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Citation for published version:
Aubin, V, Blais, M & Anjos, MF 2021, 'How Québec can support the energy transition of northeastern North America', *The Electricity Journal*, vol. 34, no. 6, 106972. https://doi.org/10.1016/j.tej.2021.106972

Digital Object Identifier (DOI):
10.1016/j.tej.2021.106972

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
The Electricity Journal

How Québec can support the energy transition of northeastern North America

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ARTICLE INFO

Keywords:
Hydropower
Energy transition
Renewable intermittency
American Northeast
Modelling
Optimization

ABSTRACT

Northeastern North America is transitioning rapidly from fossil fuel generation to variable renewable energy (VRE) sources such as wind and solar. Their integration into electricity grids poses challenges in terms of matching supply with demand. When VRE represent a large share of installed capacity, intermittency and variability of their production will become an issue. Hydro-Québec, the public electric utility in the Canadian province of Québec, has a large hydropower generation fleet. Its storage capacity that enables postponing hydro production, when the system needs it, can support VRE integration. Potential impacts of the VRE growth within neighbouring grids are simulated through modified operational production management models. Results show that Hydro-Québec has the potential to facilitate this energy transition. However, the current electricity market structure does not provide incentives for an optimal contribution.

1. Introduction

In the current context of seeking to reduce reliance on fossil fuels, a significant growth of variable renewable energy sources (VRE) such as wind and solar within energy networks is foreseen in the next few years [8]. Their integration into electricity grids poses challenges in terms of matching supply with demand. When VRE represent a large share of installed capacity, intermittency and variability of their production will become an issue. VRE must therefore be combined with technologies offering flexibility in terms of network management. This flexibility can be provided by storage devices that can buffer VRE surplus as well as power plants with overcapacity allowing rapid variations in production.

Hydropower plants can store energy using their reservoirs. Their turbine-generator units can instantly modify throughput to follow load with their adjustment range and inertia. Short unit startup and shutdown times enable quick changes of generation levels. Hydropower has the potential to facilitate integration of VRE, in addition to being inexpensive, renewable and low-greenhouse gas-emitting in northern regions [15].

In recent years, interest has grown towards large hydropower generating fleets [4, 5, 12], as it is believed that they can support decarbonization of nearby power grids. Hydro-Québec, the public electric utility in the Canadian province of Québec, has such a generation fleet. Its neighbouring markets, which encompass New England states, New York State and the provinces of Ontario and Eastern Canada, experience or plan an increased use of VRE [18, 14, 11]. At the same time, New England, New York State and the province of New Brunswick have expressed their interest in concluding new commercial agreements with Hydro-Québec, in order to buy more electricity [16, 6, 10]. Various studies investigate a potential increased coordination in the Northeast Power Coordinating Council (NPCC), the electric reliability council of this region [1, 17, 3]. They conclude that Québec's hydropower could allow VRE integration at lower costs through energy storage, and that new transmission lines combined to a reform of markets might be useful for this purpose.

This paper focuses on potential impacts of the growth of VRE within neighbouring networks on Hydro-Québec's hydropower generation fleet. In the event that Hydro-Québec's balancing potential, and no longer just its energy production, would be exploited in the future, the management of its operations would be modified. This could impact

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its facilities and operations. The study contributes to the research field by detailing specific impacts of VRE balancing on hydropower, while being supported by comprehensive simulations of its water systems and electric grid. The work presented was carried out within the Optimization and Mathematical Modelling unit of the Production and Operation Department of Hydro-Québec Production. Its operational production management models were used to simulate new dynamics associated with the growth of VRE.

Following the introduction, Section 2 outlines the methodology used to simulate Hydro-Québec's operations assuming different energy mixes in neighbouring markets. Section 3 describes the scenarios used for the case study. In Section 4 results and a discussion on their significance are presented. Section 5 summarizes the main findings and suggests further research.

2. Methodology

In order to evaluate the impacts of VRE integration for Hydro-Québec, its operational production management models were used to preview new dynamics associated with VRE growth. The adapted models can simulate the operation of the generation fleet assuming different energy mixes in neighbouring networks. These are integrated into the model by different patterns of electricity spot prices that high VRE penetration could generate.

