Wind Power Development in Sub-Arctic Conditions With Severe Rime Icing

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Introduction

The Yukon Territory is the northwestern most part of Canada and lies immediately east of Alaska. It has a population of about 31,000 people, two thirds of whom live in the capital city, Whitehorse, situated in south central Yukon.

Electrical energy is supplied principally from two hydro-electric plants located on the main (southern) power grid and a third on a small grid in central Yukon. However, peaking energy and capacity are normally supplied by diesel generators. As well, there are eight communities that are supplied by entirely by diesel plants because they are not connected to either of these hydro based power grids.

With the mining industry in full operation, electrical loads can peak at up to 78 MW on the main grid in the coldest days of winter. Annual energy requirement with this mining load on is about 450 Gwh. At present the mining load is shut down, resulting in peak loads of just over 50 MW and annual energy requirements of only 250 GWh (there is now a hydro-electric energy surplus). In the diesel-served communities, the annual energy requirement totals about 50 GWh.

The climate in Whitehorse is broadly classified as sub-arctic continental, mean daily January minimums are -23° C, and the lowest temperatures typically around -40° C, with occasional dips to -45° C or lower. Weather data analyses (Nor'Wester Energy Systems Ltd. See sources, p. 183) have shown that, at altitudes of 4,000 to 6,000 feet, rime icing can occur from 800 to 1200 hours per year—equivalent to a continuous duration of 4 to 7 weeks per year. Rime icing is the buildup of ice on anything solid from moist, supersaturated air at sub-zero temperatures. Essentially whenever and wherever there is a cloud on a mountain there is rime icing. The pretty frost that builds up on trees around open water in the winter is a form of rime ice. In our location rime icing is most severe in the early winter: mid October to the end of December.

This paper discusses how Yukon Energy, through equipment selection and modification, is minimising the detrimental effects of rime icing on wind turbines and bringing commercial wind power generation in Yukon closer to reality.

Background

The potential for commercial wind power generation in Yukon was investigated in the early and late 1980s using data from airports and two wind monitoring stations. In all cases the conclusion was that it was not economic.

In 1990, two local citizens analyzed Environment Canada's upper air data and found that wind speeds increased substantially with altitude. This led to the establishment of a 65 foot (20 meter) wind monitoring station on a shoulder of Mt. Sumanik which is known locally as Haeckel Hill, located west of the city. This site has an altitude of about 4,700 feet (1430 meters), about 2500 feet above the valley floor, and consists of a ridge perpendicular to the prevailing wind. Road access and a single phase power line to a forest fire look out tower located on top were positive factors in the selection of this site. Monitoring results confirmed the higher wind speeds at higher altitudes, but also found severe rime icing conditions at the site. Another interesting feature, since confirmed by long term monitoring, is that inversions keep the temperatures from reaching the low extremes; it seldom drops below -30° C (-22° F) even with valley temperatures dropping down to -45° C (-50° F) or lower.

Table 1
Whitehorse Upper Air Wind Speeds and Bonus Production Targets

Whitehorse, Yukon Mean Wind Speeds, 1980-1995					Bonus 150 Production Targets	
Month	**2305' ASL**	**4000' ASL**	**5000' ASL**	**6000' ASL**	**Target kWh**	**Target Capacity Factor**
January	3.6	8.5	8.7	9.2	30	26.9%
February	4.1	7.9	8.3	9.0	28	27.8%
March	4.0	6.9	7.3	7.7	28	25.1%
April	4.0	6.2	6.5	6.8	25	23.1%
May	4.0	5.6	5.8	6.1	24	21.5%
June	3.6	5.0	5.0	5.3	15	13.9%
July	3.4	4.3	4.6	4.8	15	13.4%
August	3.3	5.5	5.5	5.8	18	16.1%
September	3.4	6.6	6.9	7.6	27	25.0%
October	4.6	7.7	8.1	8.5	30	26.9%
November	4.4	7.9	8.3	8.4	30	27.8%
December	4.0	8.2	8.5	9.0	30	26.9%
Annual	3.9	6.6	6.9	7.3	300	22.8%

A subsequent analysis of upper air data (Table 1) showed that the annual average wind speed was 6.6 m/s (meters per second) at 4,000 feet, 6.9 m/s at 5,000 feet, and 7.3 m/s at 6,000 feet. Since the kinetic energy in wind increases with the cube of the wind speed, these figures are significantly better than the 3.9 m/s long term average at the airport located at an elevation of about 2300 feet. It is also very significant that the wind speeds are much higher in winter than in summer, almost perfectly following the seasonal electrical load profile. Yukon Energy staff felt that with these wind speeds commercial wind power could be cheaper than diesel generation if the effects of low temperatures and rime icing on wind turbines could be overcome. Producing electrical power at costs below the cost of diesel generation was and remains our primary goal. Environmental benefits are considered an extra.

