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A path to sustainable energy in Atlantic Canada by 2050

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SUMMARY

Atlantic Canada's power supply-demand in 2050 is based on a set of recommended energy-related solutions to global warming, air pollution mortality, energy security, and several other impact categories. A power supply mix of 65% wind, 20% hydro, 9% tidal, 3% wave, and 3% solar PV is considered. Atlantic Canada is assumed to be using electricity and electrolytic hydrogen for all purposes. Capacity estimates and assumptions are discussed. Total spacing for wind, tidal, and wave arrays, and the inundated area for new hydroelectric is examined. End-use energy systems, including wind-electric thermal storage heaters, solar water preheaters, solars-space heaters with seasonal storage, wind-battery electric vehicles, and wind-hydrogen fuel cell vehicles are discussed. A carbon assessment of the total system is given.

KEYWORDS

Atlantic Canada
hydro
solar photovoltaics
solar water heaters
solar-space heaters
tidal
wave
wind
wind-battery electric vehicles
wind-electric thermal storage heaters
wind-hydrogen fuel cell vehicles

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1. INTRODUCTION

Jacobson (2008) reviewed and ranked "major proposed energy-related solutions to global warming, air pollution mortality, and energy security while considering other impacts of the proposed solutions, such as on water supply, land use, wildlife, resource availability, thermal pollution, water chemical pollution, nuclear proliferation, and undernutrition" (p.148, see Figure 1) [1]. Jacobson asserts the "use of wind, CSP, geothermal, tidal, PV, wave, and hydro to provide electricity for battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs) and, by extension, electricity for the residential, industrial, and commercial sectors, will result in the most benefit among the options considered. The combination of these technologies should be advanced as a solution to global warming, air pollution, and energy security. Coal-CCS and nuclear offer less benefit thus represent an opportunity cost loss, and the biofuel options provide no certain benefit and the greatest negative impacts." (p.148) [2].

Figure 1

Jacobson and Delucchi (March 2011) evaluated the feasibility of providing all global energy with wind water and solar power (WWS) [3,4]. Jacobson and Delucchi assert that such energy "can be supplied reliably and economically to all energy-use sectors", with "a social cost less than the cost of fossil-fuel energy", noting that "barriers to 100% WWS power worldwide are socio-political, not techno-economic". Authours suggest replacing the preexisting energy by 2050 [5,6].

The objective of this paper is to apply the above set of solutions in order to briefly consider a path to sustainable energy for Atlantic Canada in 2050.

1. ENERGY USE AND POWER DEMAND IN ATLANTIC CANADA – 2050

A Statistics Canada Report on Energy Supply and Demand in Canada (2008) had data on energy use for Atlantic Canada which is used to estimate the average loads for the region, as converted to megawatts (MW) circa 2010 (see Table 1) [7]. For this assessment, Atlantic Canada is assumed to be using electricity and electrolytic hydrogen for all purposes. Electricity and hydrogen conservation measures (EHCM) are assumed to reduce demand to 71.2% of 2010 levels in each province by 2050, although in reality there were some province-to-province deviations in sectors, end-uses, etc. The 71.2% figure is derived from a fraction which compared US 2010 to 2030 power demand upon the 100% conversion to WWS (accompanying spreadsheet, Jacobson and Delucchi, March 2011) [8].

Table 1
Atlantic Provinces, Average Power Demand (MW): 2010-2050

	Load MW 2010	EHCM conversion factor	Load MW 2050
PEI	738	0.712	525
NB	5192	0.712	3697
NS	5435	0.712	3870
NFLD	4010	0.712	2855
Atlantic	**15376**	**0.712**	**10948**

3. GENERATOR PORTFOLIO PLAN – 2050

A generator portfolio is assumed for 2050 (see: Table 2 and Chart 1). The generator fleet includes installed capacities of 15.5 GW onshore wind, 6 GW offshore wind, 2.5 GW solar PV, 3 GW tidal, 2 GW wave, 3.074 GW new hydro, and 1.27 GW existing hydro power.

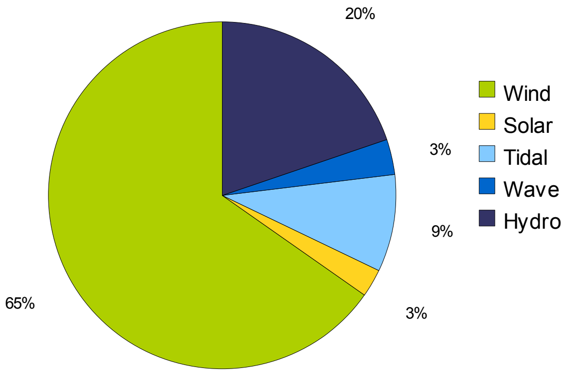
Table 2
Atlantic Provinces, Generator Portfolio: 2050

