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Windpower and its Dependence on Hydro Reservoirs : Results from Wind Farms Simulations for Quebec

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1. Context and Objectives

With the signing of the Kyoto Protocol in December 1997, the reduction of greenhouse gas emissions will become one of the greatest challenges we face when developing energy policies. These policies should promote an increase in the renewable energy portion of the energy portfolio, and hydroelectric and wind power are likely to play a key role in this respect. In this context, it seems relevant to analyze a whole series of parameters for wind power in order to evaluate the electrical service it provides as well as the impact of its integration into the electrical network. These two factors are crucial for a complete economic evaluation of wind power externalities.

Using a detailed evaluation of the service that would be provided by a network of wind farms in Québec, this study aims to fill some gaps in the current research. The objectives are to prepare a technical portrait of the electrical service provided by the wind power system, to evaluate the impact of integrating it into the electrical network, and finally, to compare the service it provides with that of the hydraulic system.

2. Methodology

In order to simulate the electrical production of a network of wind farms in Québec, real data on wind speeds from actual sites with good wind potential had to be obtained. Specific data on potential Québec wind sites are not yet available. A wind measurement program is currently being developed, but the data collected so far do not make up a complete year. Hourly data were thus obtained from Environment Canada's meteorological stations, for 1994. In addition, to compare the pattern of wind production with the pattern of demand, hourly figures for electricity demand in Québec in 1994 were obtained from Hydro-Québec.

2.1 Wind Site Selection

The power of prevailing winds in a region is a very important factor in selecting a wind site, and the power of local winds can be a determining factor. Local climatic and geomorphological conditions can be the source of local winds that augment the prevailing winds. There are two principal types of local winds, sea breezes and mountain winds (DWTMA, 1998).

Québec is not a particularly mountainous region, so coastal sites were selected. At first, 11 meteorological stations in Québec were selected on coastal sites on the Gaspé Peninsula, the North Shore, James Bay, and Hudson's Bay. Hourly wind speed data for these stations were obtained for 1994. Four of these sites were not used: two had very incomplete data sets, and the other two proved not to be windy enough. Finally, data from the following 7 meteorological stations, in 4 regions, were used:

- Gaspé Peninsula: Cap-Chat, Cap-Madeleine, Mont-Joli, Cap d'Espoir
- Québec: Île d'Orléans

- North Shore: Pointe-des-Monts
- Hudson's Bay: Kuujjuarapik

2.2 Missing Data

Because of measuring equipment breakdowns or data recording problems, data was missing from all the data sets obtained. In order not to skew the wind turbine production simulation, these data were replaced by mean figures, according to the following methods:

- if a figure was missing, such as the wind speed at time x, it was replaced by the average of the preceding figure (x - 1) and the following figure (x + 1) and so on up to 4 figures before and after x if these figures are also missing;
- if all these consecutive figures were missing, the mean annual wind speed for the site was used.

The replacement of missing data with a mean, whether the interhourly or the annual mean, reduces the effect of the erratic nature of wind, while changing the total electrical production data very little. Wind speeds vary considerably from hour to hour and even from minute to minute, and an average often represents less of a deviation from adjacent figures than the real wind speed at that time.

2.3 Wind Speeds at 50 Metres Above Ground

The data obtained were the hourly wind speeds in 1994, taken at 10 metres above ground. In order to be representative of the wind that would be captured by a modern wind turbine in these locations, these speeds had to be corrected for a height of 30 to 60 metres, depending on the turbine model.

For this study, a height of 50 metres was chosen. The following equation is used to calculate wind speed at different heights above the ground: $S_2 = S_1\,(Z_2/Z_1)^{\alpha}$, where S_2 and S_1 are the wind speeds at heights Z_2 and Z_1. The value of superscript α may vary by less than 0.10 at the top of a hill, or 0.25 in zones that are sheltered from the wind. The average figure corresponding to Québec's topography and the nature of ground cover at Québec meteorological stations is 0.17 (WECTEC and UQAR, 1996, p. 12).

Wind speeds at the meteorological stations must be revised upwards by about 30% to be representative of winds at 50 metres above ground. For the purposes of our simulations, they were all revised upwards by 30%, with the exception of those from the Cap-Chat station. Here the anemometre was situated on the top of a 110-metre hill, and the measurements were already representative of an excellent wind-power site.