The First Wind Turbine

Since the monitoring showed that wind speeds were indeed higher at the higher altitudes and close to the upper air wind regime, and found that severe rime icing was present there, Yukon Energy decided, in 1992, that a program of adaptation of commercial wind generating equipment to this climate was needed. With our limited resources we decided that we could not do anything other than take existing, proven commercial equipment and try to adapt this to our conditions. Several large, reputable manufacturers were considered and Bonus Energy A/S of Denmark was selected for their 150 kW MARK III unit. This 150 kW machine, a conventional three bladed, horizontal axis, up wind and stall regulated design, represented the small end of the commercial range available and therefore the lowest capital cost. Bonus is a large commercial equipment supplier with a good reputation, had some northern experience, was willing to work with Yukon Energy on modifications, and had a hinged tower design for a winch up raising that did not require a large crane to be brought in from southern Canada.

In consultation with Bonus a number of modifications were made to their standard design. A hinged, winch up 30-meter tower was an important feature. To overcome the effects of the cold, low temperature tolerant steels were selected for the tower and other key components, and synthetic lubricants (including hydraulic fluid) were used throughout. Electric heaters, controlled by thermostats, were installed on the gearbox, in the generator, in the computer control cabinet, and in the radio communications cabinet.

To overcome rime icing effects the anemometer and wind vane used to control the turbine were equipped with heated bearings. The blades were equipped with heating strips about 6 inches wide which ran along the entire length of the leading edge. The heat output was about 1/4 watt per square inch, or 1,700 watts for all three blades. An ice detector to turn the blade heating on and off was also supplied. The power production target was set at 300,000 kWh per year, representing a capacity factor of 22.8% (Table 1). Capacity factor is the actual production divided by the maximum theoretically possible in the time period (150 kilowatts times 8760 hours per year).

A firm order for this unit, plus a two year service agreement from the manufacturer, was placed in December 1992. The turbine was erected in July of 1993 (Photograph 2) and was commissioned on August 13. The project cost about $CDN 800,000, of which $CDN 200,000 was for upgrading the road and power line. Yukon Energy received a grant of $CDN300,000 from government sources toward the project.

Project Results

Rime icing causes were briefly described in the introduction. The practical effects can be substantial. Any solid object accumulates ice that "grows" into the wind. Trees become ice domes, towers become ice posts, power lines grow to six or eight inches in diameter, and chain link fences become solid walls. As you can imagine from looking at the photographs, it is no wonder that exposed equipment has difficulty working under these conditions. Low temperatures and severe rime icing are the challenges we need to overcome. The following features have worked well and have not needed further attention:

1. The winch up tower worked well, even though it is not as easy to winch up or down as expected;
2. The low temperature steels have not been a problem so far;
3. Lubrication with synthetic products has worked well; and
4. The heating systems in the gearbox, generator, and electronic cabinets have been very reliable.

Aspects of the project that did not work initially but have since been overcome are:

1. The heated bearing anemometer and wind vane were still immobilised by ice and were replaced with fully heated Hydro-Tech instruments which have not iced up;
2. The overhead power line was causing about five outages per month due to the heavy accumulation of ice in combination with wind, and was replaced with a buried cable that is not affected by the ice; and
3. The ice detector supplied with the turbine was not effective and was removed from the control circuit. The heating circuits are now simply switched on for the winter. A Rosemount ice detector was purchased in 1996 and has been running reliably on site since then, but has not been installed into the turbine control circuit. This ice detector has revealed that we average over 800 hours of rime icing per year on the site.

