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PERSPECTIVE

Decision support for United States–Canada energy integration is impaired by fragmentary environmental and electricity system modeling capacity

Ryan S D Calder[1,2,3,*], Emil Dimanchev[4], Stuart Cohen[5] and Ryan A McManamay[6]

[1] Department of Population Health Sciences, Virginia Tech, Blacksburg, VA 24061, United States of America
[2] Global Change Center, Virginia Tech, Blacksburg, VA 24061, United States of America
[3] Department of Civil and Environmental Engineering, Duke University, Durham, NC 27708, United States of America
[4] Department of Electric Energy, NTNU—Norwegian University of Science and Technology 7491 Trondheim, Norway
[5] National Renewable Energy Laboratory, Golden, CO 80401, United States of America
[6] Department of Environmental Science, Baylor University, Waco, TX 76798, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: rsdc@vt.edu

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Abstract

The renewable energy transition is leading to increased electricity trade between the United States and Canada, with Canadian hydropower providing firm lower-carbon power and buffering variability of wind and solar generation in the U.S. However, long-term power purchase agreements and transborder transmission projects are controversial, with two of four proposed transmission lines between Quebec, Canada and the northeast U.S. cancelled since 2018. Here, we argue that controversies are exacerbated by a lack of open-source data and tools to understand tradeoffs of new hydropower generation and transmission infrastructure in comparison to alternatives. This gap includes impacts that incremental transmission and generation projects have on the economics of the entire system, for example, how new transmission projects affect exports to existing markets or incentivize new generation. We identify priority areas for data synthesis and model development, such as integrating linked hydropower and hydrologic interactions in energy system models and openly releasing (by utilities) or back-calculating (by researchers) hydropower generation and operational parameters. Publicly available environmental (e.g. streamflow, precipitation) and techno-economic (e.g. costs, reservoir size,) data can be used to parameterize freely usable and extensible models. Existing models have been calibrated with operational data from Canadian utilities that are not publicly available, limiting the range of scientific and commercial questions these tools have been used to answer and the range of parties that have been involved. Studies conducted using highly resolved, national-scale public data exist in other countries, notably, the United States, and demonstrate how greater transparency and extensibility can drive industry action. Improved data availability in Canada could facilitate approaches that (1) increase participation in decarbonization planning by a broader range of actors; (2) allow independent characterizations of environmental, health, and economic outcomes of interest to the public; and (3) identify decarbonization pathways consistent with community values.

1. Introduction

The United States and Canada are each other's top energy partners, and integration is increasing; from 2002 to 2022, the value of bilateral energy trade across all sectors increased from \$49.2 to \$190.4 billion (2022-USD) (U.S. EIA 2023). Net electricity exports from Canada to the U.S. averaged 50 TW h yr^{-1} in 2018–2022 as compared to 27 TW h yr^{-1} in 1998–2002 (U.S. EIA 2024b). The value of those exports peaked at \$4.4 billion in 2022 (United States Census Bureau 2024). Yet, as this trade has increased, debates have intensified over the role of Canadian hydropower in U.S. electricity systems and the expansion of transborder transmission capacity.

Hydropower is central to U.S.-Canada electricity trade. Canada has >82 GW of installed hydropower capacity supplying ∼60% of generation nationally, with an estimated 160 GW of technical potential (IHA 2022, Canada Energy Regulator 2024). In 2022, Quebec and British Columbia, where hydropower accounts for >90% of electricity generation (Canada Energy Regulator 2024), accounted for 56% of transborder electricity trade (up from 45% in 2005) (Statistics Canada 2024). Canada's hydropower is likely needed to balance variable renewable generation and/or provide firm capacity as the U.S. decarbonizes its electricity sector (Arbuckle *et al* 2021, Dimanchev *et al* 2021, Rodríguez-Sarasty *et al* 2021, Canada Energy Regulator 2023).

