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Tables S1 and S2 provide details concerning the wind turbines considered here and concerning the existing electricity supply system in Canada, respectively. Figure S1 compares two representative Weibull wind speed probability distribution functions, the first yielding a mean wind speed of 7.1 m/s and the second 10.3 m/s, with a typical wind turbine power curve, while Figure S2 gives the power curves for all the turbines considered here. As can be seen from Fig. S1, for relatively low mean wind speeds, the wind speed distribution is such that the turbine output will be below the rated output most of the time, whereas for large wind speeds output will frequently be at the rated output. As seen from Fig. S2, turbines with a larger rotor relative to their rated capacity have greater output at low wind speeds than turbines with a smaller rotor, but may have a smaller cut-out wind speed (and will have greater unit cost), so the turbine that maximizes annual electricity production or minimizes unit electricity cost depends on the wind speed probability distribution.

Table S1. Characteristics of the turbines considered here. The last two entries are offshore turbines. Source: Product brochures from www.vestas.com, accessed 5 February 2012.

Model	Rated Power (MW)	Rotor dia (m)	Hub height (m)	Generator Type	Rotor rpm	Wind Speeds (m/s)		
						Cut-in	Rated	Cut-out
V90-1.8g	1.8	90	80-105	PMG	Variable[1]	4.0	12.5	25
V90-1.8	1.842	90	80-95	6-pole DFIG	9.3-16.6	4.0	12.5	25
V100-1.8g	1.8	100	80-125	PMG	Variable	3.0	12.0	20
V100-1.8	1.833	100	80-95	6-pole DFIG	9.3-16.6	3.0	12.0	20
V80-2.0g	2.0	80	65-80	PMG	Variable	4.0	14.1	25
V80-2.0	2.0	80	60-100	4-pole DFIG	10.8-19.1	4.0	14.5	25
V90-2.0g	2.0	90	80-125	PMG	Variable	4.0	12.2	25
V100-2.6	2.6	100	100[2]	4-pole DFIG	6.7-13.4	3.0	15.0	23
V90-3.0	3.0	90	65-80	4-pole DFIG	8.6-18.4	3.5	15.2	25
V112-3.0on	3.0	112	119	PMG	6.2-17.7	3.0	11.5	25
V112-3.0off	3.0	112	100[2]	PMG	8.1-19.0	3.0	12.5	25
V164-7.0	7.0	164	140[2]	PMG	4.8-12.1	4.0	15.0	25

[1] Unspecified in the product brochure
[2] Hub heights are unspecified. Shown is the value adopted here.

Table S2. Electrical powerplant capacity, electricity generation, and capacity factors in Canada in 2007. Source: Statistics Canada [1]										
Region	Capacity (MW)					Generation (GWh)				
	Hydro	Wind+ Tidal	Nuclear	Fossil Fuel	Total	Hydro	Wind+ Tidal	Nuclear	Fossil Fuel	Total
British Columbia	12609	0	0	2223	14832	64288	0	0	7545	71833
Alberta	909	439	0	10503	11851	2141	716	0	64575	67432
Saskatchewan	855	171	0	2853	3879	4393	579	0	15602	20574
Manitoba	5029	104	0	494	5627	33513	325	0	565	34403
Ontario	8350	414	11990	11413	32166	34336	493	79750	43655	158234
Quebec	37459	376	675	2508	41018	181100	617	4322	5923	191962
New Brunswick	923	0	680	2931	4534	2803	0	4119	10717	17639
Nova Scotia+PEI	404	96	0	3164	3664	925	217	0	11477	12619
Newfoundland	6796	0	0	557	7353	40049	0	0	1534	41583
Total or Average	73334	1600	13345	36645	124924	363548	2947	88191	161593	616279

Table S2 (continued).					
Region	Capacity Factor				
	Hydro	Wind+ Tidal	Nuclear	Fossil Fuel	Total
British Columbia	0.582	0.000	0.000	0.387	0.553
Alberta	0.269	0.186	0.000	0.702	0.650
Saskatchewan	0.587	0.386	0.000	0.624	0.605
Manitoba	0.761	0.357	0.000	0.131	0.698
Ontario	0.469	0.136	0.759	0.437	0.562
Quebec	0.552	0.187	0.731	0.270	0.534
New Brunswick	0.347	0.000	0.691	0.417	0.444
Nova Scotia+PEI	0.261	0.257	0.000	0.414	0.393
Newfoundland	0.673	0.000	0.000	0.314	0.646
Total or Average	0.566	0.210	0.754	0.503	0.563

Capital Cost of Wind Farms and Transmission Links

The cost of wind turbines (as well as that of fossil fuel power plants and the estimated cost of new nuclear power plants) has increased dramatically during the past five years. Total installed costs of onshore turbines in Europe in 2006 ranged from €1000-1350/kW (Cdn$1300-1800/kW), but recent total installed costs in Ontario have been in the range $2110-3430/kW, with an average of $2630/kW [2].

