Yellowknife Wind Energy
Pre-feasibility Report

Prepared for

Aurora Research Institute

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Executive Summary

As the capital of the Northwest Territories, the city of Yellowknife has a population of about 19,000 (2006 census) people whose electricity requirements are served largely by hydro power with a small portion provided by diesel plants owned and operated by Northwest Territories Power Corporation (NTPC). The city is located on the north shore of Great Slave Lake and is accessible by a highway and by air.

There are several potential wind turbine sites around Yellowknife that have been identified for further investigation. The sites north of the city are the highest and range from 210 to nearly 230 m above sea level (ASL). To the south of the City, near the Con Mine site, the high areas are at about 190 m ASL and are close to the lake shore.

The long term (1998-2007) average wind speed is estimated at 4.8 m/s at 37 meters (m) above ground level (AGL) and 5.5 m/s at 80 m AGL. These are at the hub height of two selected turbines for this study: the Northwind 100-21 which is a 100 kW turbine on a 37-m tower; and, the GE 1.5 sle which is a 1,500 kW wind turbine on a 80-m tower. The wind speed estimates are based on measurements at the Jackfish telecommunications tower, and the Yellowknife airport. These measurements have not been projected to the nearby hilltops, they are assumed to be the same at all of the sites identified for this study. In the economic sensitivity analysis however, higher wind speeds are given.

The Snare-Yellowknife power system presently has a hydro surplus of about 25 GWh per year, and although some of the electricity is generated from diesel generators, any new wind power additions may not necessarily result in significant diesel displacement. The Jackfish diesel plant can produce power at about $0.26 per kWh with diesel fuel at $1.00 per litre, but it is essentially a standby plant at the time of writing.

The capital cost for a 300 kW wind power project of three NorthWind 100-21 wind turbines is estimated to be $1.562 million or $5,205 per kW of capacity. The capital cost of a 1,500 kW project of one GE 1.5 sle wind turbine is estimated to be $4.490 million or $3,260 per kW of capacity. The NorthWind 100-21 is designed for remote diesel community applications while the GE 1.5 sle is designed for large scale grid-connected applications.

At the forecasted long term average wind speed the cost of energy from the 300 kW project was estimated to be $0.62 per kWh and from the 1,500 kW project was estimated to be $0.28 per kWh. The lower capital costs per installed kW and the higher wind speeds harvested by the taller, larger turbines yields substantially lower cost wind energy.

The incremental cost of large wind turbines at about $3,000 per kW can produce wind energy at about the same cost as diesel generation with fuel prices at $1.00 per litre.

Background

JP Pinard, P.Eng., Consulting Engineer, and John Maissan, P.Eng., Leading Edge Projects Inc., have been retained by the Aurora Research Institute to conduct a pre-feasibility study for wind energy generation in Yellowknife. This study examines wind data from the weather balloon (upper-air), the airport station, and 1.5 years of local wind monitoring data. Maps and satellite images of the community were examined to identify potential wind project installation sites. This study provides the following information:

1) Analysis of potential sites for further investigation.
2) Refined estimates of the range of wind speeds near Yellowknife.
3) Size, capacity and condition of present power system in Yellowknife.
4) Analysis of different scenarios of power demands for Yellowknife.
5) Preliminary estimates of the cost of wind generation for Yellowknife.
6) Estimates of power production and potential diesel displacement through integration of wind power.
7) An outline of next steps needed to pursue the integration of wind power in Yellowknife.

Introduction

Yellowknife is the capital of the Northwest Territories and has a population of 19,000 people. It is located on Yellowknife Bay on the north shore of Great Slave Lake which has an altitude of 157 m ASL (Figure 1). The city is accessible year-round by highway from BC and Alberta to the south. However, this route includes a ferry (ice road in winter) crossing of the Mackenzie River which can occasionally restrict heavy transport to the city. The capital city has daily flights to several southern cities and is a central take-off point for airlines to many of the remote communities in the NWT.

In Yellowknife NTPC provides wholesale power to Northland Utilities (Yellowknife) Ltd. and provides industrial service to two mining properties in the Yellowknife area (Miramar Con mine and the former Giant mine, both are in care and maintenance or reclamation activities). Power distribution is handled by an investor-owned firm, Northland Utilities (Yellowknife) Ltd., which is an ATCO company.

The generating capacity on the Snare/Yellowknife system is 65 MW, 220 GWh of electricity per year is generated from hydro (from 5 hydro plants) and 2.1 GWh/yr has been generated from diesel plants at the Jackfish station near downtown Yellowknife. The diesel-electric portion of power generation is forecasted to reduce to 1.4 GWh/yr in 2007-08[1]. However, due to low water there are periods when more diesel-electric generation is required. This occurred in 2004 where 15% (25.8 GWh) of the electric

[1] From: Northwest Territories Power Corporation 2006/07 and 2007/08 General Rate Application – Phase 1

power came from the diesel plant[2]. The Snare-Yellowknife system serves Yellowknife, as well as Behchoko and Detta.

Wind resource assessment has been carried out in the community for more than a year and a half and is ongoing. A progress report (Pinard et al, 2007) using six months of wind data from wind monitoring at NTPC's Jackfish telecommunication tower had determined that the long-term mean annual wind speed was 4.98 ± 0.5 m/s at 60 m above ground.

Yellowknife has the following attributes with respect to wind energy development:

- Abundance of technical and human resources;
- Relatively flat topography with local relief in the order of 40 m;
- Bedrock exposure which dominates the area, making high foundation loading possible;
- Year round road access with the limitation of the ferry / ice bridge across the Mackenzie River at Fort Providence; and
- A significant amount of heavy construction industry in support of the mining sector in NWT.

The purpose of this report is to examine the potential for wind power generation by providing a selection of potential sites, estimating the mean annual wind speed and estimating the economics of building a wind installation near the city.

