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Shen Wang, Jack Morris, Grant Lee, Joshua Hodge, and John E. Parsons

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Cross-Border Electricity Trade and the Future of the Grid in Northeastern North America

Shen Wang Jack Morris Grant Lee Joshua Hodge John Parsons*

*MIT Center for Energy and Environmental Policy Research,
Massachusetts Institute of Technology

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Abstract

This report examines the future 2050 electric grid across northeastern North America, including New England, New York, Ontario, Québec, and the Atlantic provinces. We evaluate the benefits of two forms of regional cooperation: enabling two-way cross-border electricity trade and expanding interregional transmission capacity. Using the GenX capacity expansion and dispatch model, we simulate long-term investment and operational outcomes under alternative trade, transmission, load growth, carbon policy, and nuclear deployment assumptions.

The results show that the 2050 grid will be fundamentally different from today's system, with substantially higher electricity demand, retirement of carbon-intensive fossil generation, and large-scale investment in wind, solar, storage, hydro, and clean firm resources. Because wind resource quality varies significantly across the region, interregional coordination can lower system costs by shifting investment toward high-quality renewable regions, particularly Québec and the Atlantic provinces. One-way trade and existing transmission constraints limit this efficient allocation and require greater local investment in lower-quality resources and flexibility assets.

Transmission expansion enables more efficient resource allocation, while two-way trade unlocks Québec's hydro flexibility by allowing surplus renewable generation from U.S. regions to be absorbed and re-dispatched during scarcity periods. Combining two-way trade and expanded transmission reduces annual system costs by nearly $1.2 billion, or approximately 4%, while improving reliability and reducing renewable curtailment. These findings highlight the value of coordinated cross-border planning, bidirectional trade arrangements, and targeted transmission expansion for achieving an affordable, reliable, and low-carbon power system in northeastern North America.

Keywords: Power trade; transmission expansion; capacity expansion planning; power system decarbonization; energy policy; renewable integration; hydro flexibility

JEL Codes: Q40, Q42, Q48, L94

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1 Executive Summary

1.1 Study Purpose and Context

This report delivers the result of a two-year study of the future 2050 electric grid across a large portion of northeastern North America spanning several provinces of Canada and several of states of the U.S. These include Ontario, Québec and the four Atlantic provinces, and New York state and the six states of New England. Our focus was on the potential benefits from two types of increased cross border cooperation.

First, we look at opening up existing key transmission interfaces to two-way trade. While the grid is often thought of as a single, interconnected system, the reality is that it has 'seams' at the boundaries joining certain states and provinces. The systems on either side of the seam are administered by different entities with different protocols determining operations and pricing. Arrangements must be made to enable and facilitate cross-border trade. At one extreme, these arrangements unify the system–for example, the six states of New England operate a single system. More often, specific contracts and other governance arrangements enable specific transactions as with the various export contracts between Hydro Québec and neighboring regions. Currently, the governance arrangements across the U.S. and Canadian borders have generally not been negotiated to take full advantage of the potential benefits of two-way trade. Recently, flows of power from New York and New England into Québec have been notable, precisely because it is an exception to the longstanding pattern of flow from Canada down to the U.S.. This stands in contrast to the east-west trade between New England and New York, for example, which regularly sees flows in either direction. This research explores what gains may be had by enabling a fuller two-way trade between the U.S. states and Canadian provinces.

Second, we look at further expanding transmission capacity, both across the U.S.-Canada border as well as east-west between the Canadian provinces. We examine expanded transmission within the current framework of one-way trade, and then we consider the combination of expanded transmission together with the facilitation of two-way trade.

We conducted the study with an appreciation of the importance of affordable and reliable electricity to all of the economies of the area. Load growth over the next quarter of a century is likely to be significant, although predictions of the future must always be accompanied by a sober appreciation of the great uncertainty involved. Alongside the potential growth, electrification is expected to shift demand toward a winter or dual-peaking system, driven largely by beneficial electrification in the United States. Simultaneously, alongside the expansion of generation, it is preserve reliability and work to achieve mandated emission reductions.

While the study covered a large region, it does not entertain any single policy crafted for the entire region. It is to be expected that individual provinces and states will make different choices over a range of generation technologies available to each, as well as different choices over how best to exploit the diverse renewable resources available across the area. Our focus is on identifying opportunities in which cooperation across the provinces and states could contribute to each individual province or state's goals.

1.2 Capacity Expansion and Dispatch Modeling

Our research utilized the GenX capacity expansion and dispatch model. GenX was developed at the MIT Energy Initiative in partnership with Princeton University's Zero Lab and New York University's Sustainable Energy Transitions group, and has been employed by many research teams for policy studies and peer-reviewed published research. In earlier work, we had used GenX in a study focused on the utilization of Québec's hydro resources and the expansion of transmission between Québec and New York and New England. This current study surveys options for a wider territory and for a broader array of resources and includes updated system assumptions to more accurately capture the future regional energy market dynamics. The GenX model allows us to examine investments in alternative portfolios of generation and transmission, detailed by individual region, and to explore the system cost by region as well as the CO2 emissions. The model is parameterized with a catalogue of legacy generation and transmission assets, and used to evaluate additional investments targeted to serve projected 2050 load. The report details results for a large set of alternative cases and scenarios which taken together provide useful insights.

A key result that surfaces from the research is the critical importance of decisions about the exploitation of wind resources across the many provinces and states. Driving this is the fact that the technology for wind generation has dramatically improved over the last decade, and that further technology improvement is expected in the coming decades. This is likely to drive down the relative cost of wind generation in the long run. Wind resources that have long been an endowment of each province and state, will become increasingly exploitable as a valuable source of affordable electricity. Prudent electricity sector planning should take advantage of this opportunity and identify how to best integrate this resource as a part of the portfolio of generation technologies.

While this can be done individually by each province and state, maximizing the returns from developing this resource also warrants examining opportunities for interregional cooperation. The quality of wind resource is greater in some provinces and states than in others, so that there are significant benefits to be had from cooperation. While key provinces and states may be pursuing or exploring specific offshore sites, in the modeling presented in this research, the results are driven primarily by the choices made for developing onshore wind capacity. The best wind resources appear to be in the north and east of the region, especially in Québec and the Atlantic provinces. Neighboring provinces and states could benefit from enabling the expansion of wind capacity in those provinces, which would require expanded interregional transmission. Enabling two-way trade between U.S. and Canadian regions can also benefit parties on both ends of any transmission interconnection. Québec and the Atlantic provinces benefit from minimizing required investments in expensive peaking capacity including that provided by storage assets. While expanding wind generation alone provides part of the solution, its value exhibits diminishing returns at high penetration levels unless paired with flexibility resources. In the near term, this flexibility is largely provided by storage, and in the longer term by long-duration storage or other firm balancing resources. It can also be provided by expanding transmission access across a larger territory.

Of course, the size of the benefits from interregional cooperation depends upon the many other choices each province and state makes about the rest of the portfolio. Nevertheless, across the many cases and scenarios, we find that the availability of benefits from cooperation is robust. Therefore, we unpack the result using a conservative case in which the benefits are modest, and then we discuss other cases where the benefits increase.

One of the variables conditioning the size of the benefits is the pace of decarbonization. The value of interregional cooperation increases with the pace of decarbonization. But we show that there is value even when the pace is modest: an 80% reduction in grid emissions by 2050, relative to a benchmark of 2005 emissions.

A second variable conditioning the size of the benefits is the availability of zero-carbon firm generation, for which the availability of nuclear power is a particular example. There is significant uncertainty about the cost of building new nuclear plants. None have been built within the northeastern North America territory since 1992. The entire continent had a two decade hiatus between 1996 and 2016, when Watts Bar 2 was completed in the U.S., followed by the Vogtle 3 and 4 units in 2023 and 2024. The Vogtle project took nearly twice as long as originally planned and the cost approximately doubled compared to the original estimate. A sister project in South Carolina was abandoned half-way through due to similar delays and cost overruns. Nevertheless, there is significant interest in pursuing new builds of nuclear power. Ontario Power Generation has begun construction of the first North American small modular reactor (SMR) at OPG's Darlington site, and the province of Ontario has incorporated new nuclear as a major feature of its energy strategy. New York state initially committed itself to construction of at least 1 GW of new nuclear capacity, and the Governor recently directed state authorities to prepare a path to a total of 5 GW. New Brunswick includes new nuclear as a feature of its energy strategy. Alongside these pronouncements, there remains significant anxiety about danger of persistent inability to deliver projects on time and on budget.

A humble attitude to predicting the future warrants entertaining wildly different possibilities. At one extreme, it may be that the intent to master the construction process proves successful, so that costs come down and the ongoing penetration of new nuclear generation is significant. At the other extreme, it may be that, despite the best efforts, experience falters, costs escalate and plans are dramatically cut back. Therefore, we test our results across a range of penetration by new nuclear. We found that the value of interregional cooperation holds in all cases, with the value increasing as the penetration of nuclear decreases. Accordingly, the conservative case we present reflects an assumption of significant penetration of nuclear. For both New York and New England the conservative case includes new capacity on top of existing plants equal to 2.4 GW each. For Ontario, our baseline already includes 1.2 GW of new capacity on top of existing plants, and the conservative case includes a further 2.4 GW. We do not assume any nuclear capacity in Québec. For the Atlantic provinces our baseline assumes New Brunswick adds another 600 MW to its current 660 MW of nuclear capacity.

To summarize, we present the main results first using a conservative set of assumptions:

- a medium scenario for load growth,
- a modest carbon policy, reducing 2050 emissions 80% from 2005 levels,
- a significant penetration of new nuclear capacity.

Then, in the full body of the report we also check the results for a variety of scenarios created by varying these assumptions:

- both a low and a high scenario for load growth,
- more aggressive decarbonization policies, reducing 2050 emissions 90% from 2005 levels, as well as 95%,

- a significantly lower penetration of new nuclear capacity, as well as an even higher penetration.

1.3 The Main Results

The main results are based on an analysis of four cases, as shown in Table 1. We start in the upper left corner, where we continue with one-way trade using the existing transmission capacity. For existing, we include the recently completed 1,250 MW New England Clean Energy Connect (NECEC) high-voltage direct current (HVDC) line between Québec and New England, as well as the 1,200 MW Champlain Hudson Power Express (CHPE) HVDC line currently under construction between Québec and New York. This is ‘Case 1’. We then move to the upper right corner, where we assume new governance arrangements facilitate two-way trade, still using the existing transmission. This case is ‘Case 2’.

Table 1: Four Cases for the Simulation Experimental Design

	One-Way Trade	Two-Way Trade
Existing Transmission	C1	C2
Expanded Transmission	C3	C4

The next two cases are in the bottom left and bottom right corners. For these we assume investments are made to expand transmission capacity between various states and provinces. In particular, we assume an additional

- 1 GW of transmission capacity between Québec and New England,
- 2 GW of transmission capacity between Québec and New York,
- 2 GW of transmission capacity between Québec and Ontario, and
- 1 GW of transmission capacity between the Atlantic provinces and the states of New England.

The bottom left case includes this added transmission capacity, but retains the assumption of one-way trade across the U.S. and Canadian border. This is ‘Case 3’. Finally, the bottom right case includes this added transmission capacity, and assumes new governance arrangements to facilitate two-way trade. This is ‘Case 4’.

In the body of the report we consider the impact of implementing two-way trade and transmission expansion individually as well as together. To evaluate two-way trade on its own, we can evaluate system changes moving from Case 1 to Case 2. To evaluate transmission expansion on its own, we can evaluate system changes moving from Case 1 to Case 3. Then, to evaluate two-way trade together with transmission expansion, we can evaluate system changes moving diagonally from Case 1 to Case 4.

While the body of the report discusses each of these comparisons, as well as the results of the various other sensitivity scenarios, this Executive Summary focuses on comparing Case 4 against Case 1, which gives us the benefits of expanding cooperation on both dimensions taken together.

1.3.1 The Baseline

Before analyzing how policies could improve the 2050 grid, we need to appreciate how, under most any assumptions, the 2050 grid is going to look very different from the current era's grid. Case 1 utilizes our conservative set of assumptions, together with the current one-way trade arrangement and the existing transmission capacity. Figure 8 shows how the cost-efficient portfolios in 2050 for Case 1 compares to the 2022 portfolios. Figure 2 shows the contrast in generation by fuel type.

Total capacity increases by 60%. The make-up of that capacity changes even more dramatically. The 2022 included nearly 60 GW of fossil capacity, mainly in New England, New York and Ontario but also including some coal and oil generation in the Atlantic provinces. By 2050, 18% of these carbon-intensive generators have retired even as total generation capacity increases. Variable renewable energy technologies–particularly onshore and offshore wind and solar PV–account for a large fraction of new capacity. Onshore wind grows from just over 13 GW in 2022 to just over 57 GW in 2050, a more than 300% increase. Offshore wind expands from almost nothing to more than 23 GW.[1] Solar rises from approximately 3 GW to more than 10 GW. This growth is complemented by expanded storage deployment, with pumped storage and batteries increasing from just 3.6 GW in 2022 to more than 20 GW in 2050, providing the flexibility required to balance variability and maintain system reliability. Wind capacity expands in all regions, but it is notable that in 2050 it has captured a sizable share of Québec's total portfolio–25%–even as hydro

[1] While near-term offshore wind deployment may face delays, the long-term expansion trajectory assumed in this study remains consistent with ISO planning studies.

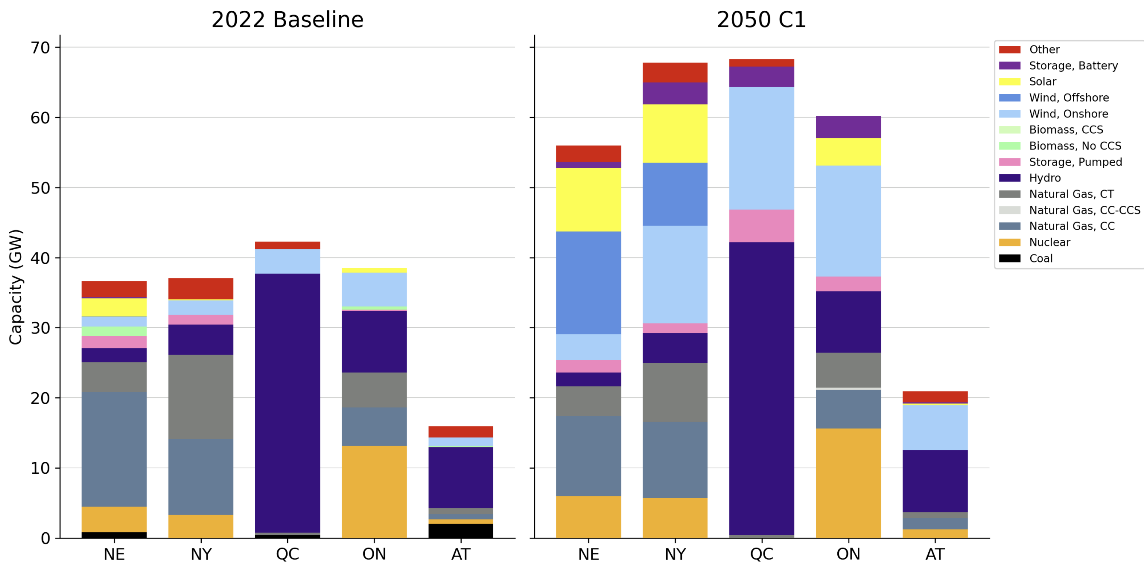

Figure 1: 2050 Installed Capacity by Technology for Case 1 Versus 2022 Actual Installed Capacities.