The two operational production management models used are deterministic optimization models. One covers medium-term horizons i.e., a few years, while the other considers short-term horizons, which go from a few days to a few weeks. Both models account for all current generation and transmission already in place, that is to say every water system as well as a simplified representation of the electric grid. For each water system, every plant is modelled with its reservoir, if it has one. Natural and river inflows are taken into account. Plants can either generate power from or spill incoming water. Transmission of generated electricity is modelled on Hydro-Québec's power lines until it reaches the demand area it must supply or an interconnection to a neighbouring market. The main constraints of the models are the following:

- Operational limits on flows, volumes, generation and transmission;
- Water conservation at each plant and water system;
- Maintenance schedule;
- Hydropower generation functions;
- Balance between supply and demand.

The models are solved by using a linear or mixed integer solver. Hydropower generation functions are approximated using piecewise linearization. Due to the size of the models ($\mathcal{O}(10^6)$ variables and $\mathcal{O}(10^7)$ constraints), a near-optimal solution is obtained through an iterative sequence. The objective is to maximize the revenues from sales to neighbouring markets while meeting the demand in Québec.

Apart from the time horizon, the models differ in two aspects. First, the short-term model contains integer variables in order to represent the number of active generating units at each plant, while the medium-term model approximates the production of combined units with a continuous function at the plant level. Second, the short-term model uses a time step of one hour whereas the medium-term model uses a time step of one week. However, each week is divided into five categories of hours. The grouping of hours is made according to the corresponding level of load: very high, high, medium, low and very low. The definition of these levels varies for each week: the high load level of a summer week may correspond to the low load level of a winter week. For each week five categories of hours are obtained, for which different values can be assigned to certain variables, such as the generation of a power station or the transmission on a power line.

For simplicity, real interconnections are aggregated into three virtual interconnections: one with New England (NE), one with the province of Ontario (ON) and one with New York State (NY). These three regions are Hydro-Québec's main export markets. At the various interconnections between Hydro-Québec and each of these markets, the current price of electricity is assumed to be sufficiently uniform to allow such aggregation of interconnections.

The operational models can simulate the operation of the generation fleet under various market conditions, represented by selected price patterns. VRE penetration should impact price patterns in the markets of the networks surrounding Hydro-Québec. Studies have been carried out and are in progress to establish quantitatively the expected transformation of the current electricity market [13, 3]. Price patterns from those studies are used in this research as inputs to represent VRE penetration in Hydro-Québec neighbouring markets. The greater the share of VRE in Hydro-Québec's export markets, the more these prices experience strong and rapid variations over time. The optimizer tends to buy during periods of high VRE production, which results in low prices, and to sell during periods of low VRE production, which results in high prices.

Revenue maximization is consistent with harnessing Hydro-Québec's potential to efficiently balance supply and demand for its neighbouring markets. The amount and timing of power exchanged depend on price patterns and interconnection limits. We consider that maximizing revenue correctly represents the hydropower generation's behaviour given nearby market prices, as it balances the VRE generation fluctuations reflected by price variations.

3. Scenarios

To assess the effect of VRE growth in Hydro-Québec's neighbouring grids on its operation, scenarios with varied price patterns are tested. An overview of these price profiles and energy mix they suppose is presented in Table 1 and in Figure 1. Price profiles for all three studied markets (NE, ON and NY) are only provided by IHS Markit. Price profiles of missing markets in the two other studies (Seel and al., 2018 [13], Dimanchev, 2020 [2]) are estimated by scaling other price profiles they provided. All of the scenarios assume an increased demand in Québec, based on Hydro-Québec Distribution forecasts [7], and median water stocks and inflows. The net energy exchanged is therefore equivalent regardless of the price profile used.