One aspect of the project that did not work and has not been overcome is the inability of the electrical contacts between the main portion of the blades and the tips to work reliably under icing conditions. Several redesigns have also failed to operate reliably. This means that there will always be air drag and power production losses when the blade tips ice up, and power production cannot be fully maximised.

The leading edge blade heaters (1/4 watt per square inch) have worked reasonably well even though one burnt out in 1996. We replaced them all in 1998 with heaters 12 inches wide, rather than 6 inches, to improve performance in very severe rime icing and in very cold temperature conditions. Perhaps because of other problems and advances we have not been able to attribute specific production improvements to the larger heaters.

The effect of rime icing on the blades of the wind turbine is such an important issue that it is worth examining in detail. Without blade heaters rime ice builds up especially heavily on the leading edges, and the build up increases with distance from the blade root. It seems to be directly related to the velocity at any point and therefore, perhaps, the result of the amount of moisture or moist ice contacted. When shut down the ice builds up on the edges of the blade surface facing the wind, the pressure side. When running through an icing event, the ice build up on the "backs," or suction sides, of the blades is much less than on the "fronts." Ice can also build up on the trailing edges. Power production drops off dramatically when the blades are coated with rime ice and without leading edge blade heaters, can stop altogether.

The 6 inch wide heaters did, under lighter icing conditions, keep portions of the blade downwind of the heater clear. Under heavier icing conditions, ice would build up on the blade right up to the heater. Build up of ice on the leading edges did not occur except under the most severe conditions, and it cleared off quite quickly afterwards. It was from this that we concluded that more heat on the front of the blade in the form of wider leading edge heaters would be of benefit if the increased area were applied to the front (pressure side) of the blade. It was also obvious that the leading edges of the blade tip would need to be heated to minimise air drag and associated production losses.

One very positive aspect of the project was the bird monitoring work. Concern over the possibility of bird kills from collisions with the turbine blades, especially during spring and fall migrations, led to a five year monitoring program. It was found that the migrating waterfowl, at least, stayed lower down in the valley well below the altitude of the turbine. The only bird mortality documented over the course of the program was a grouse that flew into the chain link fence.

Power Production

From a production perspective the project has not yet met the target, but, all things considered, we are satisfied with our accomplishments. In the first year we solved the power line and control instrument problems. Once those were resolved, performance improved substantially.

In the third year of operation we had a failure of one of the blade heaters early in winter and we had to operate without any leading edge heat for the rest of the winter. With the heaters working on only two of the blades, there was significant blade weight imbalance. At this time, annual "losses" due to rime icing were estimated to be in the range of 60,000 to 70,000 kWh per year, about 20% of the production target.

Repairs to the power line (a local feeder) were made in 1996 and, since that time, there have been very few of the electronic problems that bothered us early on, and turbine availability has been very high. Also, in 1996, we "painted" the blades with a black coating called StaClean. We believed that both the solar heating from the black colour and the special low adhesion formula for ice, would assist in clearing the blades of accumulated rime ice. We saw an immediate noticeable improvement in performance: 1998 and 1999 have been the best production years yet. Our experience shows that accumulated ice can be shed from the blades.

On the whole we are pleased with the performance, especially considering where the turbine is physically located, the unfamiliarity of maintenance personnel with this type of equipment, and our dependence on a few key people. Due to the weather exposed servicing (the access ladder is outside along the top portion of the tower), maintenance is not done during severe weather conditions. Detailed monthly performance statistics, from the time of project commissioning, are presented in Table 2. Annual figures based on revenue metering, which commenced in July 1994, are presented in Table 3.

