Energy Policy 113 (2018) 135–148

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The cost of decarbonizing the Canadian electricity system

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ARTICLE INFO

Keywords:
Electricity
Greenhouse gas emissions
Linear programming
Canada
Renewable energy
Transmission

ABSTRACT

Canada's electricity sector is predominantly low-carbon, but includes coal, natural gas, and diesel fuelled power plants. We use a new linear programming optimization model to identify least-cost pathways to decarbonize Canada's electricity sector. We co-optimize investments in new generation, storage and transmission capacity, and the hourly dispatch of available assets over the course of a year. Our model includes hourly wind speed data for 2281 locations in Canada, hourly solar irradiation data from 199 Canadian meteorological stations, hourly demand data for each province, and inter- and intra-provincial transmission line data. We model the capacity of hydropower plants to store potential energy and respond to variations in renewable energy output and demand. We find that new transmission connections between provinces and a substantial expansion of wind power in high wind locations such as southern Saskatchewan and Alberta would allow Canada to reduce electricity sector emissions at the lowest cost. We find that hydropower plants and inter-provincial trade can provide important balancing services that allow for greater integration of variable wind power. We test the impact of carbon pricing on Canada's optimal electricity system and find that prices of \$80/tonne CO_2e render the majority of Canada's coal-fired plants uneconomic.

1. Introduction

With the ratification of the Paris Agreement, the world has committed to "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels" (United Nations Framework Convention on Climate Change UNFCCC, 2015: 2). By some estimates, meeting the 2 °C target will require global per capita greenhouse gas (GHG) emissions of 1.7 tonnes carbon dioxide equivalent (CO_2e) per person by 2050 (Bataille et al., 2015). As context, Canada's per capita GHG emissions were 20.6 tonnes CO2e in 2014 (Environment and Climate Change Canada, 2016).

In this paper, we ask: how much will it cost to decarbonize the Canadian electricity system? Canada starts from an advantageous position. In 2014, Canada generated 78.4% of its electricity using low-carbon technologies such as hydropower plants (60.3%), nuclear power plants (16.2%), and wind turbines (1.8%) (Statistics Canada, 2016 CANSIM 127-0007).[1] The remainder came largely from coal and natural gas power plants. Canadian fossil fuel electricity plants emitted 79 Megatonnes (Mt) CO_2e in 2015, which accounted for 10.9% of Canada's 722 Mt CO_2e GHG emissions total (Environment and Climate Change Canada, 2017).

In our analysis we pay particular attention to the potential for Canada to develop wind and solar energy. Canada has several regions where annual average wind speeds at 50 m (m) elevation reach 7 m/sec (m/s) or better, including the southern Plains of Alberta and Saskatchewan, southern Ontario, and northern Quebec (Global Modelling and Assimilation Office GMAO, 2016; see Fig. 1a). Solar photovoltaic installations can achieve annual capacity factors as high as 16% in sunny areas such as southeast Saskatchewan (MSC & Meteorological Service of Canada MSC and Natural Research Council NRC, 2010; Fig. 1 b). Canada is also the second largest hydropower producer in the world, behind only China and on par with Brazil (Natural Resources Canada, 2016). Canada's hydropower reservoirs can provide balancing services to allow higher integration of wind and solar onto the electricity grid.

Fig. 1a Source: Global Modelling and Assimilation Office (Global Modelling and Assimilation Office GMAO) (2016); author's calculations. Fig. 1b Source: Meteorological Service of Canada (MSC) and Natural Research Council (Meteorological Service of Canada MSC and Natural Research Council NRC) (2010); author's calculations.

