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EAST GRID

Getting on an Efficient Decarbonization Track

An Economic Study of a Regional Approach to Electricity Markets in Northeastern North America

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A MESSAGE FROM CANADA GRID

Canada Grid is very pleased to release this report by Pierre-Olivier Pineau and Aïssatou Ba of HEC Montréal, which highlights the positive economic impacts of grid integration in the Canadian-American northeast, or what we call the 'East Grid' zone. This report is the first in a series of documents that will explore the who, what, when, where and why of growing and greening the power grid across Canada.

Canadians are already electrically connected from the Atlantic to the Pacific, but interconnection capacity between provinces varies greatly across the country. We are much more highly interconnected with our American neighbours. We know definitively that the fight against climate change will compel us to dramatically increase the use of electricity in our society, creating a tremendous opportunity to increase clean power trade between the provinces and across the border with our American partners. Despite this imperative, decision-making around the grid remains siloed. We simply do not govern or plan the grid as though it is a shared tool. This harms the collective economic and environmental well-being of North Americans.

Canada Grid was formed by The Transition Accelerator and a growing coalition of corporate, civil society and labour allies to provide independent thought leadership around the pivotal issue of power grid integration. A science-based organization, The Transition Accelerator mobilizes diverse actors to advance ambitious work at the political, commercial, and social levels that will transform our society into a competitive clean energy economy. The grid is vast and complex, it lacks a natural constituency and is therefore the ideal realm to apply The Transition Accelerator's unique methodology that seeks to move from critical analysis to practical action. Influenced by similar coalitions in the United States and Europe, Canada Grid is building a broad-based movement to support infrastructure development, good-paying jobs for workers, and a just energy transition for all Canadians. This report furthers the overwhelming scientific, technical, and economic support for grid integration, and supports our turn from research to consensus-building and action.

Pierre-Olivier Pineau holds the Chair in Energy Sector Management at HEC Montréal, is a Fellow of The Transition Accelerator and is a member of Canada Grid's management board. We would like to thank him and his colleague, Aïssatou Ba, for this important contribution to our understanding of the topic.

Philip Martin Duguay
Managing Director, Canada Grid
The Transition Accelerator

EXECUTIVE SUMMARY

The climate crisis and the related need to drastically reduce greenhouse gas (GHG) emissions call for a quick decarbonization of the power sector and for the electrification of many energy end-uses. The states and provinces in northeastern North America share similar decarbonization goals. There is however no official plan to integrate balkanised electricity markets in this region. Such an initiative would however reduce both the need for additional production capacity and total system costs.

This report's objective is to quantify the economic benefits of creating better intertie capacity between electricity markets in northeastern North America. The benefits of better interconnecting northeastern electricity markets are significant in nature, but not widely acknowledged. Many decarbonization studies ignore integration, which is problematic when game-changing hydropower reservoirs could be used to help reduce the cost of integrating large amounts of intermittent renewable capacity.

Our results show that new renewable capacity requirements fall with new interties. While there are currently about 180 GW of installed capacity in New York, New England, Ontario, Québec, and the Atlantic provinces, 199 GW of additional renewable generation would have to be installed to fully decarbonize, under a moderate load growth scenario (1.5x the 2018 load, with a new winter peaking demand), if more transmission interties can be built. If no more interconnections are possible, 214 GW would be necessary. Under a high load growth scenario (2.5x), it's a phenomenal 348 GW of additional capacity that would be avoided with more regional interconnections: 688 GW of new capacity, instead of 1,036 GW. Of course, total system costs would also be lower with such regional integration, as well as average energy prices.

The main economic beneficiaries of these increased interconnections are New York and New England. As they start with the highest amount of gas-fired generating capacity, they have the most capacity to replace with intermittent renewable units, and therefore the largest storage needs to balance supply and demand. Québec and Labrador hydropower storage, with a combined reservoirs capacity of more than 200 TWh, plays a central role in these results. Ontario and the Atlantic provinces are also well positioned to gain from deeper integration, both from cost reductions and trading opportunities.

KEY TAKEAWAYS

1. **Energy efficiency should be prioritized**, to limit load growth, as otherwise total system costs surge.
2. **The benefits of collaboration are more than monetary.** New interties reduce the amount of additional capacity (and lower ecological impacts from new greenfield developments) and tend to reduce price volatility.
3. **Obstacles to collaboration are multiple** – transfer payments/cost allocation principles must be well designed. As not all sub-regions benefit equally from additional interconnections, and as producers and consumers within each sub-region also face different outcomes, some compensation mechanisms will have to be developed to overcome resistance to change.

Results from this report were derived from conservative estimates, as interconnection costs used in the study are in the higher range and no reserve capacity requirement has been included. Such a requirement would boost the value of interconnections, as they provide the ability of sharing reserves. Our results are also robust to various assumptions on transmission, storage, wind and solar costs.

RÉSEAU CANADA GRID ACKNOWLEDGES THAT THE LANDS WE INHABIT ARE TRADITIONAL TERRITORIES OF INDIGENOUS PEOPLES.

We seek to act on the Truth and Reconciliation Commission's 94 Calls to Action and commit to educating ourselves, and applying the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) as a framework for reconciliation that will inform our principles, norms, policy and core operational activities.

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Pineau, P.-O., Ba, A. (2021). *Getting on an Efficient Decarbonization Track*. Transition Accelerator Reports Vol. 3, Issue 5, Pg. 1-39. (English Report)

1. INTRODUCTION

Canada and the United States have ambitious GHG emission reduction targets for 2030 and beyond. This is especially true for New York and New England, which have put in place different policies to transform their energy sectors. To reach these goals, the power sector must meet a double challenge: (1) to fully decarbonize generation; and (2) to meet increasing demand due to electrification.

Canada Grid, through its East Grid process, aims at fostering a regional dialogue and collaboration to facilitate reaching these two goals in northeastern North America – or what we call here the "East Grid zone". In Canada this region includes Ontario, Québec and the Atlantic provinces. In the United States, New York and New England are part of the region, as shown in Figure 1. These provinces and states already collaborate for reliability purposes through the Northeast Power Coordinating Council (NPCC), a not-for-profit corporation responsible for promoting and enhancing the reliability of the international, interconnected bulk power system in northeastern North America (NPCC, 2021)[1].

Given the scope of the decarbonization challenge, with ambitious 2030 and 2050 objectives, finding the most efficient approaches is key to success. Regional collaboration can offer very important benefits but is not well documented or studied. This report provides results towards this end: making it clearer that the gains from more integration in northeastern North America are well worth the difficulties involved in reforming current planning, procurement, and operating systems.

The rest of this introduction provides some key background information on northeastern North America and summarizes the findings of previous studies on decarbonization, to contextualize the specific findings and contributions of this report.

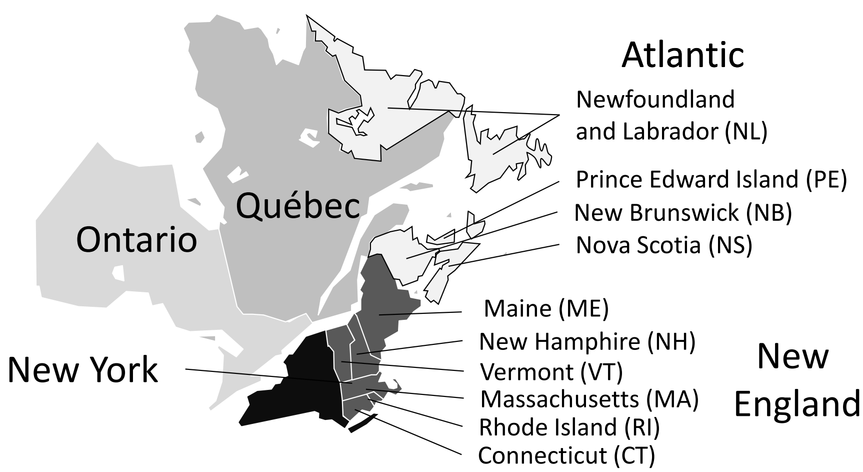


FIGURE 1. NORTHEASTERN NORTH AMERICA (EAST GRID ZONE)

1 Only the province of Newfoundland and Labrador is not formally included in the NPCC, because it was not interconnected with the rest of the NPCC system. With the Maritime Link, a 475 MW HVDC line competed in 2017, Newfoundland is now interconnected with Nova Scotia (NPCC, 2020).

1.1 NORTHEASTERN NORTH AMERICA: KEY DATA AND GHG TARGETS

Northeastern North America is a region of almost 60 million people, generating about 637 terawatt-hours (TWh) of electricity, see Figure 2. In comparison, the United Kingdom with its population of 66 million has a consumption of 326 TWh (IEA, 2020a). There are eight distinct balancing authorities or power markets in the East Grid region, with only New England administering its six-state power grid under the authority of a regional body, ISO-New England. Despite only having 2.4 million citizens, Atlantic Canada's four provinces each have separate balancing authorities and power market operations. For the purposes of this report, we divide the region into five sub-regions, Ontario, Québec, Atlantic Canada, New York and New England.

Generation is very unevenly distributed over the territory, with Québec and the Atlantic provinces having a very large generation sector, for relatively small populations. GHG emissions from the power sector range from almost zero to 27% of each sub-region's total emissions. Low percentages are explained by abundant hydropower (in Québec and Newfoundland and Labrador), and nuclear power in Ontario. The carbon intensity of electricity greatly varies, from 1.2 gram per kilowatt-hour (g/kWh) in Québec to 220 in New England (Table 1). Some provinces and states have more carbon intensive power sectors: Nova Scotia is at 712 g/kWh and Rhode Island at 427 (see Appendix 1 for details).

