Capacity Factor of Ontario Wind Energy Generating Facilities - Part 1: Ontario System

Table 1: Monthly Capacity Factor (Efficiency) Given as a Percentage: July 2009–June 2012

Month	Amaranth	Dillon	Gosfield	Kings-bridge	Port Alma I	Port Alma II	Port Burwell	Prince	Ripley	Talbot	Under-wood	Wolfe Island	Overall
Nameplate (MW)	**200**	**78**	**50**	**40**	**101**	**101**	**99**	**189**	**76**	**99**	**182**	**198**	
Jul-09, -10, -11	16, 16, 14	-, -, 15	-, -, 14	11, 13, 11	18, 16, 14	-, -, 16	14, 12, 12	15, 15, 13	12, 14, 12	-, -, 14	14, 16, 14	14, 17, 12	14, 16, 13
Aug-09, -10, -11	18, 18, 15	-, -, 16	-, -, 15	21, 17, 9	21, 14, 14	-, -, 17	17, 13, 13	19, 22, 14	21, 19, 15	-, -, 17	21, 19, 16	16, 20, 17	19, 18, 15
Sep-09, -10, -11	16, 29, 18	-, -, 26	, 22, 24	18, 34, 21	21, 31, 25	-, -, 28	17, 26, 19	16, 37, 26	17, 33, 22	-, -, 24	16, 35, 23	20, 32, 19	18, 32, 23
Oct-09, -10, -11	25, 29, 26	-, -, 20	-, - , 31	35, 35, 30	39, 37, 30	-, -, 33	34, 32, 28	29, 31, 32	30, 29, 30	-, -, 31	33, 33, 30	32, 32, 33	31, 32
Nov-09, -10, -11	23, 32, 41	-, -, 59	-, 39, 56	32, 42, 51	35, 40, 55	-, 37, 59	25, 33, 48	34, 44, 31	29, 40, 53	-, -, 50	28, 39, 52	22, 33, 45	27, 37
Dec-09, -10, -11	31, 26, 31	-, -, 41	-, 42, 37	43, 51, 39	41, 47, 38	-, 51, 42	36, 39, 35	29, 31, 32	37, 53, 43	-, -, 37	39, 48, 41	35, 34, 37	35, 39
Jan-10, -11, -12	27, 27, 38	-, -, 55	-,38, 51	39, 36, 48	48, 38, 52	-, 43, 56	36, 33, 46	28, 25, 41	39, 39, 46	-, 33, 53	38, 36, 45	27, 27, 38	33, 33
Feb-10, -11, -12	24, 43, 34	, 56, 55	-, 55, 51	25, 45, 48	31, 52, 52	-, 58, 56	23, 47, 46	21, 34, 41	25, 50, 46	-, 51, 53	24, 48, 45	23, 42, 38	24, 46
Mar-10, -11, -12	28, 27, 34	, 40, 48	-, 34, 46	27, 31, 41	37, 38, 47	-, 41, 50	26, 26, 33	26, 28, 41	28, 32, 42	-, 35, 44	26, 29, 40	37, 29, 33	29, 31
Apr-10, -11, 12	34,38, 32	, 40, 39	-, 49, 38	38, 38, 34	47, 49, 38	-, 52, 43	30, 35, 28	31, 31, 30	36, 38, 35	-, 47, 35	34, 38, 34	29, 38, 32	33, 40
May-10, -11, -12	24, 23, 17	, 25, 25	-, 31, 22	24, 25, 18	37, 32, 25	-, 35, 26	27, 20, 17	25, 25, 26	24, 26, 19	-, 29, 23	22, 25, 18	20, 30, 20	25, 27
June-10, -11, -12	19, 20, 25	, 25, 31	-, 23, 28,	18, 19, 21	27, 25, 30	-, 28, 34	18, 18, 21	19, 26, 21	18, 16, 23	-, 22, 28	18, 16, 22	17, 19, 24	19, 21
Annual Average	**24, 28, 27**	**-, - , 36**	**-, -, 33**	**28, 32, 30**	**34, 35, 34**	**- , -, 36**	**25, 28, 28**	**24, 29, 28**	**26, 33, 32**	**-, -, 33**	**26, 32, 31**	**24, 30, 29**	**26, 31, 31**

Note: The first, second and third set of numbers in the columns correspond to July 2009 to June 2010, July 2010 to June 2011 and July 2011 to June 2012 respectively.

