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The renewable energy landscape in Canada: A spatial analysis☆

Christopher Barrington-Leigh*, Mark Ouliaris

McGill University, 1130 Pine Ave West, Montreal, Quebec, Canada H3A1A3

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ABSTRACT

Numerous strategies for sourcing renewable energy are available for development and expansion, yet for many countries the idea of eventually transitioning to a completely renewable energy supply using domestic resources currently appears unfeasible. As a large country with low population density, Canada may be expected to face fewer obstacles in this regard. However, not only are Canada's population centers clustered largely in its south, but energy policy is significantly devolved to the level of provinces, making a match between energy demand and renewable supply more challenging. In order to address this challenge, we collect data from a variety of sources and combine it with our own geographical analysis to develop a scenario of renewable portfolios at the provincial level. We explicitly estimate the optimal sites, based on straightforward criteria, for development of each resource. In order to keep the analysis transparent, we focus on physical feasibility rather than economic details and, by lumping together all energy demand, we assume substitutability between electrically-provided and fuel-based energy delivery. Our assessments include wind, solar, hydro, tidal, wave, and geothermal energy, with a limited discussion of bioenergy. For comparison, we also break down current energy demand in each province according to categories intended to be meaningful to households. We find that overall with current technology Canada could more than provide for its energy needs using renewables, two-thirds of which would come from onshore and offshore wind, with much of the remainder coming from hydro. However, we find large differences across provinces in both the mix and magnitude of renewable potential. We find each province individually to be easily capable of renewable energy self-sufficiency at current levels of demand, with the exception of Ontario and Alberta. We believe this is the first combined, geographically-resolved inventory of renewable energy sources in Canada.

1. Introduction

Canada's extensive geography and existing reliance on hydropower make it a likely candidate for shifting to an entirely renewable domestic energy system. On the other hand, the concentration of Canada's population over a relatively small region makes the practical availability of renewable energy resources less obvious. Moreover, the diversity of potential renewable energy forms and their different geographic distributions poses two challenges. First, energy policy is largely devolved to the provincial level in Canada, necessitating provincial-level assessments of demand and potential supply. Second, an integrated approach across the various energy sources is needed in order to assess the total potential, which is a key question in understanding the extent to which energy conservation or new supply will need to dominate in a transition to renewable energy. Existing studies have tended to focus on a single resource or a single geographic region.

This study addresses the following questions: (1) What is the overall scope of Canada's combined renewable energy resources, and how are they geographically distributed? (2) What is the overall and regional (provincial) breakdown of potential renewable energy supply by resource? (3) How does the regional distribution of those resources compare with the distribution of energy demand?

To answer these questions, we forego an economic optimization and abstract from the changing relative prices of different resources. We also provide a new categorization of current energy demand in each province. Our classification of demand is inspired by an analysis of the U.K.'s renewable energy needs and options [26], and it is intended to be meaningful from the perspective of households' embodied energy budget.

Our work differs from a recent survey by the Trottier Energy Futures Project [62] in two major ways. First, we are able to base our estimates on detailed geographical analysis of physically feasible sites for the development of each resource. This facilitates our provincial analysis, as well as some further constraints on exploitable resources.

☆ We are grateful to the Pembina Institute for sharing data on recent energy demand, and to David MacKay for sharing his book's source code. All errors remain our own. A draft form of this paper was USAEE Working Paper No. 16-246.

* Corresponding author.
E-mail address: Christopher.Barrington-Leigh@McGill.ca (C. Barrington-Leigh).

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Secondly, we minimize the use of projected prices or discount rates, focusing instead as much as possible on the physical question of how much energy is available and feasibly usable, rather than hoping to define the optimal mix given small differences in prices across resources. In addition, we focus explicitly on renewables, therefore omitting nuclear. In the spirit of MacKay [26], we consider the current level of energy consumption in nearly all its forms as a relevant metric for society's energy needs, thus assuming a high level of substitutability between demand for electrical power and for liquid and solid fuels.

Below, we begin with an introduction to Canada's opportunities and challenges in energy provision. Then, in Section 3, we separately treat each renewable energy source, in each case describing existing literature related to the resource in Canada, followed by our methods and results for quantifying the distribution of potential exploitation. Section 4 brings together these estimates, and compares available renewable energy with a meaningful breakdown of Canada's recent total energy demand. We discuss differences across provinces, and some challenges inherent to realizing what we call feasible or potential resource capacity. Section 5 concludes, and online appendices provide further graphics, tables, and discussion.

2. Energy structure of Canada

Canada has several unique characteristics with regard to renewable energy potential that set it apart from other countries. First of all, Canada has abundant land area, on which wind and solar power is largely dependent, and has large inland water and ocean areas that can be used for off-shore wind turbines as well as wave power devices. Some of the largest tidal ranges in the world are located within Canadian waters, making it an ideal location for tidal barrages and tidal stream farms [5]. Hydroelectricity already generates the majority of Canadian electricity, or about 27 kWh/person/day [32]. Biomass, too, currently supplies a substantial portion of the nation's energy supply, largely through waste materials from the forest products and pulp and paper industries concentrated around the Canadian boreal forest region [3]. Finally, while geothermal energy has not yet been harnessed in Canada, several studies have shown that the raw resource available has the potential to satisfy a large portion of Canadian energy demand [15].

On the other hand, Canada has a very low population density which is heterogeneously distributed—the vast majority of Canadians are clustered in the south. The north is sparsely populated and has unforgiving weather. Much of the country is thus either too cold or devoid of population and infrastructure to justify a significant investment in renewable energy generation capacity.

Canada also has an extremely high per capita consumption of energy, 40% of which is used for heating purposes [37]. The average Canadian uses around 200 kWh/person/day which can be compared with the European average of 120 kWh/person/day or Hong Kong's 80 kWh/person/day [26].

Furthermore, final energy demand is unevenly distributed amongst the provinces. Alberta and Saskatchewan, in part due to their heavily resource dependent economies, use by far the most energy per capita in Canada (> 320 kWh/person/day). This uneven distribution of energy demand could potentially pose problems if areas of high renewable energy potential do not correlate with areas of high energy use, especially given that Canada does not have a robust nationwide transmission grid.[1]

We classify Canada's renewable resources as wave, tidal, wind, solar, hydroelectricity, geothermal, and biomass. Currently, only hydroelectricity, biomass, wind, and solar contribute significantly to energy production in Canada. Below we appeal to references relevant to each potential resource to generate a picture of how the mix may change over time.

3. Methods

As far as possible, we estimate resource potential based on physical constraints in order to provide the broadest measure. In certain cases, however, this is not possible or desirable and we thus utilize economic, environmental, and other constraints as needed to represent best the feasible potential. Our analysis is carried out using standard Geographic Information System (GIS) software.

3.1. Wind

Onshore and offshore wind power potential is a function of the total area suitable for wind power generation and the wind speed at those locations. Statistics of wind speed were collected from the Canadian Wind Energy Atlas [12] and cross-referenced with high potential areas to arrive at a broad estimate of total wind power potential.