Table 2

Detailed Production Record

Month	Prod. (kWh)	Total Hours	Hours in Prod.	MH[1]	BH[2]	GOH[3]	Cap. Factor	Turbine Avail.	Overall Avail.	RMG[4]	Cap. Factor
Aug-93	10,949	408	222	0	0	0	17.9%	100.0%	100.0%		
Sep-93	19,290	720	379	7	19	58	17.9%	96.4%	88.3%		
Oct-93	15,890	744	309	12	48	24	14.2%	91.9%	88.7%		
Nov-93	21,331	720	331	14	1	163	19.8%	97.9%	75.3%		
Dec-93	18,728	744	317	36	3	186	16.8%	94.8%	69.8%		
Tot-93	**86,188**	**3,336**	**1,558**	**69**	**71**	**431**	**17.2%**	**95.8%**	**82.9%**		
Jan-94	4,896	744	152	40	96	300	44.0%	81.7%	41.4%		
Feb-94	11,335	672	320	37	0	0	11.2%	94.5%	94.5%		
Mar-94	38,262	744	652	4	9	0	34.3%	98.3%	98.3%		
Apr-94	26,666	720	570	12	0	0	24.7%	98.3%	98.3%		
May-94	24,227	744	505	0	26	0	21.7%	96.6%	96.6%		
Jun-94	14,849	720	225	0	0	0	13.7%	100.0%	99.2%		
Jul-94	15,307	744	400	0	0	6	13.7%	100.0%	99.6%	17,320	15.5%
Aug-94	10,980	744	385	5	61	3	9.8%	91.2%	87.7%	12,090	10.8%
Sep-94	28,636	720	542	0	17	26	26.5%	97.3%	97.3%	29,230	27.1%
Oct-94	28,326	744	549	37	0	0	25.4%	95.0%	95.0%	30,980	27.8%
Nov-94	19,415	720	422	0	67	0	18.0%	90.7%	90.4%	22,430	20.8%

Month	Prod. (kWh)	Total Hours	Hours in Prod.	MH[1]	BH[2]	GOH[3]	Cap. Factor	Turbine Avail.	Overall Avail.	RMG[4]	Cap. Factor
Dec-94	20,541	744	442	0	0	0	18.4%	100.0%	100.0%	22,144	19.8%
Tot-94	**243,440**	**8,760**	**5,164**	**135**	**276**	**335**	**18.5%**	**95.3%**	**91.5%**		
Jan-95	21,363	744	511	0	0	12	19.1%	100.0%	98.4%	23,760	21.3%
Feb-95	27,379	672	423	0	0	0	27.2%	100.0%	100.0%	29,620	29.4%
Mar-95	18,060	744	344	0	288	0	19.2%	61.3%	61.3%	18,790	16.8%
Apr-95	24,299	720	559	0	0	0	22.5%	100.0%	100.0%	27,190	25.2%
May-95	20,395	744	478	12	0	7	18.3%	98.4%	97.4%	22,210	19.9%
Jun-95	12,751	720	339	0	99	2	11.8%	86.3%	86.1%	14,380	13.3%
Jul-95	8,298	744	306	0	49	3	7.4%	93.4%	93.1%	9,230	8.3%
Aug-95	14,785	744	306	0	0	0	13.2%	100.0%	100.0%	16,080	14.4%
Sep-95	31,919	720	571	8	0	0	29.6%	98.9%	98.9%	34,030	31.5%
Oct-95	13,911	744	368	6	0	1	12.5%	99.2%	99.0%	15,742	14.1%
Nov-95	11,265	720	313	9	0	2	10.4%	98.8%	98.6%	11,991	11.1%
Dec-95	22,736	744	477	3	11	9	20.4%	98.2%	97.0%	25,226	22.6%
Tot-95	**227,161**	**8,760**	**4,995**	**38**	**447**	**36**	**17.3%**	**94.5%**	**94.1%**	**248,249**	**18.9%**
Jan-96	971	744	42	0	702	0	0.9%	5.6%	5.6%	1,020	0.9%
Feb-96	26,597	696	470	16	0	2	25.5%	97.7%	97.5%	29,257	28.0%
Mar-96	38,309	744	559	0	0	0	34.3%	100.0%	100.0%	41,599	37.3%
Apr-96	12,060	720	226	3	114	273	11.2%	83.7%	45.8%	14,408	13.3%
May-96	16,275	744	412	6	81	0	14.6%	88.4%	88.4%	18,009	16.1%
Jun-96	17,488	720	496	0	0	2	16.2%	100.0%	99.7%	19,130	17.7%
Jul-96	6,216	744	259	192	7	0	5.6%	73.3%	73.3%	7,317	6.6%
Aug-96	11,037	744	391	205	0	0	9.9%	72.4%	72.4%	11,803	10.6%
Sep-96	24,850	720	494	6	0	10	23.0%	99.2%	97.8%	27,490	25.5%
Oct-96	14,376	744	377	43	0	0	12.9%	94.2%	94.2%	13,502	12.1%
Nov-96	24,890	720	475	0	0	0	23.0%	100.0%	100.0%	27,716	25.7%
Dec-96	27,601	744	441	6	0	0	24.7%	99.2%	99.2%	31,604	28.3%
Tot-96	**220,670**	**8,784**	**4,642**	**477**	**904**	**287**	**16.7%**	**84.3%**	**81.0%**	**242,855**	**18.4%**
Jan-98	14,600	744	n/a	0	0	n/a	13.1%	100.0%	n/a	15,698	19.2%
Feb-98	31,080	672	n/a	0	0	n/a	30.8%	100.0%	n/a	32,048	23.1%
Mar-98	26,080	744	n/a	0	0	n/a	2.3%	99.8%	n/a	26,980	26.5%
Apr-98	31,570	720	n/a	0	0	n/a	29.2%	100.0%	n/a	32,454	24.9%
May-98	32,370	744	n/a	0	0	n/a	29.0%	100.0%	n/a	33,227	17.9%
Jun-98	13,280	720	n/a	25	0	n/a	12.3%	100.0%	n/a	13,932	13.8%
Jul-98	17,600	744	n/a	111	0	n/a	15.8%	100.0%	n/a	17,781	18.5%
Aug-98	22,260	744	n/a	54	0	n/a	19.9%	99.6%	n/a	22,465	11.4%
Sep-98	21,790	720	n/a	0	0	n/a	20.2%	97.0%	n/a	22,001	24.7%
Oct-98	23,130	744	n/a	2.5	0	n/a	20.7%	98.3%	n/a	24,984	24.7%
Nov-98	10,310	720	n/a	0	0	n/a	9.5%	93.1%	n/a	10,937	11.4%
Dec-98	14,520	744	n/a	0	2	n/a	13.0%	99.0%	n/a	17,623	31.2%
Tot-98	**258,590**	**8,760**	**n/a**	**193**	**2**	**n/a**	**19.7%**	**98.9%**	**n/a**	**270,130**	**20.8%**
Jan-99	n/a	744	n/a	0	0	1	n/a	100.0%	99.9%	21,410	19.2%
Feb-99	n/a	672	n/a	0	0	0	n/a	100.0%	100.0%	23,310	23.1%
Mar-99	28,014	744	566	1	0	1	25.1%	99.8%	99.8%	29,590	26.5%
Apr-99	25,788	720	532	0	0	0	23.9%	100.0%	100.0%	26,920	24.9%
May-99	18,545	744	489	0	0	0	16.6%	100.0%	100.0%	19,980	17.9%
Jun-99	12,726	720	412	0	0	1	11.8%	100.0%	99.9%	14,940	13.8%
Jul-99	18,716	744	437	0	0	1	16.8%	100.0%	99.9%	20,680	18.5%
Aug-99	11,465	744	416	0	3	1	10.3%	99.6%	99.5%	12,730	11.4%
Sep-99	27,451	720	496	0	21	2	25.4%	97.0%	96.8%	29,620	27.4%

