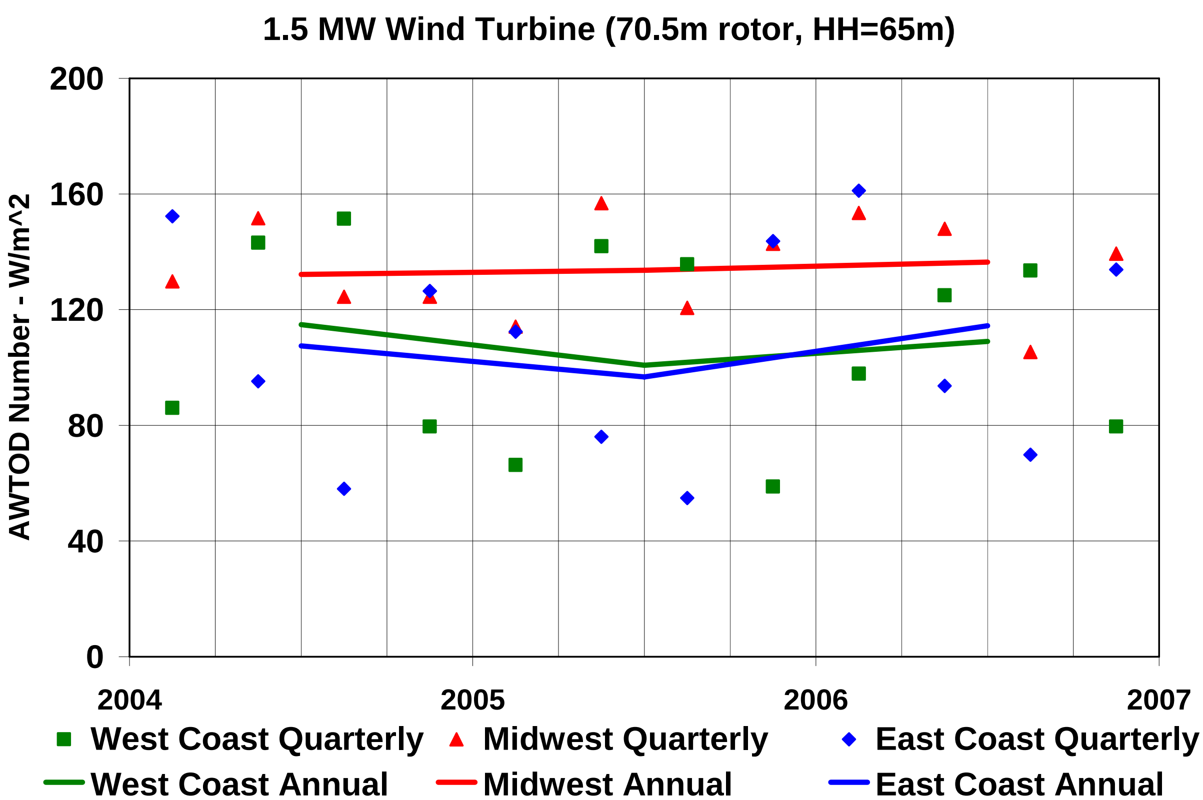
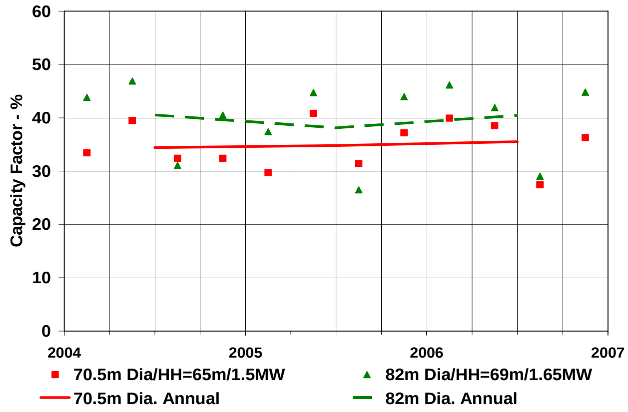


Fig 7. AWTOD Quarterly and Annual Numbers for 3 Regions in United States.