Table 1 shows the monthly capacity factor for the Ontario wind farms for the period July 2009 to June 2012; only those operating for at least a year are included (http://www.ieso.ca/imoweb/marketdata/windPower.asp). The names are those used by the Independent Energy System Operator (IESO). The capacity factor is the actual power output divided by the nameplate power; it is given as a percentage. The nameplate power for each wind farm is given in the second row. As an example, consider the July-09 entry for Amaranth: The average hourly output for that month was 32 MW. Dividing by the nameplate power of 200 MW, we get 16%. The row labeled **Annual Average** shows the 12-month averages; the overall annual average is a weighted average.

Comment: It is instructive to consider the variation of the annual average capacity factor of the Ontario wind generating systems from year to year. Table 2 shows the annual capacity factors for those systems operating for three years or more. Amaranth was brought on line in 2006 and enlarged during the 2008 – 2009 year.

Table 2: Annual Average Capacity Factor

Year July to June	Amaranth 1	Amaranth 1 and 2	Kingsbridge	Port Alma	Port Burwell	Prince	Ripley	Underwood	Wolfe Island
2006 – 2007	30		33		29				
2007 – 2008	29		35		27	29			
2008 – 2009			33		28	27	33		
2009 - 2010		24	28	34	25	24	26	26	24
2010 - 2011		28	32	35	28	29	33	32	30
2011 - 2012		27	30	34	28	28	32	31	29

Declining Capacity Factor: It is clear from the capacity factors of plants operating back to 2006 that 2009 – 2010 was a poor year across Ontario. This is most likely a fluctuation involving the variation of wind speed over time. The wind speed does vary from year to year. Wind speed records (http://toronto.weatherstats.ca/charts/wind_speed-5years.html) going back 6 years were only available to me for Toronto. The annual average wind speeds (v) are given in the second row in the Table 3.

Table 3: Wind Speed Measurements for a Selection of Ontario Sites

Year	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012
v (km/h) Toronto	17.08	16.56	16.64	16.50	17.59	16.98
$(v/v_0)^3$ Toronto	1.03	0.94	0.96	0.93	1.13	1.02
v (km/h) 5 Cities			14.44	13.90	15.11	15.02
$(v/v_0)^3$ 5 Cities (± 7%)			0.96	0.86	1.10	1.08
$(v/v_0)^3$ Blended (± 7%)	1.03	0.94	0.96	0.87	1.10	1.07

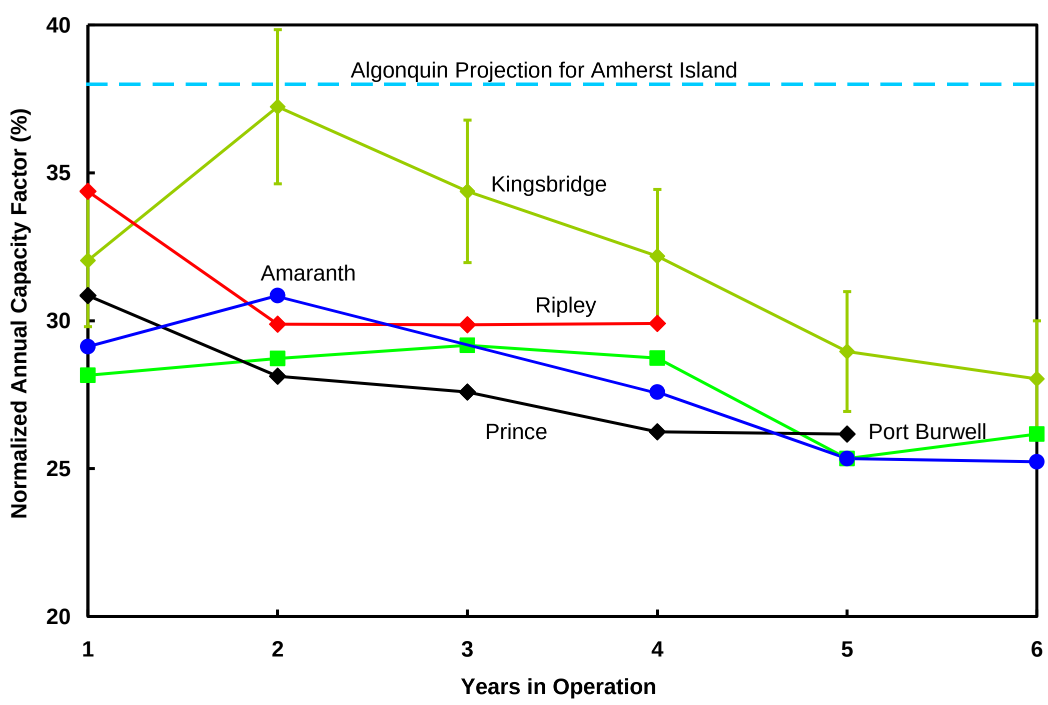
Note: The annual average wind speed measurements shown in the above table are not intended to represent the wind speeds at the wind energy generating system sites. The purpose of Table 3 is to indicate the variation of wind speed in Ontario from year to year. Although the uncertainty (± 7%) is large, the variation remains significant.