We also model whether it is beneficial to build new high-voltage transmission between Canadian provinces. Provinces have different electricity generation profiles (Fig. 2). Hydropower plants are an important source of electricity generation in Quebec, Newfoundland and

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[1] Note that these Statistics Canada numbers are known to underestimate renewable energy production. For example, as of December 2016, the Independent Electricity System Operation (IESO) in the province of Ontario had 4514 Megawatts (MW) of wind power capacity and 2206 MW of solar power capacity under contract (IESO, 2016). By contrast, Statistics Canada (2016) CANSIM 127-0009 reports 2762 MW of wind capacity and 172 MW of solar capacity in Ontario for the year ending 2015. The discrepancy arises because Statistics Canada does not survey facilities below a certain capacity threshold, and neither the IESO or Statistics Canada report generation from "embedded" wind and solar facilities connected to local distribution systems.

http://dx.doi.org/10.1016/j.enpol.2017.10.040
Received 4 February 2017; Received in revised form 10 October 2017; Accepted 20 October 2017

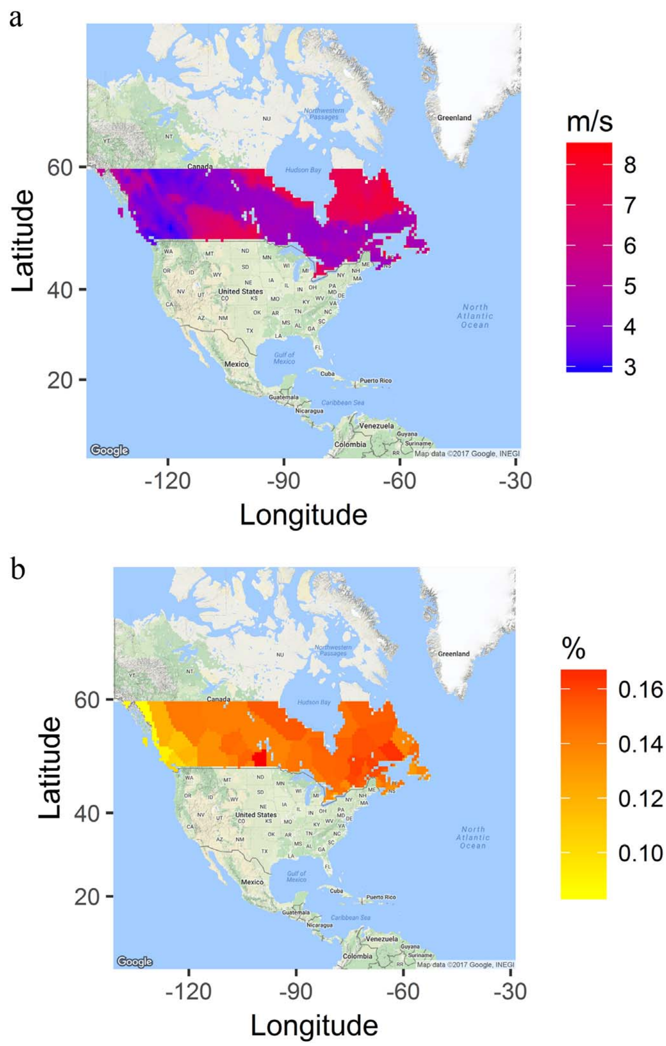

Fig. 1. a Wind speed by MERRA grid cell. b Solar capacity factors by MERRA grid cell.

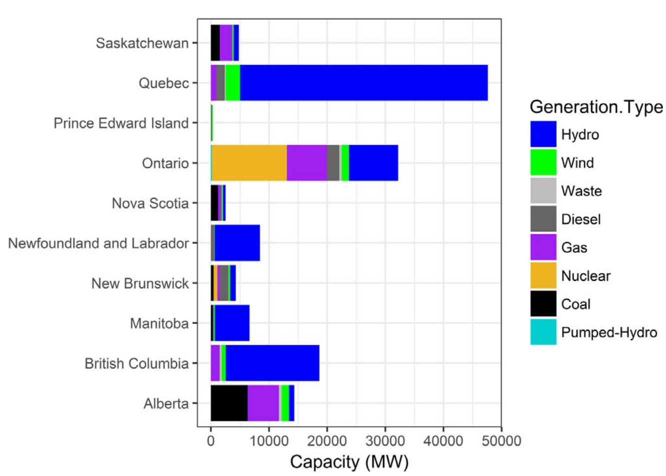

Fig. 2. Canadian electricity generation capacity by Province.[2]

Labrador, Manitoba, and British Columbia. Provinces relying on coal and natural gas fired power plants include Saskatchewan, Nova Scotia, New Brunswick, and Alberta. Geographically, each of the fossil-fuel powered provinces is adjacent to a hydropower province. However, the existing transmission network allows only limited east-west inter-provincial electricity trade. We test whether strengthened transmission connections between provinces can lower the cost of reducing electricity sector GHG emissions in Canada.