3.1.1. Onshore wind

Onshore wind is one of the most cost competitive renewable energy sources. Commercial onshore wind farms are able to supply electricity (including conventional transmission costs) at an annualized cost of 4–7 cents per kWh [8].

We defined high potential sites for wind development as areas that were not inland water areas [data available from [9]] and were neither protected [see [35]] nor reserved for First Nations peoples [33]. Furthermore, high potential areas had to be at least 5 km away from populated areas and within 75 km of a populated area and a major road network [map data from [38]]. The 5 km exclusion buffer reflects the opposition that people have to wind turbines that are located near their homes. The 75 km km proximity requirement reflects two factors. We consider the highest potential sites to be sufficiently close to a pre-existing transmission line and to a population of consumers. Logically, building long stretches of transmission lines to areas far away from a source of energy demand could render even an area of high wind speed unfeasible for wind turbine placement. Unfortunately, no geographic transmission line data were readily available to the public at the time of this study. Instead, we used major road networks as a rough proxy for transmission lines. Sufficiently developed road infrastructure is also necessary for the transportation of the large quantities of steel needed to construct wind turbines. Therefore, our method ensures that only locations which have such infrastructure are characterized as high potential areas.

Finally, we applied a wind speed filter to exclude all areas that had annualized wind speeds of less than 7 m/s at a height of 80 m. Most commercial wind turbines have a hub height of over 80 m to take advantage of higher wind speeds at greater altitudes [52,53,55]. Cross referencing wind speed data from the Canadian Wind Energy Atlas with existing wind farm sites in Canada also shows that the vast majority of commercial wind farms are situated in areas with upwards of 7 m/s wind speeds at 80 m [12].

Fig. 1 shows these regions. The total area identified as high potential for onshore wind development is approximately 240,000 square kilometers. This is over 3% of the ten provinces' land area. The broadest measure of Canadian onshore wind power potential, assuming 100% utilization of these 240,000 square kilometers, implies that Canada could generate over 200% of its 2010 energy demand utilizing onshore wind power alone.[2]

Using this much land is unrealistic, however. In identifying high potential onshore wind areas, we have neglected potential environ-

[1] Canada's three territories (Yukon, Northwest Territories, and Nunavut) will largely be excluded from results and analysis as together they constitute less than half a percent of Canada's population and energy use.

[2] See [26] for more details on calculation methodology.

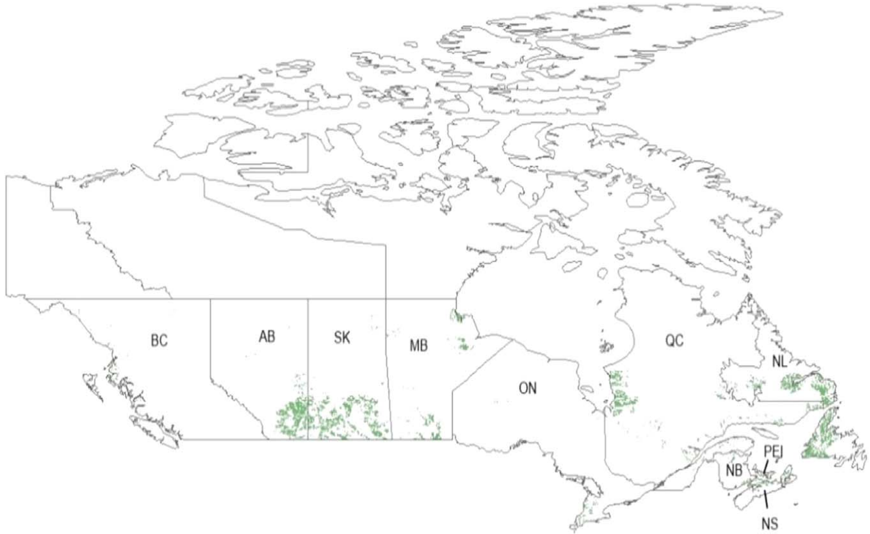

Fig. 1. High potential onshore wind areas. Areas shown in green are identified as high potential onshore sites for wind power development, based on their current land use designation, proximity (≤75 km) to population centers and major road networks, sufficient distance (≥5 km) from populated areas, and wind speeds exceeding 7 m/s at a height above ground of 80 m.

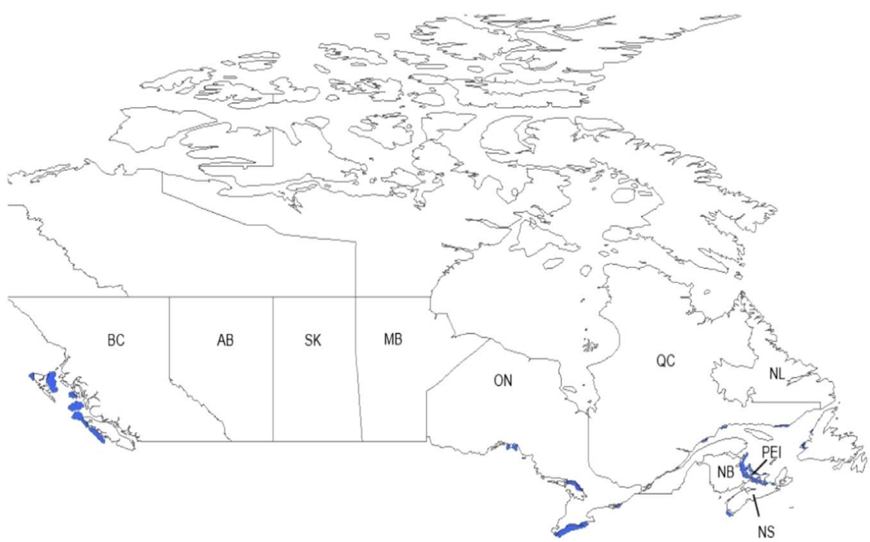

Fig. 2. High potential offshore wind areas.

mental concerns, existing land use competition, political opposition or rough terrain, which could render a large fraction of these 240,000 square kilometers unsuitable for wind energy development. We assume that a conservative 25% of the high potential area in each province is available for wind energy development.

3.1.2. *Offshore wind*

Offshore wind speeds are generally much higher than those at land; however, the costs associated with offshore wind turbine construction are also significantly greater, as are maintenance costs and transmission costs [30]. Current costs of offshore wind energy are 10–17 U.S. cents per kWh, or two to three times the cost of onshore wind energy [8].

For identifying high potential offshore wind development sites, we exclude bodies of water such as the James and Hudson Bays and those located in northern Canada, as these bodies of water are located very far away from population centers and in very cold and harsh climates. We also precluded "deep water" offshore wind development, although that may become more feasible in the future. Almost all commercial offshore wind farms today are built in relatively shallow water depths of less than 25–30 m, and commercial offshore wind farms under construction in 2011 were based in waters with average depth of 25.3 m [13]. At greater depths than these, the added difficulty of construction, maintenance, and transmission implies costs that render large scale development uneconomical.