2.4 Calculation of Electrical Production

The equation below was used to calculate the theoretical electrical production of a wind turbine (WECTEC and UQAR, 1996, p. 12, 41).

$$\mathbf{E = Eff \times Area \times WPD = t \times 10^{-3}}$$

E (kWh): Electrical energy that can be generated by a wind turbine
Eff (%): Turbine efficiency factor; this factor varies according to the wind speed and is usually between 20% and 35%
Area (m^2): Rotor surface; Area = $\pi \times d^2 / 4$, where d is the diameter of the rotor blades (m)
WPD (W/m^2): Wind power density, WPD = $1/2 \times \rho \times S^3$, where ρ is the air density (kg/m^3) and S is the wind speed (m/s), $\rho = 3.48 \times Pa / (273.15 + T)$, where Pa is atmospheric pressure (kPa) and T the temperature (°C)
t (h): Time in hours

The wind power density, and thus the electrical energy produced, depend on the atmospheric pressure and the temperature, but they are mainly a function of the wind speed. Thus, at normal temperature and pressure (NTP = 101.3 kPa and 15° C), for a wind of 5 m/s, the wind power density is 77 W/m^2, while for a wind of 10 m/s, it is 612 W/m^2, nearly eight times greater.

All turbine models have their own characteristics and constraints. Specifically, they each have three modes of production, according to the wind speed:

- there is a minimum wind speed at which the turbine starts to produce in proportion to this speed raised to the power of three;
- there is a range of speeds that allow it to constantly produce its maximum output;
- there is a maximum speed where a stopping mechanism is activated for safety reasons.

In addition, each turbine model will react differently to variations in temperature and pressure. In order to simplify the calculations, the typical power curve of a 500-kW wind turbine was used (Tellier, 1995). This turbine power corresponds with current and recent models. Much more powerful turbines are available, but they are not yet widely used. This typical curve is shown in Figure 1, which illustrates the typical and theoretical output of a wind turbine with a 50-metre rotor diameter, at NTP, with 30% efficiency (Eff).

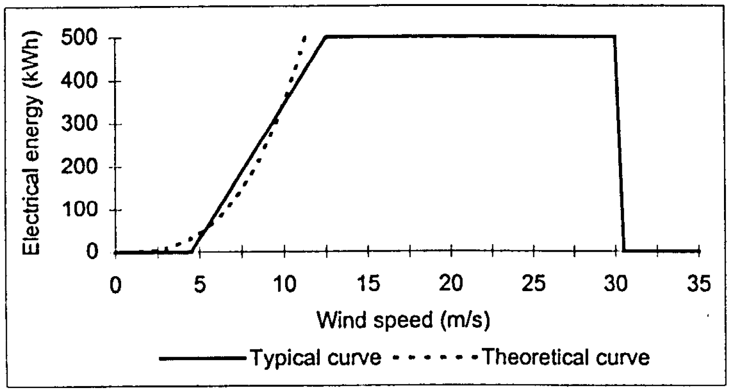

Figure 1. Typical Power Curve of a 500-kW Wind Turbine

By using this typical curve, the effects of variations in temperature and pressure on electrical production were disregarded. Winter temperatures increase air density and therefore wind power density. Thus the electrical energy that can theoretically be extracted from a wind of 8 m/s is 10% greater at -10°C than at 15°C. In addition, the wake effect, which reduces wind speed and increases the wind's turbulence after it enters the turbine, was not taken into consideration, nor was down time for maintenance, repairs, or turbine de-icing. All calculations were based on hourly, not average data.

2.5 Characteristics of Selected Sites

The principal wind characteristics of the selected sites are presented in Table 1. The first column indicates the percentage of missing data that had to be replaced by mean figures. The next three columns show the distribution of wind speeds according to the three turbine production modes, that is, when wind speeds are under the minimum level, when they are in the range where production increases with wind speed raised to the power of three, and when they are in the maximum production range (500 kW for the turbine model chosen). These distributions of wind speed frequencies are also illustrated in Figure 2 for the Cap-Madeleine site (the second best site, 95% of the data available) and for the 7 sites combined. The typical power curve was added to facilitate visual interpretation of the figures.

For 22% to 35% of the time, at all the sites, wind speeds were insufficient to activate the turbine, and for 6% to 17% of the time they were sufficient for the turbine to reach its full output. For the rest of the time, that is, 56% to 64% of the time, output was proportional to wind speeds.

The mean annual speed (S_{av}) presented in column 5 of Table 1 permits the calculation of each site's wind power class. Class 7 sites are exceptional sites ($S_{av} > 11$ m/s), while class 3 sites represent close to minimum profitability (BAPE, 1997, pp. 75, 77). Cap-Chat and Cap-Madeleine are excellent wind turbine sites (class 6), as is the combination of the 7 sites (class 5).