Month	Prod. (kWh)	Total Hours	Hours in Prod.	MH[1]	BH[2]	GOH[3]	Cap. Factor	Turbine Avail.	Overall Avail.	RMG[4]	Cap. Factor
Oct-99	25,998	744	518	9	4	5	23.3%	98.3%	97.7%	27,530	24.7%
Nov-99	12,374	720	303	0	50	2	11.5%	93.1%	92.8%	12,290	11.4%
Dec-99	34,448	744	593	0	8	0	30.9%	99.0%	99.0%	34,780	31.2%
Tot-99	**215,525**	**8,760**	**4,762**	**10**	**86**	**14**	**16.4%**	**98.9%**	**98.8%**	**273,780**	**20.8%**
Jan-00	22,524	744	438	0	0	0	20.2%	100.0%	100.0%	21,080	48.9%
Feb-00	13,961	696	426	0	0	0	13.4%	100.0%	100.0%	14,940	14.3%
Mar-00	31,152	744	570	0	13	0	27.9%	98.3%	98.3%	31,070	27.8%
Apr-00	24,539	720	502	1	0	1	22.7%	99.8%	99.7%	25,830	23.9%
May-00	12,867	744	411	0	80	0	11.5%	89.2%	89.2%	13,070	11.7%
Jun-00	10,135	720	386	14	0	0	9.4%	98.1%	98.1%	9,950	9.2%
Jul-00	14,257	744	456	0	0	1	12.8%	99.9%	99.9%	16,400	14.7%
Aug-00	18,802	744	496	0	0	0	16.8%	100.0%	100.0%	19,410	17.4%
Sep-00	20,404	720	544	2	0	0	18.9%	99.7%	99.7%	20,602	19.1%
Oct-00	30,905	744	602	0	3	0	27.7%	99.6%	99.6%	30,768	27.6%
Nov-00	19,963	720	402	0	1	0	18.5%	99.9%	99.6%	19,420	18.0%
Dec-00	23,296	744	472	0	0	0	20.9%	100.0%	100.0%	22,660	20.3%
Tot-00	**242,805**	**8,784**	**5,705**	**17**	**97**	**2**	**18.4%**	**98.7%**	**98.7%**	**245,200**	**18.6%**
Total	1,494,379	55,944	26,826	939	1,883	1,105	17.7%	93.8%	93.8%		

