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Wind-Diesel Systems in Nunavik and other Autonomous Grids

Régie de l'énergie R-3550-2004

Expert Testimony of
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Summary

The primary purpose of this analysis is to evaluate the report from IREQ/Hydro-Québec Distribution: *Systèmes jumelés éolien-diesel au Nunavik – Établissement des configurations et VAN optimales pour les quatorze villages – mise à jour 2004*, henceforth referred to as « the report ».[1] This evaluation focuses on the key recommendations of the report, i.e. to commence a more detailed planning for the economically most promising locations, where large, standard wind turbines with appropriate cold climate packages can be used.

We shall also comment on the potential for the use of wind-diesel systems in other off-grid systems, particularly on the Iles-de-la-Madeleine.

The general impression of the IREQ report is that it is a high quality paper, which is well documented, particularly in terms of its sensitivity analyses of key variables. These analyses facilitate the discussion of the paper considerably, so that relatively few questions have to be asked.

The report is in general very *cautious* in its assessment of the technical possibilities and costs of introducing high-penetration wind-diesel systems in Nunavik. This cautiousness is well placed in view of the fact that the climate conditions and accessibility to the potential wind sites are quite difficult. Given that this is a pre-feasibility study, it is also understandable that the report uses a large safety margin for the costs involved in introducing the hybrid wind-diesel systems in Nunavik.

1. The preliminary estimates of mean wind speeds are important for the economics of the projects. It appears that the wind speed estimates in the report are quite close to what can be estimated using the latest state-of-the-art models for wind speeds in Canada, and that the wind speeds on the proposed sites may be some 12% above wind turbine sites in the Gaspésie.

2. The report does not go into detail on the cold climate conditions in relation to the proposed measurement campaign and the operation of the wind turbines. These are issues, which may need further clarification in the subsequent planning process. The loss of production due to low temperature *per se* is likely to be marginal, about 0.5%.

3. The energy production estimates for the wind turbines in Nunavik are about 5% above what one would have found with proper correction for air density.

[1] Source 1.

4. The proposed wind-diesel systems use the IREQ-developed controller system for very high wind power penetration in isolated grids. This system is a unique Québec development, and is internationally recognised as being the currently most proven system available on the market.

5. The wind turbine used in the calculation examples is already operating in a presumably more difficult (icing) climate at Haeckel Hill, Yukon, although with blade heating installed.

6. The minimum load requirements for diesel engines in local generator sets are set very conservatively. There are possibilities of improving the economics of the projects, if this restriction can be eased somewhat. There are examples of upgrade technologies used elsewhere in the world, which apparently enable even standard diesel engines to run at lower loads.

7. The acquisition of new, smaller diesel engines in the course of the normal replacement cycle is another possibility of improving the economics of the project, as is also pointed out in the report.

8. There appears to be good possibilities of improving the economics of the projects by demand side management and proper technology application in the villages, enabling excess electricity to be used for deferrable power and optional power (e.g. replacing heating oil). This would mean that excess electricity could have a value between 8 and 28 cents/kWh instead of zero, as assumed in the report from IREQ/HQD.

9. Given that the inflexibility of exiting diesel gensets, both real and assumed, are a significant limitation with respect to the integration of wind power, the Régie is urged to defer – until absolutely necessary – the authorisation of any new diesel gensets until such time as the future use of the wind resource is better known. An obvious corollary of this recommendation is that concentrated effort be focussed on advancing the wind-diesel approach, especially in those communities now approaching the limits of their installed capacity. If, however, expansion of diesel capacity were found to be essential within a short time-frame, the Régie is recommended to favour the use of smaller and/or low-load equipment, i.e. to follow a »no regrets« policy with respect to future wind development.

10. While the IREQ/HQD report is very thorough and well done, it appears to overstate the costs and understate the benefits of wind development in Nunavik. It would be very useful to have an analysis with a wider energy system approach, where alternative uses of excess electricity (deferrable and optional) are considered as an alternative to dump loads.

With respect to potential use of wind-diesel systems in other autonomous grids, our findings are as follows :

1. A very preliminary analysis of wind conditions on Îles-de-la-Madeleine indicates that it may be economic to use wind power on the islands, particularly if Hydro-Québec Distribution itself undertakes the investments. It is highly recommended that HQD move expeditiously to evaluate the feasibility of introducing wind power in the electricity supply of the islands. It is recommended to coordinate the replacement or addition of new diesel generating units with the technical requirements of combined wind-diesel generation.

2. Finally, the Régie is urged to use an integrated resource planning approach in the autonomous grids, to ensure that the synergies resulting from coordinated supply- and demand-side policies are not lost.

1. Wind Resources near Villages in Nunavik

Wind turbines convert the kinetic (motion) energy of the wind to electricity. The energy content of the wind varies with the third power of the wind speed, thus electricity production from wind turbines is almost as sensitive to varying wind speeds. A 5% error in a mean wind speed estimate may thus cause a difference of some 16% in annual wind energy production.

Mean speeds vary substantially from site to site, and orography variations (terrain contours) and roughness variations (the wind shading effects from trees and other surface elements) can influence wind speeds significantly.

The report uses wind analyses produced in 1995 on the basis of maps and long-term meteorology station observations in each of the villages in Nunavik. The report rightly cautions against relying on these preliminary calculations for the actual siting of wind farms. Wind measurements for general meteorology purposes are usually insufficiently accurate for the purpose of locating wind farms, and it can be difficult to extrapolate these measurements to the ideal wind turbine locations (e.g. on top of rounded hills), if the surrounding terrain is complex, i.e. rugged.

It should be noted that the preliminary calculations in the report quite reasonably are given with an accuracy of ±0.5 m/s for the mean wind speed. In practice this means an uncertainty of ±10-15% on annual production.

1.1. Verification of the estimated wind speeds

There is a new way of verifying the reasonableness of the 1995 estimates in the report, however, namely by using the new mesoscale Canadian Wind Energy Atlas[2], which was published at the end of the year 2004. The atlas uses the latest state-of-the-art technology to obtain mean wind speeds at given heights above ground level at a scale of 5 km squares. Although this resolution is too poor to do siting of wind turbines it can give a very good indication of the likely wind speeds in the relevant areas.[3]

The wind speeds from the wind atlas given for the towns themselves at 50 m above ground level are given in table 1 below. Given the fact that the proposed sites are located in more ideal spots (in terms of wind speeds) than the village centres, the wind speeds on the corresponding turbine sites (in parentheses) look fairly probable.

[2] www.windatlas.ca

[3] Source 4, the Hélimax mesoscale wind study done for la Régie de l'énergie has a much better resolution of 1 km, but unfortunately it does not cover northern Québec.

If we use the actual location of the best Inukjuak site according to the map in the report, we obtain a mean wind speed 8.4 m/s at 50 m height from the corresponding location in the Canadian Wind Energy Atlas. This is extremely close to the estimate in the report, considering the relatively poor resolution of the new Canadian Wind Energy Atlas. In the case of the next two villages, the wind speeds on the Canadian Wind Energy Atlas are slightly higher than in the table in the proposed direction towards the proposed wind farm location.