Energy Resources	Installed capacity (MW)	Capacity factor (%)	Ave power output (MW)	Annual generation (MWh)
Wind (onshore)				
- PEI	1500	0.36	**540**	**4730400**
- NB	4000	0.36	**1440**	**12614400**
- NS	2500	0.36	**900**	**7884000**
- NFLD	7500	0.36	**2700**	**23652000**
Wind (offshore)	6000	0.4	**2400**	**21024000**
Solar PV				
- PEI	120	0.13	**16**	**136656**
- NB	950	0.13	**127**	**1115148**
- NS	850	0.13	**111**	**967980**
- NFLD	580	0.11	**63**	**553807**
Tidal	3000	0.37	**1110**	**9723600**
Wave	2000	0.2	**400**	**3504000**
Hydro (new hydro)	3074	0.62	**1906**	**16695509**
Hydro (existing)				
- NB	886	0.45	**399**	**3492612**
- NS	384	0.3	**115**	**1009152**
Total mean power output			**12226**	

3. RESOURCE CAPACITY ASSESSMENT

Resource capacity estimates are considered tied to Atlantic Canada's energy use. Québec and NFLD have immense potential for power system balancing throughout eastern Canada, New England, and Ontario, due to their hydro capacity. The integration of wind and solar enable regions to use hydro sparingly to fill remaining supply gaps between variable renewable supply and continuous demand [9,10].

Chart 1
Power Supply -- 2050



Other reliability techniques include demand-response (ie. - thermostat setback, duty-cycle, price, etc.) and matching variable renewables to inherent storage in energy end-uses (ie. – heating and transportation), etc. [11,12]. Resource adequacy is discussed in Section 5.

Wind – The average capacity factor of wind farms in Canada as published by Natural Resources Canada is 36% [13]. This is considered representative of onshore wind in Atlantic Canada. In this paper, figures listed in a "proactive" Maritimes area wind development scenario to 2025 reflect the installed onshore wind for PEI, NB, and NS – 1500, 4000, and 2500 MW respectively [14]. Note that the exploitable wind potential of NB was estimated as ~41,500 MW, and a conservative physical potential for exploitation in the Maritimes area was estimated as 16,500 MW [15,16]. The Canadian Wind Energy Atlas and Statistics Canada's Population Distribution Map indicate NFLD could develop 7500 MW+ installed onshore wind [17,18]. Wind and bathymetric maps indicate 6000 MW+ installed offshore wind capacity is attainable in waters up to the 100 m isobath [19-21]. The capacity factor for offshore wind is assumed as 40%, while Dvorak et al. (2009) show California's offshore wind energy potential by deriving capacity factors from actual buoy data, etc. [22].

Solar PV – Lubitz (2010) showed that for the United States, azimuth and two axis tracking increased annual solar irradiation incident on a surface by an average of 29% and 34% respectively, relative to a fixed south-facing surface at optimum tilt angle [23]. The average capacity factor of solar PV is derived from real-time data monitoring of the 111.5 kW grid-tied rooftop solar PV array at the Jean Canfield Building in Charlottetown and the average capacity factor is calculated as ~13.4% [24]. This is treated to account for solar resources on a per province basis, and installed capacity is estimated, partly as suggested by Pelland and Poissant (2006), that evaluated the potential of building integrated PV in Canada [25]. Since azimuth and two way tracking systems improve PV system efficiency, the aggregate performance for solar PV is not reduced for losses from shading, angles, etc.

Tidal – An EPRI study (2006) indicated an average capacity factor of 40% for Bay of Fundy tidal [26]. Karsten et al., (2008) later simulated that "a maximum of 7 GW of power can be extracted by turbines" in Minas Passage and 2.5 GW of power can be extracted with a maximum 5% change in tidal amplitude at any location [27]. Here 3 GW of installed tidal is assumed to decrease the average capacity factor by 7% of the EPRI estimate down to 37%.

Wave – The annual mean wave power along the 1,000 m isobath off Canada's Atlantic coast is ~146,500 MW, but only a small fraction of available wave energy can be extracted and converted into useful energy [28]. On the Grand Banks east of NFLD, the mean annual energy flux is ~42 to 45 kW/m, while near the south east coast of NFLD is ~25-30 kW/m [29]. Annual mean wave power values ~20-25 kW/m are representative for the waters near Sable Island, and values near 10 kW/m are along the southern shore of NS [30]. A 750 kW Pelamis wave energy converter operated at a site with average power of 24 kW/m is assumed to generate mean power output of 152 kW for a capacity factor of ~20% [31]. It seems that such a capacity factor is achievable if long distances from coastlines to deeper waters and stronger waves is overcome, ie. - in terms of transmission, operation and maintenance, etc.

Hydro – Installed/average capacity of new/existing hydro are based on [32-34].

4. TOTAL SPACING AND FOOTPRINT

The estimates of total spacing required for the scenario of 2050 wind, tidal and wave arrays rely on a simple treatment of complex variables. For instance, the optimal average wind turbine spacing may be considerably larger than that conventionally used in wind farms [35]. Simple estimates are used here to indicate the approximate total spacing of the plants and devices (see Map 1). Inundated land for new hydro (not shown in Map 1) at full reservoir levels is ~145 km^2 [36].