[2] From: City of Yellowknife Energy and Emissions Baseline, June 2006

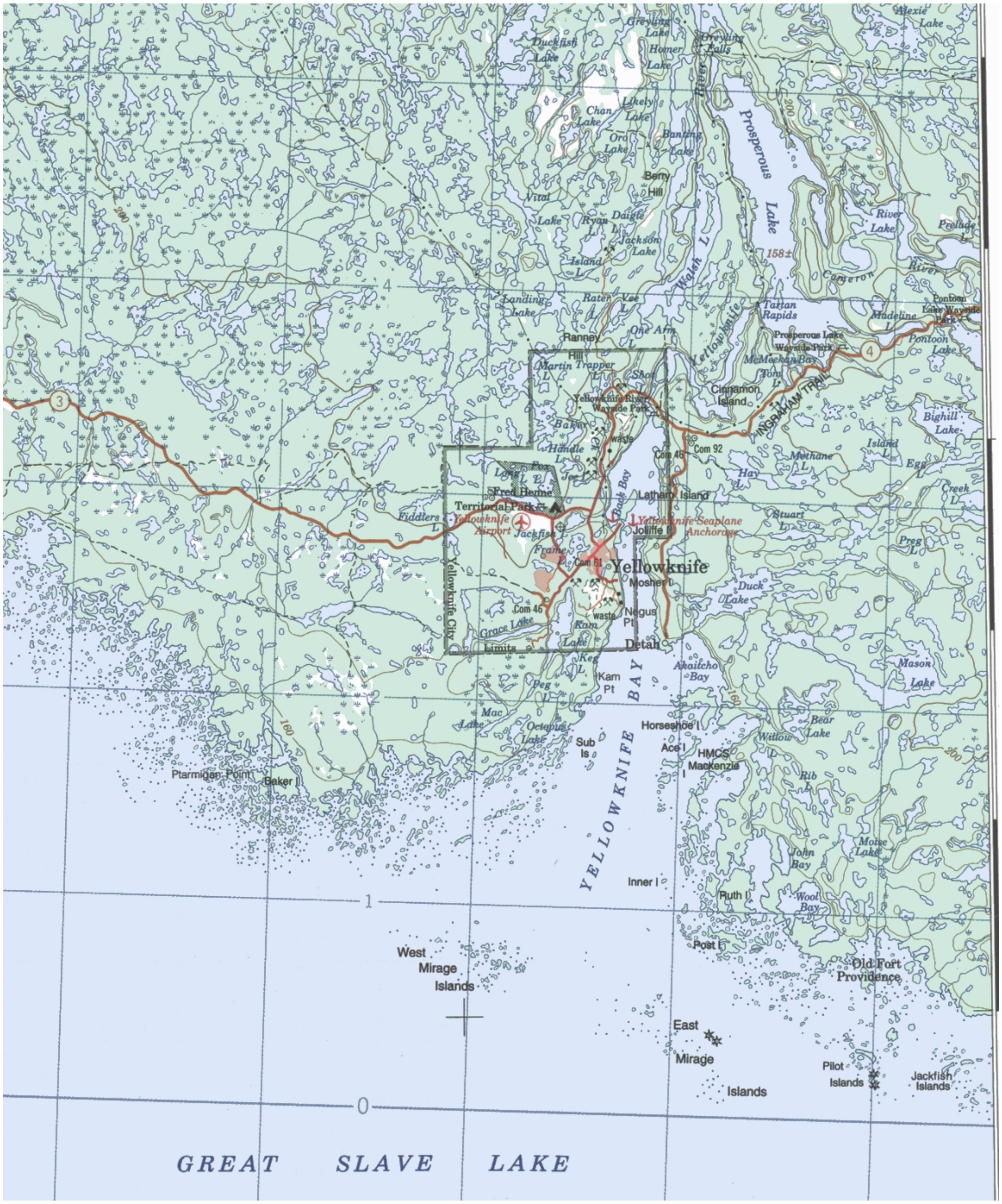
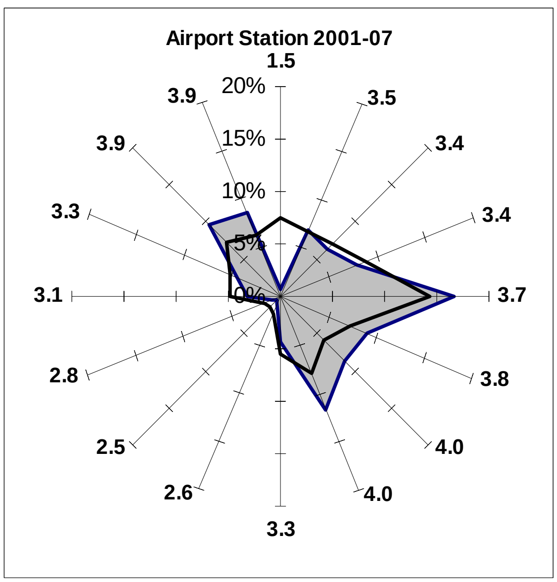


Figure 1: Map of the City of Yellowknife and surrounding area.

Measured Wind Directions

In this study data were used from two wind monitoring stations. There is a wind monitoring station at the Yellowknife airport (operated by Environment Canada) which has long term hourly measurements. The airport station is at 206 m ASL and the sensor is on a 10 m tower. The second measurement station is at NTPC's Jackfish communications tower which is at 197 m ASL. On this tower there are sensors at 10, 20, and 38 m above ground level. The wind speed and direction, and temperature, are averaged to 10-minute intervals and the data is collected by NTPC staff.

The wind roses in Figure 2 show the wind energy by direction, which is calculated as the frequency of occurrence of the wind in a given direction sector multiplied by the cube of the mean wind speed in the same direction. There are 16 direction sectors and each sector is 22.5 degrees wide. The given wind energy in each direction is a fraction of the total energy for all directions. The dominant wind direction at the Yellowknife airport (2001-07) appears to be from the east (34%) while there are smaller components of wind from the south-southeast (25%) and from the northwest (23%). The Jackfish measurements show similar tri-modal directions but with an added dominant north-easterly mode.



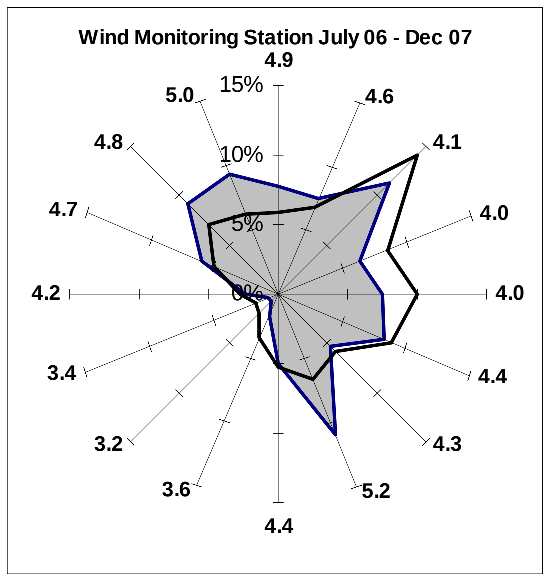


Figure 2: Wind rose from the Yellowknife airport and the Jackfish wind stations. The shaded rose shows the relative wind energy by direction, and the outlined rose is the wind frequency of occurrence by direction. The mean wind speed by direction sector is indicated at the end of each axis.

It is important to consider that wind turbines must have high exposure to dominant wind directions. For example for a multiple turbine installation a hilltop ridge should ideally be perpendicular to these directions and so should be roughly oriented north to south. For a single turbine orientation is not critical. In the absence of nearby hills, wind turbines should be located along a lakeshore with the open water on the dominant upwind side of the proposed wind farm. Open water and ice have a typically smoother surface which provides the least resistance to the near-surface winds. This is preferred over variable terrain such as a forested area where trees increase the air turbulence near ground and tend to slow the surface winds.

Wind energy, as a renewable energy is most beneficial when it is replacing non-renewable energy such as diesel-electric power. The greatest electrical demand occurs during the coldest portions of winter (December to February) --- when the water reserves are lowest and this is typically when diesel generated electricity is required. It is then useful to know what the dominant wind direction is during those coldest winter months. A wind rose was calculated for the winter months of December, January, and February (2001-2007) with the airport data (Figure 3). This rose indicates that the easterly to south-south-easterly winds are the most important directions to keep in mind when siting an area for wind turbines.