In the case of offshore wind farms, costs in Europe went from $1500-2000/kW before 2005 to $3200-5800/kW after 2005 (in terms of 2010US$, where 1US$ ~ 1Cdn$), with the main factors being growth in demand outstripping supply, limited availability of ports and vessels, increases in labour costs and commodity prices, corporate changes at the two major offshore turbine suppliers, and movement to projects in deeper water and further from shore [3]. Weißensteiner et al. (2011, Table A2) [4] give cost breakdowns for some offshore wind projects. Hardware costs (turbine purchase, delivery and erection, foundations, and internal grid) ranged from about US$1650-3750/kW, with design and management costs of $300-500/kW and main cable and substation costs of $500-1000/kW, giving a total cost of $2450-5250/kW. Heptonstall et al. (2012) [5] adopt a 2009 baseline cost for offshore wind farms in the UK of £1500/kW for turbines, £700/kW for foundations, £600/kW for electrical infrastructure, and £400/kW for planning and development costs. This gives a total cost of £3200/kW (~US$5000/kW). Costs by the mid 2020s are expected to be in the range £2200-3300 ($3400-5200/kW).

The US Energy Information Administration, in its *Annual Energy Outlook 2010*, gives a best estimate of overnight costs for onshore and offshore wind in 2009 (including project contingency factors) of $1966/kW and $3937/kW (in 2008US$), respectively [6, Table 8.2]. Costs of onshore turbines alone in the US (excluding foundations and installations but including delivery) rose from about $800/kW in 2001-2 to about $1300/kW in 2008-9, then dropped to about $1100/kW by July 2011 [7]. Northern onshore installations would cost more than southern installations, due to the need for low-temperature seals and other cold-weather packages, as well as often significantly greater foundation costs (Tim Weis, personal communication, January 2012). On the other hand, costs can be substantially reduced through economies and scale and the willingness of turbine manufacturers to offer deep discounts for large orders. For example, Junginger et al. (2005) [7] report that the purchase price of turbines has been reduced by up to 45% for orders of 500-1600 turbines. The production of wind turbine rotors requires the construction of blade moulds. Lindenberg et al. (2008) [8] suggest that segmented moulds could be transported to temporary manufacturing facilities that are established near the site of new large wind farms, thereby reducing transportation costs. For offshore wind farms, these temporary manufacturing facilities could be located on the coast, permitting delivery of all materials and components by ship in regions where there is no road access. Offshore wind energy is still relatively new and so should be amenable to greater relative cost reductions than onshore wind, although this may require a greater research and development effort, as van der Zwaan et al. (2012) [9] estimate that the progress ratio for offshore wind is 0.95 (compared to 0.80 for onshore wind, meaning that costs have fallen by only 5% for each doubling in cumulative global production).

In light of these considerations, and because we are considering a scenario with very large deployment of wind turbines, we adopt wind farm capital costs (excluding grid connection) of $2000/kW for onshore turbines and $3000/kW for offshore turbines, plus an additional cost of up to $400/kW (at a distance of 400 km or greater from the closest demand centre) for onshore turbines, in order to reflect the greater expense of shipping to and installing wind turbines in more remote locations. The $2000/kW onshore cost is assumed to apply to the VG80-1.8g turbine with a hub height of 90 m. This unit cost is altered based on departure of rotor diameter and hub height of other turbines from those in the reference turbine, as explained later.

The $3000/kW cost for offshore wind turbines is based on turbines mounted on the seabed. As noted in the main text, a few different floating offshore wind turbine concepts are currently being tested or developed. It may be that floating offshore wind turbines will be less expensive, once mature, than offshore turbines mounted on the seabed. Costs could be lower due to the absence of seabed construction, large ships, equipment out at sea, and the decommissioning of a large installed structure [10].