We therefore define high potential offshore wind sites as those with large (> 25 km^2) areas of water with average depth of less than 30 m, where average annual wind speeds at a height of 80 m above sea level were greater than 8 m/s. The resulting sites are clustered around four main areas: off the coast of British Columbia, the Great Lakes, the Gulf of St. Lawrence, and off the coast of Nova Scotia near the Bay of Fundy. Canada's first offshore wind farm, currently in development off the coast of British Columbia in the Hecate Strait, matches our criteria with an average annual wind speed of 9.6 m/s and water depths ranging from 10 to 26 m [31].

Fig. 2 shows these regions. These high potential sites may be diminished slightly upon taking into account shipping lanes, environmental concerns such as the possible disruption of marine habitats or protected areas restricted for development, the sea state, and challenges related to the winter freezing over of fresh water on the sites in

Ontario's Great Lakes [25].[3] In order to allow for these factors, we assume that only 50% of the identified high potential area can be utilized.

3.2. Hydroelectricity

Hydroelectricity is the most market-ready and mature renewable energy resource available to Canada. It is the primary source of energy that allows Quebec, Manitoba, and Newfoundland and Labrador to generate over 90% of their electricity demand through renewables [43].

We use estimates of the remaining hydroelectric resource in each province, tabulated by EEM Inc. [11] in a report commissioned by the Canadian Hydropower Association (CHA). We add estimates in this report to those of existing hydroelectricity production [32]. While the CHA report includes projections of the amount of technical hydropower potential in all provinces, it has limited data for the proportion of technical potential that is actually economically feasible to develop in each province. For the sake of consistency, in provinces where economic projections are not available, we have simply assumed that 60% of technical hydropower potential will eventually be developed.

The CHA report quotes hydropower potential in MW of nameplate power capacity. When projecting annual generation, we use a capacity factor of 60%, typical of hydroelectric plants [11].

3.3. Solar

In assessing feasible additions to solar energy collection, we consider photovoltaic (PV) systems in both rooftop installations and solar farming, rooftop solar thermal used for heat and hot water, and large scale concentrated solar power (CSP) thermal electric plants.

Solar energy potential in Canada is a function of the average daily solar energy at a given location (which has been estimated by Natural Resources Canada), the efficiency of the capture technology, and the area devoted to solar energy generation. Based on our calculations, Canada's 2010 energy demand could be satisfied by devoting approximately 125,000 square kilometers to solar farming, which, in the context of Canada's enormous land mass, is a small amount of land but would currently be prohibitively expensive by any measure.

Meaningful physical feasibility constraints on solar energy production are therefore weak as compared with other, economic factors. While solar PV and CSP farms are highly scalable in principle, both are currently expensive compared to other renewables. The National Renewable Energy Laboratory estimated that CSP plants in the U.S., with significantly more sunlight than is received in Canada, generated electricity at a cost of 11–15 cents per kWh in 2005 [54]. Numerous studies estimate a cost of 20–40 cents per kWh for solar PV in the U.S., and a Canadian industry source cites a cost of 30–41 cents per kWh [6]. By comparison, a 2012 Hydro Quebec survey found that large power customers in major Canadian cities paid only 4–10 cents per kWh for their electricity [18, p. 5].

On the other hand, the price of solar PV panels has been falling precipitously and is projected to continue doing so [8,14,48,54]. In light of the especially broad envelope between physical and economic feasibility for solar power, we employ rough proxies in estimating Canadian solar energy potential.

3.3.1. Solar PV

In Canada, non-utility scale solar PV systems have significant advantages in rural areas, but are currently expensive. According to Sound Solar, based in Saskatchewan, an average household solar PV system rated at 3.5 kW would cost about $20,000 [65]. Natural Resources Canada [41] estimates that the potential annual energy produced per kW of installed PV capacity in Canada ranges from 1000–1400 kWh/kW. Given that solar PV systems are normally under warranty for 25 years, this implies a cost of 16–23 cents/kWh. This estimate, while expensive, is still lower than that of numerous other studies which find that solar PV generates electricity at a cost of 20–40 cents/kWh [8,54].

We assume that solar PV has a comparative advantage relative to other renewables only in rural areas. Indeed, over 90% of solar PV capacity in Canada in 2009 was located in rural areas that were off the transmission grid [4]. We allot to each person in rural census subdivisions, as defined by Statistics Canada [60], 10 m^2 of solar PV panels. Given that the average size of a household in Canada is 2.5 persons [58], this implies 25 m^2 of solar PV panels per rural household. This translates to a ~3.5 kW rated PV system [56], which matches up with Sound Solar's definition of an average household solar PV system.

We also assume that solar PV panels are 20% efficient. This assumption is a bit optimistic considering that PV panels were about 15% efficient in 2012, but accounts for a continued trend of improvement [23].

3.3.2. Solar thermal

We allow for the use of rooftop solar thermal collectors, which are particularly used for pre-heating water. According to Natural Resources Canada [37], 80% of Canada's 2009 residential energy demand was devoted to either space or water heating. However, in densely populated cities, while solar thermal technology can still be useful, there is not sufficient roof space or land area to install a large area of thermal panels per person.

Therefore, we account only for rural home installations, and formulate our solar thermal estimate with much the same methodology as for our solar PV estimate. We assume that each person in rural Canada installs 10 m^2 of solar thermal collectors. Industry sources indicate that solar thermal collectors are around 40–50% efficient [42]. Using these two statistics, combined with Natural Resources Canada's estimate of daily solar radiation at a given location, we integrate geographically to generate estimates of mean potential power.

3.3.3. Solar farming

Due to the lack of meaningful physical limits to the deployment of utility-scale solar farming in Canada, we assume that only the most promising areas in each province, i.e., those that receive the most solar radiation, may be developed. In addition, we exclude the possibility of development of solar within provinces which have a large excess of unexploited potential in cheaper renewables, except if there is another province nearby that has very high energy consumption relative to its renewable energy potential.

Given these criteria, we project there is solar farming potential in four provinces — Alberta, Saskatchewan, Manitoba, and Ontario. Other provinces receive relatively little sunlight and, as we show later, can already meet their energy demands using other cheaper renewables. Alberta and Ontario, by contrast, have high energy demands relative to their renewable energy potential. Furthermore, since Manitoba and Saskatchewan border Ontario and Alberta and receive a high level of solar radiation, it makes sense for these provinces to develop solar farming capacity for export to their neighbors.

We conduct a GIS analysis using the same filters as described above for wind power to identify high potential sites for solar development. We exclude the areas already earmarked for wind power development from consideration. The map in Fig. 3 shows high potential solar areas along with a rough average of mean solar radiation density in each of these provinces.

The future of the relative costs and benefits between solar PV and CSP for farming is uncertain. Many factors beyond the changing price of PV cells, such as the water requirements, inclusion of built-in storage, differing conversion efficiencies, and the need for direct as

[3] The firm attempting to develop commercial wind farms in the Great Lakes has expressed confidence that the "challenge of ice formation is by no means insurmountable" [63].