Fig 8 shows the quarterly and annual capacity factors over a three-year period of two wind farms located about 200 km (125 miles) apart and both used towers with about the same hub height. According to Fig 8, the bigger rotor diameter (82m) wind turbine is generating more MWh per MW than the smaller diameter wind turbine (70.5m) by about 11%. Fig 9 shows the AWTOD numbers for the same two wind farms and the 70.5m diameter wind turbine is about 5% more efficient in converting the wind energy into electrical power than the larger diameter (82m diameter) wind turbine (assuming wind resources same).



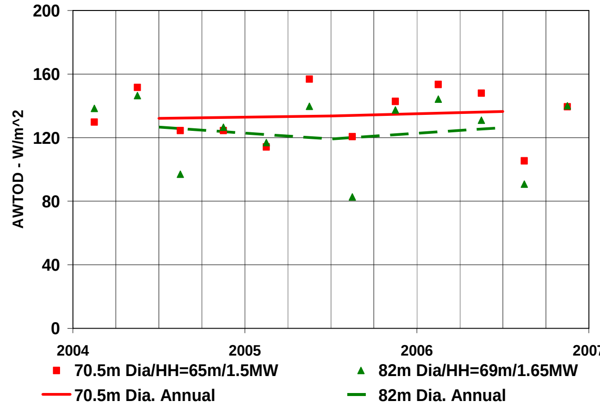


Fig 8. Quarterly & Annual Capacity Factors for Two Different Wind Turbines.

Fig 9. Quarterly & Annual AWTOD Numbers for Two Different Wind Turbines.

If the cost of installation was known for both wind farms then a $/MWh number could be determined for each wind farm, but since the future maintenance costs of the wind turbines are not known, then we still can't say which wind turbine is more economical.

Capacity factor is still a very important number, but the AWTOD number helps in determining how efficiently the wind turbine is converting wind energy into usable electrical energy. To emphasize this point, earlier in the paper the capacity factors of two wind farms in Texas and California, which had different wind turbines, were compared (refer back to Fig 6). In Fig 10 the AWTOD numbers are calculated for these two wind farms, and the results are the same as the capacity factor graph (e.g. the Northern California wind farm in July was about twice as efficient as the wind farm in West Texas during the month of July). Therefore the wind turbines, though different, had similar efficiencies for converting the usable wind energy into electricity, and the improvement in energy production is likely due to the better wind resource in California in July.

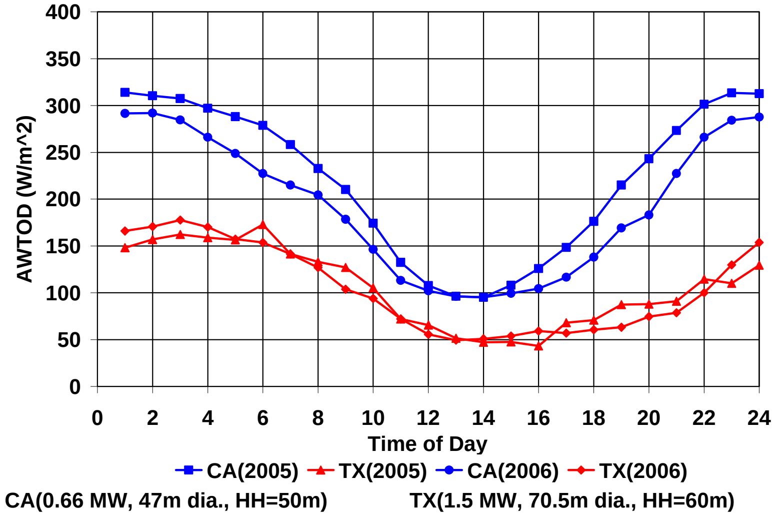


Fig 10. Comparison of AWTOD Numbers at Wind Farms in California and Texas During July.