The last column of Table 1 shows the use factor (UF) for each site and for the combination of sites. The UF is the ratio of electrical energy produced to the maximum energy that could be produced if there was always enough wind to allow the turbines to function at their maximum output level. Here, it disregards periods of maintenance, de-icing, and repair. The UF of the sites selected varies from 27% to 43%. The UFs usually cited in the literature are in the order of 25-30% (DWTMA).

Table 1. Characteristics of Sites Selected for Simulations

		Wind Speed Hourly Frequencies (%)					
Site	Missing data (%)	No output <4.5 m/s	Output proportional to speed 4.5-12.5 m/s	Maximum output 12.5-30 m/s	Mean annual speed (m/s)	Wind site class	Use factor (%)
Cap-Chat	28	22	63	15	8.0	6	43
Cap-Madeleine	5	27	56	17	7.9	6	42
Île d'Orléans	10	28	60	12	7.2	5	36
Pointe-des-Monts	12	27	64	9	7.0	5	33
Kuujjuarapik	2	31	63	6	6.5	4	31
Mont-Joli	2	35	59	7	6.3	3	29
Cap d'Espoir	18	31	62	7	6.2	3	27
Average of 7 sites	11	29	61	10	7.0	5	34

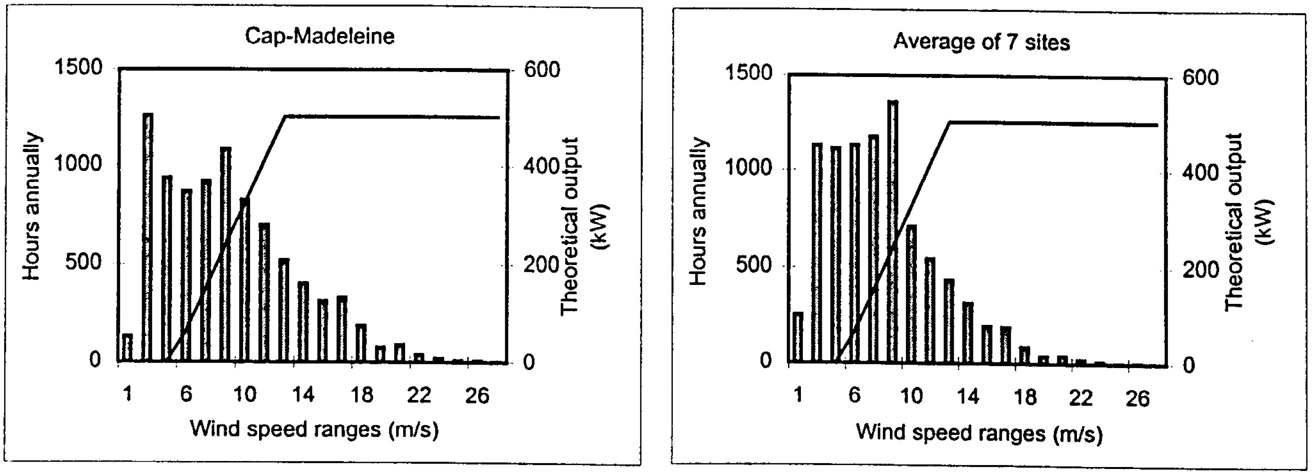

Figure 2. Distribution of Wind Speed Frequencies of a Good Site and of Average of 7 Sites.

In order to illustrate several of the parameters examined in this study, the following two wind production scenarios were simulated:

- 350 turbines of 500 kW on the best site (Cap-Chat), for an installed capacity of 175 MW
- 50 turbines of 500 kW on each of the 7 sites, for an installed capacity of 175 MW

The «best site» is the one that generates the most energy for a given installed capacity. In addition, when pertinent, the individual results for all the sites are given, and each is then equipped like the best site, with 350 turbines of 500 kW, for an installed capacity of 175 MW.

3. Results

3.1 Erratic Nature of Wind Production

There is a widespread belief that certain regions, particularly coasts, are subject to strong, incessant winds. It is true that there is often more wind on coasts, because of the presence of sea breezes. Coastal wind is nevertheless very changeable and unpredictable. All the sites selected for the simulations are located on coasts. Despite this, and despite the superior wind quality of several of these sites, the winds are erratic and unpredictable.