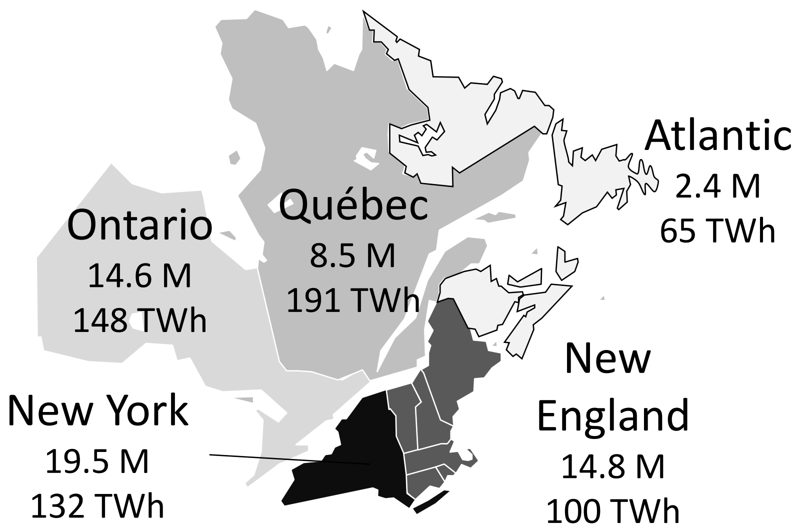


FIGURE 2. POPULATION (MILLIONS) AND GENERATION (TERAWATT-HOURS) IN NORTHEASTERN NORTH AMERICA IN 2019

TABLE 1. POPULATION, ELECTRICITY GENERATION AND EMISSIONS IN NORTHEASTERN NORTH AMERICA, 2019 (2018 FOR US GHG DATA), SOURCES IN APPENDIX 1.

	Population (M)	Electricity Generation (TWh)	GHG (Mt)	Total GHG (Mt)	Carbon intensity g/kWh	Electricity share of GHG
Ontario	14.6	149.0	3.9	163.0	26.0	2%
Québec	8.5	191.0	0.2	83.7	1.2	0%
Atlantic	2.4	65.1	11.1	41.3	170.9	27%
New York	19.5	131.6	24.5	175.9	186.2	14%
New England	14.8	100.0	22.0	148.1	220.4	15%
Total	59.9	636.7	61.8	612.1	97.0	10%

Not only are the generation levels and carbon intensities very different between the five sub-regions, but prices greatly differ. Québec, the province with the highest production capacity, benefits from the lowest residential price (5.15 US¢/kWh, see Table 2). New England has the highest price, with 24.11 US¢/kWh. The paradox in the East Grid zone is that low-price regions have the cleanest electricity. As markets are not integrated, only a limited amount of electricity can flow from low-cost, cleaner sub-regions to high-cost, dirtier sub-regions.

TABLE 2. AVERAGE RESIDENTIAL PRICE, 2020 (HYDRO-QUÉBEC, 2020)

	Reference City	Cents (US$)/kWh
Québec	Montréal	5.13
Ontario	Toronto	7.81
Atlantic	Halifax	11.88
New York	New York	23.69
New England	Boston	24.11

Hydropower in Québec and Labrador[2] can be stored as potential energy in different multi-year reservoirs. In Québec, there is an existing total storage capacity of 176 TWh, controlled by the largest Québec generation company (Hydro-Québec, 2019). In Labrador, the Smallwood reservoir associated to the Churchill Falls plant, has a maximum storage capacity of 27 TWh (Séguin, 2017). Storage in Québec and Labrador could theoretically meet New York's electricity needs for more than a year. A regional wholesale market would better balance consumption levels and prices, leading to both welfare gains and lower emission levels across the East Grid zone.[3]

All provinces and states have either set ambitious GHG reduction targets for 2030 and 2050, or have had targets set for them by the government, as in the case of Canada. Table 3 provides an overview of these targets, with more details in Appendix 1 on each Atlantic province and New England state. In sum, GHG emission reductions in the order of 40% are required for 2030 and beyond 80% for 2050.

TABLE 3. GHG REDUCTION TARGETS (C2ES, 2021A AND B)

	2030	2050
Ontario	40-45% from 2005 level	Federal net-zero target
Québec	37.5% from 1990 level	Provincial net-zero target
Atlantic	40-45% from 2005 level	Federal net-zero target
New York	40% from 1990 level	>85% and state net-zero target
New England	Various targets (see Appendix 1)	State net-zero target or 80% reduction

Given the fact that coal power emissions have already been removed from most provinces and states (only New Brunswick and Nova Scotia still have coal-fired power plants), further GHG emission reductions will have to mostly come from substituting non-emitting generating sources (renewable or nuclear) to natural gas power plants. If electricity demand grows because of electrification of heat and transportation, then additional power generation capacity is very likely to be needed. At the same time, gas-fired power plants must cease emitting GHGs.

2 Labrador is the northwestern part of the Newfoundland and Labrador province, connected by land to Québec.

3 See Billette de Villemeur and Pineau (2016) for an analysis demonstrating this in the case of Ontario and Québec.

In such a context of growing demand and supply restrictions, opportunities to optimize the growth and development of the power sector should be pursued. As we will see from existing decarbonization studies reviewed in the next section, some promising opportunities have been neglected involving regional integration of power systems.

1.2 EXISTING STUDIES AND CONTRIBUTIONS OF THIS REPORT

We summarize here four types of studies from a literature review that are either related to decarbonization or to the East Grid zone:

1. Technical studies of the regional power sector;
2. Large scale decarbonization studies in North America;
3. State-level decarbonization studies; and
4. Regional decarbonization studies.

For each of these recent studies we highlight some key features and findings.

1.2.1 TECHNICAL STUDIES OF THE REGIONAL POWER SECTOR

The NPCC regularly publishes a "Long Range Adequacy Review" for northeastern North America, considering the expected load growth (including new loads from electrification when estimates are available) and generating capacity of the sub-regions. See for instance NPCC (2020). While the title indicates that a "long-range" perspective is taken, only the next 5 years are considered, and longer term GHG emissions constraints are not part of the analysis. In addition, no cost considerations are explicitly integrated.

The analysis is regional and focuses on reliability. It uses General Electric's Multi-Area Reliability Simulation (MARS) program, without trying to optimize investment in new generation and transmission capacity to meet future demand, under new GHG constraints. This series of studies from the NPCC is worth mentioning because a rapid transformation of the grid is required to meet the 2030 targets, and reliability issues will inevitably arise and be within NPCC's area of interest.

The North American Electric Reliability Corporation (NERC), which includes the NPCC and the other five North American regional entities in charge of the reliability and security of the grid, already identifies the changing resource mix as the top perceived risk (by industry stakeholders) faced by the power system (NERC, 2021a). The number one risk profile, out of four recently documented by NERC, is grid transformation.[4] The NERC observes that "current resource planning and resource adequacy assessments are often performed with a limited scope (political or utility boundary) that does not take into account potentially significant electrical impacts and interactions due to the interconnected nature of the bulk grid outside of that limited scope." (NERC, 2021a, p.23). Implicitly acknowledging the shortcomings of the current analysis performed by the NPCC (and the other NERC regional entities), NERC recommends to "expand regionally" the analysis for resource adequacy, energy adequacy, and transmission adequacy, notably for balancing services.

4 The other ones are extreme events, security risks and critical infrastructure interdependencies (NERC, 2021a).

1.2.2 LARGE SCALE DECARBONIZATION STUDIES IN NORTH AMERICA

Typical economy-wide decarbonization studies usually only consider a single country, such as the United States in Larson et al. (2020) and Canada in Bataille et al. (2015). By their nature, they cannot consider potential benefits from increased collaboration between countries, and because of their economy-wide scope, they usually lack a high-level of detail on the power sector.

A North America-wide perspective, including Mexico, the US and Canada, was adopted in the North American Renewable Integration Study (NARIS) conducted by NREL (Brinkman et al., 2021a and b). In this study, focussing on the power sector, regional integration benefits are clearly highlighted. New generation and transmission infrastructure are economically located, based on renewable energy potentials and costs. Trade and internal market rule restrictions are not modelled, so results from this study illustrate the economic potential that could be achieved if markets were operated from a global perspective, rather than responding primarily to sub-regional goals and constraints. However, in the NARIS study, complete decarbonization was not the focus, so results do not fully speak to those interested in zero-emission targets. The continent-wide scope also limits the level of detail provided for regions like northeastern North America. Given that decarbonization of the electricity sector is a state/ provincial responsibility in North America, having state/provincial results is important to guide policies. Otherwise, policymakers in state and provinces will suffer from data gaps.

GIVEN THAT DECARBONIZATION OF THE ELECTRICITY SECTOR IS A STATE/PROVINCIAL RESPONSIBILITY IN NORTH AMERICA, HAVING STATE/ PROVINCIAL RESULTS IS IMPORTANT TO GUIDE POLICIES.

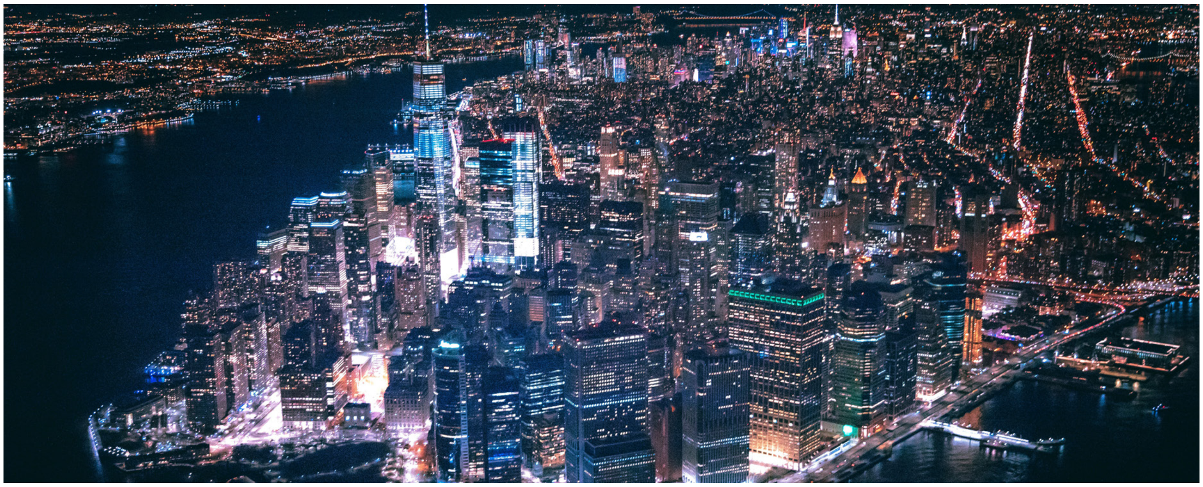


Table 4 provides a summary of key features of these three studies. They illustrate the important expected growth in electricity demand (load growth of two to four times bigger in 2050) and the required large-scale increase in renewable electricity generation.