Wind Resource Assessment Using Wind Farm Output Data

It may seem strange to evaluate a wind resource based on wind farm output, but the bottom line for money achieved with a wind farm is how much energy the wind farm produces, and how better to see how good a wind resource is then by analyzing wind farm output with the same wind turbines. Also, since wind farm output doesn't increase above a certain wind speed (i.e. wind turbine reaches rated power) while wind power density always increases with increasing wind speed, a high wind power density can sometimes be misleading if there is a significant amount of time when the wind speed is greater than 13 m/s. Of course wind farm output can be affected by operation and maintenance issues as well as wind farm array loss, so that should be kept in mind during the following discussion.

The most popular wind turbine over the past four years in the United States has been the 70.5m diameter 1.5 MW GE wind turbine. Most of these wind turbines were also installed on the same height towers, so analyzing output from these wind turbines should provide a valid wind resource assessment. Fig 11 shows the annual capacity factor for a time period of 2 to 3 years for wind farms with GE 1.5 MW 70.5m rotor wind turbines. Every wind farm in each state is shown with the same color. The symbols used also relate some information. Below is what each symbol represents:

1. square – wind farm output stayed approximately same all three years
2. triangle – wind farm output decreased from 2004 to 2005 but then increased in 2006
3. diamond – wind farm output decreased from 2005 to 2006
4. X – wind farm output increased from 2004 to 2005

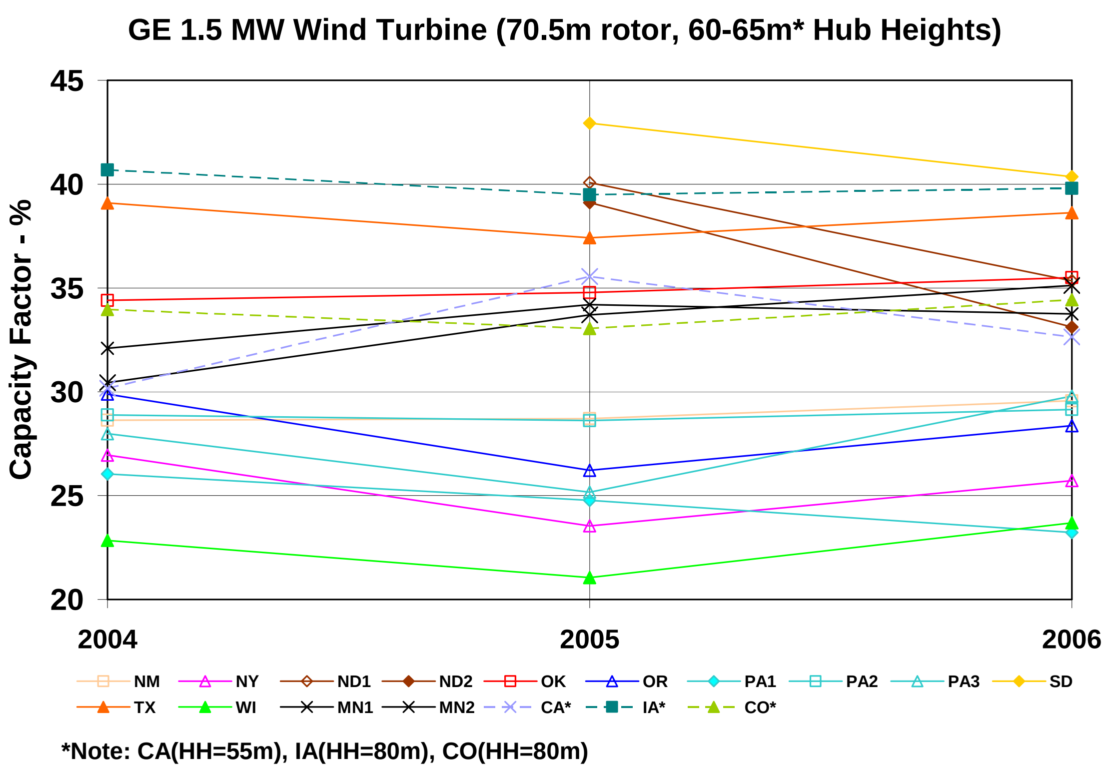


Fig 11. Wind Farm Annual Capacity Factors by State.