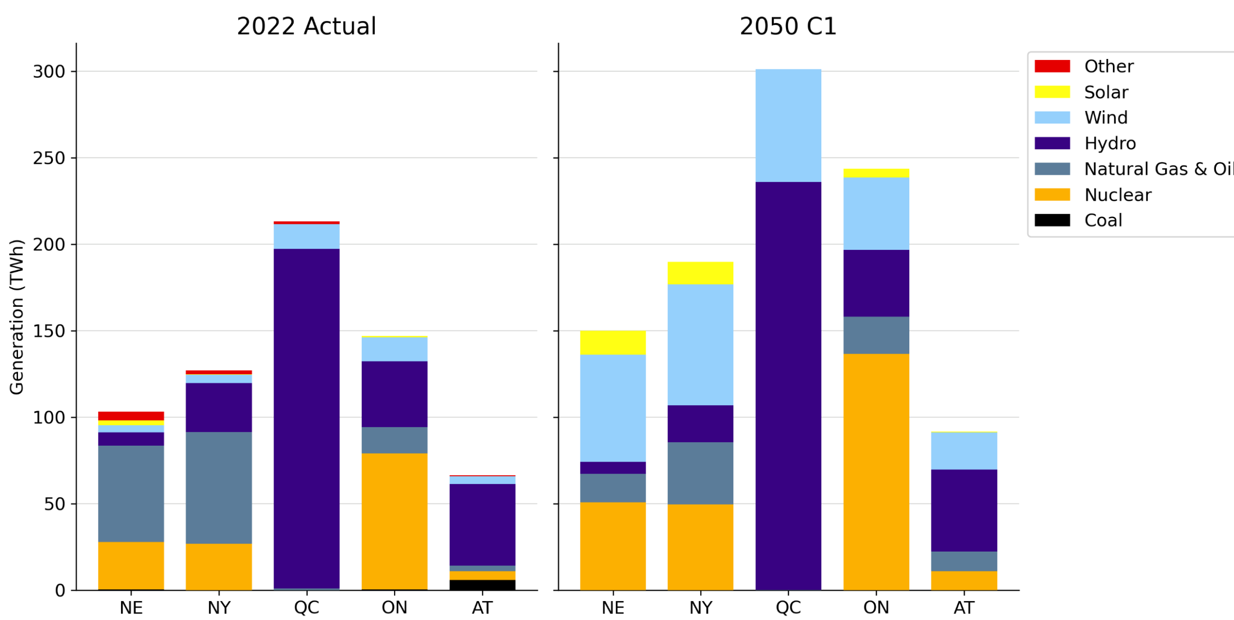

Figure 2: 2050 Generation by Fuel Type for Case 1 Versus 2022 Actual Generation.

capacity is expanded. Finally, nuclear capacity increases by almost 8 GW.

Total generation increases from 657 TWh in 2022 to 976 TWh in the 2050 Case 1, an increase of nearly 50%, matching the forecasted load increase. At the same time, generation from fossil fuels declines by 42%, going from 146 TWh to 85. Generation from nuclear, hydro, wind and solar all increase.

Our 2050 baseline transmission incorporates all existing interregional transmission connections including the new NECEC line between Québec and New England and the soon to be completed CHPE line between Québec and New York. Those two lines represent a 29% increase of interconnection capacity on a system where generation is expanding by 50% and where many sources of generation are increasingly variable. It is from this 2050 baseline of expanded capacity and generation that we evaluate the benefits of two-way trade and of further expanded interregional transmission, focusing our attention on the contrast between Cases 1 and 4.

1.3.2 The Benefit of Two-Way Trade and Expanded Transmission

The constraint of one-way trade and the existing transmission capacity limits the exploitation of the highest quality wind resources. Lower quality wind and solar resources are exploited instead, which makes the system more costly. In addition, the system is forced to maintain or invest in complementary dispatchable resources–be they batteries or pumped storage or fossil fuel plants. Figure 3 shows the change in installed capacity when two-way trade is enabled together with expanded transmission, i.e., moving from Case 1 to Case 4. Each region shows a net negative change in invested capacity. Québec and the Atlantic provinces show an increase in installed wind capacity, while this is offset by a decrease in other capacity in the respective regions. The utilization of more productive wind capacity in Québec and the Atlantic provinces also enables the reduced capacity investments in less productive areas in the U.S. and Ontario.[2]

The portfolios of capacity shown in Case 1 were optimized to reliably supply each state or province with affordable electricity, taking advantage of each state's or province's endowment of renewable resources, and making the best use of the existing interregional transmission capacity under existing institutional arrangements. As each state or province develops its chosen portfolio, it will be mindful of transmission constraints and adapt its

[2]Figure 3 shows all of the reduced U.S. capacity in wind and solar being located in NY and not NE. However, on certain dimensions, including the location of wind and solar resources in NY and NE, there are a multiplicity of solutions for Case 1.

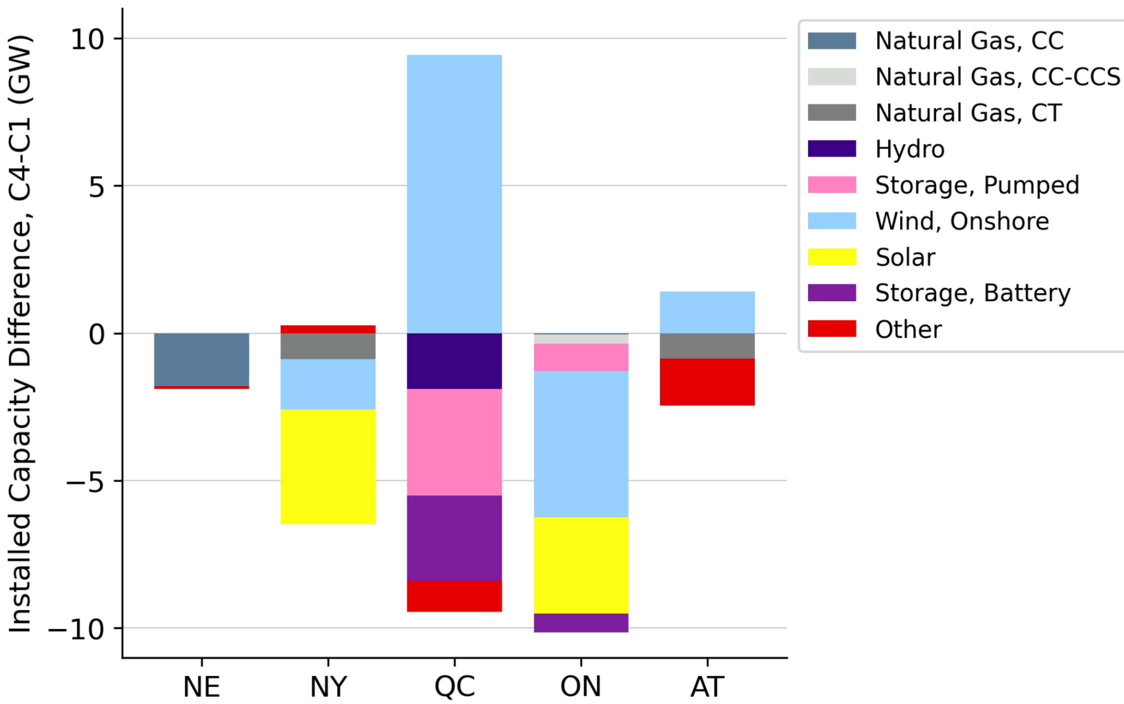

Figure 3: The Change in Installed Capacity by Technology and Region, Going from Case 1 to Case 4.

portfolio accordingly. In a system with a high penetration of renewables, a key issue that must be factored into the choice is the variability in the renewable resource. As the penetration of renewables increases, two changes occur. First it eventually becomes necessary to curtail generation in some hours. In turn, this curtailment reduces the return on investment in additional capacity. Second, metrics for resource adequacy–such as Effective Load Carrying Capability (ELCC)–show a declining contribution from the renewable resource. Therefore, the states and provinces must be cautious about over investing in certain renewable technologies, and must evaluate carefully the limits imposed by those diminishing returns. The need for curtailment and resulting diminishing returns can be managed by complementing investment in renewables with investment in storage. Of course, this increases the cost of capturing the full value of the renewable resource, which still results in diminishing returns.

Two-way cross-border electricity trade provides an additional and economically efficient mechanism to manage surplus renewable generation. By enabling bidirectional power flows, regions with excess variable renewable energy—particularly New York and New England—can export surplus generation to Québec, where flexible hydro resources can absorb and re-dispatch this energy. As a result, two-way trade substantially reduces variable renewable energy (VRE) curtailment compared to one-way trade configurations. In Case 1, just over 1 TWh of potential renewable generation is curtailed, whereas in Case 4, curtailment is de minimis, highlighting the role of bidirectional trade in improving renewable integration and system efficiency.

Two-way trade also expands the options for assuring reliability. When the system in one region is stressed, with net load potentially exhausting capacity, the ability to access generation in another region reduces the stress. An example of this benefit can be seen in Figure 4. The figure contains two graphs. The left-hand graph is for Case 1, when there is only one-way trade and only existing transmission capacity. The right-hand graph is for Case 4, when there is two-way trade and expanded transmission capacity. In each graph, each dot represents a different hour of the year. The dots are color coded to reflect the modeled 'System Lambda' in Québec. System Lambda is the marginal cost of serving an extra megawatt of load that hour. The scale for the System Lambda is logarithmic, so whereas the green events have a marginal cost of only $100, the most extreme purple events have a marginal cost of $20,000/kWh, flagging the extreme stress on the system. The axes of each graph show different combinations of wind availability and load. To the left of each graph, wind availability is low, and to the right wind availability is high. At the bottom of

Figure 4: System Lambda in Québec Across Wind Resource Availability Factors and Load.

each graph load is low, while at the top load is high. We should expect stress to show up most often when wind availability is low and load is high–i.e., in the top left of each graph. In the top left of the left-hand graph, there are several events where the System Lambda reaches an extreme. In contrast, in the top left of the right-hand graph the number of hours of extreme stress have been reduced to only two (although they appear like a single event given their similarly high load and low wind).

The total cost savings of enabling two-way trade and investing in expanded transmission come to over $1 billion annually, primarily in the form of avoided generation capacity. This reduces the incremental system costs by about 4%.

This Executive Summary has used a comparison between two cases built up from a single set of assumptions on load growth, emission constraints, and the penetration of nuclear to highlights the key role played by the regional distribution of wind resources. The full report includes a host of sensitivities on the input assumptions, and it finds that key role to be robust to the assumptions.

1.4 Summary of Key Messages

- The 2050 grid will be fundamentally different. In our base case scenario, load is 50% higher. As generation capacity increases, the profile shifts dramatically. Some of the most carbon intensive fossil plants retire. Although a large amount of gas-fired capacity is retained, its utilization drops. New capacity investment are primarily in wind, solar, storage, and clean firm resources, including nuclear.
- The relative cost of wind capacity is likely to continue falling over the long run, raising the value of each province and state's available wind resources. However, the quality of these resources varies significantly across provinces and states in the territory studied. This fact drives the value of interregional trade.
- The constraint of one-way trade and the existing transmission capacity limits the exploitation of the highest quality wind resources. Lower quality wind and solar resources are exploited instead, which makes the system more costly. In addition, the system is forced to maintain or invest in complementary dispatchable resources–be they batteries or pumped storage or fossil fuel plants.
- Transmission expansion enables efficient resource allocation, shifting new capacity toward the highest-quality renewable regions and reducing redundant investments elsewhere.

- Two-way cross-border trade unlocks hydro flexibility, reducing renewable curtailment, lowering storage and peaking investment needs, and improving reliability.
- Combining two-way trade and expanded transmission reduces system costs by nearly \$1.2 billion (4%) annually, while improving reliability.
- The value of regional cooperation grows under deeper decarbonization and higher load growth, and remains robust across nuclear deployment assumptions.

2 Report Overview

This report analyzes the future 2050 electric grid across a large portion of northeastern North America spanning several provinces of Canada and several of states of the United States. These include Ontario (ON), Québec (QC) and the four Atlantic provinces (AT: New Brunswick, Newfoundland and Labrador, Nova Scotia, and Prince Edward Island), and New York state (NY) and the six states of New England (NE: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut). Our focus was on the potential benefits from two types of increased cross border cooperation. The system is interconnected by approximately 6-7 GW of cross-border transmission capacity linking about 35 million people in the U.S. with 25 million in Canada. Québec and Ontario are usually exporters to NY and NE, with power transfers exceeding 35 TWh in 2022—equivalent to roughly 10% of total electricity demand in NY and NE. Some Canadian provinces benefit from abundant clean energy resources - including water, wind, and uranium - which position these regions to not only meet their own greenhouse gas (GHG) reduction targets but also to support decarbonization in the U.S. In particular, Québec possesses extensive hydroelectric resources, which currently supply more than 95% of its electricity needs. However, there is interannual variability of water inflows, so that the availability varies across years, and the most recent years have seen low inflows.

For the past two decades, Québec has exported clean, reliable, and competitively priced electricity into wholesale markets in northeastern North America. However, despite the physical capacity and economic potential for cross-border trade, bidirectional (two-way) electricity trade between Québec and U.S. regions has historically been limited, and its value has not been thoroughly studied. Several institutional and structural barriers constrain such trade. First, there are asymmetric market structures: New England, New York, and Ontario operate organized wholesale markets, while Québec and the Atlantic Provinces remain vertically integrated utility systems. Second, differences in tariff and transmission fee structures across jurisdictions can hinder regional integration and limit the economic efficiency of cross-border power flows. For instance, the transmission tariffs create a deadweight cost for roundtrip flows utilizing cross-border storage assets. Third, the absence of harmonized emissions regulations and policy frameworks complicates cross-border coordination. Finally, underinvestment in cross-border transmission infrastructure has further restricted the potential for deeper electricity integration [36, 13].

Many studies have examined U.S.– Canada power system expansion, cross-border electricity trade, and the role of hydro-rich systems in regional decarbonization. Ibanez et al. [20] use the NREL ReEDS model to co-optimize capacity expansion for both American and Canadian systems, finding that their base scenario projects a significant increase in wind generation in both countries alongside gradual retirements of coal and nuclear. They also show that ISO-NE and NYISO consistently import energy from Canada whereas regions in the western U.S. increase exports in the opposite direction. Another ReEDS-based study [3] assesses the value of transmission expansion under deep decarbonization, showing that unlimited transmission expansion enables greater U.S.–Canada trade and larger Canadian resource buildouts, whereas restricted transmission leads to more U.S. capacity installation (solar, wind, and natural gas), especially under carbon constraints. Rodríguez et al. [36] apply a capacity expansion model to the northeastern North American system, showing that integration and additional interconnection capacity can substantially lower decarbonization costs, though benefits are unevenly distributed across jurisdictions, potentially reducing incentives for collaboration. Ba et al. [1] highlight the tradeoff between transmission and storage, arguing that the value of transmission–reservoir coupling is robust even under very low short-term storage costs, and that optimal transmission usage reduces investment needs in batteries and other balancing technologies. Yuan et al. [40] use an integrated top-down, bottom-up modeling framework to examine the value of transmission expansion from Québec to New York and New England, finding that carbon limits increase fuel prices more than electricity prices, a result not typically observed in power-sector-only models. Finally, De Villemeur et al. [12] analyze deep market integration between hydro-based and thermal-based jurisdictions, showing that integration (e.g., between Québec and Ontario) lowers electricity prices, benefiting consumers in the thermal jurisdiction (Ontario) and producers in the hydro jurisdiction (Québec), though not necessarily Québec's consumers. Dimanchev et al. [13] argue that expanding transmission access to hydro reservoirs reduces the need for fossil-fuel plants that would otherwise be needed to balance variable renewables. They show that in deep decarbonization settings, it becomes optimal to shift from unidirectional (export-only) flows of hydropower to bidirectional trade, such that hydro reservoirs act more like system-wide storage.

While previous research has substantially advanced understanding of U.S.–Canada electricity integration, important gaps remain. Most studies emphasize the benefits of transmission expansion and hydro resource integration, but they often assume two-way trade or do not explicitly differentiate between one-way and two-way trade structures. As a result, the role of trade directionality in shaping long-term investments in generation and transmission remains underexplored. Finally, the interaction between policy misalignment (e.g., different carbon targets in American and Canadian jurisdictions) and cross-border integration has not been fully addressed, particularly in the context of long-term load growth and emerging clean firm technologies such as small modular nuclear reactors.

To address these gaps, our study employs a system optimization perspective to explore the long-term (2050) evolution of the northeastern North American power system. Our analysis is structured around the following research questions:

- How do different QC–U.S. trade structures—one-way versus two-way power flows—affect investments in generation and transmission across the northeastern North American territory?

- How does cross-border trade with and without transmission expansion reshape the location of investments across regions in the long run?

- What are the system-level impacts of carbon policies across American and Canadian jurisdictions on generation mix, emissions, reliability, and system costs?

The remainder of this report is organized as follows. Section 3 describes the modeling framework, data inputs, and experimental design, including the formulation of one-way and two-way trade configurations, transmission expansion settings, and sensitivity analyses concerning load growth, carbon policies, and nuclear deployment. Section 4 presents the simulation results and analyses, focusing on capacity expansion, operational dispatch, interregional trade, system costs, and regional location of investments under alternative trade and policy settings. Section 5 summarizes the key findings, discusses policy implications, and outlines directions for future research on regional coordination and cross-border electricity integration in the northeastern North America power system.