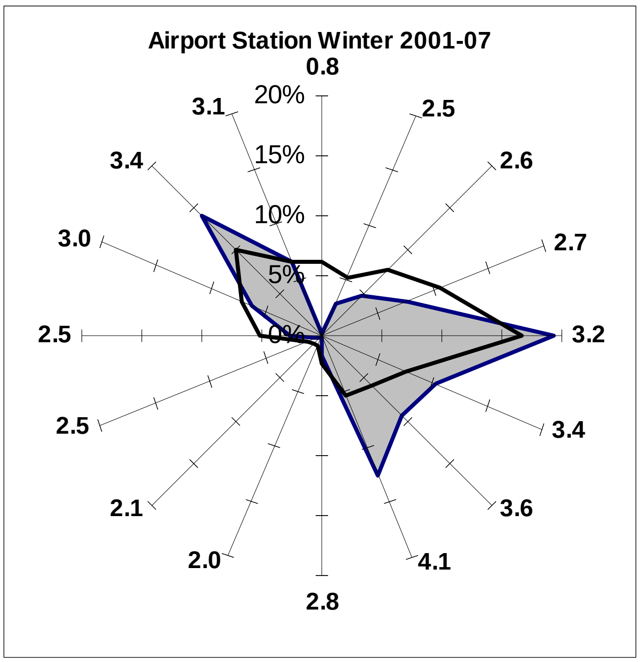


Figure 3: Wind rose for the winter months of December, January, and February for the period 2001 to 2007.

From the wind roses given above it would be best to find a site on a high ridge that is oriented approximately north-south, or in the absence of large hills, a site that is near a large body of water that is located to the east of the site.

Suitable sites for wind energy development

In surveying sites for wind farm possibilities the authors have considered a number of criteria: good wind exposure, road accessibility, nearness to power lines, and good public visibility. The first three criteria are of course most important, however, for community acceptance and pride it is important that the wind turbines are visible to the community members. From the Whitehorse experience with the Haeckel Hill wind turbines, the best advertising and community pride have resulted from the turbines' high visibility from almost anywhere in the Whitehorse vicinity. This has created a good public image for Yukon Energy, the owner of the wind turbines. There is a saying that wind turbines may provide only 1% of the total energy, but they provide 99% of the PR (public relations).

The City of Yellowknife is located on the west side of Yellowknife Bay which juts out northward from the Great Slave Lake which has an elevation of 157 m ASL (see Figure 1). The bay is about 20 km long and 2 km wide. The city itself ranges in elevation from the lake level to just over 200 m ASL. The relief within the city is relatively flat with a mean elevation around 190 m ASL, the land rises gradually towards the north and falls towards the south. The land around the city is dotted with rock outcrops of the Canadian Shield.

There are several sites that may be interesting for wind development and they are marked in Figure 4. The sites north of the city are on hills that generally peak over 210 m ASL with the tallest one reaching near 230 m ASL. Just north of downtown, the hills on the south edge of Jackfish Draw (see Figure 5) are at similar elevations to and about 500 m east-southeast of the Jackfish wind monitoring station. Being closer to the lake shore this site may have some wind speed advantage over the Jackfish site, however, it is relatively close to a residential neighbourhood about 200 m to the south. This site appears to be on municipal land.

The Joe Lake hills (see Figure 5) form a north-south ridge that is 600 m long and about 210 m ASL and about 60% of the area is within municipal-owned land which is the site of the City's landfill. This site is attractive as it is far enough from residential areas, has reasonable road access and is within 1 km of power line. It is also 1 km from NTPC's Jackfish diesel plant and the wind monitoring station, and 2.7 km from downtown.

Further north, the Giant Mine ridge is above 210 m ASL, over 800 m long, and a power line runs across this ridge. About 80% of the land is unsurveyed and the other portion is on Commissioner's land (sketched parcel) which encompasses Giant Mine to the east. The ridge is 5.5 km from downtown Yellowknife and is 500 m from the nearest road.

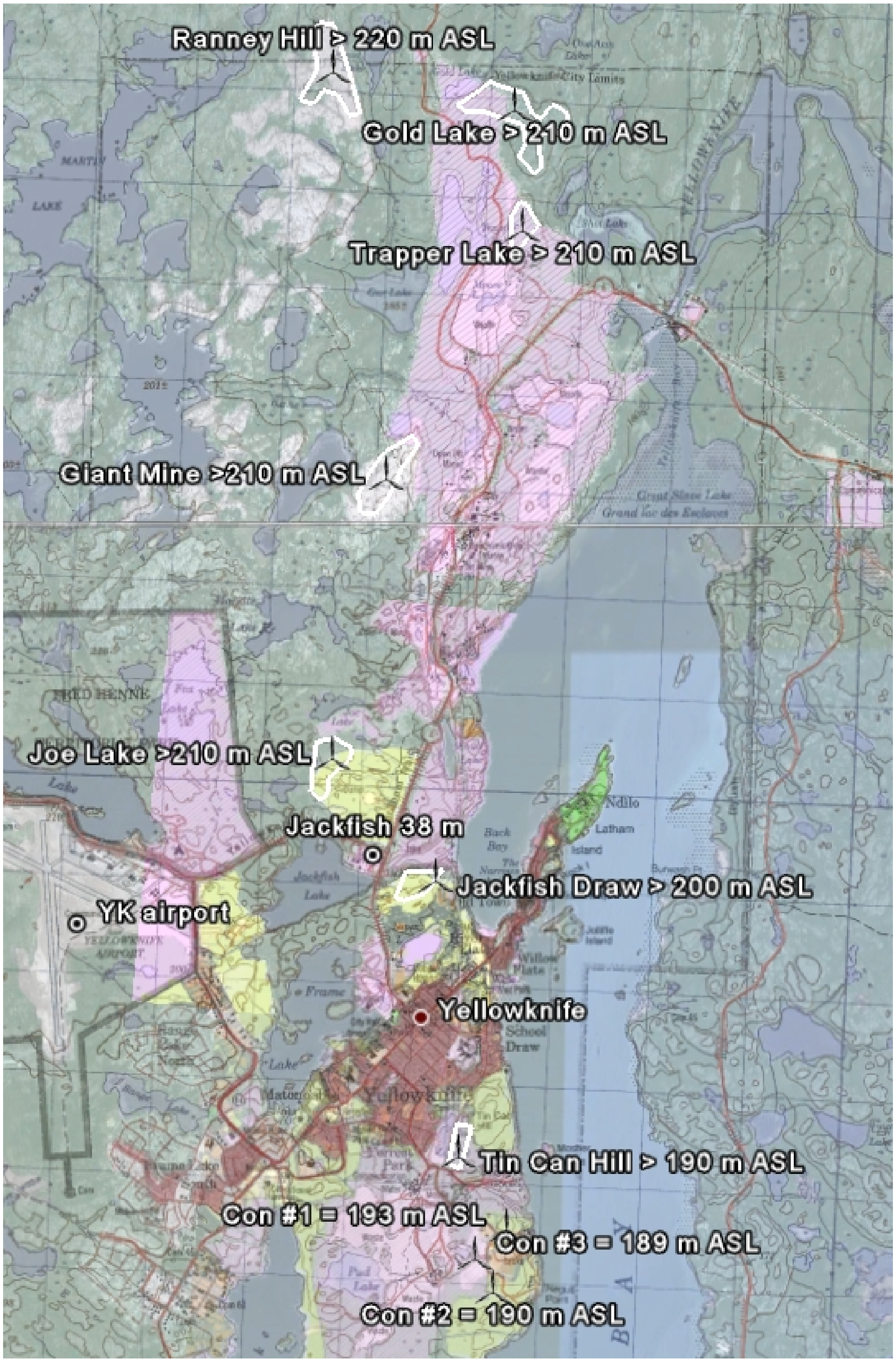


Figure 4: Map of Yellowknife and surrounding area showing possible locations for a wind farm. The pink parcels are Commissioner's land, the yellow parcels are municipal land, and the orange ones are private parcels. The parcels with diagonal lines are sketched parcel whereas the solid ones are surveyed. The legal information is from the MACA (Municipal and Community Affairs), the NTS sheets from Government of Canada, and the base image is from Google Earth.