TABLE 4. KEY ASSUMPTIONS AND RESULTS FROM LARGE-SCALE DECARBONIZATION STUDIES

	US Decarbonization	**Canadian Decarbonization**	**North American Partial Decarbonization**
Study	Larson et al. (2020)	Bataille et al. (2015)	Brinkman et al. (2021a and b)
Scenario	High electrification and 100% renewable	Oil price moderate	Electrification
Horizon	2050		
GHG reduction	Net-zero	1.7 tonnes per capita (from 19.4 in 2019, ≈88% reduction)	80% in the US and Mexico 92% in Canada (from 2005 levels)
Focus	*Articulating a granular picture of prospective transitions. Identify potential bottlenecks to success*	*Reveal resilient decarbonization pathways that can be implemented today and scaled to deeper mitigation ambition in the longer term*	*Feasibility and adequacy of high-renewable scenarios*
Load growth	4x from 2020 from 4,000 to 15,600 TWh	2.5x from 2010	2x from 2020
Renewable capacity (GW) and non-hydro storage	**US** 2020 2050 Wind 100 3,000 Solar 90 2,500 Hydro 90 90 Storage 0 200	Not detailed, but renewable energy grows 3x between 2010 and 2050	**Canada** 2024 2050 Wind 15 150 Solar 4 58 Hydro 80 82 Storage 0 4 **US** Wind 140 840 Solar 160 1,290 Hydro 90 90 Storage 20 130
US-Can Transmission	NA	NA	From 18 in 2020 to 38 GW in 2050
Value of US-Can transmission	NA	NA	$12B (over 2020-2050) $2B/year for hydropower flexibility

1.2.3 STATE-LEVEL DECARBONIZATION STUDIES

As some states and provinces are highly committed to reach their decarbonization targets, they have commissioned in-depth decarbonization studies. In the case of New York, a specific focus has been placed on the power sector as the state has explicit renewable energy goals for its power sector.

Four significant studies have been found for two states and one province in the East Grid zone:

+ **New York:** Hibbard et al. (2020), from the Analysis Group, and Lueken et al. (2020), from the Brattle Group, have conducted studies for the New York Independent System Operator, to better understand changes required to adapt the grid.
+ **Massachusetts:** Jones et al. (2020), from Evolved Energy, have taken a wider perspective to study in more details the key sectors that have to change in order meet the GHG targets.
+ **Québec:** Poirier et al. (2019), from Dunsky Energy + Climate and ESMIA, wrote a report for the Québec Ministry of the environment, on the key modelling results required to achieve net-zero emission by 2050.

Table 5, next page, summarizes the main findings of these studies.

Only the Massachusetts study (Jones et al., 2020) considers the regional benefits of interconnecting the state to its neighbors. While that study does not assess quantitatively the value of such regional interconnections, it mentions explicitly their importance for balancing. These interconnections can limit the amount of new in-state storage, that would otherwise be required to store wind and solar power.

It is worthy to point out that the New York studies indicate huge increase in wind and solar capacities: more than 100 GW of new wind and solar for Hibbard et al. (2020) and more than 80 GW for Lueken et al. (2020), plus about 15 GW of new storage capacity, for New York only. While their optimization models minimize total costs, these studies do not report any total costs and do not point out to possible alternative regional scenarios.

TABLE 5. KEY ASSUMPTIONS AND RESULTS FROM LARGE-SCALE DECARBONIZATION STUDIES[5]

	New York	New York	Massachusetts	Québec
Study	Hibbard et al. (2020) Analysis Group	Lueken et al. (2020) Brattle Group	Jones et al. (2020) Evolved Energy	Poirier et al. (2019) Dunsky and ESMIA
Scenario	CCP2-CLCPA Climate Change Phase II & Climate Leadership and Community Protection Act	High electrification load forecast	All options	Scenario C
Horizon	2040		2050	2050
GHG reduction	100% zero emission (power sector)		Net-zero	75% from 1990
Focus	*Review the potential impacts on reliability of the (1) the electricity demand projections for 2040 and (2) system load and resource availability associated with climate change.*	*Simulate the [power sector] resources that can meet state policy objectives and energy needs through 2040, in order to inform reliability and market design.*	*Focus on the largest single component of these emissions, carbon dioxide (CO2) from energy use, and how it can be dramatically reduced or eliminated while maintaining a vibrant economy.*	*Draw the major, economy-wide, required changes to meet the 2050 decarbonization target.*
Load growth	x1.4 in 2040 x1.6 in 2050 from 2020 Climate Impact Phase I study (Itron, 2019)		x1.9 in 2050 from 2020	x1.9 in 2050 from 2015
Renewable capacity[5] (GW) and non-hydro storage	2020 / 2040 Wind 2 / 56 Solar 0.7 / 50 Hydro 4 / 4 Storage ≈0 / 16	2020 / 2040 Wind 2 / 48 Solar 0.7 / 38 Hydro 4 / 4 Storage ≈0 / 14	2020 / 2050 Wind 0.1 / 16 Solar 1 / 24 Hydro 0.3 / 0.3 Storage ≈0 / 4	2015 / 2050 Wind 4 / 24 Solar ≈0 / 15 Hydro 40 / 60 Storage 0 / 0
US-Can Transmission	Limited to existing		QC-MA: +3.3 GW QC-NY: +4.7 GW	Limited increase allowed
Value of US-Can transmission	NA	NA	Not estimated, but qualitatively indicated as large	Not assessed

5 State renewable capacity in 2020 comes from EIA (2021c).

1.2.4 REGIONAL DECARBONIZATION STUDIES

A few regional studies have been made to explore the possible value of interconnecting different sets of states and provinces in Northeastern North America.

+ Williams et al. (2018), in an Evolved Energy report commissioned by Hydro-Québec, compare different transmission and renewable addition scenarios between Québec and New York and New England. It finds that the net benefits of increased coordination and transmission are in the range of $4B per year.
+ Dimanchev et al. (2021), from MIT, use an optimization model of the Québec-New York-New England region to assess the role of Québec's hydropower reservoirs to decarbonize New England. Its main result is to demonstrate the role of Québec hydropower's reservoirs to balance intermittent renewable generation. Enabled by 4 GW of additional transmission capacity, New England could avert the construction of 30 GW of wind and solar capacity. Two-way trade of electricity between Québec and New England reduces the overall cost by 5-6%, or about $1-2/MWh.
+ Rodríguez-Sarasty et al. (2021), from HEC Montréal, conduct a similar inquiry to the one presented in Dimanchev et al. (2021), but with a few distinct features. First, the analysis is more regional, as it includes Ontario and the Atlantic provinces, as shown in Figure 1. Second, contrary to Dimanchev et al. (2021), who compare cases differing by 4 GW of transmission capacity, interties are endogenously determined. This means that the optimal level of transmission can be found between all states and provinces with the model instead of coming up as a scenario. Finally, the actual financial value of regional integration is more detailed, with a breakdown of costs and benefits across states and provinces. Overall, results of this study converge towards similar findings: more transmission is needed between states and provinces, to allow more hourly and seasonal trade in both directions. Global cost savings, in a 100% decarbonization context, are estimated around $10B per year under regional collaboration (and more interties), compared to a system without new interconnections.

1.2.5 CONTRIBUTIONS OF THIS REPORT

Major decarbonization studies have demonstrated a sparse interest in exploring the benefits of regional collaboration in power system decarbonization, as illustrated in our review of large scale and state-level decarbonization studies (see Tables 4 and 5). Transmission across the Canadian-American border and between various states and provinces is seldom included in recent studies, and this is now considered by the NERC to be an issue, as discussed previously (see NERC, 2021a). Only the NARIS study from NREL (Brinkman et al., 2021a and b) and the study conducted by Evolved Energy for the state of Massachusetts (Jones et al., 2020) include such interties. However, the large scope of these studies neglects to place a focus on the full benefits of regional collaboration (increased integration) and how these gains are distributed.

Given the established potential of greater power sector collaboration to reduce decarbonization costs, there is a need for additional modelling exercises. The objective of this paper is to contribute to further document and make known the economic potential of increased collaboration in the East Grid zone, where huge storage is already available in Québec and Labrador's hydro reservoirs, and where governments have started planning the introduction of large-scale intermittent renewable resources.

THE OBJECTIVE OF THIS PAPER IS TO CONTRIBUTE TO FURTHER DOCUMENT AND MAKE KNOWN THE ECONOMIC POTENTIAL OF INCREASED COLLABORATION IN THE EAST GRID ZONE, WHERE HUGE STORAGE IS ALREADY AVAILABLE IN QUÉBEC AND LABRADOR'S HYDRO RESERVOIRS ...

Building on Rodríguez-Sarasty et al. (2021), this report makes two additional contributions:

1. **Load growth.**
   The impact of different load growth scenarios is explored, to better understand how possible energy efficiency efforts and electrification trends can affect results.

2. **Distribution of benefits.**
   Benefits and costs across states and provinces are more detailed, allowing to better understand the political economy challenges related to regional integration.