3 Methods

3.1 Power System Capacity Expansion and Dispatch

We employ the GenX capacity expansion and dispatch model, an open-source, least-cost optimization framework developed in Julia [6]. GenX co-optimizes generation, storage, and transmission investments alongside hourly system operations to meet demand and policy constraints at minimum cost. In this study, we configure GenX to simulate the northeastern North America power system, parameterizing generation and transmission candidates, operational constraints, and carbon policies to evaluate long-term capacity expansion pathways. The simulations determine one-time capacity expansion or retirement decisions for the year 2050 with respect to a baseline in the year 2022, with hourly chronological operations represented for all 8,760 hours.

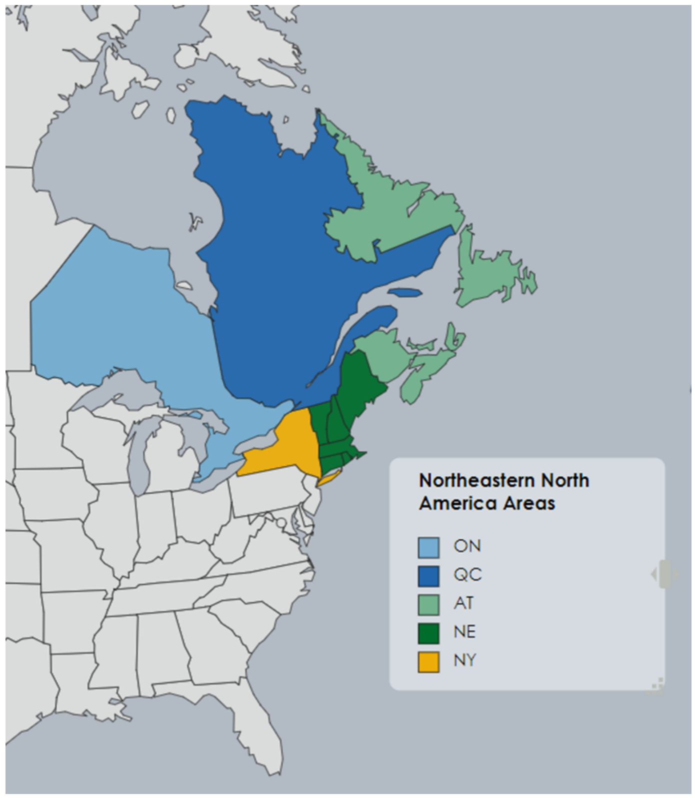

Figure 5: Northeastern North America (including Ontario, Québec, the Atlantic provinces, New England, and New York)

3.2 Region Case Assumptions

We model the northeastern North American (Figure 5) power grid as a five-region system consisting of New England (NE), New York (NY), Ontario (ON), Quebec (QC), and the Atlantic provinces (AT). The following sections detail assumptions and data for the northeastern North America power system used in the GenX model.

Table 2: Load Growth Scenarios

		NE	NY	QC	ON	AT
Actual						
	Annual Load, 2022, TWh	117	153	196	138	42
	Peak Load, 2022, GWh	24	31	40	23	8
Low						
	Annual Load, 2050, TWh	129	168	216	179	47
	Peak Load, 2050, GWh	30	35	45	29	9
	Ratio, 2050/2022	1.1	1.1	1.1	1.3	1.1
	Compound Annual Growth Rate	0.34	0.34	0.34	0.34	0.34
Medium						
	Annual Load, 2050, TWh	199	244	353	330	59
	Peak Load, 2050, GWh	47	51	73	54	12
	Ratio, 2050/2022	1.7	1.6	1.8	2.4	1.4
	Compound Annual Growth Rate	1.91	1.69	2.12	3.18	1.21
High						
	Annual Load, 2050, TWh	246	336	412	344	68
	Peak Load, 2050, GWh	58	70	85	57	14
	Ratio, 2050/2022	2.1	2.2	2.1	2.5	1.6
	Compound Annual Growth Rate	2.69	2.86	2.69	3.33	1.69

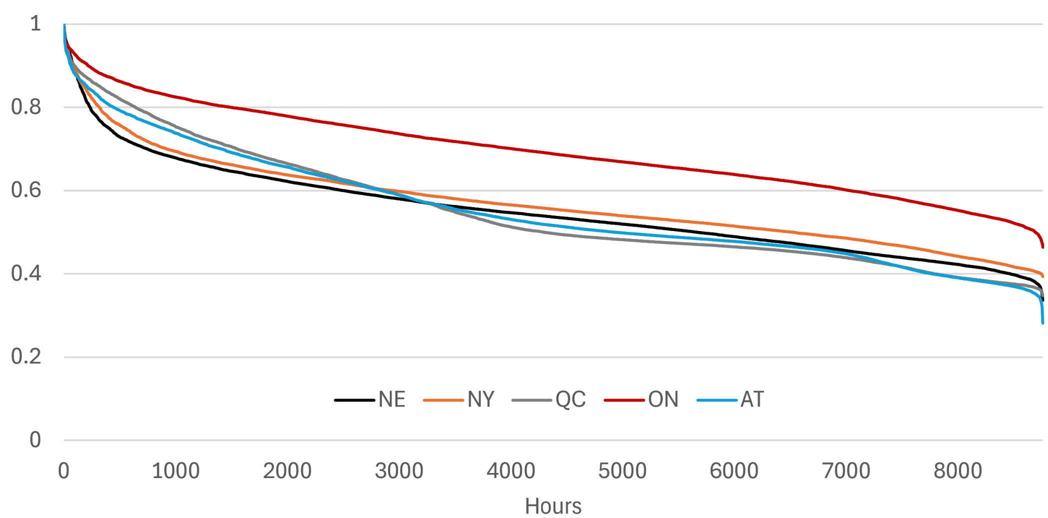

Figure 6: Normalized load duration curves for the regions in northeastern North America

3.2.1 Load Projections

We use 2022 historical hourly load data for the northeastern North America regions as baseline load profiles (Figure 6). Future 2050 load profiles are derived by applying load growth factors to these baseline profiles. As shown in Table 2, we consider three load growth scenarios: low, medium, and high. We employ the medium load growth projections in our main cases and employ the others in our sensitivity analysis. The growth factors are informed by an extensive literature review of forward-looking projections from ISO reports, government studies, and academic research, and their range encompasses all projected scenarios identified in these sources [24, 33, 21, 17, 9]. Key drivers of load growth in northeastern North America include electric vehicle adoption, building electrification, industrial electrification, residential heat pump deployment, and data center expansion. Region-specific drivers are discussed in detail in Appendix A.1.

3.2.2 Generation Technologies

Table 3 shows baseline installed capacity (including existing capacity in 2022 and planned capacity) by technology as used in the GenX model. The planned resources refer to committed projects that have already secured regulatory approval or are under construction in practice. In New England and New York, natural gas technologies dominate, with combined cycle (CC) and combustion turbine (CT) together accounting for more than half of total installed capacity in each region. Québec's system is overwhelmingly hydro-based, with a growing contribution from wind. The Atlantic provinces are diverse with differing mixes, primarily of hydropower, natural gas, and nuclear capacity. Much of the large-scale hydropower in Newfoundland and Labrador has historically been exported to Québec. Ontario's capacity mix is led by thermal generation, with significant shares of nuclear and natural gas. Other resources—including wind, solar, oil, and biomass—are present in smaller but regionally important shares across the system.

The planned additions and retirements for each resource are summarized in Table 17 in the Appendix A.3, based on information collected from ISO and utility reports [25, 34, 18, 22, 32, 23]. These planned resources are incorporated as fixed additions in the GenX model, analogous to the treatment of existing capacity. In practice, these units represent committed projects that have already secured regulatory approval, financing, or construction progress, and thus are considered non-discretionary from a planning perspective. By hard-coding these resources into the model, we ensure that the simulation reflects the expected near-term evolution of the system while allowing the model to optimize investment decisions only for unplanned future capacity.

Table 3: 2022 Installed Capacity with Planned Additions and Retirements (MW)

	Total	NE	NY	QC	ON	AT
All	**234,138**	**59,917**	**56,655**	**56,404**	**44,010**	**17,152**
Hydro	**63,754**	1,968	4,265	39,942	8,748	8,831
Natural Gas, CC	**35,785**	16,395	10,843	-	6,970	1,577
Wind, Onshore	**28,945**	3,686	5,266	13,932	4,883	1,178
Wind, Offshore	**24,242**	14,682	9,000	-	-	560
Natural Gas, CT	**22,578**	4,234	12,074	411	5,000	859
Nuclear	**21,380**	3,606	3,305	-	13,209	1,260
Solar	**14,348**	9,043	4,416	10	648	231
Oil	**6,635**	2,280	2,749	-	-	1,606
Storage, Battery	**6,551**	901	3,000	-	2,500	150
Storage, Pumped	**5,759**	1,778	1,407	1,000	1,574	-
Biomass, No CCS	**2,315**	1,299	-	419	478	119
Other	**929**	45	330	554	-	-
Coal	**917**	-	-	136	-	781

Notes: CCS stands for carbon capture and storage, which is not currently in use.
The category Other includes methane, refuse, landfill gas, etc

Unplanned resources refer to generation or flexibility assets that are not part of the baseline planned portfolio, but may emerge through market-driven investments, merchant development, or emergency procurement. These resources represent uncertain yet potentially realizable capacity additions beyond the planned trajectory. In the modeling framework, GenX endogenously determines the cost-optimal deployment of these unplanned resources within their regional availability limits. In our simulations, these limits are sufficiently high such that they are non-binding in the optimal solutions.

3.2.3 Transmission Capacity

Existing interregional transmission capacity in northeastern North America in 2022 is shown in Table 4 [19]. The reported values represent aggregated transfer capacities of multiple existing transmission lines between regions, rather than capacities along individual corridors. This aggregation provides a simplified but consistent representation of regional transfer capability for use in the GenX model.

Table 4: 2022 Transmission Capacity (MW) in northeastern North America

From \ To	NE	NY	QC	ON	AT
NE	-	1,730	2,170	-	700
NY	2,130	-	1,100	1,550	-
QC	2,287	2,079	-	2,940	1,200
ON	-	1,950	2,084	-	-
AT	700	-	5,935	-	-

Note: Values represent transfer capacities (MW) between regions. The entry in row i and column j indicates the maximum transmission capacity from region i to region j. For example, the capacity from NE to NY is 1,730 MW, while the reverse from NY to NE is 2,130 MW.

In addition to existing capacity, 2050 scenarios incorporate new transmission projects that are recently completed or expected to be completed in the near term. These include the New England Clean Energy Connect (NECEC, 1,200 MW) connecting Québec to New England, the Champlain Hudson Power Express (CHPE, 1,250 MW) linking Québec to New York, and the Québec–New Brunswick upgrade (1,150 MW) strengthening ties between Québec and the Atlantic provinces [27, 10, 11]. These additions are incorporated as fixed upgrades in the GenX model to reflect committed infrastructure that is not subject to optimization.

For unplanned transmission capacity, we specify a set of fixed and reasonable transmission expansion capacities for preferred interconnections as a sensitivity analysis discussed in detail in Section 3.4.2.

3.2.4 Cost Assumptions

We employ estimated investment costs from the 2023 NREL Annual Technology Baseline Moderate Scenario (Table 5, [28]) for generating and storage technologies. Regional capital costs are differentiated by applying regional cost multipliers (Table 6). American multipliers are derived from the U.S. Energy Information Administration (EIA) NEMS model [15], while Canadian multipliers are derived from the Trottier Energy Project [8].

The annualized incremental transmission cost is estimated based on three representative transmission projects in the northeastern North America region—Northern Pass, New England Clean Energy Connect, and Champlain Hudson Power Express—resulting in an average cost of \$49,326/MW-yr [13]. In addition, fixed transmission operation and maintenance costs of $4,000/MW-yr are included in the simulation [16].

Table 5: Technology Cost Assumptions

	CAPEX, Total	CAPEX, Annual	Fixed O&M	Variable O&M	Heat Rate	Fuel Cost
	$\frac{\$}{MW}$	$\frac{\$}{MWyr}$	$\frac{\$}{MWyr}$	$\frac{\$}{MWh}$	$\frac{MMBtu}{MWh}$	$\frac{\$}{MMBtu}$
Biomass, CCS	5,870,000	429,769	177,000	19.40	14.80	5.00
Coal	4,790,826	350,758	140,540	13.86	7.20	2.04
Hydro, Reservoir	2,994,000	153,025	87,833	0.00	-	-
Hydro, Run-of-River	6,840,834	349,638	126,576	0.00	-	-
Natural Gas, CC	891,422	65,265	28,000	2.00	6.36	3.34
Natural Gas, CC-CCS	1,854,113	135,748	61,000	6.00	6.42	3.34
Natural Gas, CT	758,750	55,551	21,000	5.00	9.72	3.34
Nuclear	6,731,000	358,749	146,000	2.84	10.44	0.71
Solar	741,340	47,878	16,217	0.00	-	-
Storage, Battery (4h)	1,035,000	69,568	4,827	0.00	-	-
Storage, Pumped	2,440,000	88,426	17,600	0.51	-	-
Wind, Offshore	3,260,144	223,359	61,370	0.00	-	-
Wind, Onshore	902,500	60,421	37,489	0.00	-	-

Notes: CCS stands for carbon capture and storage, which can be incorporated into a Biomass plant or into a Natural Gas combined cycle plant.
For the cost recovery period, we assume 30 years for nuclear and hydro, 60 years for pumped hydro storage, and 20 years for others. For average capacity factors, we assume 90% for nuclear, 60% for other thermal generators, 40% for hydro, 30% for storage and wind, and 25% for solar.

3.2.5 Variable Renewable Energy Resource Profiles

Wind resources are expected to play a significant role in the future northeastern North America power system, particularly in Québec and Atlantic provinces, where wind resource quality is exceptionally high. Wind data is pre-processed in three main steps. First, high-resolution wind speed data is collected from multiple representative sites within each region to capture spatial variability in resource quality. Second, these are converted into wind power profiles using a standard wind power function. Third, these raw profiles are rescaled to match target annual capacity factors (CFs) derived from historical records and projected future estimates reported in the literature. The resulting time series of wind availability factors are then used as inputs to the GenX capacity expansion model.

The historical wind speed data is collected from NREL [30] and [29]. The wind power profile is generated based on a truncated cubic power function [35]:

Table 6: Regional Capital Cost Multipliers

	NY	NE	QC	ON	AT
Biomass, CCS	1	1	1	1	1
Coal	1	1	1	1	1
Hydro, Reservoir	1.20	0.66	1.08	1.08	1.08
Hydro, Run-of-River	1.20	0.66	0.80	0.80	0.80
Natural Gas, CC	1.62	1.19	1.60	1.60	1.60
Natural Gas, CC-CCS	1.20	1.06	1.60	1.60	1.60
Natural Gas, CT	1.46	1.13	1.01	1.01	1.01
Nuclear	1.06	1.13	1.30	1.30	1.30
Solar	1.01	1.02	1	1	1
Storage, Battery	1.03	1.03	1	1	1
Storage, Pumped	1	1	0.95	0.95	0.95
Wind, Offshore	1	1	1	1	1
Wind, Onshore	1	1.27	1	1	1

$$P_w(v) = \begin{cases} 0, & v < V_c \text{ or } v > V_f, \\ \eta_m \, \eta_g \, C_p \, \rho \, A \, v^3, & V_c \le v < V_r, \\ \eta_m \, \eta_g \, C_p \, \rho \, A \, V_r^3, & V_r \le v \le V_f, \end{cases}$$

where P_w (MW) is the wind plant output, v is the wind speed (m/s), V_c is the cut-in speed, V_r is the rated speed, V_f is the cut-off speed at which the turbine stops for protection, ρ is the air density (kg/m^3), A is the rotor swept area (m^2); η_m is the mechanical efficiency; η_g is the generator efficiency; and C_p is the coefficient of performance. For most commercial turbines, V_c and V_f are about 4 and 25 m/s. Wind profiles are normalized and rescaled to match the capacity factor (CF) of each candidate; because the same technology is assumed across regions, parameters (η_m, η_g, C_p, ρ, A) cancel during normalization.

We derive wind availability assumptions for each region based on a synthesis of historical data and forward-looking projections from ISO reports, government studies, and national lab datasets [38, 7, 4, 24, 33, 37, 14, 5] as detailed in Appendix A.2. In general, CFs for existing wind plants reflect historical performance, while ISO projections inform those for new wind capacity. For Québec, we assume an average 2050 CF exceeding 40%, supported by PCWIS forecasts. Ontario's average CF is set at 30% for existing wind and 36% for new builds, reflecting IESO data and the region's seasonal wind variability. In New England and

New York, we assume a 34% average CF for new wind resources aligned with ISO-NE and NYISO outlooks, while historical performance (20–30%) suggests lower CFs for existing fleets. To capture spatial heterogeneity, we model multiple wind sites with distinct CF profiles across New England, New York, and Québec. The maximum developable capacity of each candidate is within land use constraints estimated by prior studies [26]. A summary of current assumptions is provided in Table 7.