Table 1
Mean wind speed estimates at 50 m height
in certain town centres (and corresponding wind turbine sites)

Village	Latitude Degrees	Longitude Degrees	Mean Wind Speed 50m height m/s
Inukjuak	58.4542	-78.1033	7.78 (8.82/8.27)
Kuujjuarapik	55.2833	-77.7499	7.72 (8.27)
Kangiqsualujjuaq	58.6911	-65.9542	7.61 (8.82)
Kangirsuk	60.0243	-70.0293	7.11 (8.82)
Kangiqsujuaq	61.5949	-71.948	6.99 (9.93)
Umiujaq	56.5519	-76.515	7.81 (12.13/8.82)

Source: Canadian Wind Energy Atlas & HQD report.
Note: The accuracy of wind speeds on wind turbines sites is ±0.5 m/s

1.2. Reliability of the Canadian Wind Energy Atlas

In order to verify whether the Canadian Wind Energy Atlas is a reliable guide to wind speeds in wind farms in general, we can use published data about the future wind farms on the Gaspé peninsula. Hydro-Québec Distribution and the wind developers have published the total estimated annual energy production figures, i.e. 3.2 TWh from the 660 GE 1.5 MW turbines.[4] Using the power curve specifications of the proposed turbine and assuming energy losses of 15%, we can calculate that the average wind speed at a hub height of 80m on the sites in Gaspésie should be around 8 m/s.[5]

If we find the simple average mean wind speed of the nearby village centres for the eight proposed locations in Nunavik in the Canadian Wind Energy Atlas at 80 m height, we obtain

[4] Hydro-Québec Distribution Press Release, 4 October 2004.

[5] The assumption of 15% energy losses corresponds to the assumptions of the report by Hélimax Énergie inc.: *Étude sur l'évaluation du potentiel éolien, de son prix de revient et des retombées économiques pouvant en découler au Québec.* (Régie de l'énergie, dossier R-3526-2004), Montréal, 2004. Similarly, we assume a statistical Rayleigh distribution of wind speeds, and a normal atmosphere at sea level with regard to air density. The calculation thus assumes a 15°C year round temperature, and does not account for the rather low air temperatures in the Gaspésie, which will increase wind energy production slightly (about 1%).

7.58 m/s, i.e. the sites should have about 0.5 m/s higher wind speeds than those indicated for the neighbouring village in the wind atlas.

Hence, indications are that the wind speed estimates presented in the report on wind-diesel appear plausible, and wind conditions on the proposed sites even seem to be better than on the Gaspé peninsula.

This may not be obvious to the reader by looking at the figures in Table 1, but it should be borne in mind, that these figures refer to wind speeds at 50 m height, whereas the Gaspésie estimates refer to wind speeds at 80 m height, which are significantly higher.[6] If we wish to compare with the Gaspésie, we should look at wind speeds in Nunavik at 80 m height, where the Canadian Wind Energy Atlas has 8.44, 8.83 and 8.26 m/s for the first three village locations.

On average we may thus have 12% higher wind speeds than in the Gaspésie near the future wind farms.

It should be kept in mind, however, that the economically optimal wind turbines are likely to have a fairly low hub height, probably around 50-65m instead of the 80 mentioned before, which in terms of annual energy production may largely cancel out the probable wind speed difference between the two sets of sites (Gaspé/Nunavik).[7]

2. Cold Climate Issues

In the IREQ/HQD report cold climate issues are mostly addressed in connection with the operating strategy of the wind-diesel system, and to a certain extent in relation to installation issues, but less so in relation to the operation of the wind turbines.

The report does not address the cold climate issues related to the proposed wind measurement campaign. It should be noted, that in general it is necessary to use heated wind measurement equipment in arctic climates, which almost invariably means that there has to be grid electricity available at the measurement site. This will have to be dealt with in the subsequent planning process.

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[6] Wind speeds are in general higher, the farther one moves from ground level. The difference depends on both relative height difference and surrounding terrain roughness.

[7] The primary reason for using a relatively low hub height may be the maximum size of the crane, which can economically be transported to the site in view of the rather limited number of turbines per site. These issues are routine parts of the optimisation of wind turbines for a given site.

2.1. Low Temperatures

2.1.1. The Effect of High Air Density is Overestimated

The report rightly notes that cold climate on the proposed sites implies a high air density with a somewhat larger energy production from the wind turbines. This effect is much less pronounced than anticipated in the report (about 50% of the effect estimated by IREQ), however, particularly for the active pitch-controlled machine used in the example calculations.[8]

Annexe N of the report obtains a production figure for Inukjuak of 7393 MWh/year.[9] A more realistic estimate would be 7011 GWh, or 5% less than in the report. The authors have apparently multiplied the wind turbine energy production at normal air density with a factor corresponding to the change in air density (on average an upward adjustment of some 10%). Since each wind turbine will not produce beyond its maximum rated power of 660 kW, however, this correction will overestimate the effect of high air density by about 100%. This is explained in more detail in appendix A of this paper.

2.1.2. Cold Weather Stoppages

The report does not address the fact that operating temperatures in Nunavik may occasionally drop somewhat below what is foreseen in standard cold climate packages for wind turbines.[10] This may obviously necessary to deal with in the next stage of the planning process.[11] To compare the difference in climate conditions from the Gaspé peninsula, the following table shows the number of days with temperatures below –30°C:

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[8] The authors may be excused for this problem, since most wind turbine calculation programmes are simplified, so that they do not account correctly for variations in air density. See the footnote in the last line of table 8 below for further documentation. It makes good sense to opt for active pitch or active stall controlled turbines in climates such as in Nunavik, as is done in the report. In areas where there is a high variation of air density stall-controlled machines risk either overloading the machine or under-production depending on how the angle of attack of the blades are adjusted.

[9] Using the same data as the authors of the report, the annual production at a standard air density of 1.225 kg/m^3 and 14% energy losses would be 6713 MWh/year. This implies that the production result has been corrected with a factor of 1.1013, equivalent to an air density of 1.3491 kg/m^3.

[10] Extreme cold climate packages are now available for operating temperatures down to -30°C. It should be noted, however, that survival temperature requirements may be down to -50°C.

[11] An exhaustive outline of the issues related to wind energy in cold climates may be found in T.Laakso, H.Holttinen, G.Ronsten, L.Tallhaug, R.Hobaty, I.Baring-Gould, A.Lacroix, E.Peltola, B.Tammelin: *State-of-the-art of wind energy in cold climates.* IEA, R&D Wind, Paris, April, 2003.

Table 2 Number of Days per Year With Minimum Temperatures Below -30°C (Canadian Climate Normals 1971-2000)													
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Inukjuak	14.4	16.0	11.1	0.26	0	0	0	0	0	0	0.14	4.8	46.7
Kuujjuarapik	14.0	13.4	8.0	0.24	0	0	0	0	0	0	0	4.2	39.9
Gaspé	0.81	0.38	0	0	0	0	0	0	0	0	0	0.04	1.2

Low operating temperatures *per se* are usually not a major problem for the operation of modern wind turbines, where cold climate packages generally include heated gearboxes, heated generators, heated electronics and heated hydraulics systems.[12] Composite materials generally have a longer useful life expectancy in cold climates, and there are standard methods (killed steel etc.) to deal with the behaviour of metals under cold climate conditions.

Operating temperatures down to -30°C may be satisfactory for the sites in Nunavik, however, if the number of effective production hours lost is sufficiently small, e.g. if extremely low temperatures tend to coincide with low wind speeds, which is often the case in arctic and sub-arctic areas.

A spot check of climate data for Inukjuak during winter 2004-2005 reveals that on a total of 40 days with temperatures below -30°C, 292 production hours would have been lost. The wind speed during those hours was on average only 54% of the mean site wind speed, however, and the wind turbines would only have been above cut-in wind speed during 152 hours with temperatures below -30°C. During those hours the turbines would have produced approximately 37 MWh, i.e. 0.5% of the average annual production would have been lost due to temperatures below -30°C.