Mathematically, the output of a turbine varies as the cube of the wind speed. This is easy to understand. The kinetic energy density of the atmosphere varies as the square of the wind speed. The volume of air passing through the blade circle varies linearly with the wind speed. Multiply these two factors and the power output varies as the cube of the wind speed. That is, if the wind speed doubles the power increases eight-fold. There is a limit to the cube law at which the power output flattens off. However, for the range of wind speeds corresponding to most of the power output, the cube law is a reasonable representation.

The third row of the Table 3 shows the cube of the ratio of the annual average (v) to the 6-year average (v_0) for Toronto. The annual average capacity factor should be proportional to this ratio, $(v/v_0)^3$. Row 3 demonstrates that annual swings in the annual average capacity factor of 10% are to be expected.

In order to get a more representative picture of the wind speed variation across Ontario, the wind speed data for the past 4 years for Hamilton, Thunder Bay, Kingston, North Bay and Ottawa were blended with the data for Toronto for the past 6 years. The fourth row shows the annual average wind speeds for these 5 cities. These are converted to the average of $(v/v_0)^3$ for the 5 cities in row 5. The standard deviation is 7%. Finally, row 6 shows a blending of $(v/v_0)^3$ for Toronto and the 5 cities. Again, the standard deviation is 7%. Although the standard deviation is large, the variation from year to year can be larger and is significant.

To appreciate the variation of capacity factor with time, the measured annual average capacity factors shown in Table 2 have been corrected by dividing by the blended factor $(v/v_0)^3$ for that year. For the wind energy generating systems that have been



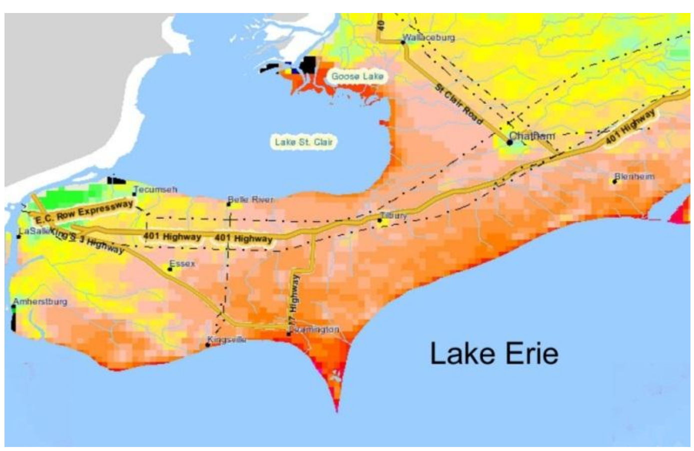
operating for 4 years or more, these normalized capacity factors are shown as a function of the number of years of operation in the figure above. The uncertainty (standard deviation) in the values of $(v/v_0)^3$ is reflected in the uncertainty in the normalized annual capacity factor. This is demonstrated in the figure only for the Kingsbridge data set.