Table 7: Average Capacity Factor and Maximum Capacity for Candidate Wind Technologies

Technology	Region	Bin	Average CF %	Max Capacity GW
Wind, Onshore	NE	0	38.7	4
		1	33.7	8
		2	19.9	8
	NY	0	38.6	4
		1	34.5	8
		2	21.8	8
	QC	0	47.0	4
		1	41.1	20
		2	32.1	16
	ON	-	30.2	40
	AT	-	42.8	20
Wind, Offshore	NE	-	41.7	20
	NY	-	40.4	20
	AT	-	42.2	20

Solar resource potential in northeastern North America is relatively limited compared to southern areas of North America due to higher latitudes, shorter winter daylight hours, and more frequent cloud cover. To represent solar generation, we use hourly profiles generated from the NREL PVWatts calculator and rescale them to match observed regional annual capacity factors of approximately 15% (Table 8). This adjustment ensures that the modeled solar output is consistent with the lower insolation levels characteristic of the region.

We set the maximum capacity limits for unplanned solar and wind in each region based on general projections from the literature and practical availability constraints (e.g., land use for solar and wind) [26], as shown in Table 18 in the Appendix.

Table 8: Seasonal Average Solar Capacity Factors (%)

	NE	NY	QC	ON	AT
Annual	**17.9**	**18.1**	**14.5**	**15.0**	**12.9**
Winter	16.0	15.4	11.4	10.2	8.8
Spring	20.9	21.8	19.5	19.0	18.4
Summer	19.7	20.7	17.8	19.9	16.6
Fall	15.0	14.4	9.1	10.5	8.0

3.3 Cross-Border Trade Modeling

In order to examine the value of improved two-way flow across the seam between Canadian and American regions, we represent interregional power flows in our model using two alternative topologies: one-way or two-way (Figure 7). In the one-way configuration, power flows are allowed only from Canadian provinces (Ontario, Québec, and Atlantic Provinces) to U.S. regions (New York and New England). In the two-way configuration, bidirectional flows are permitted between Québec and U.S. regions. These trade constraints are implemented in the GenX transmission network representation by specifying directional flow limits for each intertie. The one-way configuration closely reflects the historic pattern of actual flows. Recently, in response to unusually low hydrologic conditions in Québec, there have been notable flows from the U.S. to Québec. This event notwithstanding, analyzing the difference in system optimization under these two topologies is instructive of the potential value to governance changes to facilitate more regular two-way flow. Contrasting the system optimization under the two topologies allows us to isolate the impact of trade reciprocity on capacity expansion decisions, operational dispatch, and overall system costs.

3.4 Experiment Design

To investigate the impact of cross-border trade between Québec and U.S. regions (New England and New York) on northeastern North America generation and transmission planning and operation under carbon policies, we design and conduct a set of numerical experiments described in this section.

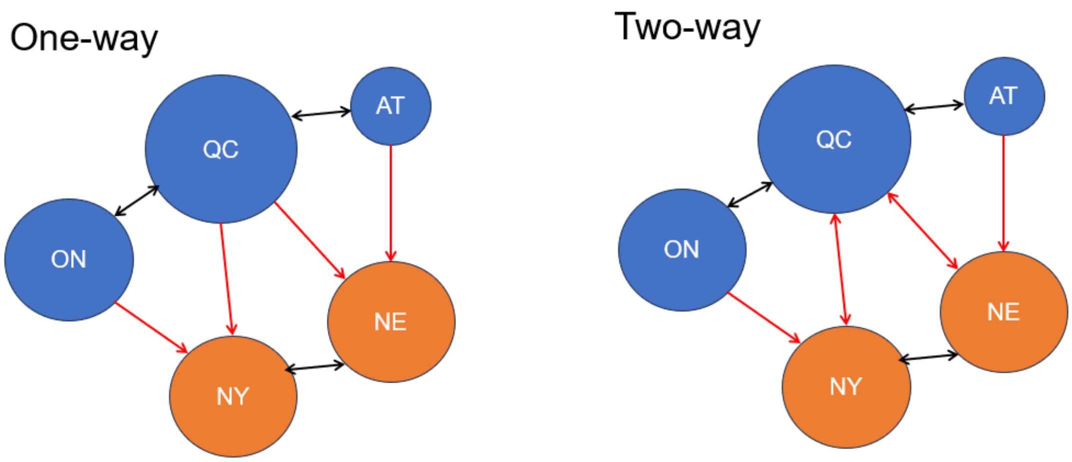

Figure 7: One-Way vs. Two-Way Trade Topology in Northeastern North America

3.4.1 Main Experiments

For the main experiments, we define four cases (C1–C4), each representing capacity decisions and 2050 power system operations under one-way or two-way trade structures with the presence or absence of transmission expansion, as summarized in Table 9. For example, the first case (C1) represents the northeastern North America power system under the one-way trade topology and with only existing transmission, inclusive of the transmission lines currently under construction between Quebec, New York, and New England. The comparison of these modeling cases allows us to isolate the effects of both trade directionality and transmission expansion on the northeastern North America power system. By contrasting one-way (C1, C3) and two-way (C2, C4) trade structures, we can evaluate how bidirectional exchanges influence capacity expansion decisions, system costs, and the regional distribution of costs. Similarly, comparing the existing transmission (C1, C2) and the expanded transmission (C3, C4) cases highlights the role of additional transfer capability in facilitating cross-border trade and reducing system costs.

These simulations can be conducted under varying scenario assumptions about load growth, carbon policies, transmission expansion levels, and the penetration of nuclear. To illustrate a moderate low-carbon transition, our main cases assume medium load growth, an 80% carbon reduction policy, 2,400 MW of additional nuclear capacity in New England, New York, and Ontario, and fixed transmission expansion. To capture uncertainty around these assumptions, we also conduct a set of sensitivity analyses which are described in the

Table 9: Four Cases for the Simulation Experimental Design

	One-Way Trade	Two-Way Trade
Existing Transmission	C1	C2
Expanded Transmission	C3	C4

following section.

3.4.2 Sensitivity Analysis

We conduct sensitivity analyses on key assumptions for each case, varying load growth, carbon policies, transmission expansion levels, and nuclear penetration to understand how uncertainties in each factor influence energy system outcomes.

The High, Medium, and Low load scenarios are discussed above and presented in Table 2.

We evaluate carbon policy sensitivity using regional emissions caps, measured with respect to 2005 levels to be consistent with the current carbon policy base year in Canada (Table 10). Scenarios range from 0% to 99% reductions, with caps reflecting regional baseline differences in the GenX model.

Table 10: Regional Emissions Limits (MtCO2) by Carbon Reduction Policy (%)

Carbon Policy	NE	NY	QC	ON	AT
2005 Base	27.50	61.84	0.60	32.80	19.50
2050 Unconstrained	22.15	30.59	0.05	21.72	3.93
80%	5.50	12.37	0.12	6.56	3.90
90%	2.75	6.18	0.06	3.28	0.95
95%	1.37	3.09	0.03	1.64	0.97
99%	0.28	0.62	0.01	0.33	0.19

Note: Emissions in 2050 Unconstrained are the result of an optimized 2050 scenario without a carbon policy. Emissions in 2005 Base show actual regional emissions from 2005.

We find significant need for additional capacity on several interconnections. Accordingly, we construct two sets of fixed transmission expansion scenarios for sensitivity analysis as shown in Table 11. The first set assumes 1 GW of additional capacity on QC–NE and AT–NE, and 2 GW on QC–NY and ON–QC. The second set doubles these values, with 2 GW on QC–NE and AT–NE, and 4 GW on QC–NY and ON–QC.

Table 11: Transmission Expansion and Incremental Capacity (MW)

	Existing + Planned	Proposed Expansion #1		Proposed Expansion #2	
Total	**20,415**	**+6,000**	**26,415**	**+12,000**	**32,415**
NY-NE	1,730		1,730		1,730
QC-NE	3,537	+1,000	4,537	+2,000	5,537
QC-NY	3,329	+2,000	5,329	+4,000	7,329
ON-QC	2,084	+2,000	4,084	+4,000	6,084
AT-NE	700	+1,000	1,700	+2,000	2,700
AT-QC	7,085		7,085		7,085
ON-NY	1,950		1,950		1,950

Though an established technology, there is significant uncertainty surrounding the cost of new nuclear power plants. This is true also for new designs such as small modular reactors (SMRs). Ontario has already initiated its first SMR project, with four reactors totaling 1,200 MW. The availability of clean, firm generation technologies–such as nuclear power–has significant potential to contribute to grid decarbonization. To reflect varying levels of nuclear adoption, we conduct a sensitivity analysis on nuclear penetration, as summarized in Table 12. The first row reports the total existing and planned nuclear capacity in 2050, while the subsequent rows incorporate incremental additions (Nuc1, Nuc2, Nuc3) of 1,200 MW, 2,400 MW, and 4,800 MW, respectively.

Table 12: Nuclear Incremental Capacity Scenarios (MW)

	Increment	NE	NY	ON
Existing	-	3,606	3,305	12,009
Baseline	-	3,606	3,305	13,209
Baseline+Nuc1	1,200	4,806	4,505	14,409
Baseline+Nuc2	2,400	6,006	5,705	15,609
Baseline+Nuc3	4,800	8,406	8,105	18,009

Note: "Existing" refers to 2022 installed capacity. "Baseline" refers to 2022 installed capacity plus planned additions.

4 Results

Our two major experiments involve (i) enabling two-way trade, (ii) expanding interregional transmission. Both experiments are conducted for a projected 2050 system. Before turning to those experiments, we document the changes to the system going forward to 2050, without those changes. The main cases are conducted under the basic assumptions of medium load growth, an 80% carbon reduction policy, and 2,400 MW of additional nuclear capacity in New England, New York, and Ontario.

Figure 8 shows a comparison of the portfolio of capacities for the 2022 baseline and for the 2050 Case 1, with one-way trade and no expansion of transmission capcacity. It reveals a fundamental transformation of the northeastern North America power system. The system shifts from a fossil-dominated portfolio, with coal and natural gas providing much of the firm capacity in New England, New York, and Ontario (over 55 GW combined in 2022) towards a lower-carbon resource mix. By 2050, the most carbon-intensive of these generators are retired and replaced by a mix of clean resources. Variable renewable energy (VRE) technologies—particularly onshore wind, offshore wind, and solar PV—emerge as the dominant sources of new capacity, alongside new nuclear: onshore wind grows from 9.9 GW in 2022 to 57.4 GW in 2050, offshore wind expands from 0.2 GW to 23.7 GW, and solar rises from 5.9 GW to 21.5 GW. This growth is complemented by expanded storage deployment, with pumped storage and batteries increasing from just 3.6 GW in 2022 to more than 20 GW in 2050, providing the flexibility required to balance variability and maintain system reliability. Some peaker generators (e.g., oil, landfill gas) also remain in the system to provide reliability.

New England, New York, and Ontario experience large-scale VRE growth alongside the retirement of fossil plants. In New England, solar rises from 2.6 GW in 2022 to 9.0 GW in 2050, and offshore wind grows from virtually zero to 14.7 GW, while the capacity of natural gas combined-cycle (NGCC) plants declines from 16.4 GW to 11.4 GW (and the utilization of these plants falls more sharply). In NY, onshore wind expands from 1.4 GW to 13.9 GW, while the capacity of natural gas combustion turbines (NGCT) falls from 12.1 GW to 8.4 GW. ON similarly adds 15.8 GW of onshore wind by 2050 while incorporating Carbon Capture and Storage (CCS) into some of its NGCC capacity. In contrast, Québec and the Atlantic provinces expand primarily through wind and storage additions, building on their existing hydropower resources—Québec adds 17.5 GW of onshore wind by 2050, while the Atlantic provinces reaches 6.4 GW of onshore wind and maintains over 8.8 GW

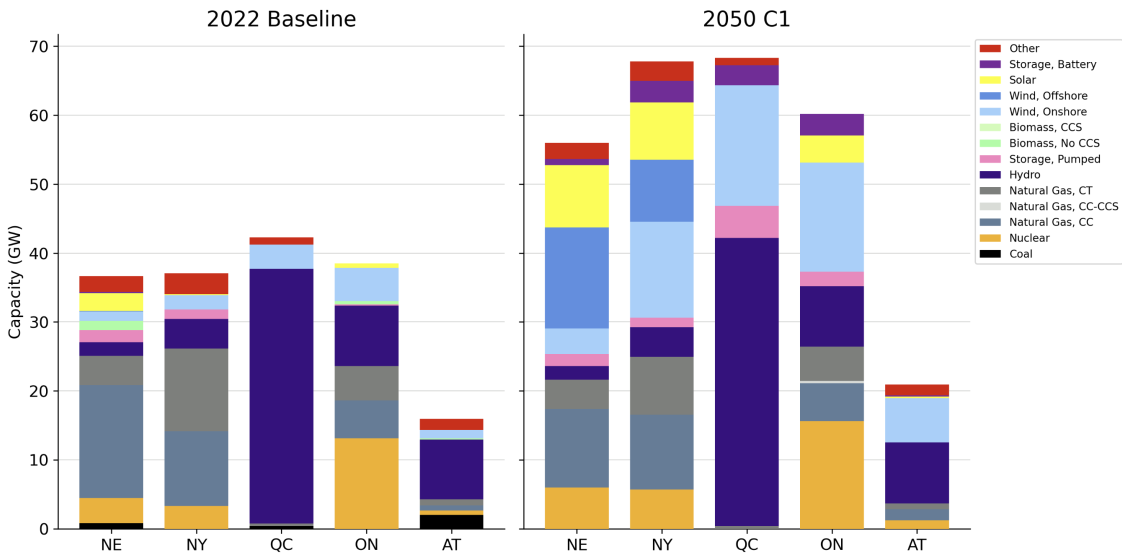

Figure 8:
2050 Installed Capacity by Technology for Case 1 Versus 2022 Actual Installed Capacities.
Note: "Other" includes oil, methane, refuse, landfill gas, etc.

of hydropower. Nuclear capacity increases from about 18.9 GW in 2022 to 28.6 GW in 2050, supported by the assumed 2,400 MW of additional nuclear capacity across New England, New York, and Ontario. Québec and Atlantic provinces continue to rely on their large hydro resources (about 42–66 GW) while supplementing them with additional wind development.

4.1 Impacts of Two-Way Trade

In this section, we examine the impacts of two-way trade, both without transmission expansion (C2 versus C1) and with transmission expansion (C4 versus C3). We focus first on differences in the installed capacity mix, and then we show a representative day of dispatch results for selected regions to illustrate system operational differences under two-way trade.

4.1.1 Capacity Differences

In the two-way trade case, Québec is able to import power from New England or New York when economical. The investment impacts of enabling this bidirectional power transfer capability on generation capacity is shown in Figure 9. The left-hand figure shows the change in capacities as we go from case C1 to C2, i.e., without tranmission expansion. The results indicate relatively modest differences overall, with the main adjustments concentrated in Québec and New York. In Québec, installed capacity additions fall for hydro and storage, reflecting reduced pressure to build new local resources once exports can be more effectively balanced by imports. Correspondingly, New York shows small increases in wind and peaking capacity, suggesting that greater bidirectional flows allow New York to diversify its supply mix with local resources. The other regions–New England, Ontario, and the Atlantic provinces–experience negligible capacity changes between the two cases.

The right-hand figure shows the change in capacities as we go from case C3 to C4, i.e., with tranmission expansion. The results show that the largest adjustments occur in Québec, where capacity additions for wind and storage decline when two-way trade is enabled, showing reduced need for local investment. At the same time, New York shows modest increases in clean capacity, primarily onshore wind, reflecting export opportunities for New York. The Atlantic provinces also exhibit a slight reduction in peaking capacity (i.e., oil plants) as stronger bidirectional exchanges improve system adequacy.

Contrasting the change as we move from case C1 to C2 against the change as we more from case C3 to C4 illustrates the effects of enabling two-way trade under different transmission settings. In both cases, the most visible adjustments occur in Québec, where the need for new hydro, pumped storage, and battery capacity declines once imports are permitted. One-way trade constrains Québec's ability to access U.S. power when local supply is expensive, driving larger investments in local flexible resources. Two-way trade relaxes this constraint, allowing Québec to rely more on regional exchanges. Correspondingly, New York shows modest increases in VRE—particularly wind—while the Atlantic provinces see slight reductions in peaking capacity due to improved adequacy across the interconnected grid. Importantly, the impacts of two-way trade are qualitatively similar with or without transmission expansion, though expanded transmission amplifies the redistribution of capacity. Overall, two-way trade favors greater VRE penetration in U.S. regions and reduces Québec's reliance on local flexibility investments (i.e., battery storage, pumped hydro storage and peaking generators), leading to a more specialization into the resources for which each region has a comparative advantage.