Map 1
Total Spacing – Wind, Wave, Tidal Arrays

To minimize inter-turbine wake losses of wind, spacing of 10 rotor diameters downwind and 5 rotor diameters crosswind is imposed for the 126 m diameter blade of the REpower 5M turbine, so ~0.8 km^2 per 5MW turbine is needed [37,38]. This corresponds to 240, 640, 400, and 1200 km^2 in PEI, NB, NS, and NFLD respectively for total spacing of onshore wind, and 960 km^2 for offshore wind capacity. 4Dx7D (less spacing) is often used [39]. Actual footprint of towers on ground is only ~25.5 m^2 per 100 m tower [40]. For 3,100 onshore REpower 5Ms installed in Atlantic Canada (15.5 GW), the tower footprint occupies less than 0.08 km^2 of land; ~ 90% of Parliament Hill. Area for spacing can still be used for agriculture, etc.

Tidal arrays are assumed to require ~0.5 km^2 per 30MW [41]. This corresponds to 50 km^2 per 3000 MW tidal capacity. Wave arrays are assumed to require ~4km^2 per 50MW [42]. This translates to 160km^2 per 2000 MW wave capacity.

5. RESOURCE ADEQUACY ASSESSMENT

The seasonality of wind power in Atlantic Canada varies by location and is generally almost twice in the winter compared to summer [43,44]. The Canadian Wind Energy Atlas shows winter, spring, summer and fall seasonality [45]. The wave power in the winter is generally four to seven times greater than in summer [46]. Co-locating wind and wave devices may increase capacity credits compared to wind or wave farms alone, although this requires a site-specific analysis [47]. Photovoltaic potential and solar resource maps of Canada for fixed surface and two axis sun-tracking systems show monthly seasonality of solar for the region [48]. An inventory of marine energy resources in Canada shows depth averaged tidal power density near the centre of Minas Passage over a typical 15 day cycle. [49]. Global climate change is expected to continue shifting the timing of spring peak river flows (from a few days to more than a month early), as well as variations in flow volumes and inter-year flow variation, although hydro reservoirs will continue to be responsive and flexible resources [50].

Solar water preheaters can provide a significant fraction of water heating needs in summer, ie. - 80% to 90% per household, during periods when limited wind energy is ideally useful in BEVs, etc. [51]. PEI (and presumably Atlantic Canada's) gasoline sales (ie. - personal vehicles) are much higher in the summer than in winter. As driving decreases in wintertime, the wind power increases. Heating, which must be met in winter by the electric power grid in the 2050 scenario, can be supplied by wind [52]. Taken together, solar water heating, wind-BEVs and wind-electric thermal storage for space heating and winter water heating can be very complementary. Seasonal solar energy storage using borehole thermal energy storage systems could also allow Atlantic Canadians to meet a significant fraction of space heating requirements with solar [53,54]. Conservation, efficiency, demand response, electric thermal storage heaters, solar energy with seasonal storage, battery electric vehicles, vehicle-to-grid, hydrogen fuel cells, etc. can all be used in combination to improve the reliability of the 2050 power system in Atlantic Canada. In addition, hydro reservoirs can fill remaining supply gaps, although to accurately model the generation, transmission and interconnection requirements for system balance of regions: Québec, Newfoundland and Labrador, the Maritimes, New England, etc., requires large amounts of meteorological, load, and cost data, computing time, and new models and methods for power systems planning such as described and applied by Hart et al. (2011) [55].

Next steps: reliability model/simulation – Hart et al. (2011) used stochastic models and Monte Carlo approaches to simulate generator portfolios for power systems with high amounts of variable renewable energies. Results indicate that storage capacities may enhance power systems planning for networked renewable energy systems in Atlantic Canada by optimizing the CO_2 reductions and reducing the natural gas required, relative costs, etc.

6. END-USES

Wind-electric thermal storage (ETS) heaters – Kempton et al. (2007) examined the potential for large CO_2 reductions via offshore wind power matched to inherent storage in energy end-uses – ETS heaters and batteries for transport [56]. Hughes (2009) showed if power from the 5.24 MW North Cape Wind Farm (Phase One) is supplied to the residential heat loads of detached PEI homes, using electric thermal storage heaters, approximately 500 homes could be supplied with more than 95% wind from the farm [57]. Hughes (2010) examined the technical potential of off-peak electricity to serve as backup in wind-ETS systems [58]. Muralidhar and Hughes (2010) and Muralidhar (2010), examined integrating wind-ETS heaters and wind-BEVs for Halifax, NS [59,60]. Dhanju (2010) wrote four essays on offshore wind power potential, development, regulatory framework, and integration, the fourth of which analysed the potential of responsive ETS in integrating offshore wind power for Delaware [61]. For Atlantic Canada, a household with space heating demands of ~ 18,500 kWh/yr, assuming a 95% wind plus 5% hydro back-up supply mix, might result in ~ 200kg of CO_2equiv./yr. [62].

Solar water preheaters – Dempsey (2010) provided case studies of solar domestic hot water systems installed on PEI [63-65]. In one case, a home of four installed two, flat-plate solar collectors oriented at 15º SE and mounted on a roof with a tilt angle of 39.8º above horizontal (10 in 12 pitch). The solar fraction was about 87% in the summer and 7% in winter and in electricity the annual hot water demand represented ~2,418 kWh/yr. Supplies of 40%+ of the hot water per year appear attainable in many instances across the region. Note that the impact of high amounts of solar water preheaters is not built into the power system as modeled in Section 1.