The cost adopted for offshore wind energy is particularly uncertain, as it is based on turbines mounted in the seabed, whereas many of the ocean grid cells pertain to sufficiently deep water that any offshore wind turbines in these cells would be floating (for which reliable cost data are not yet available).

With regard to onshore transmission lines, various estimates are given in Table S3.

Table S3. Recent estimates of the costs of onshore HVDC lines.

Voltage	Capacity (MW)	Cost (million$/km)	Cost ($/kW/km)	Source
345 kV	1250*	0.65-0.68	0.70	
500 kV	3000*	0.93-1.61	0.59	Hoppock and Patiño-Echeverri (2010)
800 kV	7500*	2.29-2.48	0.42	[11]
	1250	1.45	1.16	Pattanariyankool and Lave (2010)
	3000	2.41	0.80	[12],Curve fit equation,
	7500	4.08	0.54	Cost($/km)=$23959 $T^{0.5759}$, where
	10000	4.82	0.48	*T*=transmission capacity (MW)
500 kV	3000	0.99	0.33	
600 kV	3000	1.12	0.37	Bahrman and Johnson (2007) [13]
800 kV	3000	1.21	0.40	
500 kV	3000*	0.68-0.86	0.42	Mills et al (2009) [14]
800 kV	7500*	2.30	0.31	
800 kV	5700		0.31	EnerNex Corporation [15]

*Representative value assumed here.

The costs given here pertain to bipolar lines, which have the advantage that if one cable is broken, the other cable can temporarily transmit half the power by itself with grounded return (long term, operation in this mode would induce corrosion of buried pipes). The cost of a 500-kV HVDC line is 0.54-0.70 that of the cost of a double circuit 500-kV HVAC line [15].

With regard to offshore HVDC cables, costs estimated for a proposed HVDC line from Victoria, British Columbia to Port Angeles, Washington are $1.51/kW/km for transmission of 530 MW at 150 kV and $1.05/kW/km for transmission of 700 MW at 300 kV.[3]

With regard to AC-DC transformer station costs, Kim et al. (2009) [15] indicate costs of $170/kW and $145/kW for the termini of 1000-MW and 2000-MW 500-kV lines, respectively, and a cost of $150/kW for the termini of a 3000-MW, 600-kV line, but they stress that these costs are highly uncertain and do not include purchasers costs, which (they note) can be substantial. Mills et al. (2009) [16] indicate station costs of $100-200/kW. Bahrman and Johnson (2007) [13] indicate costs of $140/kW, $155/kW and $170/kW for the two stations at the ends of a 3000 MW line with voltages of 500 kV, 600 kV and 800 kV, respectively.

A 2003-2004 study of a proposed 500-kV, 1300-MW DC line that was to run from Manitoba to Sudbury, Ontario estimated line costs of $0.54/kW/km and station costs of $450/kW (based on information provided by Jatin Nathwani, personal communication, November 2011). The line costs are consistent with those shown in Table S3 for various voltage-power combinations, but the station costs are substantially greater.

The appropriate costs depend on the transmission voltage and capacity, with lower costs per kW of transmission capacity for higher capacity lines and greater costs for higher voltage at a given capacity. Here, we assume a capacity of at least 3000 MW for most of the lines that would need to be constructed to serve the 9 demand centres. This should result in lower line costs but greater

[3] See http://www.bcuc.com/Documents/Proceedings/2005/DOC_7599_C12-2%20SeaBreeze_IR-1.pdf.

station costs than given above for the proposed Manitoba-Ontario link. However, costs would have increased since 2003-2004. In light of the above, we adopt transmission costs of \$0.5/kW/km and \$0.75/kW/km for onshore and offshore lines, respectively. We adopt transformer costs of \$250/kW, which is less than estimated for the Manitoba-Ontario link but greater than the more recent US estimates. Our costs are substantially greater than the line and transformer costs expected in Europe (\$0.06-0.09/kW/km and \$150/kW, respectively, according to GAC (2006)) [17] or the average costs of 0.2€/kW/km and 50€/kW adopted by Weigt et al. (2010) [18] for a system of 3 lines in Germany at voltages of 110 kV, 220 kV and 380 kV.

Fixed O&M costs are assumed to be 0.7%/yr, 2.1%/yr, and 0.7%/yr of the capital cost for onshore wind turbines, offshore wind turbines, and transmission lines, respectively, while the variable wind turbine O&M cost is assumed to be \$0.007/kWh (based on various sources summarized in [19, Table 3.14].