Proposed transborder transmission projects have generated controversy regarding: the potential for new transmission to stimulate hydropower development in Canada (Gazar *et al* 2024); their ability to increase imports versus simply reallocate imports from other markets (Energyzt Advisors 2020); the population over which to calculate costs and benefits (e.g. costs to ratepayers in the U.S. vs. global social costs of greenhouse gas emissions) (Calder *et al* 2020); measures of the 'cost' of hydropower, which has negligible marginal cost but uncertain opportunity cost (Calder *et al* 2022); and the fairness of sales prices negotiated in the absence of publicly verifiable models of buyer and seller alternatives (Wald 2012). Of four large (∼1 GW) transmission projects between Quebec and the northeast U.S. proposed since 2018, two (through New Hampshire) have been cancelled, while a third (through Maine) was suspended following a statewide referendum before a legal challenge allowed work to resume (Gazar *et al* 2024).

Likewise, environmental and economic controversies have delayed hydropower development in Canada. Capital costs for the 824-MW Muskrat Falls project in Labrador are now estimated at $13.5 billion, as compared to $7.4 billion at sanction in 2012, and first power was delivered in 2020 rather than 2017 (Nalcor Energy 2018, CIMFP 2020, Butler 2023). Environmental assessment excluded impacts on the Labrador Inuit, leading to social unrest and the creation of a committee that proposed last-minute engineering interventions to reduce health impacts (Calder *et al* 2021). Similar controversies have occurred with Site C in British Columbia (Bakker and Hendriks 2019). Accounting for observed cost overruns (14%–100%) reduces projected growth of Canadian hydropower between 2015 and 2050 from +149 TW h yr^{-1} to +35 to +118 TW h yr^{-1} (Hollmann *et al* 2014, Arbuckle *et al* 2021). Overall, these controversies jeopardize public perceptions of the legitimacy of decarbonization pathways pursued by policymakers.

Regional or national planning studies identify least-cost energy portfolios subject to technical, environmental, and socio-political constraints (Pérez-Arriaga *et al* 2008, Dimanchev *et al* 2021, Rodríguez-Sarasty *et al* 2021). Project-scale studies can capture certain site-specific costs and benefits in more detail, but there is a lack of open-source tools to model second-order impacts of individual projects on the electrical system more broadly (Calder *et al* 2022, Dolter *et al* 2022). In general, there is a need for tools to (1) screen new projects that balance direct economic costs with environmental, economic, or other impacts; (2) account for detailed hydrologic constraints that govern the economics of hydropower; and (3) estimate how individual projects affect the economics of electricity markets, which governs decisions over new projects.

This article describes how controversies and tradeoffs can be better anticipated and managed through (1) enhanced data availability; (2) the development of models to better capture the impact of individual projects on economic and environmental outcomes governed by the energy system as a whole; and (3) engagement of stakeholders in model development and execution to inform characterizations of environmental, economic, and health outcomes of interest. While such open-source tools exist to guide decision-making within the U.S., models involving the Canadian electricity system are limited by poorer data availability in Canada, thus complicating the realization of an integrated, low-carbon energy system consistent with public values (Mowers *et al* 2023, MIT Energy Initiative and Princeton University ZERO Lab 2024).

2. Hydropower and integrated environmental modeling

2.1. Database of candidate sites

There is a need for a publicly accessible atlas of hydropower potential to identify candidate sites for development. This database should (1) query a hydrographic model (section 2.2) to characterize how dam height and location would affect reservoir size and generation profile; (2) display environmental (e.g. presence of key species) and socioeconomic (e.g. proximity to vulnerable populations) information to allow environmental risk assessment (section 2.3); (3) display configuration parameters (e.g. distance from existing electrical and transportation networks) to enable cost estimation; and (4) be used in the parameterization of more detailed energy systems models (section 3).

Yukon, British Columbia, and Manitoba have undertaken formal screening analyses to identify sites for hydropower development (Monk *et al* 2009, Esri Canada 2013, Manitoba Hydro 2013, Midgard Consulting

Inc 2015). Yukon's analysis included economic and technical considerations but not environmental or health impacts. B.C.'s analysis is not openly accessible. Only Manitoba offers public data on unutilized hydropower potential. These efforts underline the need for a publicly available platform that supports screening based on user-supplied constraints and valuation of diverse economic and environmental criteria. By contrast, the United States Department of Energy supports hydropower resource assessment based on a variety of technical, economic, and environmental parameters, offering a template (McManamay *et al* 2014).