Solar-space heaters – Solar-space heaters include systems such as Cansolair, SolarWall, passive solar with thermal mass, etc. [66-68]. Hughes and Wood (2007) assessed solar energy (using seasonal energy storage) and multi-storey residential buildings for Halifax [69]. Solar-space heaters with seasonal energy storage using in-ground borehole thermal energy storage systems, heat the ground in the summer and supply it back to loads for space heating in winter. The Drake Landing Solar Community in Okotoks Alberta receives somewhat more solar energy than in Atlantic Canada, but has a solar fraction of ~ 90% for space heating (and 60% for water heating). Information on seasonal energy storage for solar-space heaters, including the costs, real-time monitoring, etc. are available [70,71]. It is conceivable that costs may be reduced in some cases, such as with DIY solar collectors, etc. [72]. The impact of high amounts of solar-space heaters is not modeled in Section 1.

Wind-battery electric vehicles (BEVs) – Kempton et al. (2007) examined offshore wind power for BEVs in New England [73]. Muralidhar and Hughes (2010) and Muralidhar (2010), examined integrating wind-ETS heaters and wind-BEVs for Halifax, NS [74,75]. The number of vehicles on registration lists by type of vehicle and jurisdiction in Atlantic Canada is available [76]. For now, assume that one million BEVs requires 3 TWh per year as on the Hydro Québec website [77]. Of the light-duty vehicle fleet in Atlantic Canada, those weighing up to 4.5 tonnes, perhaps ~ 85% are BEVs and 15% are HFCVs based on [78]. This translates to ~ 1.2 million BEVs and 210 thousand HFCVs; about 3.6 TWh per year for a fleet of 1.2 million BEVs in Atlantic Canada. This represents just over 5% of total wind generation in the proposed 2050 generator fleet. Statistics of vehicle-kilometres for provinces by type of vehicle and day of week, type and time of day, monthly fuel sales, etc. are available and useful for actual simulation [79].

Wind-hydrogen fuel cell vehicles (HFCVs) – Various studies, such as on the effects of converting vehicles to wind-hydrogen fuel cell vehicles, and of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate are available [80-82]. Hydrogen fuel cell buses, tractors, passenger ships, liquid hydrogen aircraft, etc., were assumed in the scenario for Atlantic Canada to 2050 [83-86].

Demand response – An example of demand response is sending automatic signals to customer thermostats, etc. ie. - with customizable presets and override functions to balance the region's grid ie. - in cold weather with simultaneous low winds in the winter. This reduces back-up supplies (ie. - hydro, etc.) for wind-ETS space heaters at key times, and high demand response participation levels cascade benefits into the inter-regional system (ie. - reduced costs, emissions, materials, infrastructure, etc.).

Vehicle-to-grid (V2G) – Kempton et al. (2009) provided a test of vehicle-to-grid (V2G) for energy storage and frequency regulation in the PJM system. Detailed results from the industry-university research partnership are available here [87]. V2G provides real-time frequency regulation from an electric car as a way to meet key energy requirements of the electric power system by using electric vehicles when they are parked and underutilized. Of several V2G applications, the most economic entry market is for ancillary services (A/S), and a second market of interest is for spinning reserves, with much less frequent dispatch.

7. CARBON ASSESSMENT

Results from the stochastic simulation of power systems with large penetrations of renewable energy by Hart et al. (2011) for the California ISO operating area show that deterministic grid integration studies may overestimate the achievable carbon emissions reductions by ~ 33% [88]. However, as the installed capacities of wind and solar continue to increase, beyond 60% energy penetration, the emissions can be further reduced. It is suggested, in the context of a highly variable generation portfolio, clean technologies with reliably large capacities, but low (to zero) annual generation, may better contribute to emissions reductions than clean technologies that boast larger capacity factors [89].

Initial carbon assessment of the Atlantic Canada power system in 2050 indicates the total life-cycle CO_2 equivalent emissions, ie. - fabrication, planning-to-operation delays, etc.

69,904,800,000 kWh of wind x 8 g CO_2e/kWh ~ 559 kilotonnes (kt) CO2e/yr.
9,723,600,000 kWh of tidal x 45 g CO_2e/kWh ~ 437 kt CO2e/yr.
3,504,000,000 kWh of wave x 50 g CO_2e/kWh ~ 175 kt CO2e/yr.
2,773,591,000 kWh of solar PV x 85 g CO_2e/kWh ~ 235 kt CO2e/yr.
21,197,273,000 kWh of hydro x 65 g CO_2e/kWh ~ 1377 kt CO2e/yr.
Total CO_2e/yr from Atlantic Canada energy use ~ 2.783 Mt; < 1.2 tonnes per person.

Estimates of total CO_2e/kWh are derived from ranges of data (Jacobson, 2009) [90]. The solar estimate is increased by a factor of 2.5 to reflect resource availability in Canada. An actual carbon assessment should accompany a realistic simulation of the power system.