2.2. Icing

The report does not mention icing conditions, which is a separate problem, distinct from the low temperature issue, and more difficult to deal with, in the sense that it requires heated wind turbine rotor blades, if icing is a frequent phenomenon.[13]

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[12] The energy spent for heating purposes is typically 2-3% of the total annual energy production by the turbine. If blade heating is also needed, this may double energy use.

[13] Icing alters the aerodynamic properties of the rotor blades, leading to lower production. Uneven icing may lead to increased mechanical loads on the entire turbine structure. Icing may also cause aerodynamic noise from the uneven surfaces of the rotor blades. Finally, icing may pose dangers from ice throw in the vicinity of a glazed turbine.

Generally speaking, climates tend to be drier as one moves closer to the polar areas. A key condition for rime formation is air, which is supersaturated with water droplets at temperatures around 0°C. Since icing problems usually appear at temperatures close to 0°C, the problem may thus not be relevant for the sites in question. But the relatively high altitude of some of the proposed sites in conjunction with frequent low hanging cloud cover in spring may give an additional reason to ask this question. The cloud base tends to adapt to the average height of the terrain, but not to the presence of isolated hilltops, which from a pure wind speed analysis are often indicated as the best sites. In northern Scandinavia icing problems occur most frequently in areas, which are elevated 100-200m above mean terrain altitude.[14]

No doubt Hydro-Québec with its experience with local power lines will have parts of the requisite knowledge in-house.

2.3. Freezing Precipitation

Freezing precipitation is a far less problematic issue than icing, since the duration of the frozen condition is fairly short. From available sources it appears that this is largely a problem in the Atlantic areas, and not in the far North.[15]

3. Operating Strategy – Technical Issues

3.1. Proven Controller System

The proposal to operate the wind-diesel systems with high wind penetration, i.e. to stop the diesel generators completely at high wind speeds is a rather unique feature of the control system developed by IREQ. Other researchers and technology developers have attempted to develop similar systems, but according to industry sources around the world, the IREQ system is currently the only one that has really shown that it works in practice for an extended period of time.[16]

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[14] Source 19, p. 21.

[15] R.A. Stuart and G.A. Isaac: *Freezing Precipitation in Canada*, Atmosphere-Ocean 37 (1) 1999, pp. 87-102.

[16] Based on interviews with researchers and arctic wind turbine operators at the Boreas VII Wind Energy in Cold Climates Conference, Saariselkä, Finland, March 2005 and interviews at Risoe National Laboratory, Roskilde, Denmark, February 2005.

The fact that the system has proven that it works at St. Paul Island in Alaska indicates that the basic technology concept has been proven, and that there is adequate Québec expertise available for other implementations.

In many ways a successful demonstration effect from the future energy supply systems in Nunavik could be a stepping-stone towards exporting this rather unique system to elsewhere in the world.

3.2. Excess Electrical Energy

The proposed wind-diesel system relies on stopping the diesel gensets whenever wind energy production exceeds a certain safety margin compared to actual or forecast demand, e.g. 110% in the base scenario. This implies that there will be excess electricity production compared to demand most of the time.

Possible uses of this excess electricity, and their implication for project economics, are discussed in section 4.2, below.

3.3. Minimum Load Requirements for Diesel Engines

The operating costs of the proposed wind-diesel system are influenced heavily by the HQD requirement that diesel engines should run at a minimum load of at least 50% of rated power, regardless of the need for electricity. This need is mostly related to the fact that low operating temperatures in diesel engines may cause build-up of slag substances inside the cylinders of the engine.[17]

In Europe, Australia and elsewhere, however, it appears that certain wind-diesel system developers are able to run conventional diesel engines at lower power loads by using different heating methods, e.g. recycling exhaust and using excess electricity to provide extra heat for the engine cylinders. It also appears that genset manufacturers may be willing to supply low-load diesel engines with their gensets.[18] [19]The report does mention the possibility of reviewing this 50% criterion (p. 19), which would clearly improve the economics of the projects.

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[17] The damage from running engines at low load is generally not permanent. The engines can be cleaned by returning them to full load and/or by employing certain other operational techniques.

[18] Interview with Per Lundsager, Risoe National Laboratory, Denmark, February 2005.

[19] Interestingly, RetScreen, the renewable energy calculation system provided Natural Resources Canada assumes a minimum load of 30% on diesel gensets in its calculation example for stand-alone grids, source: www.retscreen.net. The wind-diesel system on Miquelon Island requires a minimum load of 35-50% on the diesel gensets, source 15.

Another potential cost reduction measure, which is mentioned in the report (p. 19) is the possibility of acquiring smaller diesel units, particularly in the course of normal retirement of aged gensets. This strategy can clearly be used to optimise the wind-diesel systems further in the course of time.

In Appendix F of the report, however, it is assumed that the replacement policy for diesel units remains unchanged, which means that e.g. in the case of Inukjuak the smaller gensets of 400, 600 and 855 kW are scheduled to be replaced by 1135-1505 kW units in 2006 and 2013. This clearly deteriorates the economics of the projects.

It would seem obvious to delay the replacement of some of the gensets while actual feasibility studies and wind measurements are being completed for the most promising locations – with a view to optimise the combined system of wind and diesel generators. The optimal project size, i.e. the optimal number of wind turbines for each village system will clearly be influenced by the decisions about genset replacement and vice versa.

These strategies are thus examples of how it is necessary to use an integrated resource planning approach once a new technology such as wind-diesel is introduced. The next session deals further with this issue, where demand side management is discussed.

4. Operating Strategy – Economic Issues

The report assumes in its base scenario that excess electrical energy has no value, and that it is burned in a resistive dump load. It is mentioned, however, that excess energy may be usefully employed for purposes where it can be interrupted at no notice.

4.1. Marginal Generation (Fuel) Cost Estimate

Since the generating efficiency of the diesel units (including electricity distribution losses) typically is around 33%, about 3 kWh of thermal energy from diesel is spent in order to deliver 1 kWh of electrical energy at the point of use. With a fuel cost of 0.705 CAD/l in the base scenario,[20] an electricity production of on average 3.67 kWh/l[21] and 10% grid losses,[22] this implies a marginal fuel cost of about 0.21 CAD/kWh in the present system.[23]

It is clear that average generating and distribution costs per kWh of electricity are far higher than this figure indicates, hence it would be economically counterproductive to encourage electricity consumers to consume more electricity, even it occasionally will become a waste product in the wind-diesel system. HQD already pursues a number of demand side management programmes in the autonomous grids to encourage consumers to save electricity, (e.g. dissuasive tariffs) and it seems sensible to continue that policy.[24]

4.2. Value of Excess Energy Estimates

Rather than wasting the excess energy, it can clearly be put to use in the villages in Nunavik, without leading to increased base load demand. There are at least two distinct ways this excess electricity can be put to use: by replacing electricity used for deferrable loads, and by replacing fossil-fuel heating (optional power).

4.2.1. Deferrable Power – Replacing Electricity

Given the large conversion and distribution losses for electricity, it will be most economic to replace electrical energy consumption, which is *deferrable* in time, e.g. for applications like water storage pumping etc. Each of these applications should have a reasonable volume, which can bear the excess cost of separately metering this use and of installing control systems, which can automatically remotely signal use of »waste electricity«. To find such applications requires a more thorough revision of the energy use in the villages concerned.