The state with the highest capacity factor was South Dakota (average 41.5%) and the state with the lowest capacity factor shown was Wisconsin (average 22.5%) – a difference of 84% in MWh's produced per MW {((41.5-22.5)/22.5)x100% = 84%}. If a state had more than one wind farm then the capacity factor of those wind farms had the same trend with time except for Pennsylvania. We feel possibly some of the wind farms in Pennsylvania may have experienced some down time or the wind farm output was incorrectly reported. Dashed lines still represent the GE 1.5 MW 70.5m rotor turbine, but these wind turbines are installed on different height towers, so these curves are shown for information only and shouldn't be directly compared to the solid curves. Some wind farms are not indicative of the resource in that state. For instance, in 2006 the wind farm shown in Fig 11 for New Mexico had an average capacity factor of 29.6% while the average of all the wind farms in New Mexico for that year was 36% (see Table 1). The capacity factor shown for the wind farm in California for 2006 in Fig 11 is 32.6%, but the average capacity factor for all the wind farms in California for 2006 (see Table 1) was only 25%. The average is lower in California because there are still significant amounts of wind turbines operating there which were installed in the 1980's and the wind turbines installed in recent years have higher capacity factors. The capacity factor shown for the wind farm in Texas for 2006 in Fig 11 was 38.6%, but the average capacity factor for all the wind farms in Texas for 2006 was 32%. The average is lower for Texas because there are still a significant amount of wind farms being curtailed by ERCOT (some with availabilities of only 50%) due to inadequate transmission line capacity, but the Texas Public Utility Commission will release a plan in the next few months on building additional transmission line capacity for these wind farms and future wind farms.

While one year of data is not enough to characterize a wind site, Fig 12 shows the quarterly capacity factors for 2006 wind farms with GE 1.5 MW wind turbine with a 77 meter rotor. Although Oklahoma (45.6%) had the highest annual capacity factor and Idaho (24.6%) had the lowest, California demonstrated the highest quarterly capacity factor – 64% in the spring (1st quarter in California not shown due to wind farm starting up in that quarter).