Further to the north, at least 8 km from downtown, are three more hills: Trapper Lake, Gold Lake and Ranney Hill. The Trapper Lake hill appears to be within 200 m of road and power line, it is over 210 m and peaks at about 215 m ASL, and is about 450 m across. Ranney and Gold Lake hills are about 1 km across providing significant room for many turbines. They are both about 1.5 km from power lines. Gold Lake hill is over 210 m ASL and Ranney Hill is over 220 m ASL with a long (north-south) ridge that peaks at 228 m ASL. At the north end of Ranney ridge is a small knob that peaks at 245 m ASL. It has not been determined whether this knob (only 100 m wide) is easily accessible for a wind development; the authors assume that it is not accessible. The ridge of Ranney Hill is about 800 m from the nearest road. Ranney Hill is attractive as it is 30 m above the surrounding landscape. The land at Ranney ridge is not surveyed.

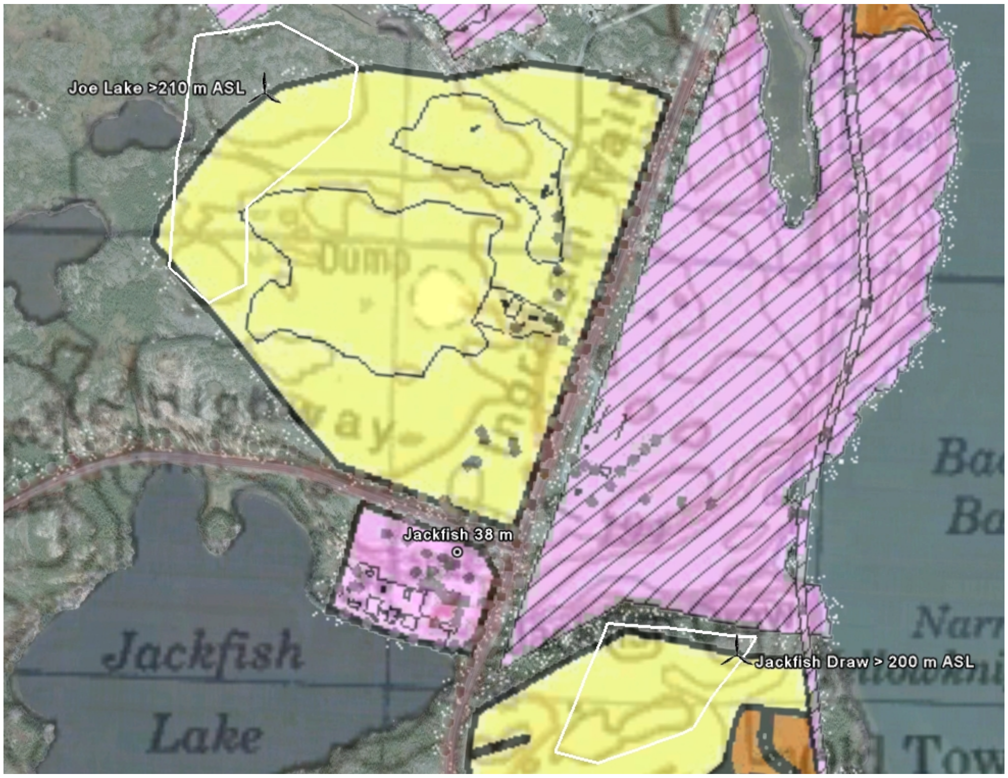


Figure 5: Possible locations for a wind turbine near the Jackfish station. The blades of the wind turbine images are approximately 80 m diameter, to scale with the underlying map. The contours are at 10-m intervals, the ones at Jackfish Draw are at 200 m ASL and those at Joe Lake are 210 m ASL.

To the south of the City the land peaks to above 190 m ASL. This area is closer to the lake shore and the larger body of Yellowknife Bay.

Tin Can Hill is just east of Rae Lakes, the ridge is 300 m from residential neighbourhood to the west and southern end of the ridge is within 100 m from a mobile home park to the south. This proposed location may encounter resistance from the nearby residents. However, the ridge has good exposure to the dominant wintertime easterly winds, is road accessible and is within a few hundred metres of power lines. The ridge is above 190 m ASL and peaks to 200 m ASL. It is on Commissioner’s land (sketched parcel).

The Con Mine area is an industrial zone and has power running to the area. There are three sites in the Con Mine area that have been identified as potential candidates for single wind turbines. There are certainly other locations that can be selected in this area, however without having thoroughly surveyed it, the authors choose the highest sites based on existing elevation data. These three sites are also on bedrock which provides a stronger foundation for the towers. The Con #1 and Con #2 are both on municipal land and are at 193 and 190 m ASL respectively. These two sites are 300 and 450 m west of the lakeshore and with a relatively smooth gradient from the shoreline to each site they should have clear exposure to the dominant easterly winds. The site Con #3 is slightly west of the other two and is on Commissioner's land, encompassing the Con Mine. The sites Con #1 and #3 appear to be within 200 m of power line while #2 is approximately 400 m away.

Figure 6: Possible locations for a wind turbine at the Con Mine area. The blades of the wind turbine images are approximately 80 m diameter, to scale with the underlying map. Note the shadow of the mine shaft on the left side middle of image. The contours are at 10-m intervals, the ones around each site is the 190-m ASL contour.

All of the sites described above are being identified as a first step in an iterative process of determining the possibilities for wind development in Yellowknife. If there is desire and commitment to establish a wind farm or a wind demonstration project in the Yellowknife area given the economics of the project, then the next steps are to investigate which sites are possible to develop given their designated or intended purposes. Some of these sites are on titled land owned either by the municipality or the Commissioner. Some of these may already have intended purposes that will not permit wind development. And some of these sites may be too close to residences. The follow sections will quantify the wind speed and then the economics of a wind farm. For the purpose of this study, the sites suggested above are assumed to have similar wind speeds. Further work will be needed to establish which site will be most suitable. Numerical modelling, land title investigation, dialogues with land owners may be required. When one (or more) site has been selected, a measurement tower will be required at the site of interest to quantify the wind climate at this location.