2. ECONOMIC BENEFITS OF A REGIONAL DECARBONIZATION APPROACH

2.1 DESCRIPTION OF THE APPROACH

Based on the capacity expansion and hourly operation power sector model used in Rodríguez-Sarasty et al. (2021), the regional economic impacts of two decarbonization approaches is detailed through the following metrics:

+ **Investment in capacity.** The model's results provide the required investment in generation capacity, storage and interties (transmission links) in each sub-region.
+ **Wholesale price.** Based on marginal production costs, that can be used as a proxy for wholesale prices, estimates of the price impact in each sub-region are documented.
+ **Cost of the decarbonized power system, exports and imports.** The cost of the zero-emission power system, exports and imports by sub-region are provided, allowing a comparison of how different approaches result in different economic impacts.

The model's objective is to find the least cost investment options in all five sub-regions to meet their 8,760 hours (a full year) of power demand (or hourly loads). A constraint on GHG emissions limits to zero such emissions. A portfolio of technologies (wind, solar, storage, interties, etc.) and demand response[6] options are available and are used by the model to minimize the cost of meeting the demand. The existing hydropower capacity in all states and provinces, as well as the current natural gas power capacity remain available. With the strict emission constraint (zero emissions), this natural gas capacity can only be used with "carbon-neutral natural gas": either renewable natural gas, or fossil natural gas with carbon capture and storage. The existing level of nuclear power remains available, but new nuclear for the East Grid zone is not considered in this report.[7] Only Québec's hydro reservoirs (total of 176 TWh) are modelled for storage in this study, due to the lack of available information on the Smallwood reservoir in Labrador.

Two approaches are used with respect to transmission between the five sub-regions (see Figure 1): either no additional interties are possible, or on the contrary as much transmission as needed, and economically justified, is built. The first possibility corresponds to a decarbonization approach "in isolation". The second reflects a "regional collaboration", as such interties require significant discussions between states and provinces. The transmission and distribution networks within states and provinces is not modelled. We assume that adequate upgrades are made to allow for the decarbonization of the generation system. Finally, no difference is made between distributed energy resources and large wind/solar farms. Investments in wind and solar can be interpreted to be small or utility-scale investments.

6 "Demand response provides an opportunity for consumers to play a significant role in the operation of the electric grid by *reducing* or *shifting* [emphasis added] their electricity usage during peak periods in response to time-based rates or other forms of financial incentives" (DoE, 2021). In the model used here, load is only reduced, without shifting, as explained in Appendix 2.

7 In Rodríguez-Sarasty et al. (2021) some scenarios with no nuclear are explored, leading to much greater renewable investments. Sepulveda et al. (2018) look at the importance of nuclear and other "firm low-carbon resources", but they ignore the large-scale storage possibility of hydropower reservoirs.

These two intertie approaches are combined with two load growth scenarios: a moderate load growth (1.5x the 2018 load and a winter peaking demand) and a high load growth one (2.5x with winter peaking demand). The first one corresponds to a scenario where consumption efficiency limits load growth, while the second on corresponds to a scenario where electrification of end-uses, without an efficiency focus, leads to a high demand increase.

This leads to four decarbonization scenarios, as summarized in Table 6.

All assumptions on parameters' value are presented in the Appendix 2. The complete description of the model can be found in Rodríguez-Sarasty et al. (2021).

TABLE 6. FOUR DECARBONIZATION SCENARIOS FOR NORTHEASTERN NORTH AMERICA

		Transmission Interties	
		Same as existing "Decarbonization in isolation"	As much as needed "Regional collaboration"
Load growth	Moderate (1.5x & winter peak)	Scenario 1 *Isolation and moderate load growth*	Scenario 3 *Collaboration and moderate load growth*
	High (2.5x & winter peak)	Scenario 2 *Isolation and high load growth*	Scenario 4*Collaboration and high load growth*

Gross domestic product (GDP) and job change estimates cannot be obtained with this model. Any assessment would in any case be highly speculative given the difficulty of modelling the economic impact of an energy transition, with deep changes in consumption and production patterns. Social implications of the different results can however be discussed (see section 2.3).

2.2 RESULTS

These results are not associated to any particular year, such as 2040 or 2050. They represent what would be needed to supply electricity every hour of a year in the five sub-regions, at minimum total cost, without GHG emissions.

2.2.1 REQUIRED NEW CAPACITY

While the current installed capacity in the East Grid zone is about 180 GW (see Appendix 2 for the breakdown by technology and sub-region), decarbonization would require installing between about the same and five times this amount, depending on the scenario.

TABLE 7. TOTAL REQUIRED NEW GENERATION AND STORAGE CAPACITY

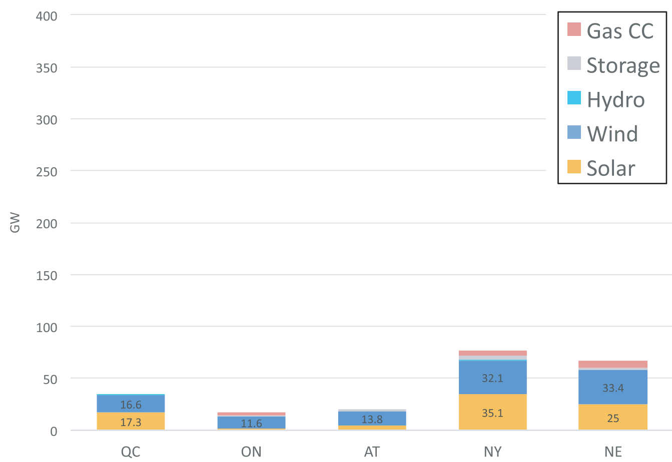
		Transmission Interties		
		Same as existing "Decarbonization in isolation"	*Difference GW*	As much as needed "Regional collaboration"
Load growth	Moderate (1.5x & winter peak)	214 GW	*15*	199 GW
	High (2.5x & winter peak)	1,036 GW	*348*	688 GW

Table 7 illustrates that if load growth is moderate and under regional collaboration, only 199 GW of new capacity would be required. If, on the contrary, there is a high load growth and no regional collaboration, a staggering 1,036 GW are required.

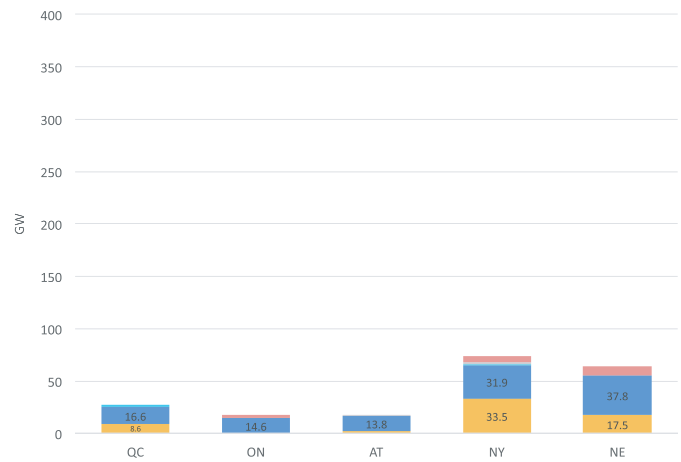
The possibility to build as much transmission interties as needed reduces the overall need for new capacity: 15 GW are avoided if load growth is moderate (difference between scenarios 1 and 3), while 348 GW would be avoided if there is a high load growth (difference between scenarios 2 and 4).

New York and New England are the markets with the most non-renewable capacity (see Figure 2 and Appendix 2). Therefore, they would have to add the largest amount of renewable capacity, under any scenario, as illustrated in Figure 3 (with data in Tables 8a and 8b). For New York and New England, collaboration (adding interconnections) means avoiding significant amounts of additional generation capacity.

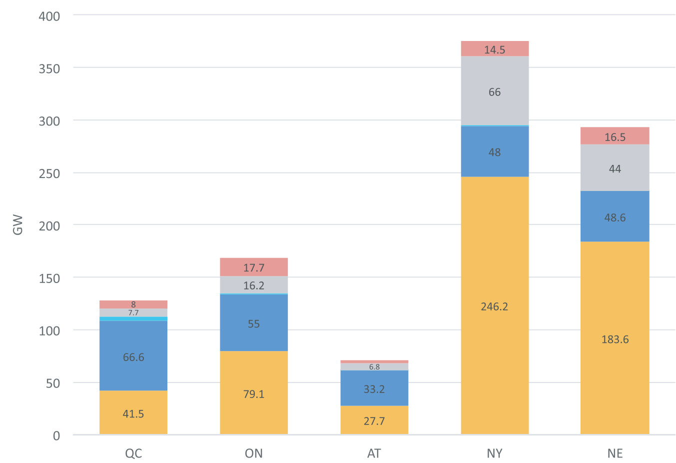
SCENARIO 1-ISOLATION AND MODERATE LOAD GROWTH



SCENARIO 3-COLLABORATION AND MODERATE LOAD GROWTH



SCENARIO-2 ISOLATION AND HIGH LOAD GROWTH



SCENARIO-4 COLLABORATION AND HIGH LOAD GROWTH

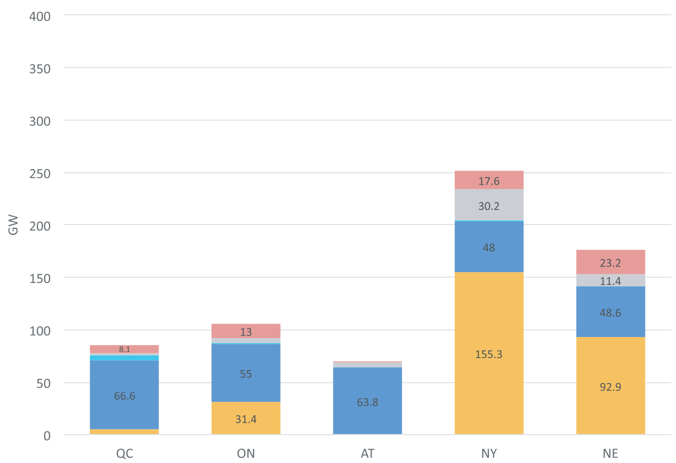


FIGURE 3. NEW CAPACITY IN THE FIVE SUB-REGIONS IN THE FOUR SCENARIOS

TABLE 8A. NEW CAPACITY IN THE FIVE SUB-REGIONS IN IN THE MODERATE LOAD GROWTH SCENARIOS

	1-Isolation and moderate load growth						3-Collaboration and moderate load growth					
	QC	*ON*	*AT*	*NY*	*NE*	***Total***	*QC*	*ON*	*AT*	*NY*	*NE*	***Total***
Solar	17.3	1.8	4.6	35.1	25	**83.7**	8.6	0	2.6	33.5	17.5	**62.2**
Wind	16.6	11.6	13.8	32.1	33.4	**107.5**	16.6	14.6	13.8	31.9	37.8	**114.7**
Hydro	0.01	–	–	0.5	–	**0.5**	1.83	–	–	0.5	–	**2.3**
Storage	–	0.9	1.4	4.2	1.7	**8.1**	–	0.5	0.5	2.4	0	**3.4**
Gas CC	–	3.1	–	4.3	6.9	**14.3**	–	2.3	0	5.3	9.1	**16.7**
Total	34	17	20	76	67	**214**	27	17	17	74	64	**199**