BIBLIOGRAPHY

[1] Jacobson., M. Z. (2008), Review of solutions to global warming, air pollution, and energy security, Energy Environ. Sci., 2, 148–173 DOI: 10.1039/b809990c

[2] Jacobson., M. Z. (2008), Review of solutions to global warming, air pollution, and energy security, Energy Environ. Sci., 2, 148–173 DOI: 10.1039/b809990c

[3] Mark Z. Jacobson, Mark A. Delucchi (2011), Providing all global energy with wind, water and solar power, Energy Policy,39, Part 1, 1154–1169, DOI: 10.1016/j.enpol. 2010.11.040

[4] Mark Z. Jacobson, Mark A. Delucchi (2011), Providing all global energy with wind, water and solar power, Energy Policy,39, Part 2, 1170-1190, DOI:10.1016/j.enpol. 2010.11.045

[5] Mark Z. Jacobson, Mark A. Delucchi (2011), Providing all global energy with wind, water and solar power, Energy Policy,39, Part 1, 1154–1169, DOI: 10.1016/j.enpol. 2010.11.040

[6] Mark Z. Jacobson, Mark A. Delucchi (2011), Providing all global energy with wind, water and solar power, Energy Policy,39, Part 2, 1170-1190, DOI:10.1016/j.enpol. 2010.11.045

[7] Statistics Canada Report on Energy Supply and Demand in Canada, Catalogue no. 57-003-X, http://www.statcan.gc.ca/pub/57-003-x/57-003-x2008000-eng.pdf

[8] See the sheet "End use energy US and World", cells D33 and M33 of the "WWS Energy Policy Spreadsheet" accompanying "Providing all global energy with wind, water and solar power", (xls-Spreadsheet).

[9] Hoste G.R.G., Dvorak M.J., Mark Z. Jacobson, Matching Hourly and Peak Demand by Combining Different Renewable Energy Sources -- A case study for California in 2020

[10] E.K. Hart, M.Z. Jacobson, A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables, Renewable Energy 36 (2011), 2278-2286, doi:10.1016/j.renene.2011.01.015

[11] Burke W.J., and Auslander D.M., Modular and Extensible Systemic Simulation of Demand Response Networks, CIGRÉ Canada Conference on Power Systems, Winnipeg, October 19-21, 2008

[12] Kempton W., Archer C.L., Dhanju, A., Garvine R.W., and Jacobson M.Z., Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses, Geophysical Research Letters (2007), doi:10.1029/2006GL028016

[13] Knox, N., and Royer, J., Overview of the Performance of Wind Farms Funded Under Federal Renewable Energy Programs, Natural Resources Canada, Conference Proceedings: Canadian Wind Energy Association Annual Conference and Trade Show, Vancouver, BC, October 21, 2008.

[14] EA Analysis, Large Scale Wind Power in New Brunswick - A regional scenario study towards 2025, Summary Report for NBSO and NB Department of Energy, August, 2008. http://www.nbso.ca/public/en/pm/news/article.aspx?id=eb908438-b987-416f-ad91-e4c202e0a704

[15] Thibault R., Gagnon Y., Poitras G.J., Université de Moncton, 2006. See presentation, Landry, M., and Gagnon, Y., Atlantic Canada Wind to Hydrogen Workshop, 2010. http://www.h2fcc.ca/files/nserc_landry.pdf

[16] EA Analysis, Large Scale Wind Power in New Brunswick - A regional scenario study towards 2025, Summary Report for NBSO and NB Department of Energy, August, 2008. http://www.nbso.ca/public/en/pm/news/article.aspx?id=eb908438-b987-416f-ad91-e4c202e0a704

[17] Environment Canada, Canadian Wind Energy Atlas. http://www.windatlas.ca

[18] Demography Division, Statistics Canada, Map 4.1 - Population distribution as of July, 2010 by census division, Canada, Catalogue number 21-214-XWE. http://www.statcan.gc.ca/pub/91-214-x/2009000/m001-eng.htm

[19] Environment Canada, Canadian Wind Energy Atlas. http://www.windatlas.ca

[20] Archer, C.L., and Jacobson, M.Z., Evaluation of global wind power, J. of Geophysical Research, Vol. 110, D12110, doi:10.1029/2004JD005462, 2005. See an accompanying Google Earth wind map for NA. http://wxweb.meteostar.com/maps/wind_power.shtml

[21] Cornett, A., Inventory of Canada's Marine Renewable Energy Resources, Canadian Hydraulics Centre, National Research Council Canada, 2006, CHC-TR-41, pg. 53, see Figure 46 – Bathymetry and mesh for the NW Atlantic Model. http://www.oreg.ca/web_documents/chc-tr-041.pdf

[22] Dvorak MJ, et al., California offshore wind energy potential, Renewable Energy (2009), doi:10.1016/j.renene.2009.11.022 http://www.stanford.edu/group/efmh/jacobson/Articles/I/dvorak-archer-jacobson-2009.pdf

[23] Lubitz, W.D, Effect of manual tilt adjustments on incident irradiance on fixed and tracking solar panels, Applied Energy, Volume 88, Issue 5, November 2010, Pages 1710-1719. doi:10.1016/j.physletb.2003.10.071