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[20] This price is used to make the estimates consistent with the IREQ/HQD report. At the time of writing prices are somewhat higher in Nunavik, cf. reference 10.

[21] Reference HQD reference 7 p. 32 gives a production of 3.84 kWh/l for Inukjuak, 3.62 kWh/l for Kuujjuarapik, 3.55 kWh/l for Kangiqsualujjuaq.

[22] The reason to include grid losses is that in this section we discuss the opportunity to use free excess electricity to replace diesel-generated electricity. Obviously the amount of available excess electricity should likewise be reduced by appropriate grid losses.

[23] Fuel consumption from the HQD Report, figure 6, p. 17 and Annexe G. Diesel fuel has a density of around 845 kg/m^3 and an energy content of 42.7 GJ per metric tonne, cf. www.windpower.org/en/stat/unitsenv.htm#ec

[24] Annexe B of HQD-4, Document 1, for the case R-3550-2004: *Les besoins et les équipements de production en 2003*.

The value of deferred electricity use is at least equivalent to the fuel savings mentioned above, i.e. 0.21 CAD/kWh.[25] Another guideline to assess the actual marginal cost of generation could be the 0.2768 CAD/kWh charged to residential HQD costumers for their second tranche of electricity in Nunavik.[26]

4.2.2. Optional Power – Replacing Fossil-Fuel Heating

The second best choice may be to use excess electricity for heating purposes, particularly in larger building units where the excess cost of metering and remote control will be limited. Installing electric heating in a classical water-based central heating system is simple and inexpensive.

With a cost of heating oil of about 0.70 CAD/litre in Nunavik[27], and assuming a fairly high 87% average efficiency of oil burning heating units, the fuel savings value of 1 kWh of heat is approximately 0.08 CAD/kWh.[28]

The fact that heat is in demand during all months of the year is illustrated by the following table[29] of the number of degree-days, where Montreal is inserted for comparison.

Table 3
Heat Degree Days (Climate Normals 1971-2000)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Inukjuak	1327	1238	1215	891	618	402	268	273	386	567	762	1144	9090
Kuujjuarapik	1286	1166	1095	766	516	335	235	211	317	496	689	1059	8171
Montreal	886	762	637	376	168	48	10	28	137	325	509	769	4654

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[25] Strictly speaking, variable operating costs for maintenance etc. should be added to this figure, which thus represents a lower bound for the costs. Since the introduction of wind into the diesel system will imply a different loading patters on the diesel units, the net effect on operating costs require further study, hence the estimate used in this text is quite cautious.

[26] Cf. reply to question 6.1 p. 14 from la Régie de l'énergie published in source 12.

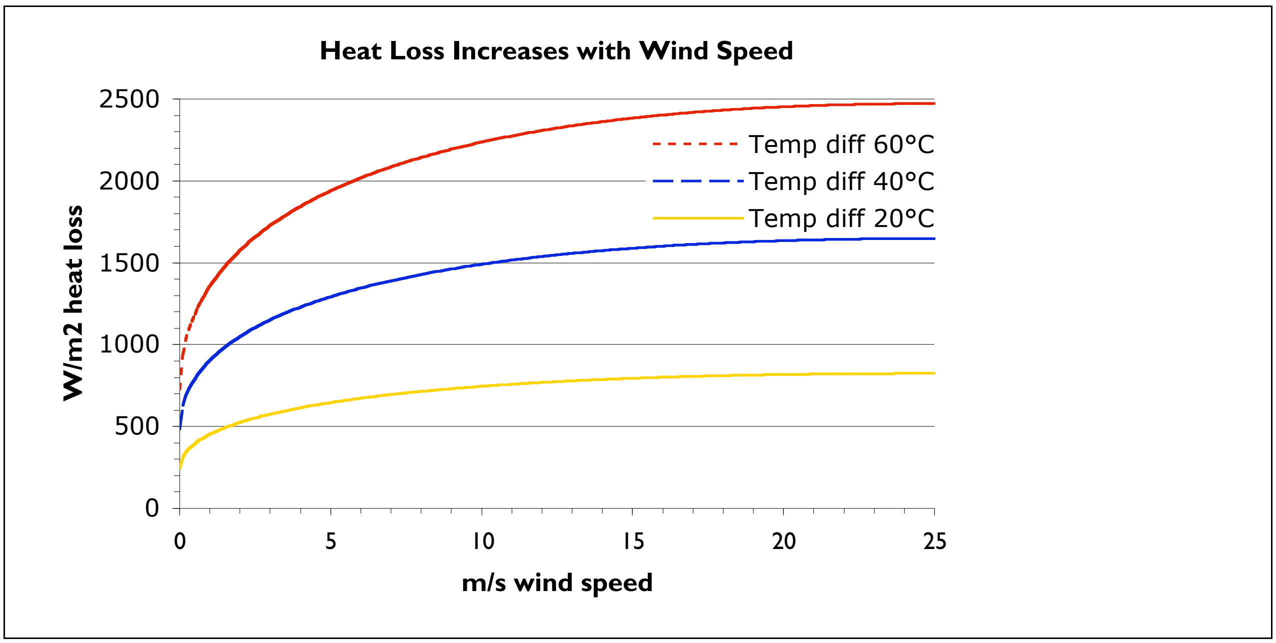
[27] The cost of heating oil sold retail in Nunavik may be some 20% higher than these figures indicate, cf. http://www.retscreen.net/ang/412/retscreen/retscreen_database_e.html. From a socioeconomic point of view it is correct to use the cost without taxes or subsidies for both the diesel used for the gensets and the heating oil used for residences.

[28] The density of light heating oil is assumed to be 845 kg/m3 and the energy content 42.7 GJ per metric tonne. The energy content of heating oil is thus 10.02 kWh/l before conversion losses.

[29] Measured relative to 18°C, which is also the standard now used by Hydro-Québec Distribution. Source: Natural Resources Canada, http://www.climate.weatheroffice.ec.gc.ca

Another interesting aspect of using wind energy for heating purposes is that heat losses due to convection[30] just like the energy production from wind turbines vary with the wind speed, as shown in the next graph:[31] It is not possible to use this graph directly to estimate energy losses from buildings, since this also requires knowledge about building geometry, insulation etc.

To compare, the next graph shows how the power output in kW varies with the wind speed for the turbine used as an example in the IREQ/HQD report.



[30] The phenomenon is better known in popular terms as *wind chill*. In Canada wind chill is calculated using Siple's formula (mentioned in the next footnote), where the skin surface temperature is set to 33°C.

[31] Siple's formula (when translated to the metric system):

$$H = (12.1452 + 16.6222\, v^{0.5} - 1.1622\, v)\, d$$

H is the heat loss in W/m^2, v is the wind speed in m/s and d is the temperature difference between the airflow and the surface in °C.

4.3. Conclusions for Optimal Energy Use: Simultaneous Optimisation of Supply and Demand Needed

Wind energy output in the Nunavik area will generally be very well correlated with electricity and heat demand, since there is much more wind in winter than in summer and more wind during daytime than at night.

The report shows that the net present value is very sensitive to the assumptions about the value of excess energy, and that the optimal number of wind turbines per site is also very sensitive to the value of excess energy.

With increasing wind penetration in the system, however, there may possibly be times when current heat demand is smaller than wind energy production. In this case, it may be economic to introduce thermal heat storage systems to optimise the combined wind-diesel supply and demand system.[32] Otherwise it may be optimal to close down some of the wind turbines, as mentioned in the report.

In any case, as demonstrated by this example, proper optimisation of the wind-diesel energy supply system requires a simultaneous treatment of the demand side of the energy system, including the need for space heating.