Measured and Projected Wind speeds

The wind speeds at the Jackfish station can be projected to longer term by correlation with the long-term measurements made at the airport station. Environment Canada keeps records of the airport measurements that go back several decades. The airport measurements were made at 10 m above ground level (AGL) which is 206 m above sea level (ASL). The mean wind speed at the airport during the period July 2006 (when the Jackfish sensors were installed) to December 2007 is 2.97 m/s. Over a ten-year period (1998-2007) the mean annual wind speed measured at the Yellowknife airport was 3.28 m/s[3] (11.8 km/h). The ten-year mean is a factor 1.10 times the shorter period mean. The results of the wind measurements are summarised in Table 1 below. The standard deviation of the mean annual wind is 0.2 m/s. It is interesting to note that the annual mean wind speed for 2007 is 2.98 m/s and it is the lowest of the 1998-2007 period.

At the Jackfish telecommunications tower there were four sensors installed; one at each of 10 and 20 m and two at 38 m AGL. The sensors were placed at the end of 1.5-m long booms that were oriented towards the northeast on the tower, except for one of the sensors at 38 m, which was oriented towards the southwest. The measurements from these sensors are given along with their projected estimates in Table 1. The measured wind speeds at the Jackfish tower are also shown in Figure 7. The two sensors at 38 m AGL measured different wind speeds and there is strong evidence that wintertime icing has adversely affected the measurements of all sensors. Because of ice contamination the measured wind speed is expected to be lower than the actual. It is very difficult, however, to determine the actual wind speed even through filtering of the data. It is reasonable to use the maximum speed of the two 38-m sensors. Using the maximum of the two sensors, the measured mean wind speed at 38 m is 4.39 m/s for the monitoring period July 2006 to December 2007 (18 months). Projecting this measurement to a ten-year mean using the airport measurement, the mean wind speed at Jackfish becomes 4.85 m/s (at 38 m AGL). Because of ice contamination this number is considered a conservative estimate.

[3] To convert m/s to km/h multiply by 3.6, and to miles/hour multiply by 2.237.

Table 1: Measured winds from the airport and the Jackfish stations.

Location and measurement period	Height	Wind speed	
Yellowknife Airport 11 July 2006 to 31 Dec 2007	10 m AGL	2.97	m/s
Jackfish WM 11 July 2006 to 31 Dec 2007	10 m AGL	3.29	m/s
	20 m AGL	3.51	m/s
(Ch 2)	38 m AGL	4.15	m/s
(Ch 1)	38 m AGL	3.93	m/s
Maximum of Ch 1 & 2	38 m AGL	4.39	m/s
Yellowknife A ten-year (1998-2007) average	10 m AGL	3.28	m/s
Ratio of ten-year to July 06 - Dec 07 means		1.10	
WM wind projected to ten years (1998-2007) at	10 m AGL	**3.62**	m/s
	20 m AGL	**4.26**	m/s
	30 m AGL	**4.63**	m/s
	37 m AGL	**4.83**	m/s
	38 m AGL	**4.85**	m/s
	50 m AGL	**5.11**	m/s
	60 m AGL	**5.27**	m/s
	70 m AGL	**5.42**	m/s
	80 m AGL	**5.54**	m/s
	90 m AGL	**5.65**	m/s
	110 m AGL	**5.83**	m/s

The wind speeds estimated at the measurement heights of 10, 20, and 38 m AGL can be projected vertically to other heights using the (natural) logarithmic law equation described as follows:

$$U_2 = U_1 \frac{\ln\left(z_2 / z_o \right)}{\ln\left(z_1 / z_o \right)}$$

where U_1 is the measured wind speed at height z_1 and U_2 is the projected wind speed at elevation z_2. The length z_o represents the surface roughness length of the surface around the wind station. The surface roughness has been adjusted to z_o = 0.2 m so that the logarithmic profile intersects through the average (measured) wind speed of 3.29 m/s at 10 m AGL and 4.39 m/s at 38 m AGL. Figure 7 shows the log profile (U(log)) crossing through the measurements at 10 and 38 m AGL. Note that at 20 m AGL the measured wind speed is less than the log equation estimate. This is likely due to ice-contamination of the measurements. In the report of Pinard et al. 2007 the value z_o = 0.2 m was also used and the log profile corresponded very well with the fall-2006 measurements at all three heights. As shown in both Table 1 and Figure 7 the log profile is projected to a ten-year mean by fitting the profile to the new ten-year wind speed of 4.85 m/s at 38 m AGL and keeping the same surface z_o = 0.2 m. From this second profile the new ten-year mean wind speed at any desired height can be used to calculate wind turbine production from any desired tower hub height. As will be shown in subsequent sections, the hub heights used in this report are 37 and 80 m AGL and these are given in Table 1. To account for annual variability (±0.2 m/s) and measurement error (5% or up to ±0.3 m/s) the authors have allowed for a total error of ± 0.5 m/s in the economic analysis.

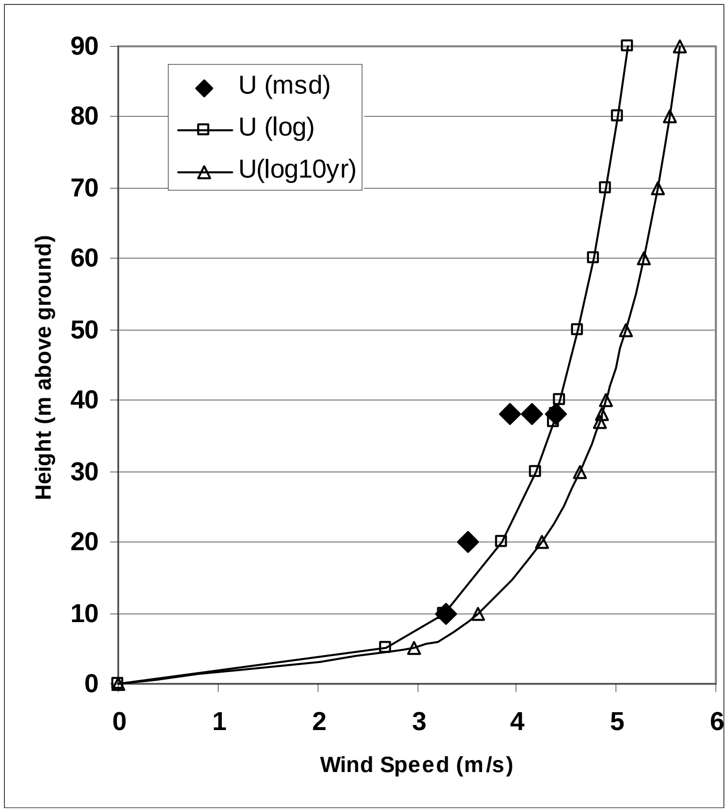


Figure 7: Measured wind at the Jackfish and projected log (natural logarithmic) profiles of wind speeds to greater heights. The measured wind speed is labelled U(msd), the third point at 38 m is the maximum of the other two. The two natural log profiles both use z_o = 0.2 m; one profile, U(log), is fitted to the measurements and the other, U(log10yr), is projected to a ten-year mean. These are also shown in Table 1.