Table 1
Price profiles in Hydro-Québec's neighbouring markets

Organization	Price profile	Forecasted year	Scenario and energy grid description
LBNL [13]	LowVRE	2030	Baseline scenario, 2016 VRE share of generation
	BalancedVRE HighSolar HighWind	2030	VRE generation share of 40%
IHS Markit	BAU2020	2020	Baseline scenario
	BAU2030 BAU2050	2030 2050	Continuity, 76% decarbonization in 2050
	FST2030 FST2050	2030 2050	High electrification, 90% decarbonization in 2050
MIT CEEPR [2]	BC90 HE90	2050	90% decarbonization

LBNL: Lawrence Berkeley National Laboratory
CEEPR: Center for Energy and Environmental Policy Research
BAU: business as usual, FST: fast transition, BC: base case, HE: high electrification

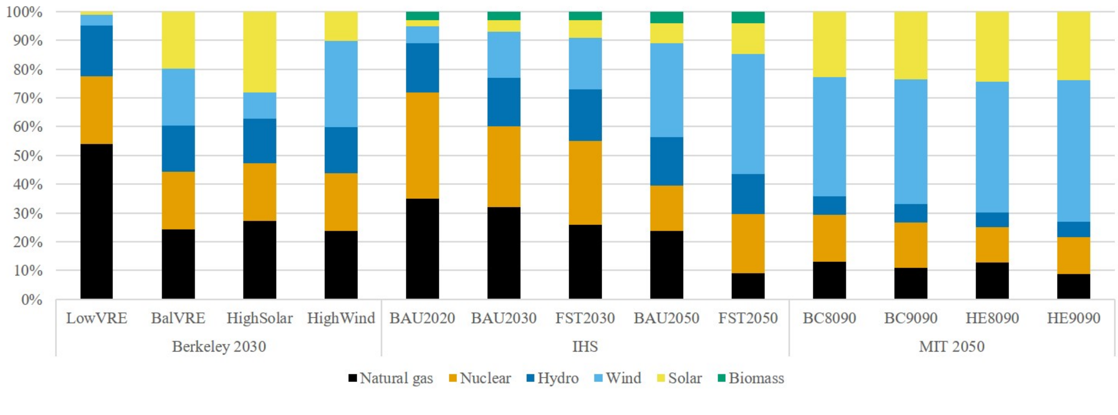

Figure 1: Comparison of Hydro-Québec's neighbouring markets' energy mix for various scenarios

4. Results and discussion

4.1. Storage potential

Hydro-Québec can virtually store excess energy generated by VRE in neighbouring markets and return it when needed, through purchase/resale operations based on price arbitrage. Hydro-Québec shifts its generation according to those exchanges and meanwhile stores water in its reservoirs of total capacity of 176 TWh. Depending on the conditions, this purchase-resale cycle can take place within an hour as well as over several years. Annual or multiannual storage is especially interesting, as it is a service that other storage technologies like batteries can hardly provide. Results from simulations show that, while maintaining net exports of at their current level, Hydro-Québec could provide annual storage ranging from 3 to 6 TWh depending on the price profile. The graph in Figure 2 shows the annual storage shift with the HighWind scenario in comparison to the LowVRE scenario, both from Seel and al. [13].

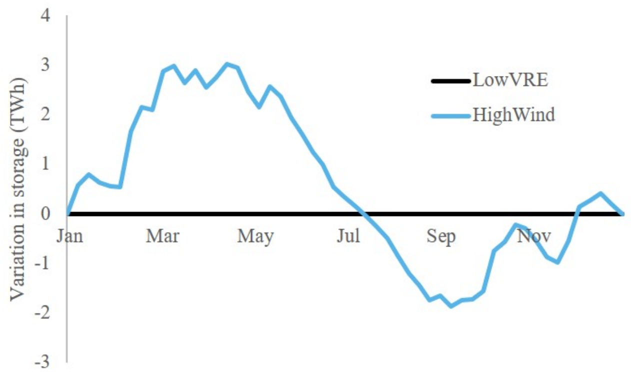

Figure 2: Storage shift compared to a reference case (LowVRE)

4.2. Sustainable changes in generation

Shifting generation due to price arbitraging with high VRE markets will drive operational changes at Hydro-Québec. Generation will be more variable as it partially balances VRE intermittency. Simulations show greater fluctuations occurring over hours as well as over weeks in higher VRE scenarios. Nevertheless, adapting generation to VRE-induced price patterns seems technically possible. Indeed, the number of units startups and shutdowns would be manageable. On a weekly basis, it would increase by no more than 20% and even occasionally decrease. This reduction would be caused by the new seasonal generation patterns that arise with VRE growth, as shown in Figure 3 which compares two scenarios from Seel and al. [13]. All scenarios with high VRE shares increase summer night sales in order to balance solar power and therefore level generation throughout the day.