It should be noted that the benefits of alternative uses of excess electricity would accrue to third parties who can use the energy, rather than to HQD.

If HQD were to recover the value of excess electricity used for special purposes this would require some modification of the present tariff policy (in addition to separate metering). The basic idea would be to use tariffs close to avoided costs for the energy user. Likewise, there would be savings on the present HQD demand side management policy of subsidizing fuel costs in Nunavik.

In case the costs of metering and administering such schemes would be prohibitive, it would be in accordance with normal principles of integrated resource planning to let these externalities be taken into account in the decision on whether to or not to proceed with the project.

As illustrated previously, the optimal future diesel configuration will be affected by the change in energy supply system. Similarly, even energy/economically optimal building construction will be affected (e.g. use of building materials with higher specific heat capacity, use of floor heating systems etc. to provide decentralised heat storage).

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[32] See e.g. http://www.grotonsd.com/city/Heat_Storage_Units.htm for a number of commercially available systems.

The model used in the HQD/IREQ report provides an excellent basis for extending the analysis to the demand side of the energy systems as outlined here. The net result of this analysis will be that the proposed projects would be more profitable (and more energy-saving) than in the base scenario in the report.

With a nonzero value of excess electricity the IREQ/HQD report demonstrates that the number of turbines per site and the number of sites that become economic will increase.

5. Investment and Operating Budget

5.1. Investment budget

An investment budget example is presented on p. 27 of the IREQ/HQD report.

At first sight the figures appear very large, with an investment of about 4 MCAD/MW.

Total investment per MW installed power in the first HQD tender for 1,000 MW of wind power is substantially lower, i.e. 1.5 MCAD/MW, but it should be kept in mind that the collection grid for the wind farm transformers, substations and grid reinforcement are not included. Total investment including grid for the 1,000 MW tender is estimated by HQD to be 1.93 MCAD/MW.[33]

If one looks at the experience with other projects in arctic and subarctic areas, however, the figures do not appear completely unreasonable. A 1-turbine 660 kW project in Yukon (apparently using an existing power line) cost 2 MCAD in 2003.

The most surprising figure in the report is the price of turbines, which is stated as being 3,093,030 CAD for three Vestas V47-660 wind turbines before transportation costs, i.e. a price per turbine of 1 MCAD per turbine fob Montreal or 1.56 MCAD/MW.

An American feasibility study for a small wind project in Marblehead, Massachusetts[34] has a price of 487,500 USD per V47 turbine with a 65 m tower = 660,953 CAD per turbine in 2003.[35] If we compensate for the fact that the European currencies have strengthened and we add 2.5% for inflation until 2004, we obtain 705,000 CAD, i.e. 2.1 million.

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[33] Source 3.

[34] Source 11.

[35] Exchange rate 1.3558 CAD/USD as of 4 July 2003.

It is difficult to explain this discrepancy of almost 50% of the turbine price compared with case from Massachusetts, but the North American wind turbine market is overheated in 2005 due to the expiry of the American PTC credit system. A competitive tender may give a lower turbine price, although turbine manufacturers tend to differentiate prices strongly between small and large orders.

One of the most expensive aspects of erecting wind turbines in remote areas is renting and transporting sufficiently large cranes to the sites. This issue is not discussed in the IREQ/HQD report, but it should be mentioned that there may be cost savings from using self-erecting tower structures. Apparently only one turbine manufacturer currently has a certified system of this type,[36] but other self-erecting structures have been at the development stage for some years.[37]

All in all, it appears the investment budgeting is on the safe side with a considerable safety margin.

5.2. Operating Budget

The operating budget likewise appears to be on the safe side with an estimated cost of 0.03 CAD/kWh, which is more than 100% above the norm in the industry for normal sites.

The remoteness of the sites with the high transportation costs – and in particular the difficult accessibility of the sites for doing, say a replacement of a heavy, major component like a gearbox or a generator requiring craning will justify part of this safety margin.

In addition, if we have to wait on average 5 months for the replacement of a large component, with a probability around 10% for this happening in any year, this would mean a loss of availability of some 5%.

Recalculating the budget example for Inukjuak in the report shows that this loss of production would have an impact of 0.005 CAD/kWh on the cost of electricity from the turbine, or in other terms justify 0.5 cents of the 3 cents/kWh allocated to operation and maintenance costs.

Wind turbines generally require little maintenance, but in remote locations such as Nunavik, it will usually be cost effective to have local staff do minor maintenance work. The personnel who presently operate the diesel units can no doubt be trained to work with the wind turbines as well.

All in all, the operating budget in the report appears quite prudent.

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[36] Enercon.

[37] E.g. Valmont.

5.3. Cost of Wind Electricity

The implicit average cost of wind electricity calculated from the very cautious budget example in the report is around 12 cents/kWh assuming a *real* rate of return of 5.2% on the project, as is done in the report. It should be noted, however, that the avoided cost in the electricity systems at Nunavik are at least about twice this level

5.4. Conclusions

While the IREQ/HQD report is very thorough and well done, it appears to overstate the costs and understate the benefits of wind development in Nunavik. It would be very useful to have an analysis with a wider energy system approach, where alternative uses of excess electricity (deferrable and optional) are considered as an alternative to dump loads.

Having contacted key manufacturers it clearly appears that very small orders for turbines are priced quite highly.

6. Wind Development on the Îles-de-la-Madeleine

It would seem that other parts of the autonomous grid of Hydro-Québec Distribution would possibly be suited for wind power, in view of the fact that wind power development will be less costly in easily accessible areas such as the Îles-de-la-Madeleine and the Île d'Anticosti, where wind resources are known to be plentiful.

Given the known high wind speeds on the islands, it would seem surprising if Hydro-Québec Distribution had not already done studies on introducing wind energy in these areas. Hydro-Québec also ran a test station for wind turbines in the late 1970s on the islands. However, HQD has affirmed that no wind energy feasibility studies have been developed for areas outside Nunavik.[38] It appears, however, that Genivar carried out such a study in 1993.[39]

The subsequent analyses in this study are carried out purely on a fuel-saving basis, like the analyses for Nunavik.

6.1. Present Generation Costs on Alternative Sites

In order to do a preliminary assessment of these possibilities, the average fuel costs per kWh in these locations have to be calculated. This is done in table 4 below:

[38] HQD-5 document 7, R. 25.2

[39] http://www.genivar.com/fr/realisations/realisation.asp?noRealisations=618&noMarche=23

Table 4
Average Fuel Costs per kWh in Selected Autonomous Grids[40]

Location	**No. of units**	**Capacity kW**	Generation kWh/l	Fuel type	Est. price CAD/l[41]	Cost CAD/kWh
Cap-aux-Meules	6	6 x 11 200	4.67	97 heavy	0.292	0,0625
Île-d'Entrée	4	3 x 290, 1 x 320	3.23	light #2	0.535	0,1656
Port-Menier	3	1 x 1135, 2 x 855	3.59	light #2	0.535	0,1490

Once again, like in the analysis of Nunavik sites the potential cost savings are probably somewhat higher than indicated by the pure average fuel cost.

The reason why fuel costs are relatively low for the Cap-aux-Meules power plant is that it uses heavy fuel oil in diesel engines of the same type, which are used in ships.