2.2. Regional, basin-specific hydrologic models

Integrated hydropower/energy systems models have been difficult to develop given the range of timescales of interest, the complexity of constraints, and the computational demands of both hydrologic and energy models (Stoll *et al* 2017). A simplified model bridging outputs of regional capacity expansion forecasts and environmental constraints on new and existing hydropower installations may be feasible through emulated i.e. statistical simplifications of mechanistic, hydrologic models and robust sensitivity analysis (Gladish *et al* 2017).

Hydropower resource potential can be characterized at the site level by coupling publicly available digital elevation models with emulated streamflow models. Cyr *et al* (2011) identified 696 sites in New Brunswick with hydro potential ⩾92 kW based on Q_{95} (95th percentile flows). Tefera and Kasiviswanathan (2022) characterized global run-of-river hydropower potential at Q_{30}, Q_{75}, and Q_{95} streamflow levels along with the likely direct costs. Available models, however, have not represented storage and buffering dynamics of reservoirs or been coupled with environmental impact or energy systems models, limiting the ability of available screening tools to inform energy planning decisions.

Other authors have characterized the impact of potential future hydrologic regimes on hydropower generation potential with temporally resolved models that simulate reservoir storage as a function of complex environmental phenomena including snow melt (Minville *et al* 2009, Beiraghdar 2019). However, these models have generally been developed to understand the role of environmental conditions on the performance of existing assets rather than to understand the pressures imposed by evolving commitments (e.g. increased exports) or the impact of added generation and transmission. These models are also parameterized with data supplied by utilities, limiting application to questions of potential commercial significance.

2.3. Environmental and health receptor models

Local hydrographic features and plant design choices determine reservoir size, which interacts with hydrologic and other environmental conditions to determine environmental impacts such as minimum flow requirements and methylmercury and methane production (Calder *et al* 2016, Beaulieu *et al* 2020). Meanwhile, the vast majority of planned or developed hydroelectric capacity in Canada is located within 100 km of Indigenous populations whose traditional foodways are adversely affected by reservoir development (Rosenberg *et al* 1997, Calder *et al* 2016). Yet, currently available screening models are underutilized in capacity expansion decision-making.

Previous work has developed screening-level models for methylmercury production, downstream transport, and uptake into food webs (Harris *et al* 2009, Calder *et al* 2016) as well as methane production and emissions (Delwiche *et al* 2022). These models can relate local environmental conditions and design parameters (e.g. residence time) to forecast the magnitude of impact. Even where forecast uncertainty is high, such models are still useful for comparing alternatives because uncertainty associated with underlying environmental parameters tends to be correlated across sites and scenarios (Reichert and Borsuk 2005).

Overall, the decision support capacity of generation expansion screening models can be integrated with environmental impact forecasting and equity considerations, such as the location and extent of treaty or traditional lands and Indigenous population centers (NRCan 2017, Native Land Digital 2024). In particular, forecasts for methane emissions are essential to compare climate benefits and impacts across alternative projects and scenarios (Marten and Newbold 2012).

Early and regular engagement of policymakers, Indigenous groups, and other advocacy organizations is necessary to ensure that models support analysis of environmental, health, and economic impacts of interest. Gaps between the output of existing models and the priorities and interests of these groups have been responsible for much of the controversy that has delayed and derailed recent transborder energy planning. Successful engagement in model development and execution may provide 'policy benefits' (Calder and Schartup 2023) by providing a scientifically defensible characterization of the tradeoffs and impacts of concern to stakeholders and rightsholders.

3. Enhancing energy systems models

3.1. Integrated hydrological modeling

Enhanced models are needed to capture the interrelationships between individual hydropower plants on the same river system. The operational regime of one hydroelectric facility can affect the economics of downstream reservoirs; in Quebec, Manitoba, and British Columbia, the largest complexes are hydrologically linked. Some previously developed models capture interactions between individual plants but some use proprietary data while others include only some reservoirs and are not publicly accessible (Minville *et al* 2009, Bouffard *et al* 2018, Rodríguez-Sarasty *et al* 2021).