TABLE 8B. NEW CAPACITY IN THE FIVE SUB-REGIONS IN THE HIGH LOAD GROWTH SCENARIOS

	2 Isolation and high load growth						4 Collaboration and high load growth					
	QC	*ON*	*AT*	*NY*	*NE*	***Total***	*QC*	*ON*	*AT*	*NY*	*NE*	***Total***
Solar	41.5	79.1	27.7	246.2	183.6	**578.2**	4.7	31.4	0	155.3	92.9	**284.4**
Wind	66.6	55	33.2	48	48.6	**251.3**	66.6	55	63.8	48	48.6	**282**
Hydro	4.4	0.9	0.1	0.5	0.2	**6.1**	4.1	0.9	0.1	0.5	0.2	**5.8**
Storage	7.7	16.2	6.8	66	44	**140.8**	2.2	5.1	4.6	30.2	11.4	**53.5**
Gas CC	8	17.7	3	14.5	16.5	**59.7**	8.1	13	0.3	17.6	23.2	**62.3**
Total	128	169	71	375	293	**1,036**	86	106	69	252	176	**688**

From the current 10 GW of intertie capacity in northeastern North America (Appendix 2), 17 GW of additional transmission capacity would be required under the moderate load growth scenario, and 60 GW under the high load growth scenario.

In both cases, most of these additional transmission lines would connect Québec to its neighbors, as detailed in Table 9.

This is unsurprising, as Québec already possesses 176 TWh of storage capacity, which could be used to balance the additional intermittent generation capacity, installed mostly in New York and New England.

TABLE 9. TOTAL REQUIRED ADDITIONAL INTERTIE CAPACITY (GW)

	Scenario 3-Moderate load growth						*Scenario 4-High load growth*					
	QC	ON	AT	NY	NE	**Total**	QC	ON	AT	NY	NE	**Total**
ON	3.7	–	–	–	–	**3.7**	10.4	–	–	–	–	**10.4**
AT	1.5	–	–	–	1.8	**3.3**	11.1	–	–	–	14.9	**26.0**
NY	5.0	1.3	–	–	–	**6.3**	12.0	7.0	–	–	–	**19.1**
NE	3.7	–	–	0.1	–	**3.7**	1.5	–	–	3.1	–	**4.5**
Total	14.4	1.3	–	0.1	1.8	**17.0**	35.0	7.0	–	3.1	14.9	**60.0**

Figure 4 illustrates the seasonal balancing role played by Québec in the moderate load growth scenarios (scenarios 1-Isolation and 3-Collaboration). We see imports peaking in the spring and in the fall when consumption is lower due to the low cooling and heating needs. During the winter, exports from Québec help supply the high electrified heating needs. Under collaboration, with more interties, this balancing role is amplified. These patterns are similar in the high load growth cases.

FIGURE 4. WEEKLY AVERAGE OF ENERGY IMPORTS AND EXPORTS, IN GWH, IN QUÉBEC OVER A YEAR (MODERATE LOAD GROWTH)

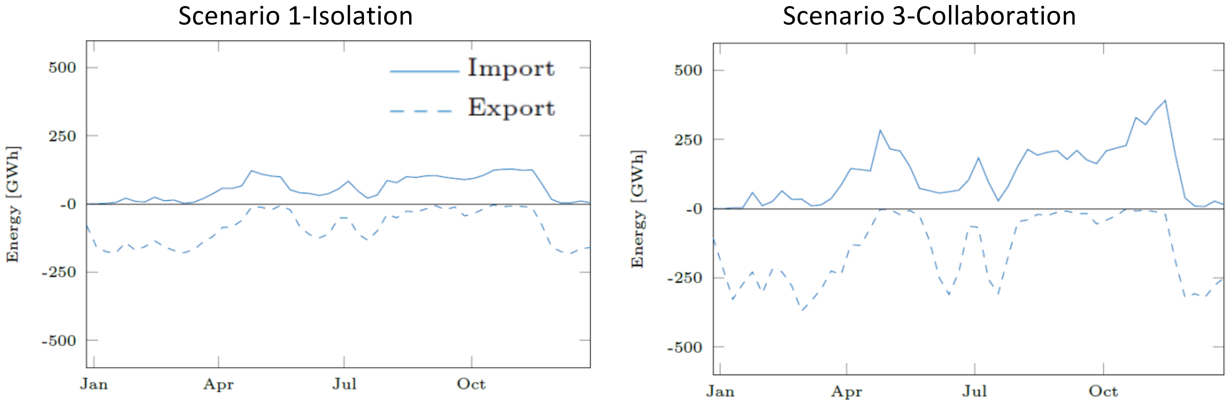
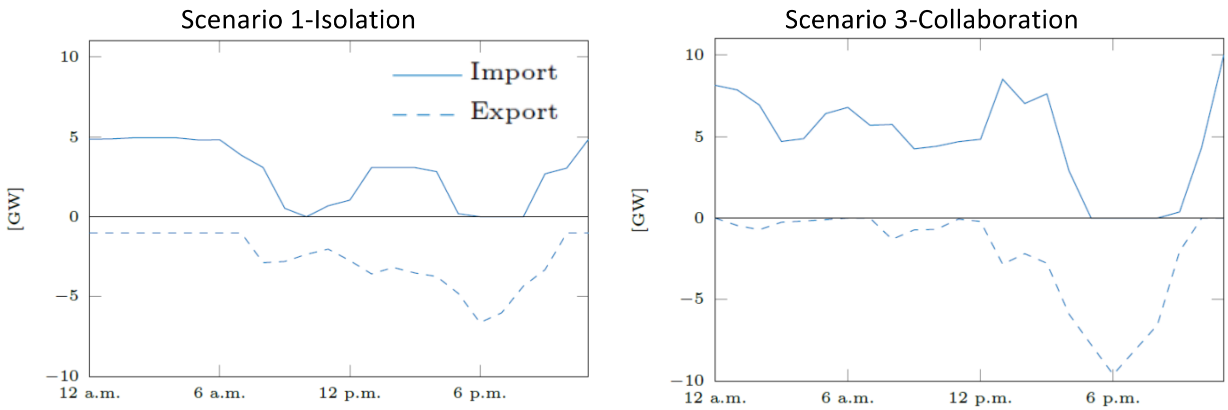


FIGURE 5. HOURLY ENERGY IMPORTS AND EXPORTS, IN GWH, IN QUÉBEC IN A SUMMER DAY (MODERATE LOAD GROWTH)



On a daily basis, we can also observe how hydropower storage from Québec helps use available energy surpluses from neighbouring jurisdictions, especially outside of the morning and evening peak hours (Figure 5). Québec imports as much as possible, up to the transmission limit visible at 5 GW on the left panel of Figure 5. Exports from Québec mostly happen during the evening peak (at about 6 pm), when solar generation fades, and residential demand rises.

2.2.2 TOTAL SYSTEM COSTS AND ITS REGIONAL DISTRIBUTION

The value of increased collaboration, in the form of additional transmission interties, materializes through lower system costs. Table 10 provides the annual system costs under the four scenarios. These costs include the annualized value of all the investments made (in generation capacity, transmission interties and storage) plus the operating costs of the power systems. These costs exclude transmission and distribution costs within states and provinces.

The value of collaboration is evident: a savings of $3.4 billion per year in the moderate load growth case (6% saving), and a $25.6B saving in the high load growth case (14%). These reductions of total system costs result directly from lower requirements for new generation and storage capacity.

TABLE 10. TOTAL ANNUAL SYSTEM COSTS, ANNUALIZED VALUE OF NEW INVESTMENTS AND OPERATING COSTS (BILLION US$)

		Transmission Interties		
		Same as existing "Decarbonization in isolation"	*Difference $/year*	As much as needed "Regional collaboration"
Load growth	Moderate (1.5x & winter peak)	$60.1	*$3.4*	$56.7
	High (2.5x & winter peak)	$181.7	*$25.6*	$156.1

To put these number in perspective, Table 11 provides the current cost estimates of wholesale electricity in the five sub-regions. Collectively, the current value of generating electricity in northeastern North America is about $27.3 billion. Decarbonizing under a moderate load growth scenario would double these costs, while a high load growth scenario would increase total costs by a factor of 5 to 6.