In Yellowknife the greatest need for wind energy is during the winter when diesel-electric generators may be operating. A graph of long term monthly mean wind speed and temperature is presented for the Yellowknife area (Figure 8). The graph shows long term mean monthly wind speed for the airport and for the Jackfish station projected to 37 and 80 m AGL. Ten-year (1997-2006) mean monthly wind speeds at 100 m AGL, above the surface at the Fort Smith upper-air station are included in Figure 9. This upper air station is the closest to Yellowknife and is located 300 km southeast of the community. The Fort Smith upper-air station is at 203 m ASL, has a comparable elevation to Yellowknife and its measured wind speed provides a good representation of the regional winds. At 100 m AGL the ten-year mean wind speed above Fort Smith is 5.6 m/s which is only slightly less than the estimated 5.65 m/s (at 90 m AGL) shown in Table 1. The monthly mean temperature is from the Yellowknife airport station; these temperatures are only a few degrees colder than those at Fort Smith.

The monthly mean wind speed at the airport reaches a maximum 3.7 m/s in May and reduces to a minimum 2.5 m/s in January under the influence of winter inversions. This translates to a maximum 5.5 and 6.3 m/s in May but a minimum of 3.7 and 4.2 m/s in January at 37 and 80 m AGL respectively. From this monthly pattern there is a distinct disadvantage for wind energy potential in Yellowknife, because the seasonal winds are lowest in the coldest months of winter when the need for diesel-electric would be greatest.

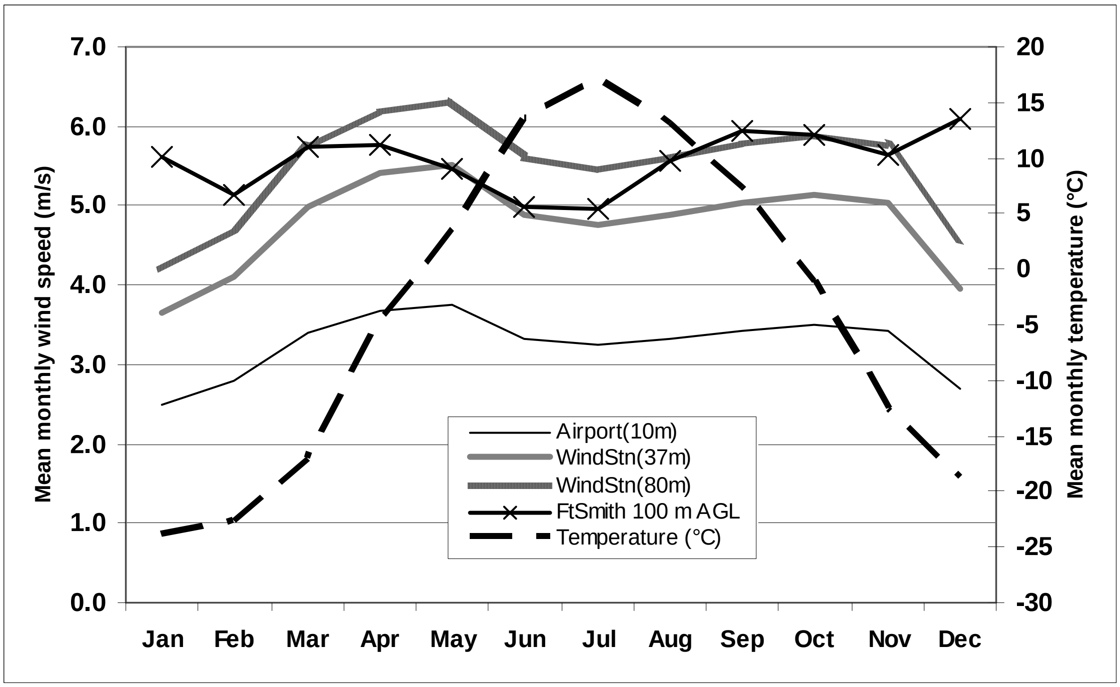


Figure 8: Estimated monthly mean wind speed at various elevations above the surface at Jackfish using long-term (2001-2007) monthly mean wind speeds measured at the airport. These are compared to the ten-year (1997-2006) mean wind speed at 100 m AGL at the Fort Smith upper-air station. The graph also includes monthly mean surface temperature at the airport.

The mean monthly wind speed at Fort Smith at 100 m AGL show that the monthly wind speeds are relatively constant through the year and the highest monthly wind speeds are recorded during the winter months. At higher elevations above Fort Smith the winter winds are even faster (See Appendix 1 in Pinard et al. 2008). These faster winter winds occur because at these higher elevations the winds are less inhibited by the winter inversions that tend to suppress the colder surface air from the faster winds above. In some cases under particularly strong winter inversions (typically at temperatures below -40°C) the surface air can be completely de-coupled from the winds above. Near Yellowknife there are hill sites that when combined with a tall tower that could reach to at least 100 m above the surrounding landscape. This is possible at a few sites near Yellowknife, one example is Ranney Hill where the ridge reaches to nearly 230 m ASL and combined with an 80 m tower this provides a hub height of 310 m ASL which is 110 m higher than the surface of the Jackfish station. At this elevation the estimated wind speed is 5.8 m/s and it is possible that the winds there are greater during the winter.

Power requirements and costs

The community of Yellowknife is part of a hydro based grid (Snare – Yellowknife or Snare system) served by two hydro power plants (Snare Rapids and Bluefish) and is supported by a diesel plant at Jackfish Lake within Yellowknife. The long term average energy available from the hydro plants is 220 GWh per year.

In the General Rate Application (GRA) of November 24, 2006 NTPC forecasted that their total power requirement for the Snare system was 195.3 GWh for 2007-2008. Of this over 99% was forecast to be met with hydro generation and only 0.7% from diesel. These figures indicate a hydro surplus of about 25 GWh per year. Relevant excerpts of the GRA are attached as Appendix 1. Prior to the shutdown of the area gold mines the electrical load was in excess of the hydro capacity and diesel generation was always on the margin. The Jackfish diesel plant has now been essentially relegated to a stand-by plant.

The annual energy requirement of the Snare system is growing by about 0.9% per year, which is the result of decreasing industrial loads and increasing residential and general service loads. These figures suggest to the authors that for the foreseeable future, hydro power will satisfy the bulk of the Snare system's energy needs. While any new source of power will not make economic sense under these circumstances, this prefeasibility study has been based on the assumption that wind power would be considered as a demonstration project and based on the avoided cost of diesel power. Any such demonstration project would be a very low penetration project and no specific wind – power system integration equipment should be required.

In this report it has been assumed that the diesel generation displaced would be from a base loaded diesel plant producing power at an efficiency of 3.85 kWh per litre of fuel (about the 2005-2006 actual Jackfish plant efficiency). This efficiency would result in power costs ranging from $0.208 per kWh with diesel fuel at $0.80 per litre to $0.312 per kWh with fuel at $1.20 per litre (see Appendix 2).

Wind power project costs

<u>Wind turbines</u>

There are two possible approaches to a wind project in Yellowknife given the present power system realities. Both approaches aim to limit the capital costs while maintaining a realistic demonstration of wind power technology and practicality. One is to install a small project composed of the type of wind turbines suitable to most of NWT's small communities, and the other is to install a single wind turbine of full commercial scale.