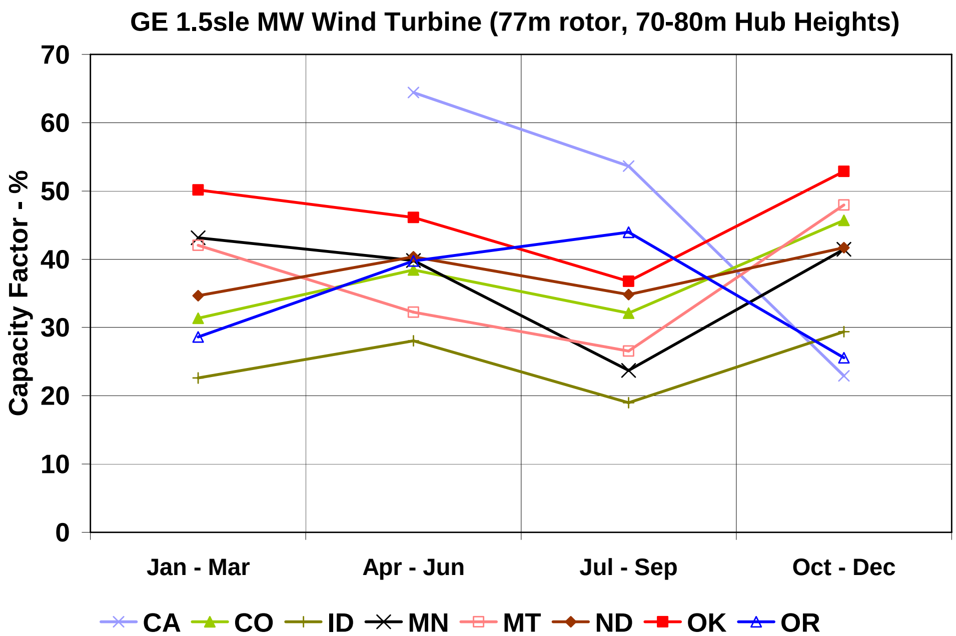


Fig 12. Wind Farm Quarterly Capacity Factors by State (only 2006).

In all, 15 states are represented in Fig's 11 and 12 which indicates what the capacity factor should approximately be for these two wind turbines in these states. Several wind turbines are being installed currently (2007) in the 2 to 2.5 MW range, but it is too early to determine whether these wind turbines have higher capacity factors.

Affect of Hub Height and Rotor Diameter on Wind Farm Output and Efficiency in Texas

Tall tower data have been collected over the past 3 to 7 years in a few states which are mainly in the Great Plains where the low level (sometimes referred to as nocturnal) atmospheric air jet is known to exist (Schwartz, 2006). Two tall towers with anemometers at 50, 75, and 100 meter heights are located in Texas, and we used that data to determine the effect of hub height and rotor diameter (with same MW rating) on capacity factor.

Using the hourly tall tower data collected at Sweetwater, Texas during 2005, a power curve of the GE 1.5 MW wind turbine with 70.5m rotor, atmospheric air density data, and a computer program written by USDA personnel, the capacity factor was calculated for the 3 hub heights of 50, 75, and 100 meters (Fig 13). The capacity factor is felt to be fairly accurate since the capacity factors of wind farms in the same general area with the same wind turbines had capacity factors within a few percent when the data was interpolated to the actual hub height. The 100 meter hub height had the highest capacity factor. However, from a 50 to 75 meter hub height the improvement in average annual capacity factor was 23% while only a 9% improvement was predicted from a 75 to 100 meter hub height. Another thing to notice is the lowest improvement in hub height occurs during the utility peak electrical load time period (4-6 pm) and the most improvement occurs during the utility's lowest electrical load (early morning hours 12am-5am).

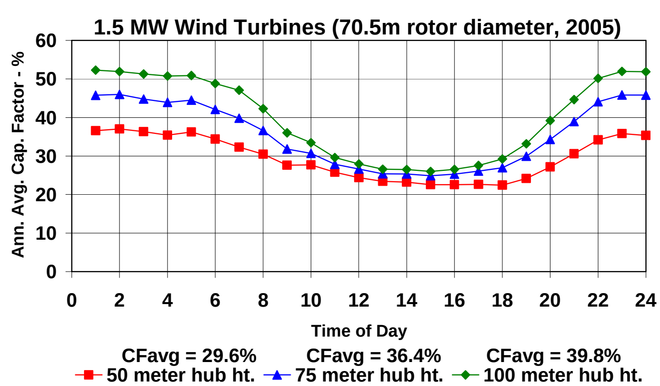


Fig 13. Affect of Hub Height on Annual Capacity Factor (on mesas near Sweetwater, Texas).