TABLE 11. COST ESTIMATES OF WHOLESALE ELECTRICITY IN THE FIVE SUB-REGIONS, 2020 US AND 2019 CANADA

	Wholesale Electricity Estimated Costs (billion $US)[8]	Source
New York	5.6	Patton et al. (2021; p. 3); NYISO (2021; p. 23)
New England	8.1	ISO-NE (2021; p. 18)
Ontario	6.9	Statistics Canada (2021); EIA (2017); Bank of Canada (2021)
Québec	5.1	
Atlantic	1.6	
Total	**27.3**	

The breakdown of the trade balance and investments (generation, storage and transmission) and operation costs by sub-region is presented in Table 12. In all cases, Québec has a positive trade balance and in one case, scenario 4, the Atlantic provinces too. The positive trade balance of Québec makes sense given its role as the battery of the northeast. It imports when there is a surplus in generation (low price periods), and it exports when demand is high and supply tight (high price periods). More intertie capacity (collaboration scenarios) slightly increases the trade balance. The impact is however limited, due to the leveling effect increased transmission capacity has on prices. Indeed, with more interconnections comes more trade, and price differentials decrease.

8 These estimates only consider generation costs, excluding transmission and distribution. For New England the value is directly taken from ISO-NE (2021; p. 18). For New York, the value is estimated from the zonal loads and zonal prices ("Average All-In Price by Region"). For Canadian regions, the value is based on Statistics Canada's electricity value for 2019, removing delivery costs by using the share of power generation costs in electricity prices (54% from EIA, 2017) and by converting to US dollar using the 2019 average exchange rate (US$1=Can$1.32).

Results in Table 12 also show which sub-regions have the largest cost decrease when collaboration happens (scenarios 3 and 4, compared to 1 and 2). In both moderate and high load growth cases, New York and New England are the main beneficiaries of collaboration: their local costs go down by $2.7 and $1.1 billion respectively in the moderate growth case, and by $12.7 and $11.9 in the high load growth case. For Québec, on the contrary, total costs increase in the moderate growth case (by $1.7 billion). New York and New England are indeed the main beneficiaries of regional collaboration, as these new interties helps them reduce the level of investment in new generation capacity and storage. For Québec and Ontario, the change in total costs is less important. In scenario 4, the Atlantic provinces see their revenues grow significantly due to increased exports, powered by high investments.

TABLE 12. BREAKDOWN OF THE TRADE BALANCE AND COSTS BY SUB-REGION FOR THE FOUR SCENARIOS

	1-Isolation & Moderate load growth.						3-Collaboration & Moderate load growth					
	QC	ON	AT	NY	NE	**Total**	QC	ON	AT	NY	NE	**Total**
Export revenue	7.0	1.6	0.7	1.1	1.4	**11.7**	10.4	1.9	1.0	1.3	1.7	**16.2**
Import cost	1.7	2.5	1.1	3.4	3.0	**11.7**	2.6	3.2	1.6	5.2	3.7	**16.2**
Trade balance	5.2	-0.9	-0.4	-2.3	-1.6	**0.0**	7.8	-1.3	-0.6	-3.9	-2.0	**0.0**
Invest.	4.3	3.1	2.9	12.5	11.3	**34.1**	4.2	3.6	2.5	12.0	11.6	**34.0**
Oper.	1.6	6.4	1.8	9.4	6.9	**26.1**	2.5	4.9	1.3	6.8	5.1	**20.7**
Trans.	–	–	–	–	–	**–**	0.8	0.3	0.2	0.4	0.3	**2.0**
Total costs	5.9	9.5	4.7	21.9	18.2	**60.1**	7.6	8.8	4.0	19.2	17.1	**56.7**

	2-Isolation & High load growth						4-Collaboration & High load growth					
	QC	ON	AT	NY	NE	**Total**	QC	ON	AT	NY	NE	**Total**
Export revenue	12.4	3.2	1.4	3.5	3.7	**24.3**	16.7	4.7	12.3	4.7	3.5	**42.0**
Import cost	4.2	6.1	2.3	6.6	5.1	**24.3**	8.2	8.9	2.8	11.4	10.7	**42.0**
Trade balance	8.2	-2.9	-0.9	-3.1	-1.4	**0.0**	8.5	-4.2	9.5	-6.7	-7.1	**0.0**
Invest.	24.1	26.9	11.6	50.1	39.9	**152.6**	19.3	19.7	16.3	34.7	25.4	**115.4**
Oper.	4.0	8.4	2.1	8.7	5.9	**29.0**	5.7	8.6	1.9	10.1	7.4	**33.8**
Trans.	–	–	–	–	–	**–**	2.0	1.0	1.5	1.3	1.1	**6.9**
Total costs	28.1	35.3	13.7	58.8	45.8	**181.7**	27.0	29.3	19.7	46.1	33.9	**156.1**

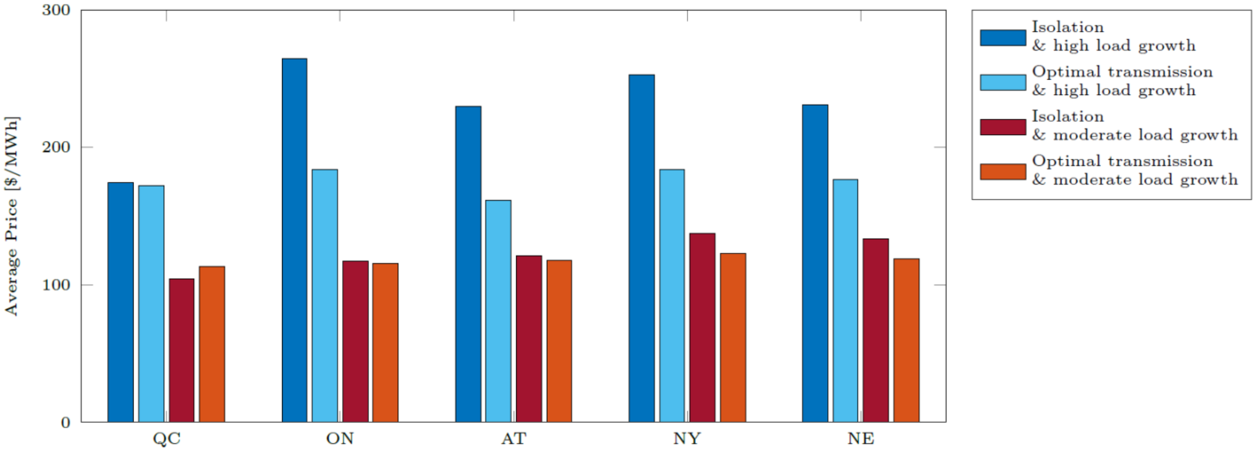
Of course, the improvement in the trade balance for Québec can justify the higher costs, in the moderate load growth case. But as it is not the same groups that benefit from the trade balance and pay the total costs, there can be internal tensions within a sub-region between exporters, that want more interties, and consumers, that will eventually face higher costs with these interties. Such internal dynamic between producers and consumers often revolves around prices, which are discussed next.

2.2.3 IMPACT ON WHOLESALE PRICES

Average wholesale prices decrease in all sub-regions with more interties, as the system costs go down. This is what can be seen in Figure 6, except for Québec. Figure 6 shows the average wholesale price for all four scenarios. See also Table 13 with more details on prices (minimum, average, maximum and standard deviation). Wholesale price comparisons should be made within the same load growth case, between isolation and collaboration (optimal transmission). In the high load growth case, as well as in the moderate one, the largest price reductions happen in New York and New England, as well as in Ontario and in the Atlantic. In Québec, the average price goes up in the moderate growth case when more interties are built. This comes from the levelling price impact of increased trade, made possible with more interconnections.

The higher wholesale price in Québec, in the moderate load growth scenario, when more interties are built, is a concern for the public acceptance of regional collaboration. Electricity being often perceived as an energy source for local consumption, putting forward the notion of more trade with neighbors could be tricky, as it could lead to higher prices. Wholesale price volatility tends to be lowered with more interconnections, as shown in Table 13 through the standard deviation's value (SD). This is especially visible in the high load growth case, where the standard deviation in the isolation case (scenario 2) range from 380 to 523, while in the collaboration case (scenario 4) it ranges from 327 to 344.

FIGURE 6. AVERAGE WHOLESALE PRICES IN THE FIVE SUB-REGIONS UNDER ALL FOUR SCENARIOS



In Québec, however, more integration does not reduce the volatility much. On the contrary, in the moderate load growth case, more regional interties raise the standard deviation from 265 to 295. This is explained by the transfer of some of the regional volatility into the Québec market, through larger transmission links.

It is interesting to note that the minimum price rises with more collaboration (more interties), as surplus power can be exported instead of depressing local prices. This provides more price stability for investors. Maximum prices (at $10,000/MWh, the cost of load shedding) are never reached in scenario 2 (Isolation & High load growth) due to the large investment in capacity in each sub-region.

TABLE 13. WHOLESALE PRICE STATISTICS BY SUB-REGION FOR THE FOUR SCENARIOS

	1-Isolation & Moderate load growth.					3-Collaboration & Moderate load growth				
	QC	ON	AT	NY	NE	QC	ON	AT	NY	NE
Min	2.5	2.3	4.8	0.0	0.0	2.8	2.6	2.9	2.5	2.6
Mean	**104.5**	**117.0**	**121.3**	**137.4**	**133.6**	**113.5**	**115.6**	**117.9**	**123.1**	**118.9**
Max	9,420		10,000			9 420		10,000		
SD	265.6	315.6	296.5	318.1	318.8	295.0	316.6	309.7	316.0	316.0
	2-Isolation & High load growth					4-Collaboration & High load growth				
Min	2.5	0.0	0.0	0.0	0.0	2.5	0.0	2.3	0.0	0.0
Mean	**174.5**	**264.4**	**229.9**	**252.8**	**230.8**	**172.1**	**184.0**	**161.6**	**183.7**	**176.6**
Max	5,212	4,875	4,341	4,875	4,910	10,000	10,000	9,420	9,420	10,000
SD	380.1	523.4	491.7	516.2	494.8	334.0	342.3	327.3	344.8	343.3

2.3 DISCUSSION

2.3.1 ECONOMIC AND SOCIAL IMPACTS

Decarbonization is now a common societal objective associated with many positive concepts: environmental protection, renewable energy development, and sustainability, amongst others. Some profound technical changes in energy and power systems, as well as in our personal behaviors and consumption habits, will however be required to decarbonize our society. Policymakers and citizens often lack detail on how these various transformations will take place. Notably, installed capacity in northeastern North America and elsewhere, will have to at least double with non-emitting sources, to generate enough carbon-free electricity to meet the new load. This will pose tremendous siting, permitting, construction and operational challenges. Energy loads are expected to grow by factors ranging from 1.4 to 4 in the various studies we reviewed.