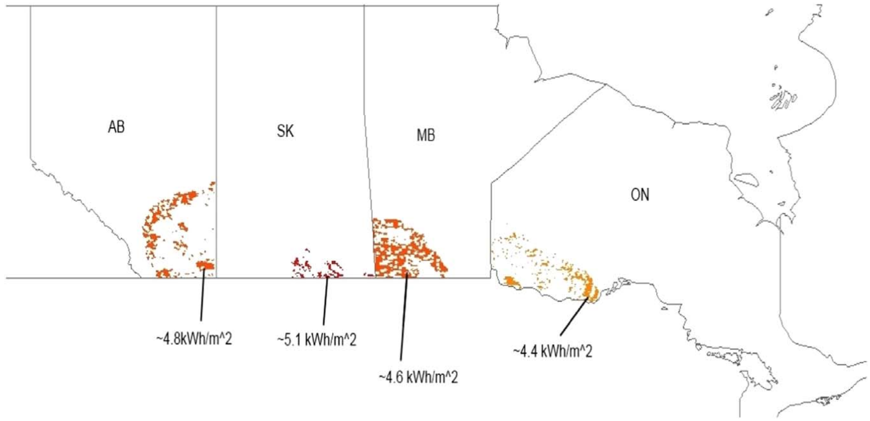

Fig. 3. High potential solar farming areas.

opposed to diffuse sunlight, differentiate the two technologies [29]. Moreover, the availability of cheaper wind power in the provinces we have identified may limit solar expansion. As a result, only a small fraction of the land identified in Fig. 3 is potentially exploitable by one technology or the other. We assume that whichever technology is used has a 15% solar-to-electricity conversion efficiency. We also assume 2000 km^2 of solar development in each of Manitoba, Saskatchewan, and Alberta, and 5000 km^2 of development in Ontario.

We must stress the considerable uncertainty inherent in this estimate. Again, from a theoretical standpoint, solar power potential in Canada is effectively unlimited and it is quite possible that solar farming becomes much more economically feasible and widely used in the future if the price of PV panels continues to fall significantly. On the other hand, it is likely that other forms of renewable energy such as wind may remain cheaper and limit the scale of solar development. As a result, it is similarly entirely possible that utility scale solar power becomes a niche player in the future Canadian energy market that fills in the gaps between energy production and demand, albeit at a high cost.

3.4. Tidal

We assume that tidal barrages, a 1960 s technology in which natural or artificial bays are closed off to create an effective dam [16], will not be developed in Canada. Instead, we focus on underwater turbines called tidal stream generators [26], which have a smaller environmental footprint and are attracting the bulk of research attention and investment [64].

Tidal stream generators can only be used in certain locations as they require high water speeds to generate large amounts of energy. Thus, their use is restricted to areas with high flow speeds. As a result, a 2006 study of Canada's 'Marine Renewable Energy Resources' conducted by the Canadian Hydraulics Centre (CHC) found that new tidal power development would "likely be restricted to sites" such as "entrances to estuaries and coastal embayments; narrow channels or passages between islands; and some major headlands" [7].

Our estimate of Canada's tidal power potential is based on the CHC's calculations of "potential tidal current energy". The CHC report identifies 190 sites in Canada with a high potential for tidal power development. These sites are largely concentrated in British Columbia, Quebec, Nova Scotia, and Nunavut. While the Nunavut figures will not be included in this analysis, it is important to note that Nunavut has by far the most potential tidal resource in Canada accounting for 72% of the potential tidal current energy identified in the CHC report [7]. Given Nunavut's sparse population, it is unlikely that much of this resource can be feasibly transmitted to energy consumers.

The CHC cautions that its estimates "represent the energy resources available in tidal flows" not the "realizable resource" and that "only a small fraction of the available energy at any site can be extracted and converted into a more useful form" [7]. Amongst other factors, the CHC study does not take into account environmental concerns, economic constraints, or the efficiency of tidal energy systems.

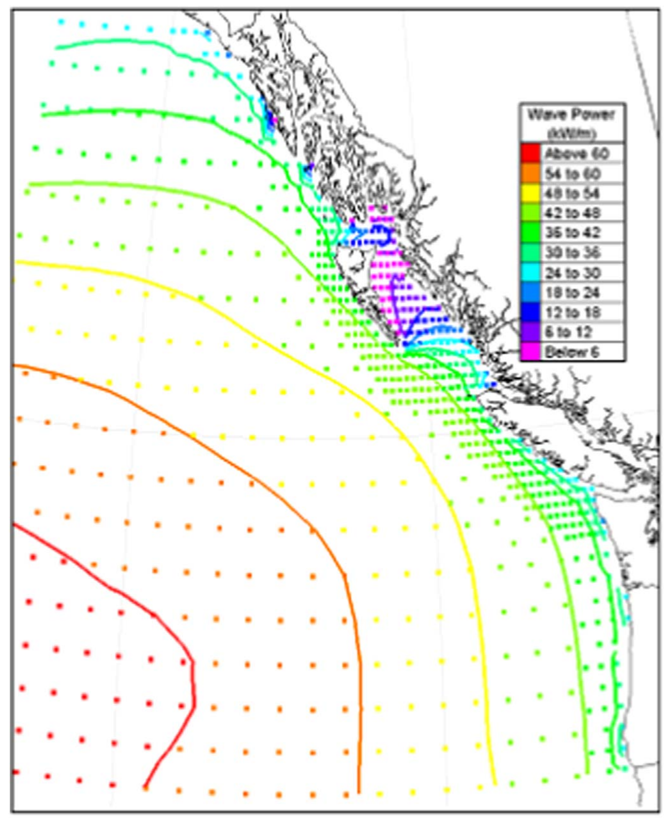

Fig. 4. Annual mean wave power: Pacific coast.

According to the author of the CHC study, Dr. Andrew Cornett, the environmental effects of tidal stream generation vary significantly from site to site and determining an exact safe level of extraction can be very difficult (personal communication, 2013). A separate review by the Electric Power Research Institute (EPRI) in the U.S. concludes only 15% of theoretical tidal energy could be safely extracted with environmental constraints in mind [16]. Extracting greater proportions of energy than this could "result in significant environmental consequences, such as slower transport of nutrients and oxygen or less turbulent mixing" [16].

Our estimates also rely on values for the extraction efficiency and

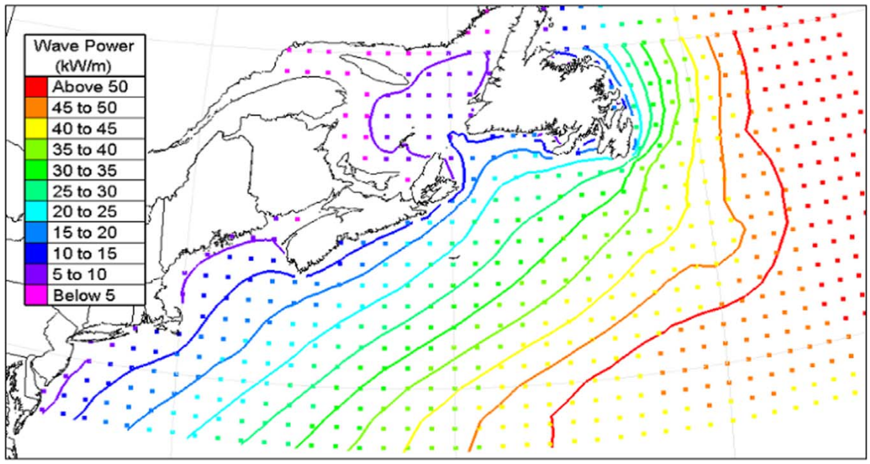

Fig. 5. Annual mean wave power: Atlantic coast.

capacity factor of tidal energy devices. The Canadian Industrial Energy End-Use Data and Analysis Centre (CIEEDAC) roughly estimates that tidal energy devices have a 17% capacity factor [43]. Another study quotes that tidal stream generators are 35–50% energy efficient [24]. Here it is important to note that there are many different types of tidal stream generators in development and considerable uncertainty remains about eventual extraction efficiency and capacity factor.