Based on recent work for other potential wind projects in NWT, the most suitable small wind turbine model for consideration at Yellowknife is Distributed Energy's NorthWind 100 with a 21 meter rotor (NW 100-21 in this report). The NW 100-21 has a large rotor which is better suited to lower wind speeds than other turbines on the market. It is available with a 37 meter tower and a cold weather option that allows it to operate in temperatures down to -40°C, which is appropriate for Yellowknife's climate. In order to get at least a small measure of economies of scale, the authors propose that three of these turbines be installed to make up a demonstration project, similar to projects that may be considered for many of the remote communities in the NWT. These wind turbines could be delivered about 6 to 8 months from receipt of a firm order.

The authors considered two large commercial scale wind turbines as better suited for Yellowknife's low wind speed regime. One is GE's 1.5 sle, a 1.5 MW wind turbine with a 77 m rotor (diameter) and the other is the Vestas V82 1.65, a 1.65 MW wind turbine with an 82 meter rotor. They are both in common use throughout Canada and are available with towers of 80 meters in height. These models are designed for lower wind speed regimes; compared to most other turbines on the market they have a larger rotor diameter for their capacity. For this prefeasibility study the authors used the GE 1.5 sle as the required information on this unit was available (more recent cost information and power curve data). These turbines are only available in a cold climate version that allows operation down to -30°C; they shut down below this temperature. Large wind turbines are difficult to purchase because of the high global demand – typical delivery times from the receipt of a firm order is approaching 2 years. It may also be that the manufacturers would not be willing to sell a single turbine to a client, thus it may be necessary to engage a project developer who has bulk purchased these turbines for such a project.

Based on the wind data analyses and a base ground elevation of 200 m above sea level (ASL), the forecasted long term average annual wind speed at 38 m AGL is 4.85 m/s, and at 80 m AGL is 5.54 m/s (± 0.5 m/s). This indicates that the NW 100-21 would be harvesting a wind resource of about 4.8 m/s (at 37 m hub height) and the GE 1.5 would be harvesting a wind resource of about 5.5 m/s.

<u>Energy production</u>

The energy produced by a NW 100-21 is based on the published power curve (as yet to be verified in actual field performance) less 5% to adjust for a turbine availability of 95%. An additional 10% of the remaining production is then subtracted to account for losses (turbulence losses, array losses, mechanical losses, cold and icing performance losses, transformer losses, and transmission line losses) to arrive at the net energy production available to displace diesel energy. Appendix 3 provides a table of energy production at different annual average wind speeds. Often there is an adjustment for increased production at higher air densities due to cold temperatures which, in Yellowknife's case, would likely be approaching 5%. However, given that the power curve has yet to be verified and the various other uncertainties in the project, it was thought prudent not to add that possible increase into the forecast energy production.

The calculations indicate that the net energy production at an annual average wind speed of 4.80 m/s represents a capacity factor of about 13.2%. This increases to about 14.7% and 18.4% at annual average wind speeds of 5.0 and 5.5 m/s respectively.

The energy produced by a GE 1.5 sle is based on the published power curve less 5% to adjust for a turbine availability of 95%. An additional 15% of the remaining production is then subtracted to account for losses (turbulence losses, array losses, low temperature shutdown losses, mechanical losses, cold and icing performance losses, transformer losses, and transmission line losses) to arrive at the net energy production available to displace diesel energy. The additional 5% of losses compared to the NW 100-21 is a fudge factor (estimate) by the authors to allow for lost operational time when the temperature is between -30°C and -40°C. A more accurate forecast of low temperature losses would need to be determined by detailed modelling. Appendix 3 provides a table of energy production at different annual average wind speeds. As previously stated, there is often an adjustment for increased production at higher air densities due to cold temperatures. However, given that the turbine does not operate below -30°C and various other uncertainties in the project, it was thought prudent not to add that possible increase into the forecast energy production.

The calculations indicate that the net energy production at an annual average wind speed of 5.5 m/s represents a capacity factor of about 17.2%. This increases to about 18.8% and 20.7% at annual average wind speeds of 5.75 and 6.0 m/s respectively. Note that despite allowing an additional 5% for low temperature losses the capacity factor anticipated from this larger turbine is higher than the smaller turbine. This is entirely due to the increased hub height and the additional wind resource available to be harvested. The power curves of the two models of turbines are virtually identical.

Capital costs

The estimated capital costs for the 300 kW NW 100-21 and the 1,500 kW GE 1.5 sle projects are presented in Appendix 4. The 300 kW project was estimated to cost $1.562 million or $5,205 per kW, and a 1,500 kW project was estimated to cost $4.890 million or $3,260 per kW. These costs assume the project would be installed very close to or within Yellowknife and the site would be close to roads, power lines, construction, and technical services. As can be seen from these figures there are significant advantages to the larger turbines on an installed cost per kW of capacity basis, even with a “one-off” installation. A budget for a single NW 100-21 turbine would have been substantially more expensive per kW of capacity than the three turbine project presented here. Further advantages for the larger turbines would be realized if multiple units were to be purchased and installed. Incremental costs would likely be in the order of $3,000 per kW or less for locations near or within Yellowknife. A larger project located out of the immediate vicinity of Yellowknife would incur additional capital costs such as road, power line, substation, site preparation, and higher construction costs.

Costs for projects in the Yellowknife area will be lower than in any small communities because of the services and power lines available there. Costs are also less because it is a relatively small amount of capacity being added into a large system so no wind-diesel integration equipment (or related design) is required.

As with smaller projects the capital costs of a project here is still a major energy cost driver, so it is important for the developer to pay attention to all capital cost components.

Annual costs

The annual costs for a project were looked at as two separate components. First the repayment of the capital costs in mortgage style fixed payments (monthly assumed, but shown as annual in the relevant tables) over 20 years. The interest rates (cost of capital) considered were 8%, 6%, and 4%, with 8% representing an approximation of an unsubsidized commercial operation, and 6% and 4% representing different levels of funding assistance. At this time the authors believe that funding assistance would likely be necessary to interest a wind project developer. A project developer would need to determine what the effective cost of capital would be in their circumstances, and a higher perceived risk would demand a higher return on equity (higher cost of capital).

The second component is the actual operating and maintenance costs. This would include all overhead, insurance, lease, and tax costs as well as the actual maintenance costs. It is difficult to estimate these costs since they cannot really be based on large wind farms; therefore a round figure of $20,000 per turbine per year for the NW 100-21 was taken as being reasonable. To examine the sensitivity of projects to this cost, figures of $10,000 and $30,000 per year per turbine were also used in the analyses as low and high operating cost scenarios.

For the GE 1.5 sle turbine a figure of $150,000 per year was selected as the likely annual operating cost. This represents a cost of about $0.066 per kWh for the useful power generated at an annual average wind speed of 5.5 m/s. Costs of $100,000 and $200,000 per year were also examined as low and high scenarios. Appendix 5 presents the total annual costs of the projects as a function of capital cost, interest rate, and annual operating costs.