To meet this new decarbonized energy demand, societies will have to be ready to make significant investments, and not in the 'business-as-usual' manner. New collaborations between provinces and states offer a promising potential to reduce the economic and social burdens of decarbonization. Costs can be lowered, installed capacity can be minimized, leaving a lighter footprint on communities and a more resilient and reliable energy system.

In all cases, a lot more wind and solar power will have to be installed, providing the green jobs that many leaders and citizens want for their communities. While new transmission interties are required in the eyes of these researchers, they are often negatively perceived by some communities. The challenge will be to balance the resistance to such interconnections with the financial cost and possible resistance to even more wind and solar farms.

2.3.2 KEY TAKE-AWAYS

Three major take-aways can be drawn from these results:

1. **Energy efficiency should be prioritized.**
   Energy efficiency and approaches to reduce energy demand must be the central focus of decarbonization, otherwise costs will explode.

2. **Collaboration benefits are more than monetary.**
   While the system costs are significantly reduced through more interties, the capacity requirements are also reduced. In a context where a lot of wind and solar generating capacity will have to be installed, a growing resistance to such installations is likely to take place. Collaboration on interties will allow avoiding many GW of capacity, in places where a lot of new capacity will already be needed and built.

3. **Obstacles to collaborations are multiple – market mechanisms must be well designed.**
   The main beneficiaries of collaboration are the regions needing the largest changes in their power systems: New York and New England. They benefit the most through avoided costs, which may not appear as real as payments for imports and balancing services (trade balance). The perception that Québec would benefit the most from regional collaboration because it would increase its trade balance is erroneous. The largest gains are made by New York and New England that reduce their total costs, while still generating much larger renewable energy from local sources. Furthermore, different groups within sub-regions have different interests. They could oppose collaboration and interconnections to protect their positions. In Québec, for instance, the allocation of costs and benefits from more interties is likely to be negative for consumers, and positive for producers, as prices would increase. Well designed market mechanisms will be necessary to ensure a wide acceptance of the necessary reforms required to achieve collaboration.

Allocation of transmission costs can be a contentious issue. New interties benefit the whole system, which would justify a socialization of these costs, as opposed to approaches based on merchant transmission lines. In order to socialize these costs, a regional transmission planner and operator would be required. The current sub-regional (state and provincial) approach to transmission planning, cost allocation and price regulation does not lend itself to an optimal transmission system.

2.3.3 LIMITATIONS AND RESEARCH AVENUE

This report highlights key results, providing detailed information on the sub-regional implications of increased integration in northeastern North America. The model used to obtain these results, while being rigorous and carefully documented in Appendix 2 and in Rodríguez-Sarasty et al. (2021), only provides a simplified version of our complex reality. Many further analyses could be conducted to refine the various estimates presented in the report. Required new capacity, costs and prices are sensitive to all assumptions made, and more explorations could be made with different assumptions. We have however conducted various sensitivity analyses, and our results are robust to changes in storage costs, transmission costs and wind and solar costs. In other words, even if storage costs were drastically reduced, new interties would still be valuable – mostly for seasonal balancing needs that new storage cannot handle.

Nuclear technologies were not excluded in this analysis, but no new investment beyond existing levels was modelled.

Another limitation of this model is its exclusion of neighboring systems: the PJM Interconnection (to the southwest of New York) and the Midcontinent Independent System Operator (MISO), to the west of Ontario. Trade with these systems already happens and could play a larger role in the future. The scope of this report could however not be broadened to include all North America (as in the NARIS report by NREL).

FUTURE RESEARCH AVENUES

Transmission and distribution.
The impact on sub-regional internal transmission and distribution networks should be explored. The extent to which adding new interties affects the state and provincial transmission grids should be assessed.

Load profiles.
The impact of different load profiles could be important on the actual generation and transmission capacity needs. Investigating these impacts will be important for the future, to better understand the value of demand response programs and of load flexibility.

Energy efficiency and consumption reduction.
Given the importance of minimizing load growth to contain costs, further analysis should be conducted on the potential to erase future energy demand instead of electrifying it. For instance, deep retrofits of buildings can reduce energy consumption at a cost possibly lower than the electricity infrastructure required to electrify heating.

Design of market mechanisms.
To reconcile the diverse outcomes of integration and incentivize collaboration, serious thoughts should be given to the types of market mechanisms that will compensate suppliers in future transactions, so that the net positive welfare gains are adequately allocated. With integration, as global net welfare gains are positive, there is a real possibility to reward everyone for positive change, compensating for perceived "losses".

Crafting a regional dialogue.
The need to have a more integrated power system will require the creation of a discussion space where all stakeholders will be able to meet, debate and find solutions to their common problems, to reach their shared objectives. While in the continental northeast climate change goals are largely shared, institutions to secure progress in the regional energy dialogue do not exist. Research will be needed to develop the adequate discussion platform.

2.3.4 A CONSERVATIVE ESTIMATE OF REGIONAL INTEGRATION BENEFITS

Despite the identified limitations, the report provides a conservative estimate of economic benefits. Firstly, transmission costs, as presented in Appendix 2, are in the high range. We consider investment costs that are very close to buried transmission lines (such as in the proposed Champlain Hudson Power Express 1,250 MW project linking Québec and New York City), rather than overhead lines (such as in the New England Clean Energy Connect project proposing to link Québec and Maine).

Also, to keep the model simple we did not include requirements for reserve margins. Such requirements are usually in the range of 10 to 20% of the installed capacity (NERC, 2021b). It consequently forces more capacity to be installed, at a greater cost. The model used in this report is only constrained to meet hourly demands in each sub-region, not to invest in 10-20% more capacity than required to meet peak demand, as reserve margins require for reliability reasons. Consequently, investments are underestimated, and regional integration benefits are also underestimated. Indeed, the ability to share capacity, through interties, for reserve margin obligations is not considered here. The value of regional integration would be further enhanced by adding this aspect.

INDEED, THE ABILITY TO SHARE CAPACITY, THROUGH INTERTIES, FOR RESERVE MARGIN OBLIGATIONS IS NOT CONSIDERED HERE. THE VALUE OF REGIONAL INTEGRATION WOULD BE FURTHER ENHANCED BY ADDING THIS ASPECT.

3. CONCLUSION

With very ambitious GHG reduction targets for 2030 and 2050, state and provinces in the East Grid zone will need to decarbonize their power sectors and electrify many energy end-uses. This double challenge requires installing a great amount of renewable generation capacity.

Many studies have been conducted on such decarbonization, finding for instance that in New York only, 80 to 100 GW of wind and solar have to be installed by 2040, while not even 3 GW were in 2020. Similar findings are found in New England and across the US and Canada. To balance such intermittent resources, huge amounts of storage are also required. Estimates are at about 15 GW in New York and more than 100 GW across the United States. These studies, however, neglect the possible role of existing hydropower reservoirs and of new interconnections between markets, to help minimize the need for new generation capacity and new storage.

This report contributes to the discussion on decarbonization by highlighting key results that could be achieved with increased intertie capacity across northeastern North America. These results confirm the findings of some previous studies, and provide more depth on the sub-regional outcomes:

+ **Less new generation capacity would be needed.** The region could avoid installing 15 to 348 GW of capacity, depending on the intensity of the load growth, by collaborating through increased interties. Additional interconnections would however be required, from 17 to 60 GW (when the sum of current regional interties is 10 GW). These interconnections help better balance supply and demand by better integrating intermittent renewable generation in the system. They are necessary to take advantage of the existing storage capacity in Québec and Labrador hydro reservoirs. New York and New England, being the places with the most fossil-fuel capacity to replace, are the main beneficiaries of the increased interties.
+ **Total decarbonization costs would decrease.** By avoiding new generating and storage capacity, and despite higher interconnections costs, the total decarbonization costs go down by $3.4 billion to $25.6 billion per year, depending on the load growth scenario. The more the load grows, the more regional integration is valuable, as larger intermittent systems benefit more from the access to balancing options offered by a variety of neighbours. Again, the cost reductions mostly concentrate in New York and New England.
+ **Lower and less volatile prices would emerge.** With more trading opportunities, average prices are lower and less volatile in integrated markets. This is important as consumers can be frustrated by both high and/or volatile prices.

From these results and the overall analysis, three take-aways should be remembered:

1. **Energy efficiency should be prioritized.**
   Energy efficiency and approaches to reduce energy demand have to be the central focus of decarbonization, otherwise costs explode.

2. **Collaboration benefits are more than monetary.** While the system costs are significantly reduced through more interties, the capacity requirements are also reduced, leading to greater system reliability and efficiency. In a context of large wind and solar investment, resistance is likely to take place. Efforts to minimize the amount of new installed wind and solar capacities should be considered, even if they involved new interties.

3. **Market mechanisms must be well designed.**
   Given the sub-regional distribution of costs and benefits, and even the internal (within states and provinces) distribution of cost and benefits, compensation will have to be considered with an eye on promoting trade and enabling local.

WHILE THE SYSTEM COSTS ARE SIGNIFICANTLY REDUCED THROUGH MORE INTERTIES, THE CAPACITY REQUIREMENTS ARE ALSO REDUCED, LEADING TO GREATER SYSTEM RELIABILITY AND EFFICIENCY.

Future research avenues are multiple, from a more detailed power system model to the design of market mechanisms. However, crafting a strong regional dialogue is probably the highest priority. Such a discussion platform will be central to the process of inducing more collaboration in the northeastern power sectors. No effort should be spared to find how we can get on an efficient decarbonization track.