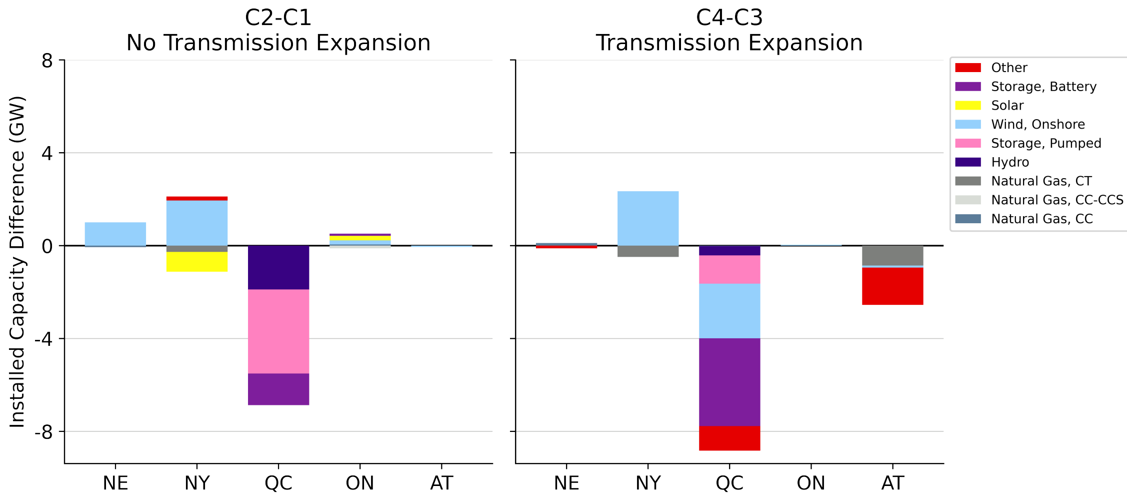

Figure 9: Impact of Two-Way Trade on the Capacity Mix (GW): (Left) No Transmission Expansion and (Right) With Transmission Expansion

4.1.2 Economic Dispatch

Figure 10 shows dispatch operations in New York (top) and Québec (bottom) for a representative summer day in 2050 under one-way (C1, left) and two-way (C2, right) trade. In C1 (Panels A and C), New York is limited to importing from Québec, which is reflected in consistently positive net inflows in NY and corresponding outflows in Québec. This one-way trade forces Québec to maintain relatively high hydro generation to supply both local demand and exports, while New York relies on imports during peak hours to complement its local mix of nuclear, natural gas, and storage resources. Storage operations in New York also show notable charging and discharging cycles aligned with peak load and import availability.

In contrast, under two-way trade (Panels B and D), New York gains the ability to export to Québec, as indicated by periods of negative net inflow in Panel B. This change allows Québec to occasionally rely on New York resources, reducing its own hydro dispatch during certain hours when water inflow is low and electricity price is high. For New York, the option to export results in increasing local wind and solar output, especially during midday when VRE generation peaks, with excess power sent to Québec rather than curtailed (20) or absorbed by local storage.

Similar to the summer case, enabling two-way trade in winter allows New York to export

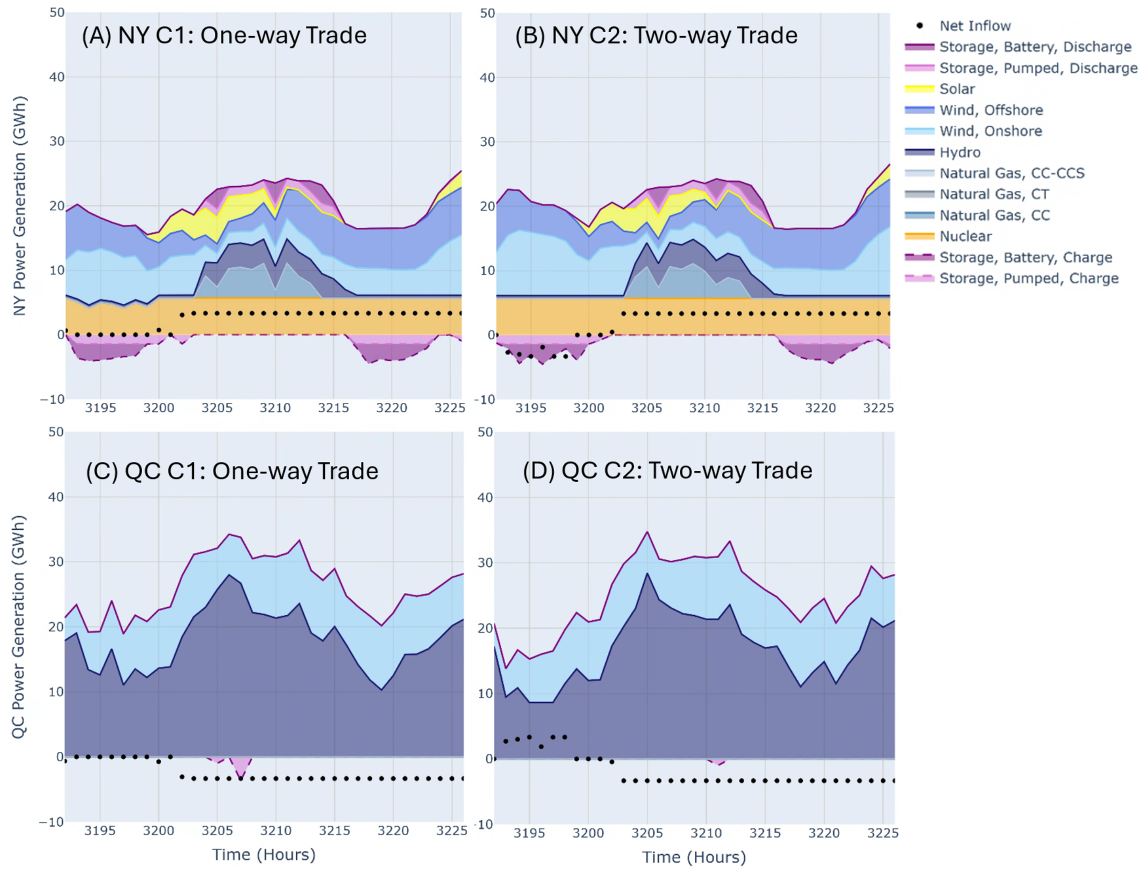

Figure 10: Generation Dispatch in New York and Quebec in a Summer Day Under One-way and Two-way Trade (GWh)

surplus wind generation to Québec, while Québec gains flexibility by slightly lowering hydro output during import hours and reserving capacity for peak hours (Figure 11). However, compared with summer, the winter system is characterized by higher demand, reduced solar availability, and stronger wind output in New York, which makes New York a more frequent exporter in C2. For Québec, this seasonal difference means hydro operates closer to its maximum in winter under C1, leaving less headroom for ramping, while in C2, imports from New York provide relief and improve hydro flexibility.

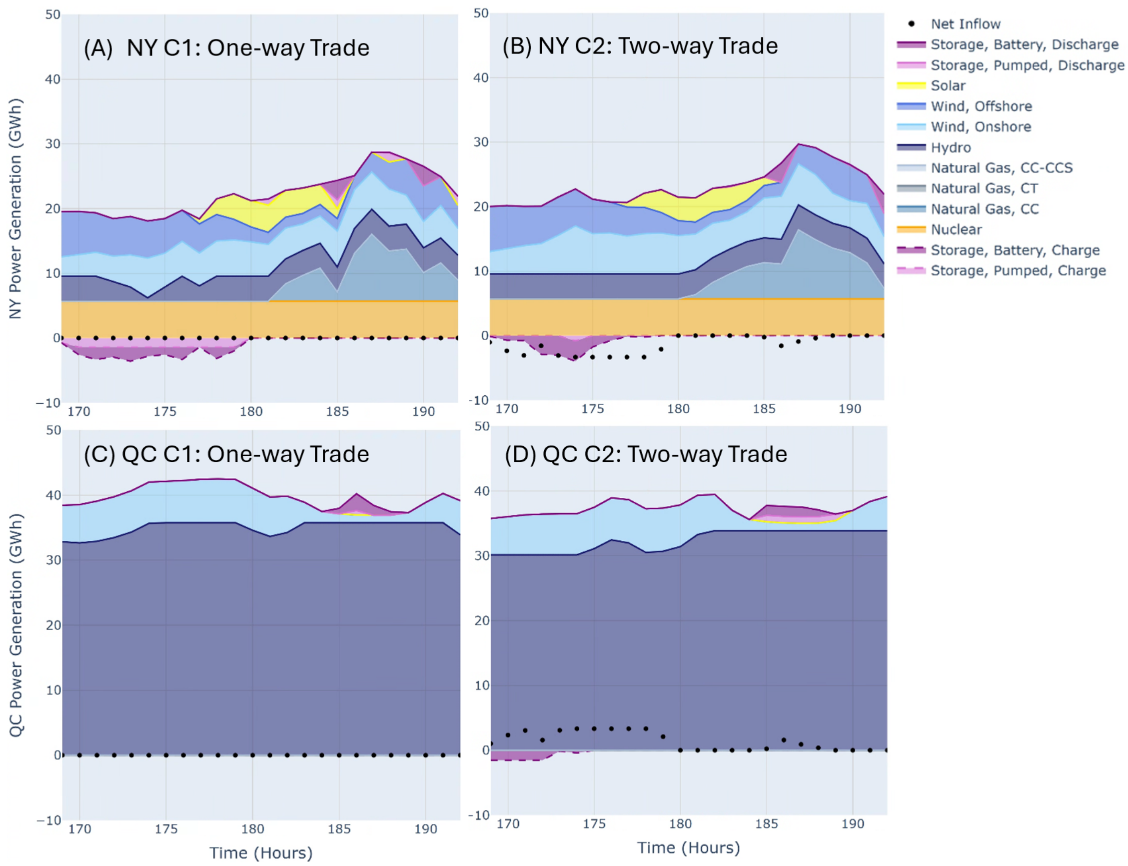

Figure 11: Generation Dispatch in a Winter Day (GWh)

4.2 Impacts of Transmission Expansion

In this section, we examine the impacts of transmission expansion (C3 and C4) on the projected 2050 Northeastern North American power system and its operation. We first compare the installed capacity mix between C1 and C3, and between C2 and C4, to show how transmission expansion affects long-term investment decisions. We then present representative-day dispatch results for selected regions to illustrate the operational changes associated with expanded transmission.

4.2.1 Capacity Differences

The fixed transmission expansion (#1: 1,000 MW on QC–NE and AT–NE, and 2,000 MW on QC–NY and ON–QC) in C3 reshapes the pattern of new investments across northeastern North America (C1 vs. C3 in Figure 12). Expanded transmission allows Québec and the Atlantic provinces to assume a more prominent role as clean energy exporters, capitalizing on their abundant hydro and high-quality wind resources. With greater cross-border transfer capability, New England, New York, and Ontario reduce their reliance on local solar and wind additions and instead increase imports from Québec and the Atlantic provinces.

This shift is clearly reflected in the capacity differences shown in Figure 12. With transmission expansion, under both one-way and two-way trade settings, Québec experiences substantial increases in onshore wind capacity (on the order of 9–12 GW), reinforcing its role as a regional clean energy supply hub. In contrast, New England and New York show notable reductions in solar capacity (roughly 4–8 GW) and onshore wind, along with slight decreases in natural gas capacity, reflecting reduced need for local generation. Ontario also exhibits declines in solar and storage capacity, consistent with increased reliance on imports. Meanwhile, the Atlantic provinces see modest increases in wind deployment under transmission expansion, particularly in the two-way trade case, further supporting regional supply.

Comparing one-way (C3–C1, Figure 12, left) and two-way (C4–C2, Figure 12, right) trade, the overall patterns are similar but more pronounced under one-way trade, where transmission expansion drives larger reallocation toward Québec. Under two-way trade, the adjustments are somewhat more balanced across regions, though the core result remains: transmission expansion shifts investment toward regions with superior renewable resources.

Overall, the results underscore the critical role of transmission in enabling an efficient and clean power system. By unlocking complementarities in resource availability across regions, expanded interconnections reduce redundant investments in lower-quality resources, and lower overall system costs. In particular, the C3 case demonstrates how transmission facilitates clean energy integration and allows Canadian resources—especially Québec hydro and wind—to contribute more directly to decarbonization efforts in U.S. regions.

4.2.2 Economic Dispatch

Figure 13 shows dispatch operations in New York and Québec for a representative summer day without transmission expansion (C1, left) and with transmission expansion (C3, right), both under one-way trade. In C1 (Panels A and C), New York relies on a combination of local nuclear, natural gas, wind, solar, and storage resources, while importing from

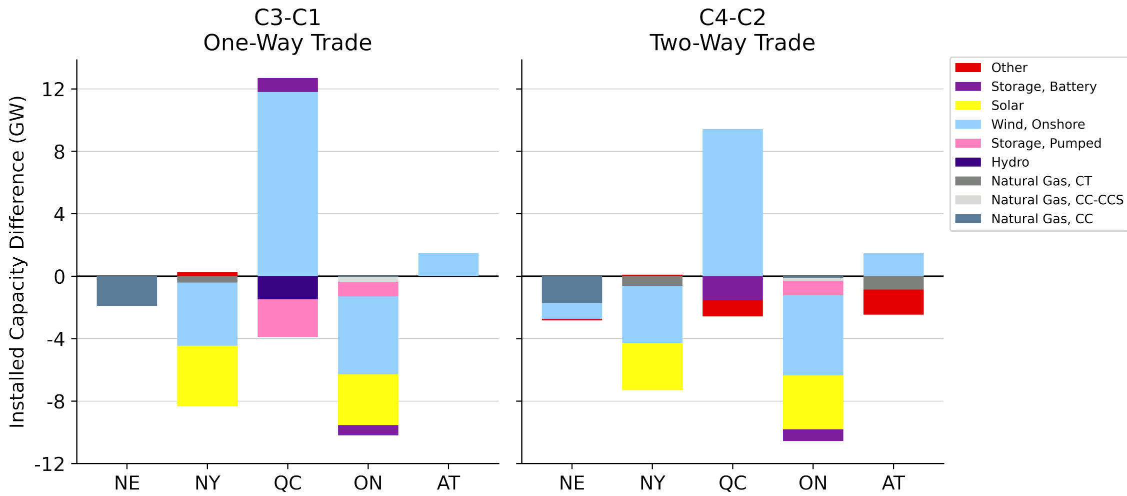

Figure 12: Impact of Transmission Expansion on the Capacity Mix (GW): (Left) One-Way Trade and (Right) Two-Way Trade

Qu´ebec during much of the day. Because cross-border transfer capability is limited, New York continues to depend on local gas generation and battery discharge during higher-load hours. On the Québec side, the hydro remains the dominant resource and supports steady exports to New York, but the limited interface constrains the extent to which Québec's clean resources can serve external demand.

In contrast, with transmission expansion (Panels B and D), New York is able to import more power from Québec, especially during peak hours, as indicated by the higher net inflows in Panel B. This reduces the need for local solar and wind generation in New York, while allowing a greater share of demand to be met through imports. For Québec, expanded transmission leads to larger and more sustained exports, supported by greater utilization of hydro and onshore wind resources. Relative to C1, wind plays a much larger role in Québec's dispatch in C3, particularly through the middle of the day, which allows hydro to operate more flexibly as a balancing resource rather than bearing as much of the export burden alone.