Figures 3a and b present the electrical production for a one-week period in January 1994 for the best wind site and for a wind farm with a given capacity distributed among 7 sites. January 28 is a particularly good illustration of the erratic nature of the wind. As shown in Figure 3a, electrical production is subject to successive periods of insufficient wind to activate the turbines, low winds, as well as winds that result in optimal output. The distribution of the sites appears to reduce fluctuations in production levels. For this example, production oscillates between the minimum and optimal output levels. The use factors for this week in January are 51% for the best site and 39% for the combination of the 7 sites.

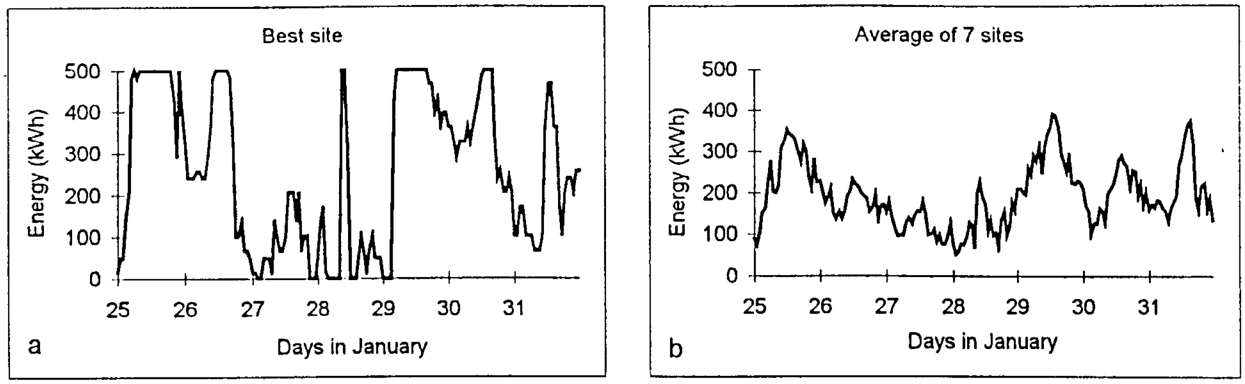

Figure 3. Wind Energy Production

3.2 Use Factor and Winter Peak Period

The use factor allow us to quantify the capacity available over a given period. In a northern climate and when heating needs are mostly met by electricity, there is a correlation between the peak demand period and wind energy production (Lambert & Marcotte, 1995). The windier it is, the greater the cooling factor in homes and the greater the demand (for heat and electricity). Table 2 shows the utilization factor for the 7 sites individually and combined, for the following periods:

- the 200 hours of the peak demand (155 in January, 43 in February, and 2 in December);
- the 1,000 hours of the peak demand (547 in January, 314 in February, 109 in December, and 30 during the rest of the year);
- the whole year.

Table 2. Use Factor and Winter Peak Period

Site	Use factor (%)		
	200 peak hours	1000 peak hours	Year
Cap-Chat	67	59	43
Cap-Madeleine	68	62	42
Île d'Orléans	47	44	36
Pointe-des-Monts	56	44	33
Kuujjuarapik	50	40	31
Mont-Joli	49	44	29
Cap d'Espoir	32	31	27
All 7 sites	53	46	34

For each of the sites, the 200 peak hours have the highest UF, and the UF for the peak 1,000 hours is higher than that of the year as a whole. This result confirms the fact that in a northern climate, there is a correlation between demand in winter and the wind. However, this phenomenon is not as evident if periods of less than the 200 peak hours of demand are used. For example, for the 1 hour and the 5 hours of peak demand in 1994, the 7 sites combined showed UFs of 25% and 38%, respectively. This phenomenon can be explained by the erratic nature of the wind and the need for a sample that is sufficiently large to produce statistically significant results.

3.3 Available Capacity

Table 3 shows the proportion of time during which available capacity is under 10% or 20% of installed capacity, first over a period of 1 year and then for the 200 peak hours. Over a year, the available capacity at each site taken individually is nearly zero for over a third of the time. However, when all 7 sites are combined, the available capacity is under 10% for 7% of the time over the year and for 2% of the time during the 200 peak hours. With the sites distributed geographically, the probability of production being zero is greatly reduced. However, the available capacity that is really guaranteed to respond to demand during the 200 peak hours proves to be very low; even with a simulated network of 7 sites, less than 20% of the installed capacity is available 13% of the time.