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APPENDIX 1: SUB-REGIONAL DATA

TABLE A1.1 POPULATION, ELECTRICITY GENERATION AND EMISSIONS IN NEW ENGLAND, 2019 (2018 FOR GHG DATA)

	Population (M)	Electricity Generation (TWh)	Electricity GHG (Mt)	Total GHG (Mt)	Carbon intensity g/kWh	Electricity share of GHG
Connecticut	3.6	40.1	8.1	37.6	201.0	21%
Maine	1.3	10.5	1.1	14.8	102.9	7%
Massachusetts	6.9	21.5	7.7	64.6	356.9	12%
New Hampshire	1.4	18.0	2.1	14.3	114.3	14%
Rhode Island	1.1	7.4	3.2	11.1	427.2	29%
Vermont	0.6	2.3	0.0	5.9	0.0	0%
New England	**14.8**	**99.8**	**22.0**	**148.1**	**220.9**	**15%**

Table A1.2 Population, Electricity Generation and Emissions in the Atlantic Provinces, 2019

	Population (M)	Electricity Generation (TWh)	Electricity GHG (Mt)	Total GHG (Mt)	Carbon intensity g/kWh	Electricity share of GHG
New Brunswick	0.8	12.8	3.3	12.2	257.8	27%
Newf. & Labrador	0.5	42.3	1.1	11.1	27.0	10%
Nova Scotia	1.0	9.4	6.7	16.2	711.7	41%
Prince Edward Isl.	0.2	0.6	0.0	1.8	1.7	0%
Atlantic	**2.4**	**65.1**	**11.1**	**41.3**	**170.9**	**27%**

Sources:
Population: U.S. Census Bureau (2021) and Statistics Canada (2021b)
Generation: ECCC (2021) and EIA (2021a)

GHG: ECCC (2021a) and EIA (2021b)

Table A1.3 GHG Reduction Targets in New England (C2ES, 2021a)

	Reference year	2025	2030	2035	2040	2050
Connecticut	2001		45%			80%
Maine	1990		45%			Net-zero
Massachusetts	1990		50%		55%	Net-zero
New Hampshire	1990	20%				80%
Rhode Island	1990			45%		80%
Vermont	2005	26%	40%			80%

Table A1.4 GHG Reduction Targets in the Atlantic Provinces (C2ES, 2021b)

	Reference year	2030	2050
New Brunswick	2001	35%	80%
Newf. & Labrador	2001		75%
Nova Scotia			
Prince Edward Island	2005	30	

APPENDIX 2: KEY ASSUMPTIONS

For all jurisdictions, hourly load data for 2018 are provided by the following sources:

- Québec: Relevé livraisons d'énergie en vertu de l'entente globale cadre pour la période du 1er janvier au 31 décembre 2017. (Hydro-Québec Distribution, 2018),
- Ontario: IESO Hourly Demand Report (IESO, 2018),
- New York: NYISO Load data: integrated real-time. (NYISO, 2018),
- New England: ISO-NE Energy, Load and Demand report (ISO-NE, 2018),
- Atlantic provinces: Hourly load estimated by scaling the New Brunswick hourly profile from NB Power (2018).

In the moderate load growth scenario, the hourly load in New York is calculated based on NYISO forecasts, such that it results in a growth factor of 1.5. Ontario and New England load profiles are estimated according to the New York one. For Québec and Atlantic provinces, a growth factor of 1.5 was applied to their 2018 load profiles. Hourly load profiles for the high load growth scenario are calculated using the same approach. Details of regional load profiles are shown in Table A2.1.

Table A2.1 Details of hourly loads

	QC	ON	AT	NY	NE	**NPCC**
Initial load (2018)						
Peak (MW)	36,144	23,240	7,885	31,861	25,568	**108,870**
Total Energy (TWh)	183	137	39	161	123	**644**
Moderate load growth (1.5x)						
Peak (MW)	54,216	44,948	11,827	53,923	43,816	**206,132**
Total Energy (TWh)	275	208	58	241	186	**967**
High load growth (2.5x)						
Peak (MW)	90,379	73,171	19,716	87,782	71,329	**338,048**
Total Energy (TWh)	458	344	97	400	308	**1606**

GENERATION AND STORAGE TECHNOLOGIES PARAMETERS

Table A2.2 shows the initial installed capacities by technology in each region.

Table A2.2 Initial generation and storage capacity per technology and region [MW]

	QC[1]	ON[1]	AT[1]	NY[2]	NE[2]
Hydro	40,438	9,122	8,099	4,561	1,960
CCGT	483	5,269	3,836	17,409	12,675
CT	824	5,153	1,069	4,352	3,169
Nuclear	0	13,328	705	5,403	4,004
Solar	0	2,296	0	265	961
Wind	3,432	5,077	1,166	1,986	1,404
Pumped Storage	0	0	0	1,409	1,797

1 Source: Statistics Canada, 2019b. Table 25-10-0022-01. Installed plants, annual generating capacity by type of electricity generation.
2 Source: EIA, 2020. Existing nameplate and net summer capacity by energy source, producer type and state.

For generation and storage, costs estimates were provided by NREL 2019 Annual Technology Baseline ATB Cost and Performance Data for Electricity Generation Technologies (NREL, 2019). Annualized investment costs are calculated using a 6% discount rate. Table A2.3 presents the lifespan and the costs used for each technology. For natural gas, the fuel cost is based on a natural gas price of $3/MBtu. For CCGT, the heat rate is 7,627 Btu/kWh and 11,138 Btu/kWh for CT.

Table A2.3 Investment and operation costs per technology

	Lifespan [year]	Investment cost [k$/MW]	Annualized Investment cost [k$/MW-yr]	Fixed O&M cost [k$/MW]	Variable O&M cost [$/MWh]	Fuel cost [$/MWh]
CCGT	25	926	68.34	13.33	3.00	22.00
CT	25	919	67.82	19.37	7.00	33.00
Hydro	75	8,000	458.63	14.85	2.46	-
Nuclear	40	6,742	422.72	101.00	2.00	7.00
Solar	25	1,111	81.99	20.00	-	-
Storage[1]	10	1,384	177.40	37.11	-	-

1 A 81% efficiency rate is assumed

For the carbon-neutral natural gas, the fuel cost starts at five times the cost of fossil natural gas (5x$3/MBtu, see IEA, 2020b). It jumps at 25 times the initial cost of $3/MBtu after 50 TWh of renewable natural gas generation, to reflect the scarcity value of such carbon-neutral natural gas. See Table A2.4.

Table A2.4 Carbon-neutral natural gas generation and cost factor

	Generation [TWh]	Cost Factor[1]
Block 1	50	5x
Block 2	250	25x

1 Applied to the fossil fuel cost

WIND PARAMETERS

Capacity potential of wind power is estimated using U.S. Installed and Potential Wind Power Capacity and Generation (U.S Department of Energy, 2020). The capacity potential and costs of wind power are shown in Table A2.5.

Table A2.5 Wind capacity potential and costs per technology and region

		QC	ON	AT	NY	NE
Capacity [GW]	W1	10	5	5	5	5
	W2	10	5	10	5	5
	W3	50	50	50	40	40
Investment cost [k$/MW]	W1	1,200	1,202	1,201	1,203	1,204
	W2	1,623	1,625	1,624	1,626	1,627
	W3	2,999	3,001	3,000	3,002	3,003
Fixed O&M cost [k$/MW]	W1 W2 W3	44				

DEMAND RESPONSE AND LOAD SHEDDING PARAMETERS

Three blocks of demand response (DR) are available with an increasing price. Given the complexity of precisely estimating the cost of demand response programs, we use these values as representative values of possible voluntary load reduction programs (such as accepting a colder or warmer temperature for one hour). These values represent the compensation received by consumers for reducing their load by 5%. These DR actions are not load shifting actions. Load shedding by the system is also possible at much higher cost. Table A2.6 presents the capacity and unitary costs of each block of demand response.

A $10,000/MWh cost of load shedding is assumed in each region.

Table A2.6 Demand response capacity and costs

	Capacity [% of load]	Cost [$/MWh]
DR1	5%	100.00
DR2	5%	150.00
DR3	5%	200.00

TRANSMISSION PARAMETERS

Interconnection capacities shown in Table A2.7 are sourced from Hydro-Québec Transmission system overview (Hydro-Québec, 2018) for interconnection with Québec. For New York interconnection with Ontario and New England, transmission capacity data are collected from NYISO Available Transfer Capability Implementation Document (NYISO, 2017). New England interconnections capacities with the Atlantic Provinces are provided by NPCC 2018 Long Range Adequacy Overview (NPCC, 2018).

Table A2.7 Initial interconnection capacities in MW

	QC	ON	AT	NY	NE
QC	-	2,705	1,029	1,999	2,275
ON	1,970	-	-	2,000	-
AT	785	-	-	-	700
NY	1,100	1,600	-	-	1,600
NE	2,170	-	700	1,400	-

We assume an 80-year lifetime for transmission lines. We use a $2 million/MW cost estimate for transmission, irrespective of distance (which are all the same range), because it is between the cost of two recent transmission projects: (1) the overhead New England Clean Energy Connect cost: $950 million for 1,200 MW or $0.79M/MW (see https://www.necleanenergyconnect.org/necec-milestones) and (2) the underground 1,250 MW Champlain Hudson Power Express project, with a reported cost of $2.9 billion (https://www.nationalobserver.com/2021/07/16/news/will-grid-diplomacy-lead-decarbonization), resulting in a cost of $2.3 million per MW. Table A2.8 presents costs and distances of new transmission lines.

Table A2.8 Transmission costs and distances

	Interconnection Transmission cost [$/MW]	Distance[1] [km]
ON-QC	2,000,000	505
AT-QC		791
NY-QC		534
NY-ON		551
NE-QC		403
NE-AT		655
NE-NY		306
1 Flying distances between main cities.		