Figure 14 presents dispatch patterns for a representative winter day, highlighting similar but more pronounced effects of transmission expansion under higher seasonal demand. In the no-expansion case (C1, Panels A and C), New York relies more heavily on local natural gas generation and storage discharge to meet winter peaks and ramping hours, while imports from Québec remain limited. Québec's dispatch is dominated by hydro, operating

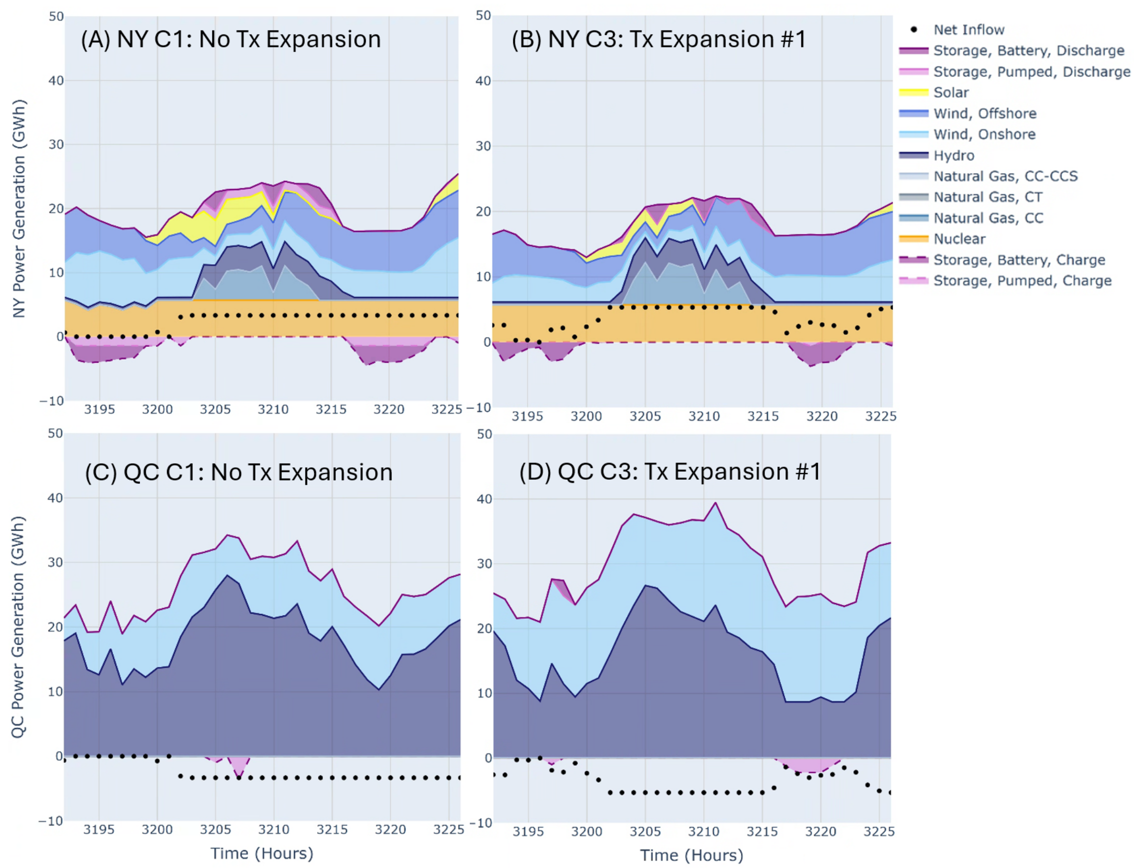

Figure 13: Generation Dispatch in a Summer Day (GWh)

at a relatively stable and high output level to meet both domestic demand and constrained exports. With transmission expansion (C2, Panels B and D), New York increases imports during peak hours, as indicated by higher net inflows, which reduces reliance on local gas generation and storage cycling. On the Québec side, expanded transmission enables its flexibility role to other region, supported by net export during New York peak time which is not observed in no-expansion case. Compared to the summer case, hydro operates closer to its upper range, while wind provides additional supply during high-demand periods. Overall, the comparison shows that transmission expansion improves regional coordination by allowing Québec's clean and flexible hydro-wind portfolio to substitute for more costly local flexibility in New York.

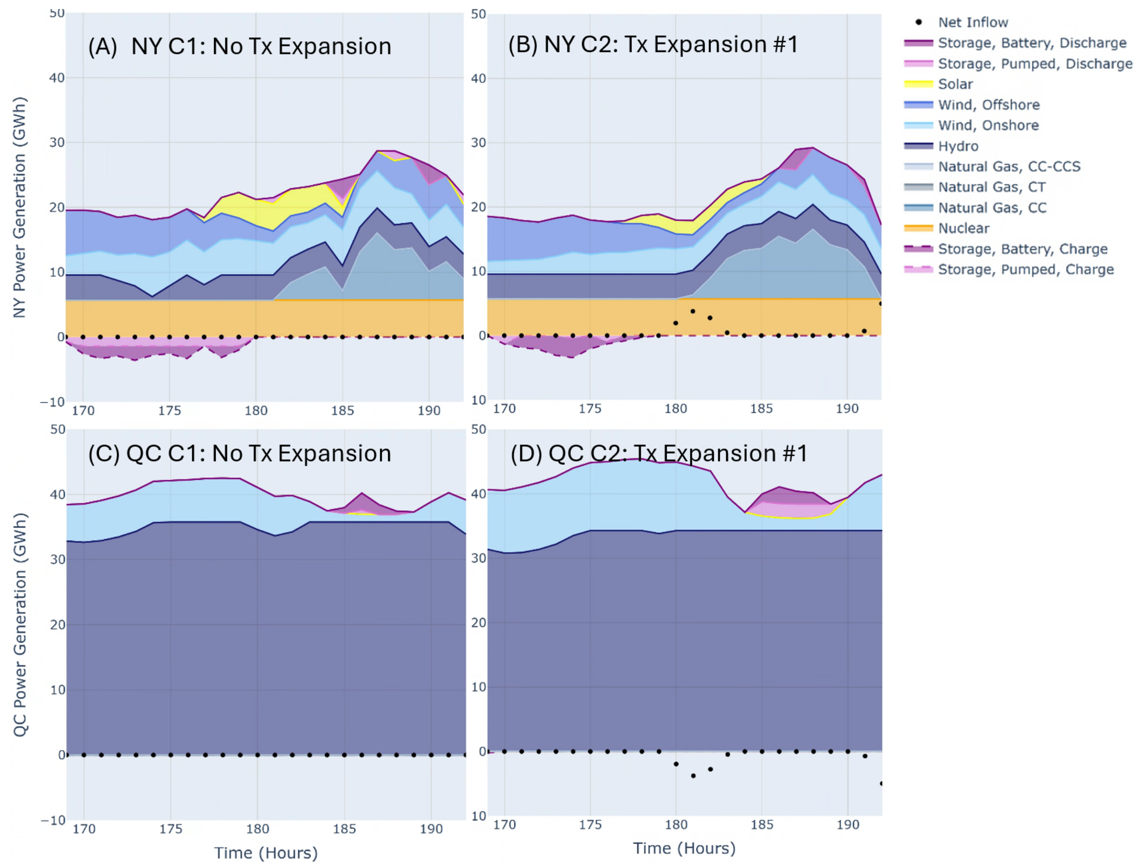

Figure 14: Generation Dispatch in a Winter Day (GWh)

4.3 System Costs

The GenX model surveys portfolios of new generation capacity across all five regions which can serve load in all hours of the year. For each portfolio, the model finds the lowest cost dispatch in each hour, incorporating allowed imports and exports between regions, and subject to the specified emissions constraint. The model then identifies the lowest cost portfolio, including both the investment cost required for new capacity and the dispatch cost. Together, these costs are called system costs. System cost does not include sunk costs for legacy generation or transmission assets, and does not include distribution system costs. GenX reports annualized costs, recognizing that investment costs are recouped over the life of the asset.

Table 13 compares total annual system costs across the four simulation cases. The results show that both two-way trade and transmission expansion reduce total system costs, with the lowest cost observed in C4 ($31,262 million annually). Relative to the baseline one-way, no-expansion case (C1, $32,441 million), this represents a reduction of $1,180 million annually, or 3.6%. Introducing two-way trade alone (C2 vs. C1) lowers costs by $654 million (2.0%), while transmission expansion alone (C3 vs. C1) saves $589 million (1.8%). The largest benefit comes when both measures are combined (C4), saving $1,179 million annually (3.6%). Savings arise primarily through lower capital investment costs in generation. Variable operating costs remain broadly similar, while transmission costs rise modestly in the two cases with transmission expansion. As a result, the system cost comparison underscores the economic value of enabling bidirectional trade and expanding transmission lines, which together reduce annual system costs by more than 1 billion dollars and improve system reliability.

Table 13: Total Annual System Costs by Case ($M)

C1	Existing Transmission	One-Way Trade	32,441
C2	Existing Transmission	Two-Way Trade	31,787
C3	Expanded Transmission	One-Way Trade	31,852
C4	Expanded Transmission	Two-Way Trade	31,262

4.4 Regional Analysis

In the following sections, we examine how the modeled system alterations change the regional distribution of system costs and the regional profile of system lambda, which is the hourly marginal cost of an additional unit of generation. First, we compare cases C2 and C1 to illustrate the value of two-way trade. Second, we compare cases C3 and C1 to illustrate the value of transmission expansion. Finally, we compare cases C4 and C1 to illustrate the value of both expanding transmission and allowing for two-way trade.

Table 14 provides an overview of the shift in where system costs are incurred. In cases where transmission expansion is considered (C2 & C4), the cost of network expansion is incurred across two regions, we do not make an allocation to regions. Consequently, the regional breakdown will not sum to the total.

Table 14: Shifts in costs ($M) by adding two-way trade (top), expanding transmission (middle), and both (bottom). Positive, red values indicate an increase in costs.

	Total	NE	NY	QC	ON	AT
C2 vs. C1	**-654**	135	158	-928	-9	-10
C3 vs. C1	**-589**	-53	-617	604	-979	136
C4 vs. C1	**-1,180**	-11	-407	-175	-979	72

4.4.1 The Value of Two-Way Trade: C2 vs. C1

We assess the value of two-way trade by comparing the C1 baseline with C2, which differs from C1 only by relaxing unidirectional trade constraints - i.e., allowing power to flow from New York and New England to Québec in accordance with the transmission capacities in Table 4. In both cases, transmission capacity is held constant. The cost results are summarized in Table 14.

Total system costs are reduced in all three case comparisons. Where a comparison shows increased costs for a region (red), that means extra generation and storage capacity investments are made there. Where a comparison shows decreases costs for a region (green), that means the region makes fewer generation and storage investments there. The decreased investments in some regions are made possible because of the increased investments in some other region. The increased investments yield increased generation that can be exported to the regions making less investment. Of course, any region with increased investments will only pursue them if it can negotiate to capture the benefits of the generation it will eventually supply. The fact that the system as a whole earns savings means that there is room to strike deals that benefit every region. However, this report makes no effort to determine the terms of any such deals.

Enabling bidirectional trade reduces the risk of American wind curtailments given the ability to sell excess low-cost power to Canada during hours of surplus. This allows New York and New England to increase their wind capacity additions. As shown in Table 14, most new costs are incurred in New York and New England, the majority of which are investments in new onshore wind capacity. Relatively smaller investments in wind, solar, and storage lead to slightly higher fixed costs incurred in Ontario, but these increased fixed costs are outweighed by decreases in variable costs of generation. Costs decrease substantially in Québec which foregoes some capacity investments in conventional hydropower, pumped hydro storage, and battery storage to instead take advantage of new imports from

New England and New York.

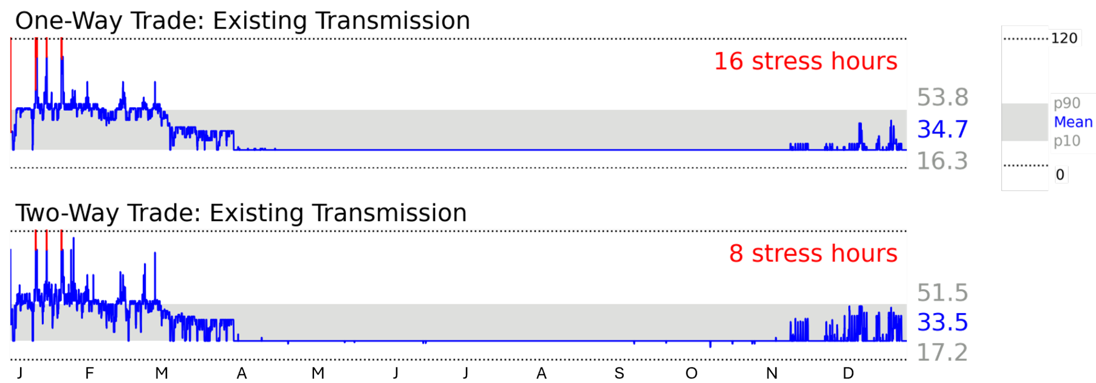

Figure 15: Hourly System Lambda, Québec, Existing Transmission ($/MWh)

Under two-way trade, northbound trade is driven by American wind generation, substantially increasing exports from New England and New York and increasing the supply in Québec and the Atlantic provinces, including during key hours of resource scarcity. These new inflows of American windpower primarily displace local hydropower in Québec and the Atlantic provinces as well as imports from Ontario. Despite increased local wind capacity, the increased demand from Canada leads to fewer hours in New England where wind is the marginal generating technology, and raising the New England system lambda in those hours. In contrast, the increased supply of power in Québec and the Atlantic provinces from New York and New England lead to a reduction in the number of hours per year when their system lambda values reach extremely high values. This is true either with or without transmission expansion, as shown in Figures 15 and 16. In other words, allowing for American imports allows Québec and the Atlantic provinces to better manage their rare, high-stress hours of operation.

Although northbound trade increases and leads to these distributed impacts, New England and New York remain net importers of power while Canadian provinces remain net exporters.

4.4.2 The Value of Transmission Expansion: C3 vs. C1

We assess the value of transmission expansion by comparing the C1 baseline with C3, which differs from C1 only by increasing transmission capacities by prescribed amounts in accordance with Table 11. In both cases, trade is constrained to one-way trade from

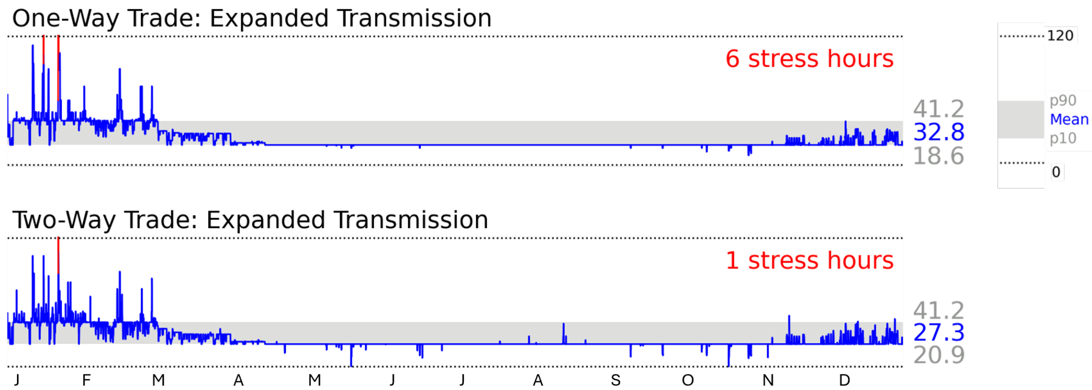

Figure 16: Hourly System Lambda, Atlantic Provinces, Expanded Transmission ($/MWh)

Canada to the United States.

Québec and the Atlantic provinces have the highest quality wind resources of all model regions. Transmission expansion allows the system to further exploit these high quality resources. Therefore, the cost of this additional capacity is incurred in Québec and the Atlantic provinces whereas Ontario, New York, and New England reduce their capacity investments as shown in Table 14.

With expanded transmission, Québec exports more wind and hydropower to Ontario, New York, and New England, decreasing the average system lambda in these regions and increasing it in Québec. Notably, Québec's mean system lambda increases when expanding transmission without two-way trade (C3) but decreases in both cases where two-way trade is included (C2, C4), leading to the conclusion that it is bidirectional trade - not transmission expansion alone - that leads to a reduction in stress on Québec's system.

4.4.3 The Value of Two-Way Trade with Expanded Transmission: C4 vs. C1

We assess the combined value of transmission expansion and the addition of two-way trade by comparing the C1 baseline with C4, which differs from C1 through both prescribed increases in transmission capacities as well as the addition of two-way trade in accordance with Tables 4 and 11.

Capacity investment costs are reduced in nearly all regions as increased grid integration allows for more efficient use of resources as shown in Table 14. Although there is an expansion of wind investment costs in Québec, that is paired with reduced investments in flexible resources including conventional hydropower, pumped hydro storage, battery storage, and peakers, resulting in net cost reductions. Although the Atlantic provinces reduce investments in natural gas combustion turbines and peakers, this reduction is outweighed slightly by increased investment in onshore wind capacity.

Increased trade of low-cost power reduces mean system lambda everywhere and reduces median system lambda in all but Québec and the Atlantic provinces, the primary wind exporting regions. Interregional differences in system lambda are reduced. Although Québec's system lambda increases in most hours due to an effective increase in demand from New York and New England, this is outweighed by the reduction in extreme stress hours in Québec by means of expanded American imports, as shown in Figure 4 in the Executive Summary.