Table 3. Proportion of Time when Available Capacity is Less than 10% and 20% of Installed Capacity

Site	Proportion of time (%) when available capacity is less than 10% and 20%			
	Year		200 peak hours	
	C_{avail} < 10 %	C_{avail} < 20 %	C_{avail} < 10 %	C_{avail} < 20 %
Cap-Chat	28	31	11	17
Cap-Madeleine	31	36	13	17
Île d'Orléans	35	42	28	36
Pointe-des-Monts	35	42	20	23
Kuujjuarapik	36	44	15	24
Mont-Joli	43	50	20	26
Cap d'Espoir	39	46	39	50
All 7 sites	7	27	2	13

3.4 Response to Demand, Contributions, and Dependence on Back-Up System

Given that wind energy production is intermittent and unpredictable, wind is an unreliable source of power. It is always possible that there might be no wind and thus little or no wind energy available during a peak period. A wind energy project that is designed to respond to an established annual demand would have to be combined with a back-up system that could make up the production shortfall during periods of little or no wind. What then would be the project's immediate response to demand, contributions in excess of demand, and dependence on the back-up system when there was insufficient production?

3.4.1 Response to Demand

For the two wind energy scenarios studied, demand is standardized to correspond to the energy delivered over a period of a year. Thus, the response to demand corresponds to the energy generated from hour to hour, relative to the standardized demand. If, during a given hour, the energy generated surpasses demand, demand is thus 100% met and a contribution in excess of demand is recorded. However, if the energy generated is less than demand, the latter is only partly met and dependence on the back-up system is recorded. Contributions and dependence are expressed as percentages of demand for the period under consideration (over the year or during the 200 peak hours). Given the standardization of demand relative to the energy generated annually, at the end of the year the total contributions will be strictly equal to the total dependence. Table 4 shows the response to demand of the two wind energy scenarios.

Table 4. Response to Demand

Wind Energy Scenario	Year			200 peak hours		
	UF (%)	Energy generated (GWh)	Response to demande (%)	UF (%)	Energy generated (GWh)	Response to demande (%)
Cap-Chat	43	657	67	67	23	74
All 7 sites	34	527	78	53	18	82

The response to demand is better when the wind farm is geographically distributed (67% for the best site and 78% for all 7 sites combined). Response to demand is also better for the 200 peak hours than for the whole year. This result corroborates that of Section 3.2, to the effect that wind energy production tends to increase with demand in regions with northern climates and where electrical heating is widespread.

3.4.2 Contributions and Dependence on the Back-Up System

In concrete terms, the coupling of a wind energy project with another energy system occurs as follows:

- When the wind blows enough for wind energy production to exceed demand, the energy surplus produced means energy can be saved in the back-up system (a fossil fuel in the case of a thermal generating station or water in the case of hydroelectricity);
- However, when the wind is not blowing enough for wind energy production to satisfy demand, recourse must be made to the back-up system to meet the demand.

To make a fair comparison between energy systems, it is important to compare options that offer equivalent services. For example, if a wind energy system is coupled with a thermal generating station, the latter could benefit from the reduction of atmospheric emissions that occur when the wind blows. However, it will also be subjected to a decrease in energy efficiency due to intermittent operations. By the same token, if the wind energy system is coupled with a hydraulic system, the impact of the new flow management as a result of intermittent wind energy production must be considered.

Thus, evaluating the contributions and dependence of a wind energy system allows the «dependence» of such a system to be quantified along with the additional impact of the back-up system. We thus measured the contributions and the dependence on hydroelectric reservoirs that are required by the wind farm network to respond to the standardized demand in 1994.

These contributions and dependence were also compared to those required by an hydro power plant to the same reservoir to offer the same service. To make this comparison, we consider the level of dependence of hydroelectricity, as a dependence of a run-of-river power station on hydro reservoir. To produce 527 GWh of energy who respond to demand, the run-of-river power station will need a cumulative dependence of 171 GWh of water stored in reservoirs. To respond to the same demand, 527 GWh of wind energy produced by our 7 sites network will require 117 GWh backup. For an equivalent service, the relative dependence of the wind energy system on the reservoirs is equivalent to 68% of the dependence of the run-of-river power station on these same reservoirs, on an annual basis. If we take into account only one wind power site (the best), wind power is just as dependent on reservoirs as a run-of-river plant.

Table 5 presents the annual and peak hour contributions and dependence of the wind energy system. To use 527 GWh of wind energy (7 sites) to respond to demand requires 117 GWh of hydraulic power (22%). In fact, the erratic nature of wind means that a period of contributions is always followed by a period of dependence on the back-up system, and only a relatively small reservoir of 11 GWh (2% of 527 GWh) is needed to compensate for the intermittent nature of the wind energy system.