Cost of wind energy and economic analyses

Appendices 6 and 7 present the costs of wind energy for the two different project cases of the 300 kW NW 100-21 and the 1,500 kW GE 1.5 sle as a function of capital costs, interest rates, wind speed, and operating costs.

An unsubsidized 300 kW NW 100-21 project (8% interest) installed for the estimated capital cost ($5,205 per kW), experiencing a medium annual operating cost of $20,000 per year per turbine, and harvesting a wind resource of about 4.8 m/s, would produce power at cost close to $0.62 per kWh. Even if capital costs could be reduced to $4,000 per kW, the cost of power would only be reduced to about $0.52 per kWh. The wind resource would need to be over 6.5 m/s for energy from such a project to be competitive with diesel generated power at a fuel cost of $1.30 per litre ($0.312 per kWh).

A proposed ReCWIP level of support of $0.03 for northern grids and large communities would provide about the same benefit as an additional fuel cost of $0.10 per litre. Clearly such a project would require a significant level of subsidy to be competitive with diesel generated power.

An unsubsidized (8% interest) 1,500 kW GE 1.5 sle project installed for the estimated capital cost of $3,260 per kW experiencing a medium operating cost and harvesting a wind resource of 5.5 m/s (equivalent to 4.8 m/s for the NW 100-21) would generate power at a cost of about $0.28 per kWh. This would be competitive with diesel generated power if fuel were $1.10 per litre, or if a proposed ReCWIP level of support were available, with diesel fuel at $1.00 per litre. If the wind resource available was 5.75 m/s rather than 5.5 m/s, the unsubsidized cost of power would be about the same as diesel generated power with a fuel cost of $1.00 per litre.

If capital costs could be reduced to below $3,000 per kW, the cost of power produced would be about the same as diesel generated power with fuel at $1.00 per litre. Additional turbines of this size could likely be installed for about $3,000 per kW.

From these analyses one can see the benefits of large scale turbines and larger scale projects. Similarly, the wind speed is an important variable, so locating a wind project at the highest possible elevation is also as important consideration. Even with its low wind resource, wind power from large wind turbines in Yellowknife is very close to being competitive with diesel generation at today's fuel prices.

GHG reductions

For the purposes of this report it has been assumed that all of the electrical energy available to reduce diesel generation does in fact reduce diesel generation. While this would have been a reasonable assumption a few years ago, it is not the reality at present due to the hydro surplus on the Snare-Yellowknife system. However, assuming complete diesel displacement is consistent with the basis of this prefeasibility study.

Table 2 below outlines the diesel fuel and GHG reductions that would be achieved by a 300 kW project using NW 100-21 wind turbines at various annual average wind speeds. The calculations are based on a diesel plant efficiency of 3.85 kWh per litre, and GHG emissions of 2.83 kg CO_2 (based on GNWT's figure for non-motive diesel) equivalent per litre of diesel fuel consumed. Table 3 presents similar information for a 1,500 kW project using one GE 1.5 sle wind turbine.

Table 2 Annual GHG reductions from a 300 kW wind project by wind speed

Wind speed, m/s	Diesel electricity displaced, kWh	Diesel fuel saved, litres	GHG reductions, kg CO_2 equivalent
4.50	284,715	73,952	209,284
4.80	345,762	89,808	254,157
5.00	385,520	100,135	283,382
5.25	435,281	113,060	319,960
5.50	484,785	125,918	356,348

Table 3 Annual GHG reductions from a 1,500 kW wind project by wind speed

Wind speed, m/s	Diesel electricity displaced, kWh	Diesel fuel saved, litres	GHG reductions, kg CO_2 equivalent
5.00	1,790,389	465,036	1,316,052
5.25	2,004,457	520,638	1,473,406
5.50	2,257,447	586,350	1,659,371
5.75	2,471,515	641,952	1,816,724
6.00	2,724,505	707,664	2,002,689

Conclusions

1. Yellowknife has a number of sites that are suitable for a potential wind development. There are an abundance of bedrock outcrops some of which are close to power lines and suitable for wind turbine installations.
2. Based on local monitoring station and local airport data the wind speed at an height of 37 m AGL (at a site which is 200 m ASL) is projected to be 4.8 m/s ± 0.5 m/s and at 80 m AGL is forecasted to be 5.5 m/s ± 0.5 m/s. The weather balloon data from Fort Smith provides confidence that these projections are reliable.
3. Due to the loss of industrial electrical load in recent years the present NTPC Jackfish diesel plant serves as a back-up since more than 99% of the 195 GWh annual load is served by hydro power. The Jackfish diesel power plant serves only as a back-up power plant at present.
4. The available information indicates that the electrical load is growing at about 0.9% per year, which suggests that there will be no substantial diesel power required for some years in the present circumstances.
5. Costs for a 300 kW NW 100-21 turbine project and 1,500 kW GE 1.5 sle turbine wind projects were forecasted to be $1.562 million ($5,205 per kW) and $4.890 million ($3,260 per kW) respectively.

6. Unsubsidized projects of 300 kW and 1,500 kW in the forecasted wind resource of 4.8 m/s and 5.5 m/s respectively would produce power at about $0.62 and $0.28 per kWh respectively. The smaller turbines do not produce power at a cost that is competitive with the cost of diesel generation. The larger turbines come close to being competitive with diesel.
7. There is a significant advantage to the larger turbine because of lower capital cost per kW of capacity and because the higher hub height provides a higher wind resource. The 1,500 kW wind project would be cost competitive with diesel fuel at $1.10 per litre. Incremental large turbine additions would be cost competitive at about $1.00 per litre fuel.
8. With a proposed ReCWIP program support of $0.03 per kWh, a wind project would be viable at a diesel cost $0.10 per litre lower than without the subsidy.
9. GHG reductions (assuming diesel displacement) on an annual basis at the forecasted long term average wind speeds are 254,157 kg and 1,659,371 kg of CO_2 equivalent per year for the NW 100-21 and 1,500 kW GE 1.5 sle projects respectively.

Next Steps

1. There is a hydro surplus on the Snare-Yellowknife system, so diesel energy would not be displaced by a wind project at present. Decision makers will need to decide if they wish to have a wind project under the present circumstances, and if so what size of project they would wish to have. The cost of wind energy with larger turbines and larger projects will be far lower (per kWh) than the cost from small turbine projects.
2. The wind speed is a critical factor in the economics of a wind power project so it is important to find the highest wind resource sites for a proposed project. This will require a combination of wind flow modelling, office and field investigation, and more on-site measurements at the new sites of interest.
3. Following confirmation of a desire for a wind power project, and the size of turbine to be used, a detailed feasibility study should be carried out. Particular attention needs to be paid to minimizing capital costs and identifying any available support programs.
4. As part of the decision to develop a wind power project, consideration needs to be given to whether this will be a “one off” demonstration project or a first step in what may become a larger wind farm. This will significantly influence the site selection.

Reference:

Pinard, Jean-Paul, Pippa Seccombe-Hett (Ed.) and John Maissan (Ed.), 2007: Executive Progress Report for Wind Energy Monitoring in Six Communities in the NWT. For the Aurora Research Institute.

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