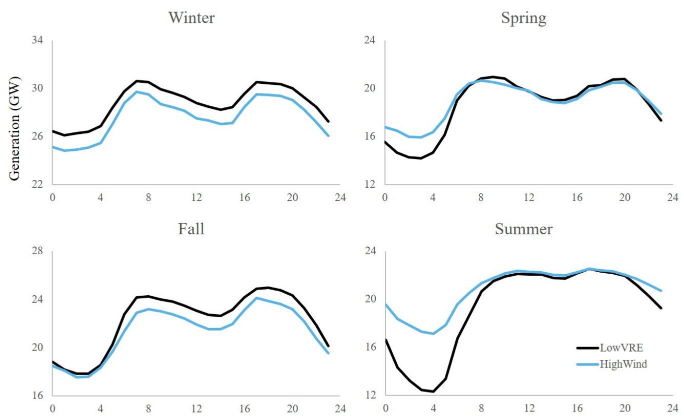

Figure 3: Hourly generation profile for all seasns

4.3. Incentive for flexibility in scheduling units releases for maintenance

As new hydro generation patterns appear more profitable in view of VRE growth in the region, optimal profiles of power availability for maintenance also change. They become more variable over weeks and days. While the analysis with the results of deterministic models is limited, the sharp fluctuations of power availability stress the importance of accurate forecasts of VRE generation and flexible scheduling of maintenance. Dependable maintenance duration estimates will grow in importance as time windows for maintenance become influenced by VRE generation.

4.4. Low revenues with price arbitrage

Greater price variance caused by VRE growth results in more purchase/resale operations because the profit margin increases. Although these transactions produce revenues, they do not compensate for the forecasted energy value drop due to the low marginal costs of VRE. In order to stabilize revenue, it might be more beneficial to Hydro-Québec to focus on the province of Québec's own changing grid. This would restrain the access of NPCC electricity markets to a valuable resource.

5. Conclusions

Hydro-Québec has the potential to facilitate the energy transition in the northeast of North America. Its significant storage capacity can help balance supply with demand throughout the year, a service of high value for energy grids with a high VRE share. Generation fluctuations Hydro-Québec would experience while providing this service would be sustainable, especially if scheduling of units releases for maintenance develops flexibility. However, we found that the income generated by balancing services based on price arbitrage is far from compensating for the forecasted energy value drop due to VRE penetration.

Our results agree with American economist and professor Paul L. Joskow who recalls that VRE are heavily subsidized and hence remunerated outside the market [9]. Electricity prices therefore do not always reflect the cost of the necessary investments. Denouncing in particular the trade barriers to the development of storage services, Joskow pleads for an in-depth reform of the market structures that regulate the electricity sector, in anticipation of the strong growth of VRE which has already started. From this perspective, incentives for an optimal contribution of hydropower to VRE integration could help NPCC electricity markets for the upcoming energy transition.

In order to an even more realistic insight at impacts of VRE on Québec's hydropower system, further research should include possible transformations on the province's own grid. Stochastic models, instead of the deterministic ones that were used for this study, would also better capture the uncertainty of VRE generation.

CRediT authorship contribution statement

Viviane Aubin: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Visualization, Funding acquisition. **Marko Blais:** Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Project Administration. **Miguel F. Anjos:** Conceptualization, Writing - Review & Editing, Supervision.

Data availability

Data used in Hydro-Québec's operational production management models is confidential.

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Acknowledgements

We thank the Lawrence Berkeley National Laboratory, MIT Center for Energy and Environmental Policy Research and IHS Markit for providing energy price data.

Funding: This work was supported by Polytechnique Montréal [grant numbers xxxx, yyyy]; Natural Sciences and Engineering Research Council of Canada (NSERC) [grant number zzzz]; and Fonds de recherche Nature et technologies (FRQNT) [grant number aaaa]. The funding sources had no involvement in the conduct of the research.