6.2. Wind Resources on Alternative Sites

Îles-de-la-Madeleine and Île-d'Anticosti are two of the windiest locations in Québec, and in a class among the best wind energy sites in the world. For all practical purposes wind turbines located in these areas will experience offshore wind conditions, i.e. high wind speeds and low turbulence when placed in coastal areas. Low turbulence means that there will be lower fatigue loads on the wind turbine structures, and therefore possibly lower maintenance costs and longer technical lifetime of the turbines.

The wind speeds according to the Canadian Wind Energy Atlas for the same locations are shown in table 5:

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[40] The calculations are based on HQD source 14 p.32.

[41] These are actually prices without transportation costs in March 2005, source reference 10.

Table 5
Mean wind speed estimates at 50 m height[42]

Location	Latitude	Longitude	Mean speed 50 m height m/s	Mean speed 80 m height m/s
Cap-aux-Meules	47.3777	-61.8716	9.20[43]	10.69
Île-d'Entrée	47.2673	-61.7035	9.33[44]	10.59
Port-Menier	49.8188	-64.3527	6.80	7.93
Wemotaci	47.916	-73,794	4.67	5.66
Opitciwan	48.66382	-74.92273	7.80	7.80
Typical mean wind speeds at hub height in Gaspésie[45]				8

In should be kept in mind that proper siting usually means higher wind speeds than indicated by the relatively low-resolution Canadian wind atlas, hence the wind speed indicated for the Île d'Anticosti is probably considerably underestimated. For the Îles-de-la-Madeleine this effect is less probable.[46]

6.3. Île-d'Entrée, Port-Menier

These site can be analysed using the same analysis tool as was used by IREQ/HQD for the sites in Nunavik, There is reason to believe that both installation costs and operation and maintenance costs will be considerably lower than on sites in Nunavik.

6.4. Cap-aux-Meules

There are good reasons to believe that there are low development costs for a wind farm at or near Cap-aux-Meules.

Firstly, the wind climate on the site has been thoroughly analysed for the Canadian wind energy programme in the 1970s, where it was one of the pioneering sites for testing vertical axis wind turbines.

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[42] Source 2.

[43] The wind speed difference between 50m height and 80m appear to be far too large for a coastal location, where one would expect a difference of less than 5%, but the wind speeds indicated by the wind atlas for this location are very large in any case.

[44] See previous note.

[45] Calculated indirectly from information published by HQD shown in table 6 below.

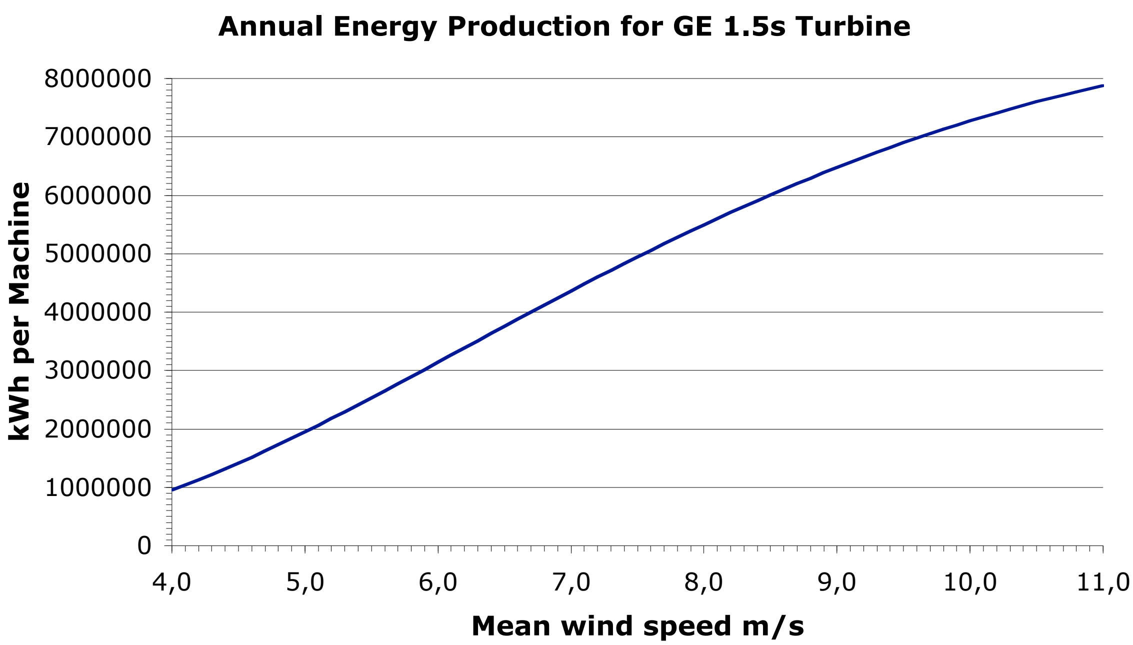
[46] There is practically low sea surface roughness of the surroundings everywhere.

Secondly, if a wind farm can be placed near Cap-aux-Meules, the grid connection costs will be very low due to the presence of the local 68 MW power plant.

The ideal size of a wind plant in this location depends to a large extent on the load pattern of the consumers and the geometry of the grid in relation to available wind turbine sites. A 20-25 MW project, e.g. 7-8 turbines of 3 MW size could provide about half the annual electrical energy needs of the island. This project size is about half of the smallest winning project in the HQD 1,000 MW tender (Montagne-Sèche 58,5 MW).[47]

6.4.1. Estimated Biddable Electricity Price for a Wind Farm at Cap-aux-Meules

The very high wind speeds on the Îles-de-la-Madeleine given in table 5 above imply an annual energy production of 31% more than what is likely to be typically found in the Gaspésie, if we assume a mean wind speed of 10.5 m/s instead of 8 m/s. The graph below shows how the annual production from a GE 1.5s turbine varies with the mean wind speed at hub height.



47 The original project at Murdochville (Mount Miller, 54 MW) has a power purchasing contract from HQP with an electricity price around 6 cents/kWh indexed.

In order to determine the likely generating costs using wind energy, this analysis takes its point of departure in the published data for the recent 1,000 MW tender for wind power in Québec.[48] This neither implies a suggestion on the form of ownership nor the choice of turbine technology for a potential wind farm on Îles-de-la-Madeleine, but is only intended to estimate the likely price/cost scenario in a competitive environment.

The published data for the HQD 1,000 MW tender are given in the left column of table 6 below, whereas a hypothetical wind farm on the Îles-de-la-Madeleine is shown in the right column.

Using the published data one can calculate an estimate of the *real* rate of return on the investments in the wind farms in the tender. Using that estimate and assuming that the cost structure and profitability requirements would be the same for a project on the Îles-de-la-Madeleine, and using the higher wind speeds as an input, we obtain *a biddable electricity price close to 5 cents/kWh*.[49]

When reading the table, some caveats should be kept in mind:

1. The number of significant digits in the table is not an indication of the accuracy of the estimates for neither profitability nor average wind speeds.

2. The figures for average profitability are based on the figures published by HQD in its press release about the 1,000 MW tender. Since the tendering conditions have complex indexation formulae, it is simply assumed that both electricity prices and investments follow the general price level. Operation and maintenance costs are assumed to be 1.2 cents/kWh indexed, which is a conventional calculation basis in the wind industry.

3. Uncertainty on the calculated mean wind speed for all sites may be some ±0.5 m/s, and there may be larger variations between individual sites.

It may be argued that development costs will be higher on the Îles-de-la-Madeleine than for the large projects in Gaspésie, and that different turbine specifications will be required for the very high wind speed sites on the islands.