Table 5. Annual and Peak Hour Contributions and Dependence*

Wind Energy Scenario	Year: Total contributions** (%)	Year: Cumulative contributions and dependence (%)	200 peak hours: Total contributions (%)	200 peak hours: Total dependence (%)	200 peak hours: Cumulative contributions and dependence (%)
Cap-Chat	33	2	25	26	5
All 7 sites	22	2	18	21	3

* Contributions in excess of demand, and dependence on the back-up system.

** Over a year, the total contributions are equal to the total dependence.

3.5 Wind and Hydraulic Energy Combination

In Québec, where more than 96% of electricity is generated hydraulically, a wind energy project would obviously be combined with the hydraulic system. What, however, would be the impact of a wind energy project on the management of hydraulic facilities?

To answer this question, Gagnon and Bélanger (1998) simulated the coupling of two wind energy production scenarios with an actual hydraulic project. The Sainte-Marguerite-3 power station, currently under construction, is located on the North Shore near Sept-Îles in Québec. Real and projected data for this project, namely water flow, the area and depth of the reservoir, the energy output, and physical and environmental constraints, were used to calculate hydraulic production.

The simulations represent a hydraulic energy production of 2.8 TWh/year, to which is added a wind energy production of 0.3 and 0.9 TWh/year, corresponding to 10% and 25% of the total energy produced, respectively. Hydraulic energy production is adjusted such that the total production—the wind/hydraulic combination—follows the pattern of electricity demand in Québec for 1994.

Figure 4 shows the production levels of wind energy (25% of total energy at Cap-Chat and distributed over 7 sites) and hydraulic energy, relative to demand, for the week of January 1994 when demand peaked.

Demand for hydraulic energy fluctuates every day and hour by hour. Whenever there is little or no wind, the hydraulic system takes over and the turbine flow increases (see Figure 5). Conversely, when there are strong winds, hydraulic energy production is reduced or even stops, and the flow is consequently also reduced. The addition of wind energy production has little effect on water level fluctuations in the hydraulic reservoir. Wind energy production impacts immediately or over short time periods on water management, especially on downstream flows. Table 6 reveals the effects of intermittent wind energy production on water management in the hydraulic system.

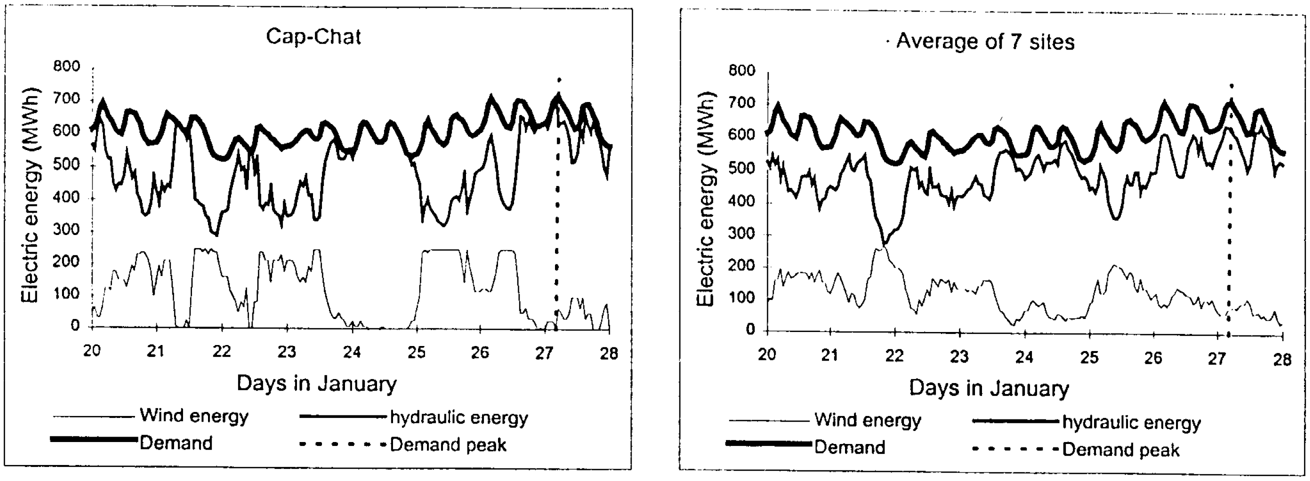

Figure 4. Demand, Wind Energy Production, and Hydraulic Energy Production

Table 6. Effects of the Wind/Hydro Combination on Water Level Fluctuations and Flow in the Hydraulic Facility