The trend of the normalized annual capacity factors is down. A linear regression for each of the 5 wind energy generating system data sets demonstrates an average decline of $(1.1 \pm 0.3)\%$ per annum.

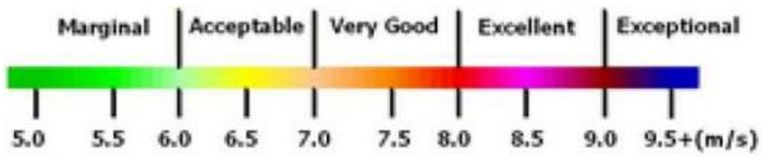
This is not the only report of capacity factor declining with time. In an extensive analysis of the Danish wind energy system Paul-Frederik Bach (2012) finds an average decline of just 0.3% per annum. Conversely, in his analysis of the Danish wind energy system over the years 2004 to 2010 Wayne Gulden (2012a) found an average decline of 1.5% per annum; Gulden normalized the capacity factors for the annual average wind speed. Gulden used the same technique to demonstrate that the Mars Hill installation in Maine, USA, is showing a declining capacity factor of a conservative 2.1% per annum (2012b).

Recent Wind Energy Generating Systems: There is some evidence that the more recent installations are generating higher capacity factors than the original ones. This can be seen for Dillon, Gosfield, Port Alma II, and Talbot. This is in part because the older installations have declined by about 4% and in part because of the use of so-called high efficiency turbines[1]. Gosfield and Talbot are using 2.3 MW turbines with101 metre blade diameters and Port Alma II is using a mix of the older Siemens 2.3 MW 93 metre blade diameter turbines and the newer Siemens 2.3 MW 101 metre blade diameter turbines (http://www.canwea.ca/farms/wind-farms_e.php).

In addition, these installations are located along the north-west shore of Lake Erie with its high wind resource (http://www.lio.ontario.ca/imf-ows/imf.jsp?site=renew_en); see over-page for the colour scale.



[1] The use of the term "high-efficiency" is a misnomer: see the Appendix.



References:

Paul-Frederik Bach (2012), Private communication

Wayne Gulden (2012a), See: http://windfarmrealities.org/?p=1284

Wayne Gulden (2012b), See: http://windfarmrealities.org/?p=1641

Appendix: High Efficiency Turbines

Wind turbine manufacturers are producing high efficiency turbines for use in regions with marginal wind resource. An example is the Siemens 2.3-113 turbine to replace the Siemens 2.3-93 turbine. The blade diameter has been increased from 93 metres to 113 metres. For power output as a function of wind speed , see: http://www.energy.siemens.com/mx/pool/hq/power-generation/wind-power/E50001-W310-A102-V6-4A00_WS_SWT-2.3-93_US.pdf and http://www.energy.siemens.com/hq/pool/hq/power-generation/renewables/wind-power/wind%20turbines/SWT-2.3-113-product-brochure.pdf

Consider as an example the power output at 7 m/s, a typical average wind speed. The wind resource is given by

$$\text{Power} = \tfrac{1}{2}\rho v^3 \pi d^2/4$$

where ρ is the density of air (1.225 kg/m^3 at 15°C and standard pressure), v is the wind speed and d is the blade diameter. The Betz limit is the maximum power that can be extracted from the wind; it is 59.3% of the wind resource. The calculated rated power at 15°C is taken from the power curves for the Siemens turbines referenced above. The efficiency of the turbines is the rated power divided by the Betz limit. These quantities are given in Table 4.

Table 4: Efficiency of Siemens Turbines with 93 and 113 Metre Blade Diameters
Wind Speed = 7 m/s

Model	Wind Resource (MW)	Betz Limit (MW)	Rated Power (MW)	Efficiency (%)
Siemens 2.3-93	1.43	0.85	0.59	70%
Siemens 2.3-113	2.10	1.25	0.88	70%

The calculation shows that the two turbines have the same efficiency. The power gain is achieved through the use of longer blades.

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