[1] Maintenance Hours
[2] Breakdown Hours
[3] Grid Outage Hours
[4] Revenue Meter Gross

Table 3
Annual Production Based on Revenue Metering
(Revenue Metering Commenced in July 1994)

Yukon Energy 150 kW Bonus Wind Turbine - Annual Production

Year	Hours	Actual Gross kWh	Actual Gross C.F.%
1994	8,760	254,429	19.4%
1995	8,760	248,249	18.9%
1996	8,784	242,855	18.4%
1997	8,760	242,307	18.4%
1998	8,760	270,130	20.6%
1999	8,760	273,780	20.8%
2000	8,784	245,200	18.6%

The Second Wind Turbine

With funding from the Yukon government, Yukon Energy installed a new, larger wind turbine this past September, a Vestas 660 kW V47 LT II, low temperature version. This turbine incorporates most of the features that we believe will move wind energy from the development phase into commercial viability. This is a pitch regulated machine designed for unrestricted operation down to –30° C (–22°F). It was fitted with fully heated wind instruments, StaClean coated (black) blades and leading edge blade heaters. Our experience with the stall regulated 150 kW machine has convinced us that a pitch regulated machine will lose less power when affected by rime ice as the lowering of the stall wind speed is not as critical with the pitch regulation design. In the higher wind speeds, the blades will remain pitched to a more aggressive angle until full output is achieved. Since the blades do not have tip brakes, maintaining electrical continuity and effective heating to the very tip should not be a problem.

Two features that we would have liked to have had but were not able to get in a turbine in the 500 to 1,000 kW size range this time, were a full surface blade heating system, and an operating temperature range down to –40°C (also –40°F).

The new turbine was installed during the first half of September. Detailed performance comparisons between the two turbines have not been possible so far. We are still in the process of fine tuning the various operating and control systems. These analyses will be part of our work in the coming years.

Suggestions for Similar Applications

For anyone contemplating a wind turbine in a cold, severe rime icing environment such as Haeckel Hill (which is, in fact, less cold than most of the interior of Yukon and Alaska) we would recommend the following:

1. Low temperature steels;
2. Low temperature synthetic lubricants and fluids;
3. Equipment heaters (gearbox, generator, control cabinets);
4. Fully heated wind instruments;
5. Black fluorourethane (StaClean) coated blades;
6. Full surface blade heating if available, otherwise leading edge heaters at least 12 inches wide;
7. For simplicity and reliability in leading edge heating one piece blades would be better than two piece blades such as we have on our Bonus machine;
8. Tubular tower for "indoor" climbing and maintenance work for shelter from the weather; and
9. Pitch or active stall regulation, as we believe this will result in higher power production.

Conclusion

In conclusion, substantial progress has been made in understanding the effects of rime icing on wind turbines and in learning how to overcome them. It is our goal to establish a track record of performance under these conditions that puts wind power into the list of realistic and practical power supply options available to us in Yukon. Like the trees that survive in these conditions, we northerners need to stand together, to be tough, to be innovative, to be persistent, and, most importantly, we need a strong positive attitude.

Note

This paper, with illustrations and one graph it was not possible to include in this version, is available from the author.

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