Parameter	Hydraulic energy only	Best wind energy site		Average of 7 wind sites	
Proportion of wind energy (%)	0	10	25	10	25
Wind power (MW)	--	82	246	102	307
Hydraulic power (MW)	537	595	709	571	659
Total combined energy (TWh)	2.77	3.08	3.69	3.08	3.69
Water level fluctuation (m)	6.0	5.7	5.6	5.7	5.7
Annual maximum turbine flow (m^3/s)	186	206	247	192	229
Annual minimum turbine flow (m^3/s)	61	55	7	60	20
Maximum variation in turbine flow in a 1-hour interval (m^3/s)	16	37	95	18	43

The annual maximum turbine flow corresponds to the hour during which hydraulic energy production has to be the highest in order to satisfy demand. The greater the proportion of wind energy, the higher this flow will be. Conversely, the annual minimum turbine flow corresponds to the hour during which wind energy is able to satisfy or almost satisfy demand. The greater the proportion of wind energy, the lower this flow will be. The maximum variation in turbine flow during a 1- hour interval is the largest deviation between two consecutive hourly flow figures. Sudden variations in flow represent a stress and even a real danger to aquatic animals and users of a waterway (wildlife and humans).

Without being coupled with a wind energy project, the hydraulic system's turbine flow varies from 61 to 186 m^3/s, and the maximum variation in flow over an hour is 16 m^3/s. Adding 10% wind energy to a site not only increases the flow range, but the hourly variation is also multiplied by a factor of 2.4. With 25% wind energy, the maximum flow is very high, the minimum flow nearly nil, and the hourly variation is six times that of a hydraulic project without wind energy. These effects, although reduced by the geographical distribution of the wind farm, remain very significant. Figures 5a and 5b illustrate the effect of increasing wind energy production on flow variations.

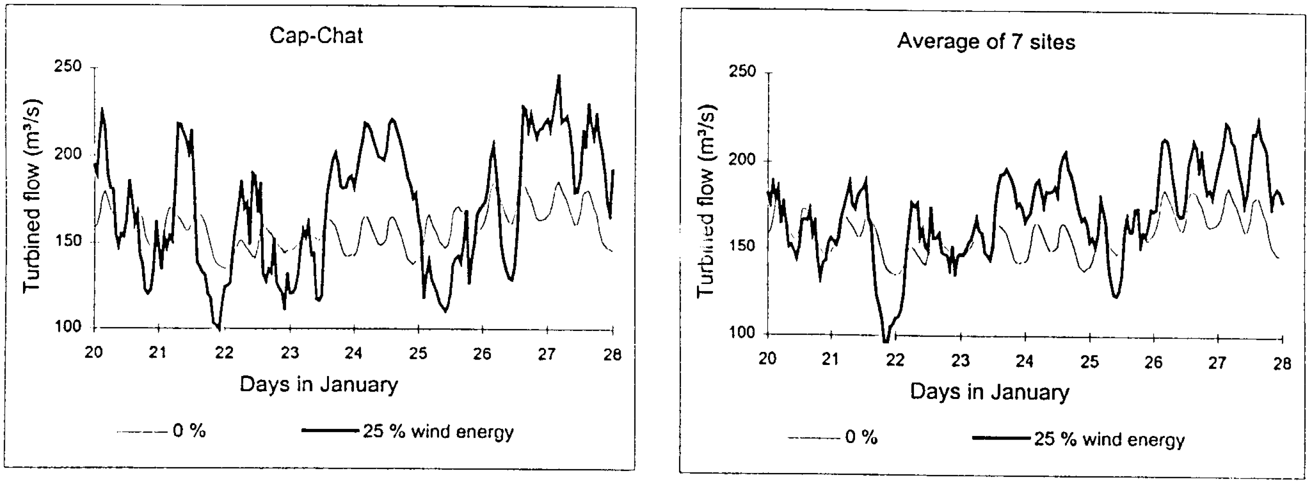

Figure 5. Effect of the Addition of Wind Energy on Turbine Flow

4. Conclusion

Modeling the production of a network of 7 wind farms distributed over several regions of Québec has enabled us to better understand the services that such a wind energy system could provide. This study has confirms the strong correlation between demand and wind distribution patterns, while revealing that wind energy production remains erratic and unpredictable. Even with 7 sites, production is less than 20% of installed capacity 13% of the time during the 200 peak hours.