4.5 Trade Analysis

The system benefits enabled by bidirectional flows and transmission expansion are facilitated through greater cross-border trade. Compared to the 2050 baseline of one-way trade with existing transmission capacity (C1), total gross trade between all five regions increases 5% when permitting two-way trade (C2), 37% when expanding transmission (C3), and 35% when both permitting two-way trade and expanding transmission (C4). For gross U.S.-Canada cross-border trade only, these increases are 10%, 39%, and 43% respectively. Even without altering assumptions of load growth, carbon policies, or zero-carbon firm generating technologies, we see that interregional trade relationships and limited transmission expansion alone can have a substantial impact on how the grid is operated in 2050.

Gross power transfers grow by even larger factors for specific grid corridors. For example, when moving from C1 to C4, gross trade grows by 62% along QC-NY, 97% along ON-QC, and 120% along AT-NE.

We do not observe any corridor where the net power transfer over the course of the year changes direction, but trade along some corridors does decrease. For example, the net power transfer from Ontario to New York falls by 60% when moving from C1 to C4.

Aggregating to the regional level, we see that existing trade roles intensify when permitting two-way trade and expanding transmission. For example, Quebec and the Atlantic provinces – net exporters under C1 – are even greater net exporters under C4. On the other hand, New England, New York, and Ontario – net importers under C1 – are even greater net importers under C4.

Gross exports, gross imports, and net exports along each corridor can be seen in Table

21 in Appendix A.3.

4.6 Sensitivity Analysis

In this section, we analyze key sensitivities of load growth, carbon policies, transmission expansion levels, and nuclear penetration levels. To evaluate the sensitivity of each factor, we focus primarily on how optimal capacity investments shift in each region.

4.6.1 Load Projection

Figure 17 illustrates the impact of different load growth scenarios on capacity expansion in northeastern North America under two-way trade with and without transmission expansion. Across all scenarios, load growth is a primary driver of new investments: installed capacity rises steeply from low to high load cases. The low and medium load cases produce broadly similar mixes, dominated by wind, solar, hydro, and storage, while the high load case triggers much larger additions of natural gas CCS. For example, in New England under high load without transmission expansion (A), solar capacity exceeds 30 GW, compared to less than 10 GW in the medium case, alongside notable increases in storage. Similarly, New York high-load sees solar rise above 50 GW, supplemented by batteries and pumped hydro storage to balance renewable variability.

Comparing panels (A) and (B), transmission expansion reshapes investment patterns. In Québec, additional wind and hydro are deployed, while New England and New York show reduced reliance on local solar and storage. For example, in the New York medium-load scenario solar and wind capacity drops over 7 GW with expansion (B) compared to without expansion (A), as imports from Québec's higher-quality resources displace local builds. Overall, transmission expansion enables greater reliance on Québec and Atlantic hydro and wind, reducing redundant investments in lower quality resources, and improving regional resource efficiency. These observations are consistent with the main experiment results, and these insights also broadly hold for one-way trade systems.

4.6.2 Carbon Policy

We show the sensitivity of capacity investments to carbon policy stringency under cases with and without transmission expansion in Figure 18. Across all carbon policies, the capacity mix consistently transitions from coal and unabated gas toward clean thermal,

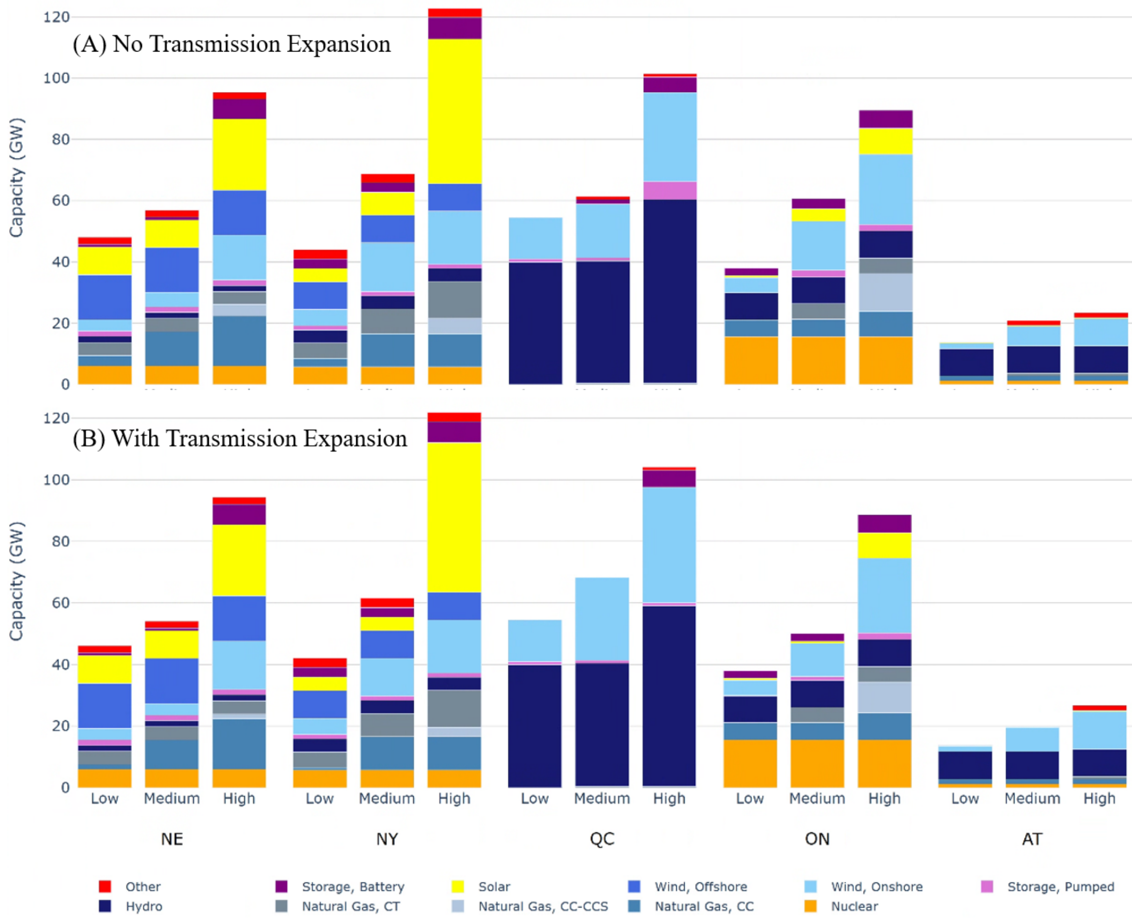

Figure 17: 2050 Capacity Mix (GW) and Load Scenario by Region in Two-Way Trade: (A) No Transmission Expansion and (B) With Transmission Expansion

renewables, and storage, showing that the direction of decarbonization is robust to policy stringency. At very high reduction levels (95% and 99%), the system is compelled to add NGCC with CCS. Transmission expansion reshapes the regional allocation of new investments: while New England, New York, and Ontario bear much of the buildout under constrained transmission, expanded interties allow capacity to shift into Québec and the Atlantic provinces, where abundant hydro and high-quality wind resources can be more effectively utilized, especially for more moderate decarbonization levels (80-90%). At the highest carbon reduction levels (95% and 99%), the assumed limits on transmission expansion constrain Québec's ability to export clean power to neighboring regions. As a

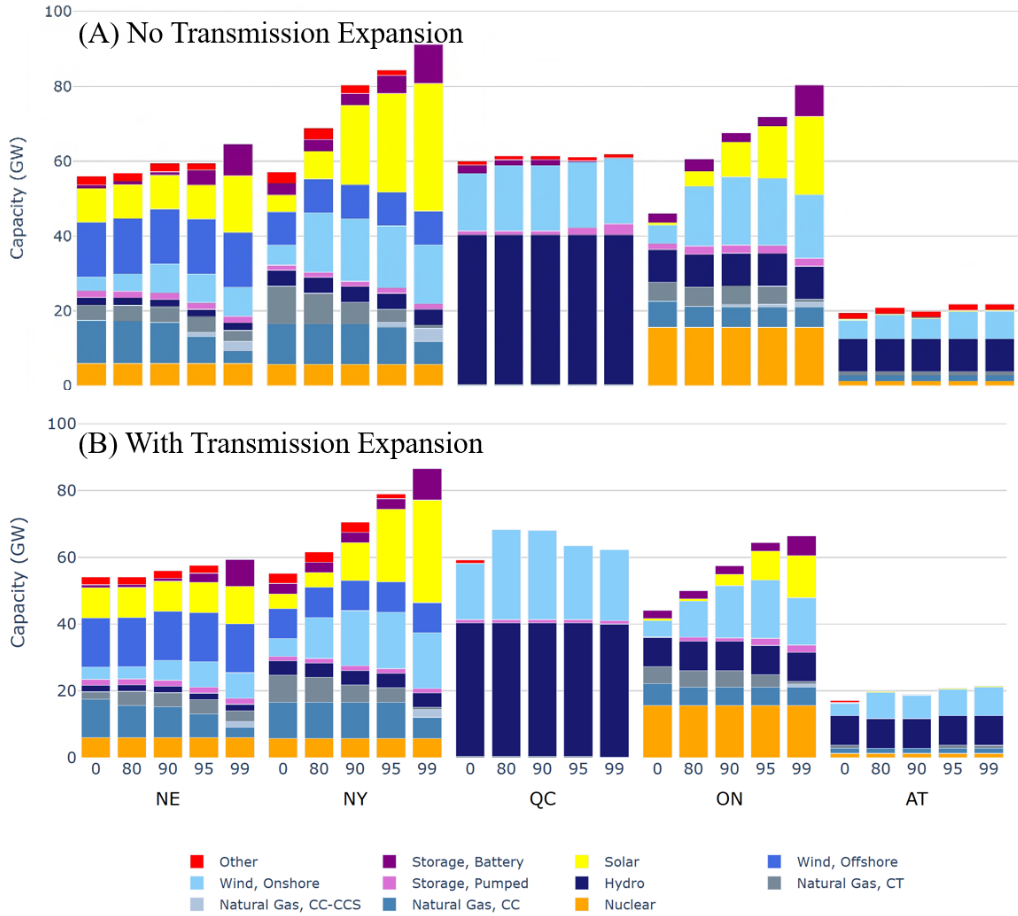

Figure 18: 2050 Capacity Mix (GW) by Carbon Policy Scenario and Region in Two-way Trade: (A) No Transmission Expansion (B) With Transmission Expansion

result, other regions must rely more heavily on local clean energy investments to meet their decarbonization targets. This reallocation underscores the role of transmission in reducing overall system costs and improving efficiency by directing investment toward the most resource-rich regions.

4.6.3 Transmission Expansion

As explained in Section 3.4.2, we implemented three sets of transmission expansion scenarios. The corresponding capacity expansion results are illustrated in Figure 19. Overall, limited transmission expansion does not alter the main conclusions regarding the importance of two-way trade or the central role of renewable energy growth in decarbonization. However, limiting transmission expansion reshapes the spatial distribution of new investments. In particular, constrained expansion on key interconnections such as AT–NE, QC–NY, and ON–QC reduces the ability of Québec and the Atlantic provinces to export their abundant renewable resources. As a result, less new wind is built in Québec and the Atlantic provinces, while New England, New York, and Ontario compensate with greater local investments in solar and wind to meet their decarbonization needs. By contrast, in scenarios with unlimited transmission, Québec and Atlantic Provinces accommodate more of the regional renewable buildout, displacing some of the additions in New England, New York, and Ontario. This highlights that while overall system decarbonization trends remain consistent, transmission availability critically shapes new resource siting and regional comparative advantages.

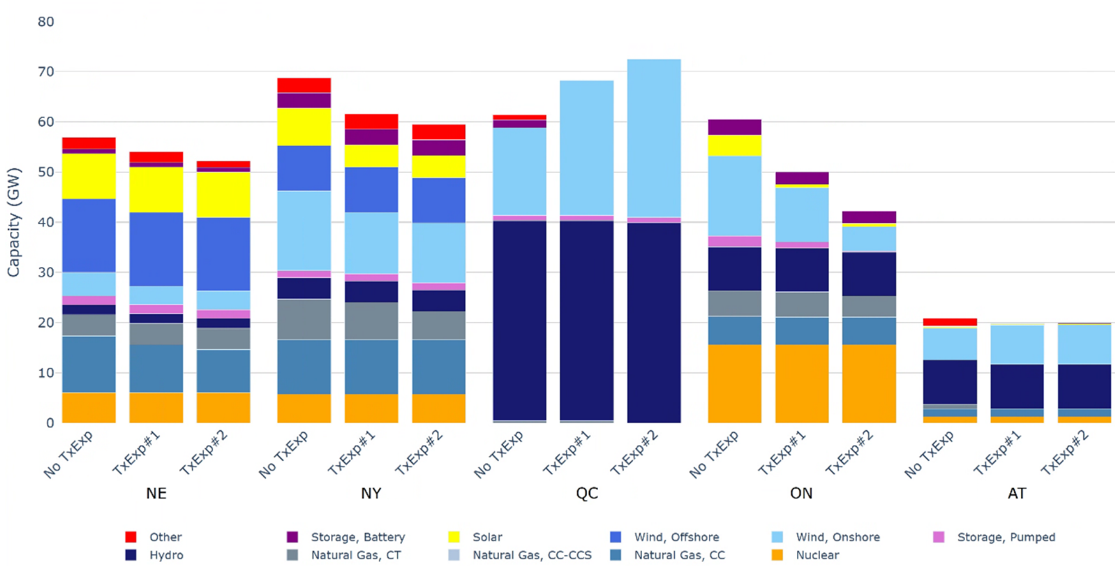

Figure 19: 2050 Capacity Mix (GW) and Transmission Expansion Scenario by Region in Two-Way Trade

4.6.4 Nuclear Penetration

As shown in Figure 20, the nuclear sensitivity analysis shows that adding 1,200/2,400/4,800 MW of nuclear across New England, New York, and Ontario (Table 12) yields broadly similar capacity mixes under one-way and two-way trade. Nuclear mainly substitutes for other clean resources rather than changing the overall direction of the system. Trade assumptions continue to influence the optimal portfolio composition, although their effects are relatively modest. Under one-way trade, Québec holds about 3–4 GW more pumped hydro storage and battery storage to cover hours when reverse flows are unavailable. Under two-way trade, U.S. regions can rely more on cross-border exchanges, enabling 1–3 GW more VRE (mostly wind) in New England and New York as well as a corresponding 1–2 GW reduction in local flexible builds. Nuclear acts as clean firm replacements, while allowing bidirectional flows shifts millions of dollars of investments away from local flexibility and VRE resources.

5 Conclusions and Policy Implications

This study examined the long-term evolution of the northeastern North American power system under alternative trade structures, transmission expansion scenarios, and carbon policy settings. Using the GenX capacity expansion model, the results describe a fundamental restructuring of generation portfolios in the region by 2050 across a wide range of scenarios: coal and unabated natural gas are retired and replaced by a diverse mix of variable renewable energy, storage, and clean thermal technologies. Key drivers of this transformation are load growth and technical improvements in wind generation. Advances in turbine technology and significant cost declines over the past decade have made the region's long-recognized wind potential increasingly exploitable as a source of affordable, large-scale clean electricity, especially when paired with storage and transmission to match the output with load profiles at higher penetrations. Québec and the Atlantic provinces emerge as central exporters of additional quantities of clean electricity, leveraging abundant hydro and high-quality wind resources, whereas Ontario, New York, and New England transition from thermal reliance to expanded VRE deployment and greater imports from neighboring regions. This spatial diversity in renewable resources reduces integration costs, underscoring the importance of coordinated regional planning to fully capture the benefits of wind and other variable renewables across the northeastern North America system.