[24] Grid-Tie Solar Power Sytems, Project Porfolio, Complete Project Reference List, Jean Canfield Building, Carmanah Technologies Corporation website, May, 2011. http://view2.fatspaniel.net/CarmanahTech/jeancanfield/HostedAdminView.html?&eid=58376

[25] Pelland, S., and Poissant, Y., An Evaluation of the Potential of Building Integrated Photovoltaics in Canada, 31st Annual Conference of the Solar Energy Society of Canada (SESCI). Montréal, QC, August 20-24, 2006. http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/fichier.php/codectec/En/2006-047/2006-047_OP-J_411-SOLRES_BIPV_new.pdf

[26] Hagerman, G., Fader G., Carlin G., Bedard R., Nova Scotia Tidal In-Stream Energy Conversion Project (TISEC): Survey and Characterization of Potential Project Sites, Electric Power Research Institute, 2006. http://oceanenergy.epri.com/attachments/streamenergy/reports/Tidal_003_NS_Site_Survey_Report_REV_2.pdf

[27] Karsten, RH, McMillan, JM, Lickley, MJ, and Haynes, RD, Assessment of tidal current energy in the Minas Passage, Bay of Fundy, 2008, Vol. 222, Part A, J. Power and Energy, 493-507. doi: 10.1243/09576509JPE555 http://www.math.mun.ca/~rhaynes/karsten_etal.pdf

[28] Cornett, A., Inventory of Canada's Marine Renewable Energy Resources, Canadian Hydraulics Centre, National Research Council Canada, pg. i, CHC-TR-41, 2006. http://www.oreg.ca/web_documents/chc-tr-041.pdf

[29] Cornett, A., Inventory of Canada's Marine Renewable Energy Resources, Canadian Hydraulics Centre, National Research Council Canada, pg. 20, CHC-TR-41, 2006. http://www.oreg.ca/web_documents/chc-tr-041.pdf

[30] Cornett, A., Inventory of Canada's Marine Renewable Energy Resources, Canadian Hydraulics Centre, National Research Council Canada, pg. 20, CHC-TR-41, 2006. http://www.oreg.ca/web_documents/chc-tr-041.pdf

[31] Previsic, M., Overview of Wave Energy Technologies, EPRI Ocean Energy Programs, See presentation, pg. 18, 2008. http://cordellbank.noaa.gov/council/MirkoPrevisic.pdf

[32] New Brunswick System Operator, Nova Scotia Power Incorporated, Maritime Electric Company, Limited, Northern Maine ISA, Inc., NPCC 2010 Maritimes Area Comprehensive Review of Resource Adequacy, Table A - 2: Maritimes Area Resources, p. 18-20.

[33] Dalhousie University Eco-Efficiency Centre, Nova Scotia Renewable Energy Strategy – Scenarios and Policy Options, output from Scenario Session, September 10th, 2009 . http://eco-efficiency.management.dal.ca/Files/NSREC/NSREC_Scenarios_and_Policy_Options_Draft_Report.pdf

[34] Statistics Canada, Human Activity and the Environment: Annual Statistics: Table 3.41 – Hydro-electric power generation by province and territory, 2008 http://www.statcan.gc.ca/pub/16-201-x/2009000/t193-eng.htm

[35] Meyers, J. and Meneveau, C. (2011), Optimal turbine spacing in fully developed wind farm boundary layers. Wind Energy, 14: n/a. doi: 10.1002/we.469

[36] Lower Churchill Generation Project, Nalcor Energy website, May 2011. http://nalcorenergy.com/generation-project.asp

[37] Kempton W., Archer C.L., Dhanju, A., Garvine R.W., and Jacobson M.Z., Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses, Geophysical Research Letters (2007), doi:10.1029/2006GL028016

[38] Manwell, J. F., J. G. McGowan, and A. L. Rogers (2002), Wind Power Explained: Theory, Design and Application, John Wiley, Hoboken, N. J.

[39] Dvorak MJ, et al., California offshore wind energy potential, Renewable Energy (2009), doi:10.1016/j.renene.2009.11.022 http://www.stanford.edu/group/efmh/jacobson/Articles/I/dvorak-archer-jacobson-2009.pdf

[40] Wind power Update, newsletter published by Nordex AG, Germany, pg. 16, Edition no. 17, Issues: 8.000 http://www.nordex-online.com/fileadmin/MEDIA/Kundenzeitschrift/EN/WPU_17_EN.pdf

[41] PMSS (2010) Offshore Renewables Resource Assessment and Development (ORRAD) Project – Technical Report. Report prepared for South West Regional Development Agency. See Appendix 1: Tidal Technology Assumptions, pg. 50 http://www.wavec.org/client/files/ORRAD_Development_Report.pdf

[42] PMSS (2010) Offshore Renewables Resource Assessment and Development (ORRAD) Project – Technical Report. Report prepared for South West Regional Development Agency. See Appendix 3: Offshore Wave Technology Assumptions, pg. 54 http://www.wavec.org/client/files/ORRAD_Development_Report.pdf

[43] Hughes L., Meeting residential space heating demand with wind generated electricity, Renewable Energy (2009), Figure 2, p. 5, doi:10.1016/j.renene.2009.11.014