The affect of rotor diameter was analyzed with the Washburn, Texas tall tower data in 2005 because there were two wind farms with the same wind turbine power head (e.g. 1 MW generator, gear box, controller, etc) but different rotor diameters, and they were located within 110 km (70 miles) of the tall tower, so theoretical results could be compared to wind farm data to determine approximate accuracy. It is important to use the same wind resource data though instead of comparing data of the two different wind farms in order to determine effect just due to rotor diameter and not to wind resource (there also was a 9 meter difference in hub height between the two wind farms). For those not familiar with the Texas Panhandle, Washburn, TX is a small town located 16 km (10 miles) SW of Amarillo, Texas. The power curves of the two different diameter Mitsubishi Heavy Industries (MWT) wind turbines are shown in Fig 14. Again (as was done hub height analysis), the effect on capacity factor of rotor diameter change was estimated using hourly tall tower wind speed data, atmospheric air density data, power curve data, and a computer program written by USDA personnel. Fig 15 shows the improvement in capacity factor for the two different rotor diameters, but same wind turbine power head and hub height. The average annual capacity factor is improved 17% with the bigger rotor diameter. In addition, the improvement in capacity factor occurs at all times of the day (not just mainly in the early morning hours which is what an increase in hub height would do). So what is the AWTOD number for these two different rotor diameter wind turbines? For the 57 meter rotor diameter wind turbine, the annual AWTOD number is 145.6 W/m^2 and for the 61.4 meter rotor diameter wind turbine the AWTOD number is 146.8 W/m^2 (e.g. almost the same). This implies that the 61.4 meter rotor is as efficient as the 57 meter rotor in converting the wind energy into usable electricity. So it appears that increasing the rotor diameter is better than increasing the hub height since the capacity factor was increased 17% by lengthening the 28m blades to 30.2m (92ft to 99ft) while only an increase of 9% in capacity factor was achieved by increasing the hub height from 75m to 100m (246ft to 328ft).

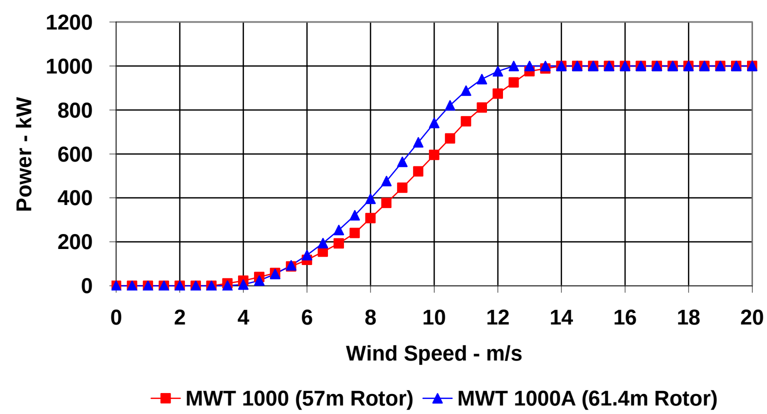


Fig 14. Power Curves of MWT 1000 & 1000A (Sea Level Std. Day).

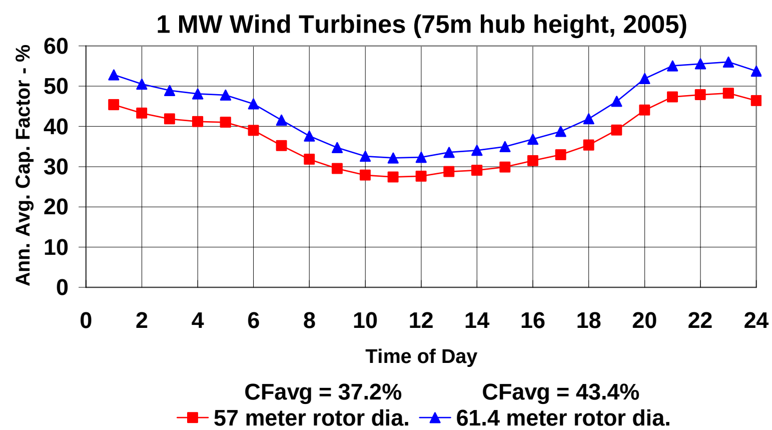


Fig 15. Affect of Rotor Diameter on Annual Capacity Factor (near Washburn, Texas).