Given the considerable uncertainty surrounding the technological constraints of tidal stream generators, for the purposes of our tidal power estimate we assume that, on average, 15% of the potential tidal current energy quoted in the CHC report can be safely extracted [16] and that all of the sites identified in the CHC report are developed.

3.5. Ocean wave

Although ocean wave energy capture will likely remain a small contributor to Canada's energy budget, we nevertheless estimate the potential scale of this contribution. Wave energy potential is a function of the length of ocean coastline used for production, the linear wave energy density along that coastline, and the conversion efficiency of the technology used. This technology is still essentially experimental [49], making the latter parameter uncertain. Also, wave energy density decreases with proximity to land, while the feasibility of deployment decreases with distance from land due to transmission and maintenance costs.

Cornett [7] calculates the annual mean wave power along Canada's Atlantic and Pacific coastlines. The report finds that annual mean wave power is as high as 45 kW/m at deep-water locations 100 km from Canada's Pacific coast and as high as 50 kW/m 200 miles off Canada's Atlantic coast [7]. Wave power decreases sharply nearer shore, however, dropping to 25 kW/m near Vancouver Island and 9 kW/m near Nova Scotia's coastline [7].

While there are floating wave energy converters designed to function several kilometers offshore, we assume that wave energy at even greater distances, in deep water, is practically unavailable for large-scale harvesting. Instead, we use the magnitude of wave power at sites relatively close to land. Fig. 4 plots annual mean wave power off the coast of British Columbia [reproduced from [7]], where mean wave power is approximately 36–42 kW/m at locations close to the coastline. Although wave power density does dip significantly near Vancouver Island, we simply assume a value of 40 kW/m. We assume that 500 km of this coastline could be developed for wave energy capture. For reference, the largest wave farm currently under construction consists of only 200 converters and covers a 4 km stretch of Oregon's coastline [45].

Fig. 5 shows an analogous picture for the Atlantic coast [7]. For the Atlantic Provinces of Nova Scotia, Prince Edward Island, Newfoundland and Labrador, and New Brunswick, we allow for potential wave energy harvesting in locations with annual mean wave power ≥25 kW/m. We also assume that 500 km of Atlantic coastline is used for wave energy generation, divided up equally amongst the four provinces.

We assume an energy conversion rate of 10%. A study from the Nova University of Lisbon in Portugal, where the world's first wave farm was constructed, quotes 10–15% efficiency while the CHC report assumes 10% efficiency [7,51].

3.6. Geothermal

Geothermal energy refers to heat generated naturally deep underground from the Earth's molten core and ongoing radioactive decay in the Earth's crust.[4] Low to medium temperature geothermal resources are useful for water and space heating purposes while high temperature geothermal resources (> 150 °C) can be harnessed to produce electricity.

Canada has yet to generate any electricity using its geothermal resources, even though, according to a 2012 study by the Geological Survey of Canada, "Canada's in-place geothermal power exceeds one million times Canada's current electrical consumption" [15].

Three requirements for accessing thermal resources are the existence of sufficiently hot rock, typically at high depth; the existence of a fluid to absorb and transfer heat; and a pathway for this carrier fluid to travel closer to the surface. In Canada, the easily accessible high temperature geothermal resource is concentrated in western and northern Canada, specifically around northeastern British Columbia, the southern regions of the Northwest Territories, and northern Alberta [15]. Unfortunately, these are also areas that are predominately sparsely populated and do not have the population density and clusters of high energy demand that are needed to justify the high capital costs of geothermal electrical production. In addition, only a small subset of those locations have a basin of existing groundwater that can act as a carrier fluid or consist of rock permeable enough to allow a carrier fluid to flow through it and transmit its heat to the surface. Instead, most high temperature geothermal resource accessible with conventional methods is made up of hot, dry, and impermeable rock [10].

Recent technological advances have brightened the outlook for geothermal power in Canada. Specifically, Enhanced Geothermal Systems (EGS) utilize a process similar to hydrofracking for natural gas, injecting water into hot dry rock at extremely high pressures,

[4] "Geothermal energy" should not be confused with a more widespread exploitation of shallow underground thermal reservoirs through ground source heat pumps, used for heating and cooling purposes. In principle, this is an energy efficiency measure rather than a source of renewable energy, and it has potential over most of Canada [28,39].

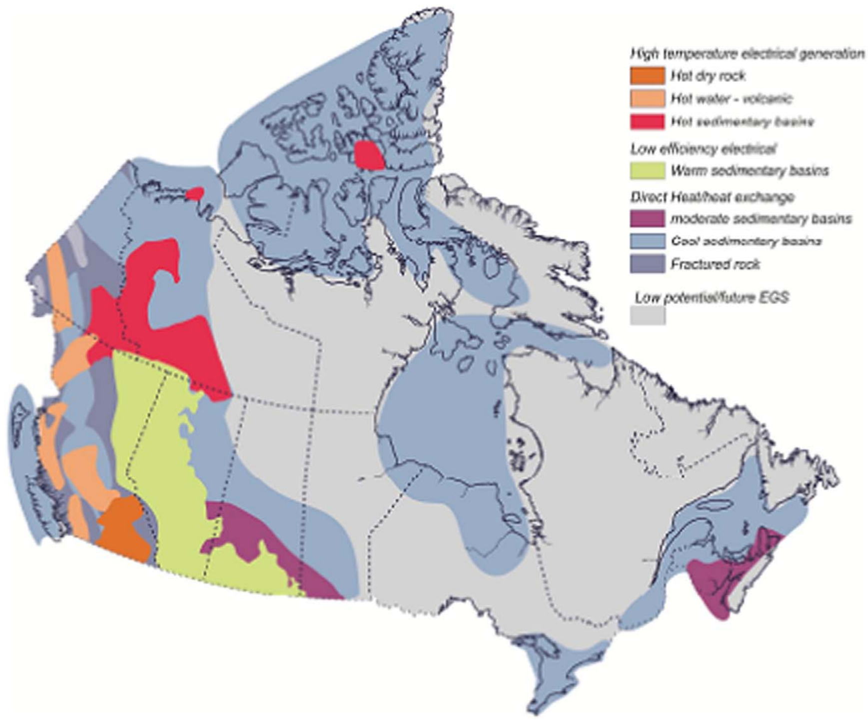

Fig. 6. Regional distribution of geothermal energy potential. Reproduced from Grasby, et al. (2012, p. 219) [15].

causing the rock to fracture and thus allowing water to permeate the rock and act as a carrier fluid. EGS, while still unproven on a commercial scale, can in theory significantly increase Canada's potential for geothermal energy [27]. Grasby et al. [15] conclude that as few as 100 EGS projects could meet Canada's energy needs.