The issues examined in this study demonstrate that there are often methodological errors in comparisons of energy options. It is important to consider all the characteristics of each system and compare them on the basis of an equivalent service:

- Electrical service is not limited to putting electrons into circulation; production must be reliable and predictable, and it must closely follow demand patterns. At this juncture, wind energy production is intermittent and erratic, whereas hydraulic energy production is as reliable as it is flexible;
- When wind energy is coupled with another system, its intermittent production and essentially nonexistent firm capacity mean that a power back-up system is required. Moreover, wind energy combined with hydraulic production involves the management of sudden changes in reservoir water flow.
- A wind energy system provides energy but not power.
- A wind energy system must be coupled with another system that is reliable and, particularly, flexible. Thus, in environmental, economic, and social impact studies, the system must be evaluated along with its back-up system. In the case of a wind/fossil fuel combination, the wind energy system can claim a decrease in gas emissions as a positive result. However, the calculation of this decrease must take into account changes in the efficiency of the thermal generating station to compensate for fluctuations in wind energy production. In the case of a wind and hydroelectric energy combination, the new flow management must be taken into account.

  Some of the hydroelectric system's negative environmental externalities must thus be attributed to the wind energy system. By the same token, the fact that the reliability of the hydroelectric system can help compensate for the erratic nature of intermittent renewable systems must be considered a positive externality of the hydroelectric system.

Finally, we recommend that future research include the following aspects: the use of several years of wind data; an economic study that takes into account the service provided and the greenhouse gas emissions prevented; and the design of a dependence factor that integrates the impact on reservoirs and river flows.

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APPENDIX

A1 Effect of Using Mean Annual Wind Speeds

According to the Danish Wind Turbine Manufacturers Association (DWTMA 1998), using the power curve of a wind turbine and a site's mean annual wind speed produces erroneous figures for annual electric energy output. Thus, if two sites have the same mean annual wind speed, but the wind is highly variable in one case and very stable in the other, their electrical production can be very different. For example:

- When wind speed figures are very closely grouped around the mean, they will be well represented by it;
- When wind speed figures vary greatly from the mean, the figures above it will proportionally provide more energy than those below it since energy production is a function of wind speed raised to the power of three.

Table A1 illustrates these principles. The first row of the table shows the mean annual wind speed for each site along with its standard deviation. The next two rows show the annual electric energy output, calculated using hourly data and mean annual wind speed. The last row shows the relative percentage of error between the figures calculated using each method.

It is obvious from the table that the two methods produce different results. In particular, the Mont-Joli, Kuujjuarapik, and Cap d'Espoir sites have high relative percentages of error (22%, 20%, and 18%, respectively). These sites are also the ones with the lowest mean annual wind speeds and the lowest frequencies of wind speeds in the maximum output range of the turbine (cf. Table 1). Figure A1 demonstrates the apparent relation between mean annual wind speed and the error in calculating energy produced using these annual figures instead of hourly figures. The higher the mean annual wind speed, the lower the percentage of error.

Table A1. Effect of Using Mean Annual Wind Speeds

Parameter	Cap-Chat	Cap-Madeleine	Île d'Orléans	Pte-des-Monts	Kuujjuarapik	Mont-Joli	Cap d'Espoir	All 7 sites
Mean annual speed (m/s)	8.0	7.9	7.2	7.0	6.5	6.3	6.2	7.0
Standard deviation (m/s)	4.4	4.7	4.2	3.8	3.7	3.6	3.6	4.1
Energy output (MWh/turbine/yr)								
- Hourly data	657	640	546	512	474	448	409	527
- Yearly mean data	675	656	514	476	379	351	334	484
Relative error between the two types of calculations (%)	3	2	6	7	20	22	18	8

It is clear that mean annual wind speed must be used with caution and should not be used during site selection, for example.

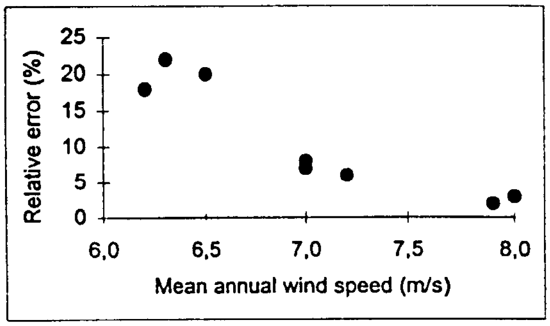

Figure A1. Relation Between the Mean Annual Wind Speed of a Wind Turbine Site and the Error in Estimating the Energy Produced at that Site