[44] Hatch Ltd., Nova Scotia Wind Integration Study for Department of Energy, Government of Nova Scotia, Final Report, 2008. http://www.gov.ns.ca/energy/publications/NS-Wind-Integration-Study-FINAL-(Sep-1-2009)-(RE-WEN-RP).pdf

[45] Environment Canada, Canadian Wind Energy Atlas. http://www.windatlas.ca

[46] Cornett, A., Inventory of Canada's Marine Renewable Energy Resources, Canadian Hydraulics Centre, National Research Council Canada, pg. i, CHC-TR-41, 2006. http://www.oreg.ca/web_documents/chc-tr-041.pdf

[47] Stoutenburg ED, et al., Power output variations of co-located offshore wind turbines and wave energy converters in California, Renewable Energy (2010), doi:10.1016/j.renene.2010.04.033

[48] Photovoltaic potential and solar resource maps of Canada, Natural Resources Canada. https://glfc.cfsnet.nfis.org/mapserver/pv/rank.php?lang=e

[49] Cornett, A., Inventory of Canada's Marine Renewable Energy Resources, Canadian Hydraulics Centre, National Research Council Canada, Figure 50, pg. 59, CHC-TR-41, 2006. http://www.oreg.ca/web_documents/chc-tr-041.pdf

[50] Singh B., Gagnon S., Davey N., Incorporating Climate Change Considerations in the Environmental Assessment of Hydroelectric Projects in Eastern and Northern Canada, 2002. http://www.ceaa.gc.ca/default.asp?lang=En&n=61C3B714-1

[51] Rod Dempsey, P.Eng., Case study: Economic Performance of a Glazed Flat Plate Solar Domestic Hot Water (SDHW) System (I), Atlantic EcoWorks, August 2010. http://www.ecopei.ca/Case_Study_1_SDHW_System_2010_09_12.pdf

[52] A plan for a sustainable future, ECOPEI Energy Project, Presentation to PEI Standing Committee on Agriculture, Environment, Energy and Forestry, October 24, 2010. http://www.ecopei.ca/A_Plan_for_a_Sustainable_Future_slides-notes.pdf

[53] Borehole Field in the Drake Landing Solar Community, Okotoks, Alberta, Presentation American Association of Physics Teachers by Gordon Howell, P.Eng., Howell-Mayhew Engineering, July21, 2008. http://www.hme.ca/presentations/Drake_Landing_Solar_Community--AAPT.pdf

[54] Hughes L., Wood T., Solar energy and multi-storey residential buildings, March 2007. http://dclh.electricalandcomputerengineering.dal.ca/enen/2007/ERG200702.pdf

[55] E.K. Hart, M.Z. Jacobson, A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables, Renewable Energy 36 (2011), 2278-2286, doi:10.1016/j.renene.2011.01.015

[56] Kempton W., Archer C.L., Dhanju, A., Garvine R.W., and Jacobson M.Z., Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses, Geophysical Research Letters (2007), doi:10.1029/2006GL028016

[57] Hughes L., Meeting residential space heating demand with wind generated electricity, Renewable Energy (2009), doi:10.1016/j.renene.2009.11.014

[58] Hughes L., The technical potential for off-peak electricity to serve as backup in wind-electric thermal storage systems, International Journal of Green Energy (2010)

[59] Muralidhar A.,Hughes L., Integrating wind generated electricity with space heating and storage batteries, Presented at the International Green Energy Conference, Waterloo, Ontario, June 2010.