If development costs are higher, the same calculations can be used to show that if the electricity price remains 6.2 (2004) cents/kWh indexed, the same real gross rate of profitability can be achieved for a project where investments are 1.967 MCAD/MW, or 31% higher than in the past

[48] Broadly speaking the data for the tender (both investments and electricity price) are very similar to what has been published for the Murdochville projects.

[49] The reader may verify these calculations and test alternative hypotheses using the wind energy calculator and wind energy economics calculator in the Guided Tour on the web site www.windpower.org (developed by the author).

1,000 MW tender. (Since energy output is estimated to be 31% higher than in Gaspésie, this result is hardly surprising).

The calculations give a very high capacity factor of almost 50% for the wind turbines used in the example.[50] This is related to the fact that the turbine in question has a relatively high ratio of swept rotor surface area relative to the rated power of the generator. This configuration may not be economically ideal in a high-wind area, since the turbine will relatively often be running at the maximum rated capacity of the generator.

[50] The annual energy production per MW installed is 4.358 GWh.

Table 6 HQD 1,000 MW Wind Power Tender 2003/2004 and Îles-de-la-Madeleine Case	
Published Information	**Assumptions for Cap-aux-Meules**
Investment: 1.5 MCAD/MW installed[51] Energy production: 3.323 GWh/MW/year Electricity price (2004) 6.2 cents/kWh indexed Power purchasing contract period 20 years Grid costs 0.434 MCAD/MW (Does not influence calculation below) Electricity tax 3% Turbines: GE 1.5sle or 1.5s	Same, (sensitivity calculated below) (Calculated below) (Bid price calculated below) Same Grid costs possibly 0.150-0.200 MCAD/MW (Does not influence calculation below) Same GE 1.5s[52]
Assumptions	**Other Assumptions**
Operation & Maintenance 1.2 cents/kWh indexed[53] Energy losses 14%[54] Turbine: GE 1.5sle (Influences only estimated wind speed, but neither annual production nor profitability estimate). Hub height does not influence calculations below Rayleigh wind distribution Air density 1.225 kg/m^3 (Does not influence profitability calculation, since annual energy production is given)	Same Same Turbine: GE 1.5s 80m hub height Same Same
Calculated Data	**Other Assumptions**
Implicit wind speed = 7.93 m/s at hub height[55] Implicit gross rate of profit after turnover tax, but before financing & income tax = 8.62% p.a.[56]	Wind speed 10.5 m/s at hub height at Cap-aux-Meules (Canadian Wind Energy Atlas) Same

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[51] It could be argued that the investment should be indexed like the electricity price, and hence be some 6% lower in 2004. This effect is somewhat uncertain, however, since the price of wind turbines over time may be expected to decline slightly compared to the general price level.

[52] The GE 1.5sle model is suited for low and medium wind speed sites.

[53] 1 US cent/kWh for O&M is a common standard in the wind industry. Includes land rent.

[54] Same percentage as that used by IREQ/HQD in source 1.

[55] Calculated on the basis of the published energy production, the published power curve for the GE 1.5sle turbine and assuming a Rayleigh wind distribution, an air density of 1.225 kg/m^3 and 14% energy losses. If the GE 1.5s machine is used instead, the result is 8.28 m/s mean wind speed.

	Calculated Data for Cap-aux-Meules
	Energy production = 4.358 GWh/MW/year Biddable electricity price (2004) for unchanged profitability = **5.02 cents/kWh indexed**

But even other turbine models show similar results, as demonstrated in table 7. The table includes different wind speeds corresponding to lower hub heights. (The table does not indicate whether one turbine is preferable to another. That will depend on turbine prices, their suitability for the high wind speed regime and electro-technical considerations about the grid and the varying load on the grid.)

If the wind speed of 10.5 m/s is valid for 80 m height, then the next two rows will correspond to 40 and 25 m height at true offshore conditions.[57]

Table 7
Annual Wind Energy Production per MW Installed Power at High Wind Speeds

Turbine[58]	GE 1.5s	Vestas V80/1.8MW	Vestas V90/3MW	Vestas V47 660/200kW
Generator	1.5 MW	1.8 MW	3 MW	0,660 MW
Rotor diameter	70.5 m	80 m	90 m	47 m
Annual energy production per MW installed @ 10.5 m/s mean wind speed, 14% energy losses (Capacity factor) [kWh/m^2 rotor area]	4.358 GWh (50%) [1675]	4.445 GWh (51%) [1595]	3.996 GWh (46%) [1884]	4.284 GWh (49%) [1630]
Ibid. 10 m/s	4.171 GWh (48%) [1603]	4.270 GWh (49%) [1529]	3.802 GWh (43%) [1793]	4.100 GWh (47%) [1560]
Ibid. 9.5 m/s	3.956 GWh (45%) [1520]	4.058 GWh (46%) [1453]	3.582 GWh (41%) [1689]	3.888 GWh (44%) [1479]

56 Calculated as a 20-year real annuity on the basis of the published annual energy production of 3.2 TWh/990MW, published investment of 1.5 MCAD/MW, an electricity price of 0.062 CAD/kWh (2004) indexed, 3% turnover tax and 1.2 cent/kWh indexed in O&M costs.

57 Roughness class 0 = roughness length of 0.0002 m, assuming logarithmic wind shear. 25 m height is of course unrealistic with the rotor diameters involved. The purpose of the table is just to demonstrate the sensitivity of energy production to different mean wind speeds.

58 These are general examples of turbines on the market, which are known to be in operation in wind climates similar to the Îles-de-la-Madeleine.

As can be seen from the figures, lower hub heights have a very limited influence on the annual energy production, since there is little difference in wind speeds with varying height, when turbines are facing a smooth sea surface (low wind shear).

Capacity factors i.e. annual energy production per MW installed power for each machine are given in parentheses, but capacity factors are actually quite misleading, if used to judge the efficiency of wind turbines.

The key component of a wind turbine is not the generator, but the swept rotor area, where the energy is harvested. The required strength and the cost of building the whole structure are much more related to the area of the rotor rather than the size of the generator. In this case the most efficient machine is clearly the Vestas 3 MW turbine, which is 10-15% more efficient per square metre rotor area than the other machines – despite the fact that it has the lowest capacity factor.

In the final analysis what matters are not these frequently discussed statistics, but is the price per kWh generated.

6.4.2. Sensitivity Analysis of Electricity Price/Cost

Table 8 shows how sensitive the electricity price is to various changes in parameters given an unchanged gross real rate of return for the developer. The table has been calculated using the same wind turbine, which was used in table 6, i.e. a GE 1.5s machine.

Table 8
Sensitivity Analysis on Biddable Electricity Prices @ 8.62% Real Rate of Return

Item	Change	Electricity price cents/kWh	Difference cents/kWh
Basic estimate		**5.02**	
10% higher investment	1.650 MCAD/MW inst. of 1.5	5.40	+0.38
33.3% higher investment	2 MCAD/MW inst. of 1.5	6.28	+1.26
0.5 m/s higher wind speed	11 m/s instead of 10.5	4.88	-0,14
0.5 m/s lower wind speed	10 m/s instead of 10.5	5.19	+0.17
60m hub height inst. of 80m	10.27 m/s instead of 10.5	5.09	+0.07
50% higher O&M costs	1.8 cents/kWh instead of 1.5	5.64	+0.62
2% point higher energy loss	16% instead of 14%	5,11	+0.09
5°C average operating temperature inst. of 15°C[59]	Air density 3.67% lower, i.e. 1.027 kg/m^3 inst. of 1.0225	4.99	-0.03

[59] The annual average air temperature at Gaspé is 2.9°C, which means the air density is about 4% higher than the standard wind turbine measurement conditions at 15°C. Contrary to popular belief among engineers this does *not* mean that annual energy production will increase proportionately. The increase is only about 0.96% in this case. The reason is that active pitch- or active stall-controlled machines always adjust the blade angle of attack automatically in accordance with current air density. This calculation was done using the Vestas V80 1.8 MW machine, since the appropriate data were not available for the GE turbine. The same percentage change was applied to the figures for the GE machine. Source 16.