Nevertheless, while considerable research into Canada's theoretical geothermal potential has been conducted in order to spur further investment, Canadian geothermal resource development and especially EGS is still at a very early stage. We present in Fig. 6 the results of existing research but note that these estimates reflect an extremely broad measure of Canadian geothermal potential. Given the uncertainty surrounding geothermal resource development in Canada, it is not currently possible to estimate with any confidence the proportion of theoretical geothermal resource that can be feasibly developed. In effect, we assume that it will not form a significant part of Canada's energy portfolio.

3.7. Bioenergy

Natural Resources Canada [34] estimates that biomass already supplies 4–5% of Canada's annual primary energy demand. Wood is by far the most significant source of bioenergy in Canada [3], largely as a by-product of the manufacturing process in the forest industry [36]. Bioenergy can also be derived from many other sources including municipal solid waste (MSW), animal manure, agricultural residues, and specially grown biomass crops.

Because bioenergy comes from so many different sources, bioenergy's contribution to Canada's energy future will depend on a myriad of factors including forest management, competing uses of forest residues, agricultural practices, and new technology. While independent estimates of bioenergy potential have been published for some provinces, other provinces have collected little data or conducted limited research into their biomass resources.

Due to limited data and the extreme complexity of estimating potential biomass resources, we rely for most provinces on current bioenergy production in lieu of a prediction of future bioenergy potential [61, p. 112]. However, we use estimates of bioenergy potential that exist for Alberta [21], for wood [20] and other resources [50] in British Columbia, and for Ontario [22]. Where relevant, we assume that all biomass is converted to electricity[5] with 31% efficiency [44].

3.8. Energy demand

We estimate final energy demand for each province, calculated using Statistics Canada's (2011) Adjusted Final Demand, population data from Statistics Canada [59], and adjustments for residential wood use, pipeline energy use, and industry energy consumption according to Natural Resources Canada [37, p. 46]. However, for the main results to follow we generate a more detailed accounting of the total energy demand by disaggregating it into six categories. These are food, air travel, heating and cooling, cars and transit, fuel production, and a broad category to capture the remaining commercial and industrial activities, which are represented as the durables ("stuff") purchased by households and the other services provided to them. These values represent energy use within Canada only. Thus, the "services and stuff" does not include energy used to produce imported goods, and the goods and services produced are not necessarily consumed by domestic households. Our categories are modelled after MacKay [26]. The data were provided by the Pembina Institute (personal communication with Tim Weis, 2014) and are based on calibrations from *whatIf? Technology*'s Canadian Energy System Simulator model (CanESS).

4. Results and discussion

We summarize all of our results in Fig. 7, with more detailed tabular data in Online Appendix A and province-by-province analysis available in Online Appendix B. Our nine categories of renewable power are shown in the right hand bars of each panel.

Total energy demand in 2010 in each province is shown in the left-

[5] There is controversy over whether some sources of bioenergy truly constitute a form of sustainable energy. Several studies have concluded that turning biomass into electricity is more efficient than converting it into biofuels [17].

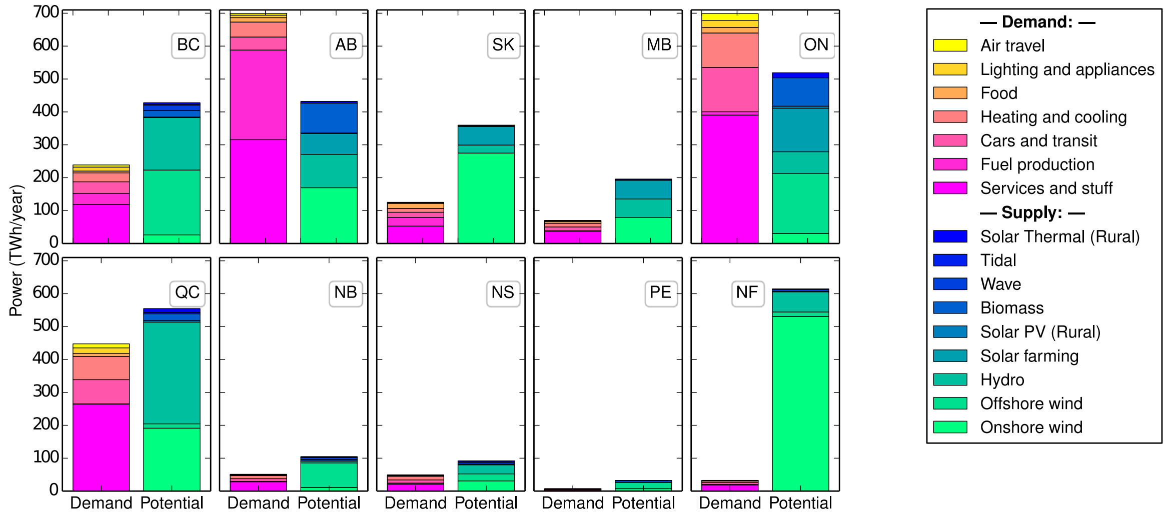

Fig. 7. Provincial comparisons: demand and renewable potential. Energy demand and potential renewable supplies, measured as total power.

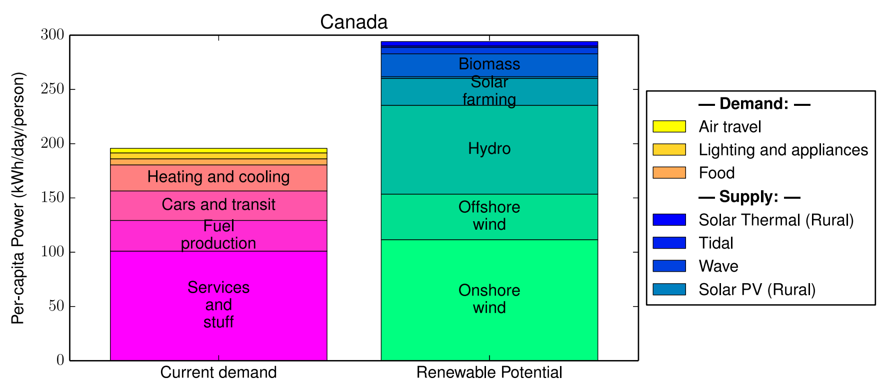

Fig. 8. National summary: per capita demand and potential supply.

Table 1
Summary of renewable energy resources, by type.

	Renewable potential (TWh/year)	Renewable potential (kWh/day/ person)	Fraction of energy supplied
Electric energy			
Onshore wind	1380	111	57%
Offshore wind	522	42	21%
Hydro	1020	82	42%
Solar farming	308	25	13%
Solar PV (Rural)	21	1.7	0.9%
Biomass	262	21	11%
Wave	73	5.9	3.0%
Tidal	16	1.3	0.7%
Total	**3620**	**291**	**149%**
Thermal energy			
Solar thermal (rural)	52	4.2	2.1%
Grand total	**3670**	**296**	**151%**

hand bars, split into our six categories, explained in Section 3.8.