[60] Muralidhar, A., Integrating wind generated electricity with space heating and storage batteries, December 2010, http://dalspace.library.dal.ca/bitstream/handle/10222/13181/Muralidhar,Anirudh,MASc,ECED,December2010.pdf?sequence=1
[61] Dhanju, A., Four essays on offshore wind power potential, development, regulatory framework, and integration, A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Marine Studies, Summer 2010. http://gradworks.umi.com/3423406.pdf
[62] McCarville M., Review of solutions to global warming, air pollution and energy security – A path to sustainable energy in Canada, Testimonial briefing to Parliament of Canada Senate Committee on Energy, the Environment and Natural Resources, March 3, 2011 Notes - (Committee proceedings, Briefing notes for SCEENR)
[63] Rod Dempsey, P.Eng., Case study: Solar domestic hot water system (II), Atlantic EcoWorks, July 2010. http://www.ecopei.ca/Case_Study_3_SDHW_System_2010_09_07.pdf
[64] Rod Dempsey, P.Eng., Case study: Economic Performance of a Glazed Flat Plate Solar Domestic Hot Water (SDHW) System (I), Atlantic EcoWorks, August 2010. http://www.ecopei.ca/Case_Study_1_SDHW_System_2010_09_12.pdf
[65] Rod Dempsey, P.Eng., Case study: Solar domestic hot water system (III), Atlantic EcoWorks, November 2010. http://www.ecopei.ca/Case_Study_7_SDHW_System_2010_11_30.pdf
[66] Cansolair Inc., see website: http://www.cansolair.com
[67] SolarWall, Conserval Engineering Inc., see webste: http://solarwall.com/en/home.php
[68] Solar Nova Scotia, see website: http://www.solarns.ca
[69] Hughes L., Wood T., Solar energy and multi-storey residential buildings, March 2007. http://dclh.electricalandcomputerengineering.dal.ca/enen/2007/ERG200702.pdf
[70] Borehole Field in the Drake Landing Solar Community, Okotoks, Alberta, Presentation to American Association of Physics Teachers, by Gordon Howell, P.Eng., Howell-Mayhew Engineering, July21, 2008. http://www.hme.ca/presentations/Drake_Landing_Solar_Community--AAPT.pdf
[71] Drake Landing Solar Community, see website: http://www.dlsc.ca
[72] DIY, Scott's 24 x 8 Foot Solar Collector, see website: http://www.builditsolar.com/Projects/SpaceHeating/24by8Collector.htm
[73] Kempton W., Archer C.L., Dhanju, A., Garvine R.W., and Jacobson M.Z., Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses, Geophysical Research Letters (2007), doi:10.1029/2006GL028016
[74] Muralidhar A.,Hughes L., Integrating wind generated electricity with space heating and storage batteries, Presented at the International Green Energy Conference, Waterloo, Ontario, June 2010.
[75] Muralidhar, A., Integrating wind generated electricity with space heating and storage batteries, December 2010, http://dalspace.library.dal.ca/bitstream/handle/10222/13181/Muralidhar,Anirudh,MASc,ECED,December2010.pdf?sequence=1
[76] Statistics Canada, Canadian Vehicle Survey for year 2009, Table 1, Number of vehicles on the registration lists by type of vehicle and jurisdiction: http://www.statcan.gc.ca/pub/53-223-x/2009000/t054-eng.htm
[77] Convincing facts and figures, Transportation electrification, Hydro Québec website:

http://www.hydroquebec.com/transportation-electrification/facts-figures.html

[78] Statistics Canada, Canadian Vehicle Survey for year 2009, vehicle body types are indicated, etc. indicating rough percentage of light-duty vehicles which may require hydrogen fuel-cell (ie. - diesel and some gasoline pickups), see various Tables: http://www.statcan.gc.ca/pub/53-223-x/2009000/tablesectlist-listetableauxsect-eng.htm

[79] Statistics Canada, Canadian Vehicle Survey for year 2009, vehicle-kilometres for provinces by type of vehicle and day of week, type and time of day, etc. are indicated, see various Tables: http://www.statcan.gc.ca/pub/53-223-x/2009000/tablesectlist-listetableauxsect-eng.htm

[80] Jacobson M.Z., Colella W.G., Golden D.M.,Cleaning the air and improving health with hydrogen fuel-cell vehicles, Science, Vol. 308, 2005. http://www.stanford.edu/group/efmh/jacobson/Articles/I/SciencePubHyd.pdf
Notes – P. 1904, paragraph 4, units of water vapor and carbon dioxide emission should all be in megatonnes (four times) rather than "metric tons" or "tons”. Supporting online material published online with the Science article (pdf).

[81] Colella W.G., Jacobson M.Z., Golden D.M.,Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases, Journal of Power Sources 150, 150–181, 2005. http://www.stanford.edu/group/efmh/jacobson/Articles/I/JPowerSources2005.pdf

[82] Jacobson, M.Z., Effects of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate, Geophysical Research Letters, Vol. 35, L19803, doi: 10.1029/2008GL035102, 2008. http://www.stanford.edu/group/efmh/jacobson/Articles/I/2008GL035102.pdf
Notes – Supplementary Material (pdf). Reaction list (pdf)

[83] The Hydrogen Bus Project, North Cape, PEI, ran from 2007-2011, see the following information: http://www.weican.ca/news/2007/071130-hydrogen-bus-pei.php
Test project ends: http://www.cbc.ca/news/technology/story/2011/03/03/pei-hydrogen-bus-experiment-584.html

[84] 100 passenger hydrogen ship, http://www.zemships.eu/en/project/introduction/index.php

[85] New Holland hydrogen fuel cell tractor, http://agriculture.newholland.com/uk/en/WNH/hydrogen/Pages/Hydrogen.aspx

[86] Liquid-hydrogen aircraft, systems analysis overview, http://ec.europa.eu/research/growth/gcc/projects/in-action-cryoplane.html

[87] Kempton W., Udo V., Huber K., Komara K., Letendre S., Baker S., Brunner D., Pearre N., A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System, Results from an Industry-University Research Partnership, November 2008 (Clarifications and corrections added January 2009). http://www.magicconsortium.org/_Media/test-v2g-in-pjm-jan09.pdf

[88,89] E.K. Hart, M.Z. Jacobson, A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables, Renewable Energy 36 (2011), 2278-2286, doi:10.1016/j.renene.2011.01.015

[90] See slides by M.Z. Jacobson in TED Debate, Does the world need nuclear energy? February 11, 2010. Note – the total CO2e/kWh of electricity sources is used in the initial carbon assessment of the Atlantic Canada power system.
http://www.stanford.edu/group/efmh/jacobson/renew_vs_nuclear.html