Scaling relations to estimate the relative costs of different wind turbines

The distribution of costs for a 1.5-MW turbine with a 70m rotor and a 65m hub height, and scaling relationships given in [20], were used to estimate the costs of other onshore turbines relative to the cost of the Vestas V80-1.8g turbine, which is assumed to have total installed cost in Canada of \$2000/kW. The scaled cost C_s of a component with reference cost C_r is a given by

$$C_s = C_r\left(\frac{D_s}{D_r}\right)^d\left(\frac{R_s}{R_r}\right)^r\left(\frac{H_s}{H_r}\right)^h\left(\frac{S_s}{S_r}\right)^s \qquad \text{(S.1)}$$

where D_r, R_r, H_r and S_r are the reference rotor diameter, generator rating, hub height and rotor swept area, respectively, and D_s, R_s, H_s and S_s are the scaled values (for the alternative turbines under consideration). Table S4 gives the distribution of costs in 2002 for the reference turbine used in [20], the costs for the V80-1.8g as scaled from the 2002 reference turbine, with all turbine components adjusted uniformly in cost so as to give a total cost of \$2000/kW, and the exponents d, r, h and s used in the scaling relationships. Table S5 gives the resulting turbine costs, which are adopted here. Turbines with a low rotor diameter and a low hub height for a given power rating have lower costs per kW of capacity.

Table S4. Component costs and scaling relationships used to estimate the relative costs of the different onshore turbines considered here. Source: Fingersh et al. (2006) [20].

Component	Component cost (1000$)		Scaling Exponent			
	2002 1500-kW Reference turbine	V80-1.8g turbine scaled to $2000/kW	*d*	*r*	*h*	*s*
Rotor						
Blades	152	478	2.600	0.000	0.000	0.000
Hub	43	133	2.530	0.000	0.000	0.000
Pitch mechanism & bearings	38	121	2.660	0.000	0.000	0.000
Spinner, nose cone	4	8	1.000	0.000	0.000	0.000
Total	237	740				
Drive train, nacelle						
Low speed shaft	21	71	2.887	0.000	0.000	0.000
Bearings	12	37	2.500	0.000	0.000	0.000
Gear box	153	314	0.000	1.250	0.000	0.000
Mechanical brake	3	6	0.000	1.000	0.000	0.000
Generator	98	190	0.000	0.920	0.000	0.000
Variable speed electronics	119	234	0.000	1.000	0.000	0.000
Yaw drive and bearing	20	69	2.964	0.000	0.000	0.000
Main frame	93	231	1.670	0.000	0.000	0.000
Electrical connections	60	118	0.000	1.000	0.000	0.000
Hydraulics, cooling system	18	35	0.000	1.000	0.000	0.000
Nacelle cover	21	41	0.000	1.000	0.000	0.000
Total	618	1346				
Control, safety, monitoring						
Total	35	57	0.000	0.000	0.000	0.000
Tower						
Total	147	642	0.000	0.000	1.000	1.000
Balance of system						
Foundations	46	112	0.000	0.000	0.404	0.404
Transportation	50	113	1.581E-05	2.000	-0.038	54.7
Roads, Civil Work	79	149	2.170E-06	2.000	-0.015	69.54
Assembly and Installation	38	135	1.174	0.000	0.000	1.000
Electrical Interface	122	239	3.490E-06	2.000	-0.022	109.7
Engineering & Permits	32	67	1.000	0.000	0.000	0.000
Total	367	815				
Total Cost (1000$)	1404	3600				
Total Cost ($/kW)	936	2000				

Table S5. Capital costs of the different turbine models adopted here.

Model	Cost ($/kW)
V90-1.8g	2000
V90-1.8	1931
V100-1.8g	2395
V100-1.8	2213
V80-2.0g	1579
V80-2.0	1643
V90-2.0g	1964
V100-2.6	1854
V90-3.0	1530
V112-3.0	2065

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Figure Captions for the Online Supplement

Figure S1. Representative Weibull wind speed distributions in comparison to a typical wind turbine power curve, where Case 1 is derived using c = 8 m/s and k = 1.6 and Case 2 using c = 12 m/s and k = 1.6.

Figure S1. Power curves (normalized by peak power) for the 10 turbines that were considered here. Source: Brochures for each turbine model from the manufacturers website, www.vestas.com, accessed 5 February 2012.