This gap limits the ability of energy systems models to evaluate impacts of proposed projects, notably with respect to: how incremental transmission or generation projects affect the economics of the system as a whole; the environmental, economic, or health tradeoffs of proposed projects in comparison to alternatives; the operational flexibility of the hydropower system, increasingly important with the increasing prevalence of variable renewables; and equal access to information between U.S. states and Canadian utilities in contractual negotiations.

Open-source energy models should use public data on historical and projected inflows by reservoir (section 2.2). While meteorological time series used to inform wind and solar availability in these models commonly feature an hourly resolution, hydropower availability is typically available only at seasonal or monthly resolution. Therefore, existing hydrologic datasets at the hourly scale (ECCC 2024a) need to be processed into a format usable as inputs into energy systems models.

While open-source models may not be as accurate as those developed with proprietary data, they would be more extensible and usable by a broader range of actors. Models with enhanced hydrological representations do not have to start from scratch but instead researchers can add improvements to existing open-source tools such as GenX (MIT Energy Initiative and Princeton University ZERO Lab 2024), used in Dimanchev *et al* (2021). This tool already covers both U.S. and Canadian power systems. Interactions between energy and hydrological systems can leverage recent open-source hydrological models (Miara *et al* 2019, Tomlinson *et al* 2020, Stark *et al* 2023)

3.2. Generator characteristics and operational data

Basic information about Canada's generating fleet is fragmentary and incomplete. Available data include lists of (1) all assets with installed capacity ⩾100 MW and (2) renewable assets (including hydropower) with installed capacity ⩾1MW (U.S. EIA 2024c, WRI 2024). These databases include geographic coordinates, nameplate capacity, fuel type, and name of operator. As of August 2024, the most recent data are several years out of date, excluding projects such as Romaine-3 (395 MW, completed in 2017), Romaine-4 (245 MW, completed in 2020), and Muskrat Falls (824 MW, completed in 2021).

Utilities in each province publish this data for generators they own and operate, but reporting for privately owned assets is less consistent. Hydro-Québec publishes a list of generators with watershed and river name, installed capacity, number of units, hydraulic head, and commissioning date (Hydro-Québec 2024). It also publishes a less detailed list of privately owned generators connected to its grid (Hydro-Québec 2023). Other provinces publish less information. For example, the testimony of the president of Newfoundland Power to the Commission of Inquiry Respecting the Muskrat Falls Project included a list of generating assets printed from Wikipedia (Alteen 2018). More detailed characteristics such as average capacity factor, site-specific emissions data, etc is unavailable for any province.

By contrast, annual capacity factors, heat rate, and emissions factors are available for all U.S. generators of at least 1 MW in capacity (U.S. EIA 2024a). Hourly generation and emissions data are available for fossil fuel generators throughout the U.S., although hydropower-specific operation data is limited in the U.S. as well (U.S. EPA 2024). Further information is provided by grid operators including planned capacity additions and retirements (NYISO 2021) and real and synthetic performance statistics for wind and solar generators (ISO New England 2024).

3.3. Transmission characteristics

Energy system models can be further enhanced through more realistic representation of the transmission system. This includes line flow capacity limits between nodes and/or regions, planned new builds, transmission types (e.g. AC vs. DC), and characteristics such as impedance. Detailed characteristics such as transmission type are important because they establish the flexibility and efficiency of a given transmission line for managing bidirectional flows. Energy system models should capture the existing transmission system and allow future expansion to be co-optimized together with generation investments. They should also consider interconnection distance and cost. These factors are becoming increasingly important in the context of growing electricity demand often met by remote generators.