CONCLUSIONS

Wind farm energy generation is growing exponentially while the MW capacity is increasing linearly. The amount of energy generated by wind farms in the United States in 2006 was approximately 26.3 terawatt-hours with 11,600 MW of installed capacity (0.64% of the total U.S. generated electricity). The amount of wind generated electricity in Texas is growing exponentially although the growth in the other large wind farm states (California, Iowa, and Minnesota) is only growing at a linear rate. The wind farm capacity factor during 2006 was highest in the Midwest, but about the same on the East and West coast. The West Coast had a better match to utility loading than the Midwest or the East Coast since capacity factor was highest in the summer for the West Coast, but even on the West Coast there was a diurnal (hourly) mismatch of wind generation output compared to utility loading. The affect on capacity factor by either increasing hub height or by increasing the rotor diameter was analyzed for Texas, and increasing the rotor diameter appeared to be the best way of increasing capacity factor at the least cost. A new parameter was used in analyzing the efficiency of wind farms we called "AWTOD". AWTOD is different from capacity factor in that the wind farm energy is divided by the wind farm rotor swept area instead of the rated MW capacity of the wind farm. The graphs and table in this paper may be helpful in initial wind farm planning purposes (especially for federal government officials wanting to achieve a significant amount of renewable energy by 2020), but they are not meant to replace wind resource site assessment.

ACKNOWLEDGEMENTS

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Table 1. Wind Generated Capacity, Energy Production, and Capacity Factor in the United States

State	2002 Cap. MW	2002 Energy GWh	2003 Cap. MW	2003 Energy GWh	2004 Cap. MW	2004 Energy GWh	2005 Cap. MW	2005 Energy GWh	2006 Cap. MW	2006 Energy GWh	2006 Cap.Fac. %
Alaska			1	0	1		2		2		
California	1701	3803	1910	3895	2086	4258	2149	4446	2361	4927	25
Colorado	37	139	199	147	223	681	231	729	291	889	35
Hawaii	11	2	11	2	9		9		49		
Idaho							75	6	75	163	25
Illinois			50	18	51		107	125	107	267	29
Iowa	416	919	460	982	632	1176	936	1679	936	2139	34
Kansas	112	467	114	366	114	356	264	425	364	989	38
Maine							0		9	1	
Massachusetts					1		1		4		
Michigan	1	0	1	3	2		3		3		
Minnesota	312	906	434	978	615	1247	745	1496	895	2054	34
Montana					2		136	18	145	440	37
Nebraska	3	8	13	38	14	39	73	98	73	263	41
New Hampshire							0		1		
New Jersey							8		8		
New Mexico			204	212	287	513	407	795	497	1257	36
New York	48	82	48	41	48	113	337	105	370	672	28
North Dakota			64	59	66	111	127	227	178	396	35
Ohio			4	0	7		7		7		
Oklahoma			176	75	176	573	475	817	535	1709	41
Oregon	182	376	223	444	263	614	329	633	439	871	29
Pennsylvania	34	58	132	112	129	310	129	285	179	364	28
South Dakota	3	6	43	44	44	82	44	160	44	151	40
Tennessee	2	4	2	4	29	44	29	43	29	56	22
Texas	1085	2451	1286	2515	1293	3210	1991	4222	2768	6529	32
Vermont	1	10	5	11	6		6		6		
Washington	225	417	228	604	240	556	390	532	818	1092	28
West Virginia	66	9	66	170	66	162	66	154	66	174	30
Wisconsin	36	46	36	98	53	108	53	97	53	111	24
Wyoming	141	447	285	366	285	574	288	719	288	778	31
Total Capacity (MW)	4416		5994		6741		9413		11599		
Total Energy (GWh)		10149		11182		14725		17809		26289	

Notes: 1. 2002 & 2003 MW Capacity and Energy estimated by Energy Information Agency (http://www.eia.doe.gov)

2. 2004 --> 2006 MW Capacity estimated by AWEA(http://www.awea.org)

3. 2004 --> 2006 Energy and Capacity Factor estimated by USDA-Agricultural Research Service (http://www.cprl.ars.usda.gov) and WTAMU-Alternative Energy Institute (http://www.windenergy.org)