Fig. 8 and Table 1 show the same data aggregated across provinces and converted to our preferred units of kWh per person per day. This format relates most closely to the units used in energy markets and known by most households and consumers. We estimate that Canada's renewable potential is 150% of its 2010 energy demand. While energy consumption may indeed increase substantially in the future as Canada's population increases, there are of course concomitant opportunities for economical reduction of per-capita energy use.

Below, we describe our findings for each potential resource type, followed by some comments on the overall picture for particular provinces. We then discuss some general implications of our findings.

4.1. Estimates of resource potential

4.1.1. Onshore wind

We estimate that onshore wind is able to deliver almost half of Canada's 2010 energy demand, eclipsing the contribution from hydropower. The distribution of the onshore wind resource is heavily unbalanced with respect to energy demand, however. Ontario, Quebec, Alberta, and British Columbia together represent over 85% of 2010 Canadian energy demand. Unfortunately, these four provinces, and in particular British Columbia and Ontario, are relatively unpromising areas for onshore wind energy development. By contrast, Newfoundland and Labrador, which only consumed 1% of Canada's total energy demand in 2010, is blessed with extremely high wind speeds and a large area suitable for wind turbine placement. It could generate almost 20% of Canada's 2010 energy demand by making use of only 25% of its high potential area.

4.1.2. Offshore wind

Offshore wind resources are the second largest potential resource, with over 500 TWh/year potential nationally. Our estimate for Ontario, 180 TWh/year, accords roughly with a 2008 report commissioned by the Ontario Power Authority, which identified 64 high potential sites capable of generating 110 TWh per year [46]. Our estimate is about 60% larger, but the aforementioned study only considered the most promising subset of all sites in the Great Lakes, stating that "there are wind power projects that can be feasibly developed beyond the sites that are identified in the present study" [46].

British Columbia and Ontario possess by far the most potential for offshore wind. However, while British Columbia is clearly open to developing offshore wind, the Ontario government has placed a moratorium on offshore wind development pending further study [57]. Concerns revolve around the environmental effect of offshore wind development, and particularly offshore wind's effect on aquatic life [1].

4.1.3. Hydroelectricity

We find that hydroelectricity has the potential eventually to more than double its current contribution to Canada's energy budget, with important contributions in every province except P.E.I. Not only could hydropower supply almost a third of Canada's 2010 energy demand, but due to it having high reliability and being throttleable, hydropower has a special role to play in facilitating mixed energy portfolios. We mention these below in Section 4.4.

4.1.4. Distributed solar PV

Our projections of rural solar PV potential, accounting for 1% of total 2010 demand, appear small in the context of the entire population. Considering that only 20% of Canada's population was classified as rural in 2011, the contribution of 10 m^2 of solar PV panels for each person in rural Canada would amount to 7kWh per day per rural person and, assuming rural Canada uses roughly the same amount of energy per capita as urban Canada, less than 4% of rural Canada's 2010 energy demand. Seven kWh is roughly the amount of energy used to take a 30 min hot shower [40]. This figure is low because the rural area locations, taken into account in our GIS analysis, are largely located in northern Canada which has relatively low levels of sunlight. Even increasing our already-generous allocation of solar panels by several multiples would not generate a significant proportion of total energy demand. This reflects our assumption that non-utility scale solar PV in Canada will play the role of an adaptable and versatile source of power for areas disconnected from a grid, but cannot by itself make a large impact in meeting Canada's large energy demand.

4.1.5. Distributed solar thermal

Solar thermal potential is approximately double that of solar PV. For the 20% of Canadians who live in a rural area, we conclude that solar thermal can provide 20 kWh per day per person or about 10% of 2010 rural Canadian energy demand. This assumes that the demand for heating (for instance, domestic hot water) is sufficient and steady enough to make use of the potential generation, which is optimistic.

If we combine the solar thermal and solar PV estimates, we find that non-utility scale solar energy generation can meet up to approximately 15% of rural Canadian energy demand, or 3% of total national demand. Since the residential sector comprises only a small fraction (17%) of Canada's total energy demand [37, p. 6], the contribution from domestic solar in rural areas may be similar to the total household energy requirement in those areas. We have, on the other hand, assumed generous and expensive allocations for these investments.

4.1.6. Solar farming

Our estimates suggest an enormous potential for solar farming, which we project to be able to contribute 13% of the national energy budget. This contribution still lies below those of onshore wind, hydropower, and offshore wind.

4.1.7. Tidal

Our estimates of future tidal energy potential are small. We project that tidal stream generation can satisfy less than 1% of 2010 Canadian energy demand and no more than 3% of any province's 2010 energy requirements. Even if we include Nunavut's tidal potential in our estimate, which as we have argued is an unlikely proposition, tidal potential would still not comprise above 3–4% of 2010 Canadian energy demand.

Tidal energy also appears to be relatively expensive.[6] However, the cost of generation is projected to decrease as tidal stream generator technology matures. Furthermore, while tidal current speeds fluctuate significantly from hour to hour and season to season, these fluctuations are easily predictable [2]. If Canada comes to rely heavily on renewables, this predictability has significant value, especially if energy is predominately produced by both intermittent and unpredictable renewables such as wind and solar in the future.

4.1.8. Ocean wave

We project that even with considerable technological progress, wave energy only has the potential to satisfy 3% of 2010 Canadian energy demand. On the other hand, in the coastal provinces this proportion is naturally larger, at nearly 17% in the Atlantic Provinces and 7% in British Columbia. For P.E.I. taken alone, our estimate comes to 78% of its 2010 energy demand. As explained above, these projections are based on largely unproven technology and scaling potential.

4.1.9. Uncertainty

Our estimates rely on numerous assumptions outlined earlier. Nevertheless, we conclude that on a national scale, Canada's renewable future appears to be dominated by wind and hydro, both of which are also relatively feasible with current technology. Most of the rest of our projection consists of solar and biomass. Solar systems continue to grow more efficient and inexpensive. As a result, solar farming may become economically feasible in the near future and would thus have the potential to generate enormous amounts of power. We stated existing bioenergy generation instead of future bioenergy potential for all but three provinces. Due to Canada's large fertile and forested land areas, the large uncertainties that surround the future of bioenergy technology translate to large uncertainties in potential for Canada. Lastly, geothermal power, while not included in our estimate, has great theoretical potential and, given technological advances and investment, could at some point satisfy a substantial portion of Canada's energy needs in the West or Northwest.

4.2. Provincial analysis

A key feature of our approach is that we are able to resolve regional differences in the mix and magnitude of potential renewable energy portfolios. Indeed, there are stark differences across the country.