Such tools might have clarified certain aspects of recent debates had they been available. For example, opponents to a recent corridor between Quebec and New York City claimed that existing transmission infrastructure was underutilized; proponents claimed that new transmission was needed to bypass bottlenecks and prevent hydropower from competing against upstate wind and solar (Calder *et al* 2020, Energyzt Advisors 2020). Likewise, a perception that a corridor through New Hampshire would only benefit Massachusetts played a role in its ultimate cancellation (Society for the Protection of New Hampshire Forests 2021, Kroot 2021).

3.4. Hydropower costs

In addition to the hydropower resource data described in section 2.1, updated cost estimates for new Canadian hydropower are critical to assess its competitiveness with other technologies. This is especially urgent considering the recent history of cost overruns. The median Canadian hydropower project has costs 64% higher than the class-5 estimate (186% at the 90th percentile) (Hollmann *et al* 2014). NREL's Annual Technology Baseline (ATB) provides a template for future cost estimates in the Canadian context, identifying capital, fixed operation and maintenance, and variable operation and maintenance costs by technology (NREL 2024). The ATB demonstrates that even aggregate cost numbers can have broad analytical use without infringing on intellectual property rights or divulging business-sensitive information.

4. Conclusion

An extensive literature describes how the active involvement of affected communities (including Indigenous rightsholders), environmental advocates, researchers, and other parties is essential for social acceptance of renewable energy projects (Shaw *et al* 2015, Colmenares-Quintero *et al* 2020, Segreto *et al* 2020). This article has identified priorities for model and data synthesis that, while not sufficient on their own, would support more participatory decision making in the context of deepening U.S.–Canada electricity integration.

So far, such efforts have been hindered by data availability that is poorer in Canada than in peer countries (Music *et al* 2022, Stewart *et al* 2023). Canadian governments have operated on a cost-recovery model for data, pushing costs beyond the means of researchers (Klinkenberg 2003, ECCC 2024b). Supply of this data is hindered by there being few decision-making actors: utilities are publicly owned and coordinate project reviews with governments in a 'flexible' regulatory system that presents fewer opportunities for meaningful challenge and intervention of outside actors than in the United States (Warner and Coppinger 1999, Holburn 2012). Finally, governments can be hesitant to disseminate commercially relevant data for facilities they own through public utilities. At present, reliable analysis of dynamics connecting the project scale to the energy system scale can be done by relatively few entities, which inherently limits the diversity of opinions and concerns when deciding the range of scenarios they characterize, modeling assumptions made, etc.

In the United States, data on costs and operational characteristics of individual generators is typically available through regulatory processes or public resource and cost assessments, and sometimes component or subsystem cost and performance data is available as well. This allows for finely resolved models of the electricity system capable of characterizing the impacts of alternative technology adoption scenarios on costs, reliability, emissions, and other outcomes of interest (Ho *et al* 2021). Finely resolved models can characterize the spatial distribution of impacts and benefits, which is crucial, as perceptions of inequitable distribution of impacts and benefits have played a major role in the failure of proposed renewable energy projects. As described above, these perceptions have played a major role in the recent difficulties increasing transborder transmission capacity. Current gaps in data availability limit the extent to which widely used tools can identify optimal pathways involving Canadian hydroelectric resources. For example, the NREL ReEDS model is limited by unavailability of Canadian hydropower supply curves and other features that are by contrast available in the United States (Zinaman *et al* 2015).

Impactful analysis using the tools discussed herein will require synthesis of existing limited data and creation of new datasets from mining engineering and commercial documents and other sources, such as remote sensing technologies. This undertaking will also need to overcome challenges typical of interdisciplinary research, such as fewer funding mechanisms, incompatible analysis paradigms, and dispersed audiences (Seitter *et al* 2022, Calder and Schartup 2023). If successful, both Canada and the U.S. could more effectively plan for a reliable, just, low-carbon future.

Data availability statement

No new data were created or analysed in this study.

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ORCID iDs

Ryan S D Calder https://orcid.org/0000-0001-5618-9840
Emil Dimanchev https://orcid.org/0000-0001-8240-5922
Stuart Cohen https://orcid.org/0000-0001-8389-6516
Ryan A McManamay https://orcid.org/0000-0002-5551-3140

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