Other recent studies of decarbonizing the Canadian electricity sector include the Trottier Energy Futures Project TEFP (2016), General Electric International GE (2016), and Ibanez and Zinaman (2016).

The Trottier Energy Futures Project (TEFP) (2016) study uses a proprietary version of the *North American Times Energy Model (NATEM)* to identify 11 scenarios for lowering GHG emissions in Canada. The NATEM model represents the electricity sector spatially at the provincial scale and temporally using 16 time-slices to represent the variation of electricity demand (ESMIA, 2017). The Trottier Energy Futures Project (TEFP) (2016) concludes that decarbonizing the electricity sector is an important measure to facilitate GHG emissions reduction in Canada.

The GE (2016) study uses a “heuristic generation expansion planning approach” to understand the potential for integrating wind energy into the Canadian electricity system (p. 23). The GE (2016) study finds that it is technically feasible for wind energy to make up 35% of Canadian electricity generation. This is achieved by expanding wind power capacity to 65 Gigawatts (GW) in Canada with concentrations of 15 GW or more in Ontario, Quebec, and Alberta. In our results, we find similar potential for wind energy, but with a different provincial distribution of installations. The GE (2016) study also identifies one potential set of transmission lines that could be built to aid wind energy integration. Our study uses an optimization approach to assess the value of constructing additional transmission links.

The analysis by Ibanez and Zinaman (2016) jointly optimizes Canadian and United States (US) electricity futures using the NREL *Regional Energy Deployment System (ReEDs)* model. This is a useful approach since there are greater transmission connections north-south from Canada to the United States than there are east-west between provinces within Canada. We model the interdependent nature of the Canadian and US electricity system by including hourly export data from Canadian provinces to the US. This simplification means that we do not co-optimize investments in generation and transmission capacity between Canada and the United States. Instead we focus on actions Canada can take within its borders to decarbonize and optimize electricity supply. The NREL ReEDs model contains 47 wind and solar power resource regions within Canada and 17 time-slices to represent spatial and temporal variation in renewable energy supply and electricity demand (Ibanez and Zinaman, 2016).

Our contribution to the literature is threefold. First, we model the Canadian electricity system with much greater spatial and temporal resolution than previous studies. We include hourly demand data over the course of a year for each province (8760 hourly time steps), hourly wind resource data for 2281 grid cells south of 60° latitude in Canada, and hourly solar resource data for 199 meteorological stations south of 60° latitude. In contrast, the NATEM (Trottier Energy Futures Project (TEFP), 2016) and ReEDS (Ibanez and Zinaman, 2016) models use representative temporal snapshots of electrical grid operation (called time-slices), and lower spatial resolution for their wind and solar data.

We use the high resolution spatial and temporal data to co-optimize investments in new generation with the hourly dispatch of available generation assets over the course of a year. The hourly wind and solar resource data in our model allows us to account for the variability of electricity supplied by renewable energy. Our co-optimization approach is most similar to MacDonald et al. (2016) who evaluate the potential for greater renewable energy integration in the United States. MacDonald et al. (2016) find that increased investment in wind and solar power could allow the United States to reduce electricity sector GHG emissions by 80% below 1990 levels without increasing electricity costs. We find that wind energy is a low-cost means of reducing GHG emissions in Canada. At a carbon price of \$200/tCO_2, investments in wind can achieve GHG reductions of 83–87% below 2025 reference scenario emissions and would increase average electricity costs by \$12 to \$13/Megawatt-hour (MWh). In these low-carbon scenarios, wind energy meets 30–35% of electricity demand despite its variability.

Our second contribution to the literature is evaluating the desirability

[2] This figures shows existing Canadian electricity capacity, minus expected retirements by 2025. Data is collected from various sources outlined in the Supplementary Information (SI) document that accompanies this paper.