In our scenario, B.C., Saskatchewan, Manitoba, New Brunswick, Nova Scotia, and P.E.I. have about twice the renewable potential they need to meet their present demand. Quebec also has sufficient potential to meet its demand, while Alberta and Ontario do not. It should be emphasized that we could have chosen significantly larger values for solar and wind power in several provinces. Also, Alberta has plenty of renewable potential compared with a normal (Canadian) level of energy consumption; its deficit in our accounting is due to its per capita power consumption being nearly 60% greater than that of the next most voracious province, Saskatchewan. Interestingly, Saskatchewan and Manitoba, which neighbor the deficit provinces Alberta and Ontario, respectively, have particularly large excesses of renewable power, which may pose opportunities for a relatively simple resolution to the nearby deficits.

Another significant finding from our provincial analysis is that New Brunswick and P.E.I. are, in a per capita sense, richly endowed with

[6] A 2002 BC Hydro report conducted case studies on two potential tidal sites in British Columbia and calculated a cost of generation of 14–31 cents/kWh [2, adjusted for inflation to 2012 dollars]. This is well above current electricity costs of 4–10 cents/kWh in major Canadian cities [18, p. 5]. There is, however, considerable uncertainty in BC Hydro's estimate, given its small sample size.

potential renewable energy income, in particular in offshore wind. Even more remarkable is the case of Newfoundland and Labrador. In per capita terms, the onshore wind potential for this province dwarfs its own needs and at current energy prices could generate over $200,000 per household of annual revenue if a market existed for it.[7]

In the Online Appendix B we provide further details and commentary on each province's potential portfolio, including graphical breakdowns of our projections, along with current demand, calculated in per capita units rather than overall power.

4.3. Regional challenges

Despite Canada's vast renewable potential, there are several significant hurdles involved in transitioning to a sustainable energy system. First, there is an uneven regional distribution of energy supply and energy demand. Areas of high renewable energy potential do not correlate with areas of high energy use. Ontario and Alberta cannot meet their energy needs entirely through renewables and Newfoundland and Labrador has 15 times its energy demand in renewables. Even within provinces, tidal, hydroelectric, and some of the most high potential wind sites are not necessarily located near the large population centers.

This unbalanced distribution of energy supply and demand has important policy implications. For example, it does not make sense for Newfoundland and Labrador to fully develop its sizeable wind resource based only on its own low energy demand. Meanwhile, nearby Quebec and Ontario have poor renewable potential relative to their large consumption of energy.

The average annual wind speeds at high potential sites in Ontario and Quebec are only 7.23 m/s and 7.54 m/s respectively, while annual wind speeds at high potential areas in Newfoundland and Labrador average 9.18 m/s. Wind power is proportional to the cube of wind speed, which implies that the average high potential wind site in Newfoundland and Labrador can theoretically generate more than twice the power of average sites in Ontario and Quebec. Transmission costs from Newfoundland and Labrador to Quebec would have to be extraordinarily high to outweigh the benefit of developing Newfoundland and Labrador's wind resource.

Instead of investing heavily in developing its own relatively poor onshore wind resource, as Ontario is now [19,47], perhaps investing in wind farms in Newfoundland and Labrador and High Voltage Direct Current (HVDC) transmission lines to transport power from those wind farms to areas of high demand would be a more optimal use of Ontario's resources. Indeed, for Newfoundland and Labrador to be able to profit from its enormous potential, HVDC links to the northeastern U.S., possibly via Quebec, would likely be a necessary long-term investment.

Similarly, Saskatchewan could share some of its high-potential wind resource with its neighbors in British Columbia and Alberta, and Quebec could also benefit from taking advantage of Newfoundland and Labrador's wind resource.

The gains to trade in this area highlight the need for greater cooperation between provinces with respect to energy planning. Furthermore, it is also important that Canada's transmission grid be upgraded in light of the necessary electrification transformation which would be needed to realize the picture we paint, and to support the transport of large amounts of electricity from province to province. Otherwise, large scale energy trading will not be possible.

[7] The average household size in Newfoundland and Labrador is 2.4. At a domestic energy price of $0.10/kWh, the value of 3000kWh/day would be, annually, ~$110k per *individual*.

4.4. Intermittency challenges

In practice, energy supply does not add up in the fashion of our simple arithmetic, but must be integrated not just geographically but on a host of time scales and over distributions of stochastic production. Canada's renewable energy potential is disproportionately concentrated in two intermittent resources: we find that wind and solar power account for over 60% of Canada's total renewable potential (amounting to 92% of its 2010 demand). However, wind turbines and solar panels can only generate energy when wind speeds are sufficiently high and during the daytime when the sun is shining. These periods do not always coincide with times of high energy demand. Therefore, a power grid heavily reliant on wind and solar power may produce too little or even too much energy at a given time, depending on weather conditions.

Fortunately, most of Canada is rather well suited to implement the known strategies for mitigating this intermittency problem. First, spreading wind and solar power sites over dispersed areas within and across provinces will significantly reduce the variance in their energy output [8]. Second, a large reservoir of hydroelectric power goes a long way to countering intermittency related issues.

Hydropower has the potential to supply over 82 kWh/person/day — equivalent to 42% of Canada's 2010 energy needs. Not only do hydropower plants have a very high (~60%) capacity factor, allowing them to be a reliable and invariant source of energy when needed, but by modulating their flow they can also be used to predictably counteract, and even respond, to some of the variation in power generated from other, less-steady renewable sources. Pumped-storage hydropower plants can even absorb surplus power from wind and solar generation and store it for later use [e.g., 26]. In this regard, B.C., Manitoba, Quebec, and Nova Scotia have particularly enviable mixes of renewable options.

4.5. Electrification and distribution challenges

While we have treated all energy as fungible, in fact the renewable resources we investigate, excepting biomass, can be used only to generate electricity and heat. A large proportion of current energy demand, however, is satisfied through the in situ use of fossil fuels instead of electricity. The transportation sector, for example, almost exclusively uses liquid fuel and heavy industry is also a substantial user of oil and natural gas. While biomass could theoretically be used in place of fossil fuels, as mentioned before, turning biomass into fuel instead of electricity involves another layer of technological development and possible efficiency losses.

While this aspect of adopting a renewable energy system is beyond the scope of this review, it seems likely that it would require the electrification of transportation and industry. In particular, electric cars and trucks may have a large role to play. Their widespread adoption can not only shift energy consumption away from fossil fuels, but could mitigate the intermittency and storage problem, as electric cars' batteries can in principle be used as a store of energy at times of low demand and possibly even as a supplier at times of high demand.

5. Conclusion

This study has revealed that Canada clearly has the physical potential to meet its energy needs exclusively through renewable sources and that the bulk of research and investment should be concentrated in three of these renewables – wind, solar, and hydropower. The technologies needed to develop these three resources are also already presently known and tested and are steadily decreasing in cost. However, we find large heterogeneity across provinces in their likely future renewable portfolio, so that other technologies will have important roles locally. While there are considerable challenges on the path to a Canada powered exclusively through renewable sources — including the uneven distribution of energy supply and demand, intermittency and energy storage issues, and the difficulties inherent in electrifying the economy — these problems are likely surmountable with the right incentives or concerted effort. No doubt transitioning to an exclusively renewable energy system will require massive investment, research, and labor, but Canada does possess the potential to achieve that tall task.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2016.11.061.

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