6.4.3. Wind Farm Built by Hydro-Québec Distribution

If we assume a gross *real* rate of return on investment of 5.2% (the *real* rate of return required by Hydro-Québec Distribution for its own investments) instead of the 8.62% used above, we obtain a *cost of electricity of 4.13 cents/kWh* in the basic case with 10.5 m/s mean wind speed at hub height. This assumes that HQD has the same efficiency as developers in a tendering process. We assume that Hydro-Québec Distribution also pays the 3% electricity turnover tax.

Table 9
Sensitivity Analysis on Electricity Cost @ 5.2% Real Rate of Return

Item	**Change**	**Electricity price cents/kWh**	**Difference cents/kWh**
Basic estimate		**4.13**	
10% higher investment	1.650 MCAD/MW inst. of 1.5	4.42	+0.29
33.3% higher investment	2 MCAD inst. of 1.5	5.10	+0.97
0.5 m/s higher wind speed	11 m/s instead of 10.5	4.03	-0,10
0.5 m/s lower wind speed	10 m/s instead of 10.5	4,26	+0.13
60m hub height inst. of 80m	10.27 m/s instead of 10.5	4.19	+0.06
50% higher O&M costs	1.8 cents/kWh instead of 1.5	4.75	+0.62
2% point higher energy loss	16% instead of 14%	4.20	+0.07
5°C average operating temperature inst. of 15°C[60]	Air density 3.67% lower, i.e. 1.027 kg/m^3 inst. of 1.0225	4.11	-0.02

6.4.4. Environmental Benefits from the Wind Project

It should be kept in mind that a wind energy project in the autonomous diesel grids of Hydro-Québec will displace domestic Québec emissions from the burning of fossil fuels, as it was also mentioned in the IREQ/HQD report.

In the case of Cap-aux-meules, where power generation uses heavy fuel oil, the CO_2 emissions can be calculated from table 4. We obtain an emission of 0.634 kg CO_2/kWh,[61] which is about

[60] The annual average air temperature at Gaspé is 2.9°C, which means the air density is about 4% higher than the standard wind turbine measurement conditions at 15°C. Contrary to popular belief among engineers this does *not* mean that annual energy production will increase proportionately. The increase is only about 1% in this case. The reason is that active pitch- or active stall-controlled machines always adjust the angle of attack automatically in accordance with current air density. This calculation was done using the Vestas V80 1.8 MW machine, since the appropriate data were not available for the GE turbine. The same percentage change was applied to the figures for the GE machine. Source 16.

[61] Assuming a density of heavy fuel of 0.94 kg/l and 3.15 kg CO_2/kg fuel.

75% of the emissions from modern coal-fired power plant. These benefits are not included in the above calculations.

In addition, the annual emissions of NO_X and SO_2 from heavy fuel oil are quite considerable. According to NPRI information from Hydro-Québec, emissions in 2002 were 4,242.2 metric tonnes of NO_X and 564.7 tonnes of SO_2.[62]

6.5. Conclusions

According to HQD-4, document 1, section 2.1.3, new generating capacity will be needed in the Îles-de-la-Madeleine starting in 2011.

It is recommended to coordinate the replacement or addition of new diesel gensets on the Îles-de-la-Madeleine with the technical requirements of combined wind-diesel generation.

It is highly recommended that HQD move expeditiously to evaluate the feasibility of introducing wind power in the electricity supply system of the Îles-de-la-Madeleine.

[62] Source: www.cec.org/files/PDF/POLLUTANTS/ Canada_2002_metric_en.xls

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Appendix A
Wind Turbine Power Curve Adjustment for Air Density

The IREQ/HQD report uses the classical adjustment method for power curves for wind turbines, which is strictly speaking only valid for passive stall-controlled wind turbines. The method consists of multiplying the power output of the wind turbines at all wind speeds with a factor corresponding to the air density divided by a standard air density at 15°C of 1.225 kg/m^3. This method works well for passive stall controlled machines, since airfoil lift is proportional to air density. The implicit power curve used by IREQ/HQD is shown in the last column of the table below.

Active pitch (or stall) controlled turbines will work differently, however, since the pitch mechanism will adjust automatically with changing air density, and will ensure that power production does not exceed the rated power of the generator.

Table A
Power Curve for Vestas V47, 660 kW 60 Hz Wind Turbine at Different Air Densities

Air density kg/m^3	1.060	1.090	1.120	1.150	1.180	1.210	**1.225**	1.240	1.270	1.300 *)	1.330 *)	**1.349** *)	1.360 *)	1.390 *)	Multiplied **)
m/s	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW
4	0.6	1.1	1.5	1.9	2.3	2.7	**2.9**	3.1	3.5	3.9	4.3	**4.6**	4.7	5.1	3.2
5	36.2	37.5	38.9	40.3	41.7	43.1	**43.8**	44.5	45.8	47.2	48.6	**49.5**	50.0	51.4	48.2
6	81.8	84.5	87.2	89.9	92.6	95.4	**96.7**	98.1	101	103.8	106.6	**108.4**	109.4	112.2	106.5
7	141	146	150	155	159	164	**166**	168	173	177.5	182.0	**184.9**	186.5	191.0	182.8
8	215	222	228	235	242	248	**252**	255	262	268.7	275.3	**279.6**	282.0	288.7	277.5
9	300	309	318	327	337	346	**350**	354	363	372.0	381.0	**386.7**	390.0	399.0	385.5
10	392	402	413	424	435	446	**450**	455	464	473.0	482.0	**487.7**	491.0	500.0	495.6
11	480	491	502	512	523	534	**538**	542	549	556.0	563.0	**567.5**	570.0	577.0	592.5
12	554	563	572	580	589	598	**600**	602	607	612.0	617.0	**620.2**	622.0	627.0	660.8
13	607	612	618	623	629	634	**635**	636	639	642.0	645.0	**646.9**	648.0	651.0	699.3
14	637	640	643	646	648	651	**651**	652	653	654.0	655.0	**655.6**	656.0	657.0	717.0
15	652	653	654	655	656	657	**657**	658	658	658.5	659.0	**659.3**	659.5	660.0	723.6
16	657	658	658	659	659	659	**659**	659	659	660.0	660.0	**660.0**	660.0	660.0	725.8
17	659	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
18	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
19	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
20	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
21	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
22	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
23	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
24	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9
25	660	660	660	660	660	660	**660**	660	660	660.0	660.0	**660.0**	660.0	660.0	726.9

*) Data extrapolated from the manufacturer's figures by the author.
**) Original power curve for an air density of 1.225 kg/m^3 multiplied by 1.349/1.225, as used by IREQ/HQD

The figures for the power curve are from Vestas Wind Systems (source 12). They differ slightly form the figures used by IREQ/HQD, but the two sets of curves give the same result for a standard air density of 1.225 kg/m^3. The manufacturer has published power curves for air densities up to 1.27 kg/m^3. The remaining air densities were interpolated linearly using the final trend difference from 1.24 to 1.27 kg/m^3 for each wind speed.