Trade directionality is shown to have considerable impacts on investment outcomes and to unlock additional value from Québec's hydro resources during critical hours. Under one-way trade, U.S. regions compensate for limited flexibility by investing more heavily in local VRE and flexible resources, while Québec builds additional storage to accommodate

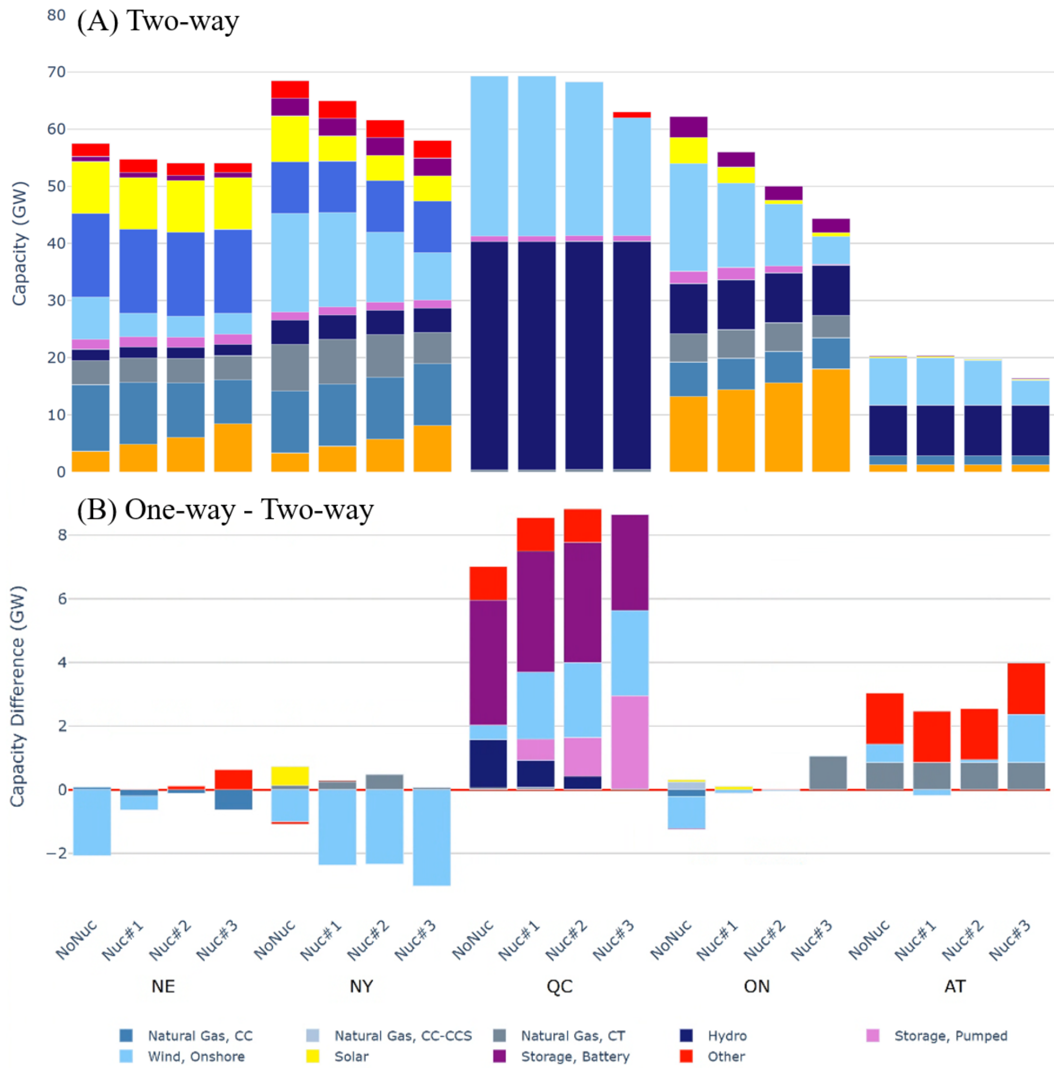

Figure 20: 2050 Capacity Mix (GW) and Nuclear Scenario by Region without Transmission Expansion A) Two-way B) One-way - Two-way Difference

its high wind penetration. By contrast, enabling two-way trade allows Québec's hydro reservoirs to function as system-wide balancing assets, absorbing surplus U.S. generation and providing exports during scarcity periods. This bidirectional flexibility reduces the need for expensive flexibility assets such storage and peaking capacity and also allows for greater investment in wind resources in U.S. regions, consistent with prior findings on the system-wide value of hydro flexibility [13].

Transmission expansion is also found to be a decisive enabler of efficient decarbonization, unlocking access to the superior wind resources concentrated in Québec and the Atlantic provinces. By facilitating large-scale renewable development in these resource-rich areas and enabling two-way electricity trade, neighboring provinces and states can benefit from lower system costs, reduced reliance on expensive peaking capacity, and improved overall reliability [2, 36].

Finally, the analysis highlights the importance of carbon policy implementation across jurisdictions. Stricter carbon policies accelerate the displacement of fossil generation with VRE and clean firm technologies, such as NGCC with CCS and nuclear.

Policy implications follow directly from these insights. First, facilitating two-way electricity trade by addressing institutional and regulatory barriers would unlock significant system-level benefits. Second, coordinated transmission planning should prioritize cross-border interconnections, supported by fair cost-sharing arrangements across jurisdictions.

Appendix

A Data and Assumptions

A.1 Load Projections

A.1.1 New England

According to the Acadia Center New England study [39], electric vehicle adoption and building electrification are the primary drivers of projected load growth in the New England region. While economic growth will also play a role, there is only marginal population growth projected to 2050. Additionally, widespread usage of electric air source heat pumps will further drive an increase in electricity demand and will cause the region to become winter peaking.

A.1.2 New York

Similar to New England, EVs and building electrification will drive a bulk of the load growth out to 2050 for New York. The state is projected to experience moderate economic growth with "population and household decline… during the later forecast years" (NYISO). The

NYISO Gold Book projects "100% light duty vehicle EV sales share in 2035", justifying their strong EV-driven load assumption for 2050.

A.1.3 Québec

Much like the main drivers of future load growth in all of the other regions, Québec's main sources of demand growth are transportation electrification and building decarbonization. In addition to these overarching themes, industrial decarbonization and economic growth are also expected to play major roles in Québec's load growth in the coming years. In fact, by 2035 Hydro Québec projects that 25% of additional electricity use will be due to economic growth (as opposed to other regions where economic growth's future load contribution is more moderate). Hydro Québec also projects that by 2035 a little over a third of additional electricity use will be due to industrial decarbonization. In 2050, Québec will achieve 100% decarbonization of its electricity with load projected to be double that of the current year.

A.1.4 Ontario

Electricity demand is expected to grow fastest in Ontario out of all of the regions in this study, with the medium load growth scenario projected at slightly over two percent annual growth. This projection comes from Ontario's ISO (Independent Electricity System Operator, or IESO). In IESO's 2024 Annual Planning Outlook demand forecast, they projected that load would increase 60% by 2050, but in the most recent 2025 APO demand forecast, they are even more aggressive with a projected 75% growth in electricity demand by then. Driving this high load growth forecast is the projected explosion in industrial sector and data center growth in the region. Other contributors to Ontario's high projected load growth are commercial sector growth, increasing population, and increasing electrification.

A.1.5 Atlantic Provinces

Due to less availability of literature on load growth projections for the Atlantic provinces - comprising New Brunswick, Newfoundland and Labrador, Nova Scotia, and Prince Edward Island - there is less detailed analysis on how this region's primary load drivers exactly differ from Canada's national trends. Nonetheless, Canada Energy Regulator provided detailed load forecasts for the Atlantic provinces backed by their "Canada's Energy Future 2023" report. In this report, transportation, building, and industrial electrification are all highlighted as notable drivers for Canada as a whole, and it was from this national report that specific values for the Atlantic provinces were produced.

A.2 Wind Capacity Factor

This section provides a summary of studies and data sources pertaining to onshore wind CF in key regions of northeastern North America, namely Québec, New England, and New York. We conducted a review and comparison of literature and reports that are extensively utilized in both industry and academia, covering both historical and projected CF values. Based on this analysis, we propose a recommended range of capacity factors to be used in the 2050 simulation.

A.2.1 New England

Numerous wind data sources are available for the regions of the United States, providing valuable insights. A primary and reliable data source is the ISO-NE, whose New England 2030 Power System Study projects the CFs for onshore wind to range from 29.3% in Maine to 35.4% across the rest of New England . This projection offers a dependable basis for estimating future capacity factors in our HQ 2050 projections. The U.S. Energy Information Administration (EIA) gathers power data from each ISO or utility company and provides historical annual electricity system data through the State Energy Data System (SEDS). This system includes the average CF for various energy technologies differentiated by state. Table 1 presents the wind energy capacity factors from SEDS for selected states. The data indicates that the average wind CF in the New England states for the period 2008-2022 ranges between 20% and 30%, which is considerably lower than the forecasts provided by ISO-NE. These findings imply that it may be necessary to adjust the capacity factors downwards for existing wind power plants in this region to align better with historical performance. By doing so, projections and planning for wind energy in New England can become more accurate and realistic. While for potential new wind plants, we use the average CF 34% consistent with ISO-NE's projections.

A.2.2 New York

NYISO's 2023-2042 System Resource Outlook [33] assumes an average onshore wind CF of 34% by 2032, significantly higher than the historical average performance of 24% as noted in Table 1 . However, some skepticism exists regarding this projection. A critical blog

Table 15: Historical Average Wind Capacity Factors (%) by Year in Selected US States

	MA	ME	NH	NY	RI	VT	TX
2008	23.2	35.4	-	23.6	-	22.4	32.2
2009	33.3	28.8	29.7	21.9	-	25.4	26.4
2010	24.4	25.4	36.0	22.8	23.8	30.5	31.1
2011	26.8	27.8	31.4	23.9	22.2	28.6	34.3
2012	27.0	25.0	20.5	23.4	10.5	21.8	34.0
2013	33.3	27.8	26.0	24.6	9.9	22.4	33.6
2014	31.1	29.1	27.5	26.1	29.8	29.6	35.9
2015	29.7	31.3	28.3	26.0	15.3	30.9	32.6
2016	27.4	28.4	26.8	25.6	19.1	27.6	35.6
2017	28.4	29.5	25.7	25.9	33.0	28.5	36.2
2018	26.4	29.5	25.4	24.5	35.0	28.4	37.3
2019	24.7	30.9	26.6	25.6	32.5	28.7	36.8
2020	25.7	29.4	28.2	25.9	33.6	29.1	36.0
2021	22.5	29.2	27.2	23.0	27.0	25.7	34.6
2022	24.0	30.6	26.0	23.8	30.9	31.1	35.2
Mean	**27.2**	**29.2**	**27.5**	**24.4**	**24.8**	**27.4**	**34.1**
Median	**26.8**	**29.2**	**27.0**	**24.5**	**27.0**	**28.5**	**34.6**
Std. Dev.	**3.4**	**2.5**	**3.5**	**1.4**	**8.8**	**3.1**	**2.8**

Note: Texas average wind capacity factors are provided for context.

argues that NYISO has overestimated wind CF, highlighting that out of 31 wind farms in New York, only two achieved a CF above 34%, and only three others reached over 30%. The overall capacity factor for these facilities was recorded at 21.8% .

In this project, we can maintain assumptions of an average 34% CF for the year 2050. This projection is considered plausible given the anticipated advancements in wind technology over the next two decades. As technology continues to improve, the likelihood of achieving higher capacity factors increases, supporting a more optimistic outlook for future wind energy performance.

A.2.3 Québec

Natural Resources Canada [9] conducted a study to evaluate wind quality across Canada by analyzing data from 59 existing wind farms . The study revealed that the onshore wind CFs in Québec and the Maritime provinces are relatively higher than in Ontario. Historical data from 2007 to 2011 indicates that the CF in Québec ranged from 30% to 34%. Given that this data is relatively dated and may reflect the performance of less efficient wind turbines, it is plausible that the current (2024) and future capacity factors in Québec could be higher (wind turbine siting, wind turbine technology, hub height, and curtailed wind energy are the main drivers). Advances in wind turbine technology and improved efficiencies are likely contributing factors to potentially increased CFs. Consequently, updated assessments are necessary to accurately reflect current wind energy potential in the region.

The Pan-Canadian Wind Integration Study (PCWIS) [7] recently utilized a capacity expansion planning model to forecast wind power resource penetration and its potential impacts on Canada's power grids . The study developed four distinct scenarios, each representing varying levels of wind penetration at 5%, 20%, and 35%. Additionally, these scenarios explored different distribution strategies, with wind resources either dispersed across multiple locations or concentrated in areas with the highest capacity factor.

The average wind CFs in QC are projected to be the highest among Canadian provinces (in most scenarios), at approximately 40%. This study also highlights that Canada possesses an overall high-quality wind resource. The data has been utilized in numerous academic studies to construct scenarios for 2050 projections. Consequently, it is reasonable to assume that Québec's average wind capacity factor in 2050 would exceed 40%.

A.2.4 Ontario

From Natural Resources Canada's wind study, we have seen the wind resources in ON is relatively worse than the wind resource in the other Canada regions. A more recent study also confirms these observations, where average CFs of onshore wind in ON for year 2020-2023 (based on IESO) is around 31% . It also pointed out the main drivers for lower CFs in ON region is because its more pronounced and prolonged summer with very low wind values (below 25% through May to October). In this study, we use 30% CF for existing onshore wind form which is based IESO's 2022 values. We also assume an increase to around 36% for new onshore wind forms in 2050.

A.2.5 NREL Data Sources

The National Renewable Energy Laboratory has published several databases [31, 30, 29] related to renewable energy profiles and CFs. We have used their National Solar Radiation Database (NSRDB) and Wind Toolkit for our research. The NSRDB offers hourly profiles of solar radiation and wind speed based on 2020 weather data, while the Wind Toolkit contains historical wind data collected from 2007 to 2013. The average capacity factor provided by the Wind Toolkit for the regions of New England and New York is approximately 20%, which aligns with data reported by the U.S. EIA. A recent NREL Wind Supply Curve Study projects wind resource CF for the year 2030. However, we have identified several concerns with this database. The study's projected average wind CFs for New York and New England exceed 42%, which appears excessively high when compared with projections from ISOs. Upon reviewing their assumptions regarding technology innovations and wind speeds, we found inconsistencies within their results. For example, Texas (TX) is projected to have a wind CF of 44%, similar to New York and New England, despite having superior wind resources and higher wind speeds. This suggests that it is unrealistic to expect similar CFs using identical wind turbine technology across these regions. Furthermore, assuming a significant change in the local climate to justify potential wind speed increases in the New England and New York within the next five years does not seem reasonable. Consequently, due to these discrepancies and assumptions, we have decided not to rely on this new study for our analysis.

A.3 Supplementary Tables

Table 16: Installed Capacity in 2022 (MW)

	Total	NE	NY	QC	ON	AT
All	**169,630**	**36,684**	**37,178**	**42,404**	**37,410**	**15,954**
Hydro	**60,600**	1,968	4,265	36,942	8,748	8,677
Natural Gas, CC	**33,455**	16,395	10,843	-	5,470	747
Natural Gas, CT	**22,578**	4,234	12,074	411	5,000	859
Nuclear	**19,580**	3,606	3,305	-	12,009	660
Wind, Onshore	**13,405**	1,361	2,051	3,932	4,883	1,178
Oil	**6,635**	2,280	2,749	-	-	1,606
Solar	**3,446**	2,603	154	10	648	31
Storage, Pumped	**3,359**	1,778	1,407	-	174	-
Coal	**2,988**	842	-	136	-	2,010
Biomass, No CCS	**2,382**	1,299	-	419	478	186
Other	**929**	45	330	554	-	-
Storage, Battery	**191**	191	-	-	-	-
Wind, Offshore	**82**	82	-	-	-	-

Table 17: Planned Capacity Additions and Retirements (MW)

	Total	NE	NY	QC	ON	AT
All	**64,508**	**23,233**	**19,477**	**14,000**	**6,600**	**1,198**
Wind, Offshore	**24,160**	14,600	9,000	-	-	560
Wind, Onshore	**15,540**	2,325	3,215	10,000	-	-
Solar	**10,902**	6,440	4,262	-	-	200
Storage, Battery	**6,360**	710	3,000	-	2,500	150
Hydro	**3,154**	-	-	3,000	-	154
Storage, Pumped	**2,400**	-	-	1,000	1,400	-
Natural Gas, CC	**2,330**	-	-	-	1,500	830
Nuclear	**1,800**	-	-	-	1,200	600
Biomass, No CCS	**-67**	-	-	-	-	-67
Coal	**-2,071**	-842	-	-	-	-1,229

Table 18: Maximum Unplanned Capacity Additions for Candidate Technologies (GW)

	Total	NE	NY	QC	ON	AT
All	**900**	**190**	**190**	**180**	**180**	**160**
Solar	**160**	50	50	20	20	20
Wind, Onshore	**140**	20	20	40	40	20
Nuclear	**100**	20	20	20	20	20
Storage, Pumped	**100**	20	20	20	20	20
Storage, Battery	**100**	20	20	20	20	20
Natural Gas, CC	**100**	20	20	20	20	20
Natural Gas, CC-CCS	**100**	20	20	20	20	20
Wind, Offshore	**60**	20	20	-	-	20
Hydro	**40**	-	-	20	20	-

Table 19: Generation Mix in Northeastern North America Regions, 2022

	NE		NY		QC		ON		AT	
Resource	TWh	%	TWh	%	TWh	%	TWh	%	TWh	%
Hydro	7.74	6	28.24	18	196.31	104	38.00	28	47.05	75
Natural Gas, Oil	55.71	46	64.60	42	0.94	0	15.20	11	3.37	7
Nuclear	27.39	23	26.88	17	-	0	78.80	57	5.08	8
Wind	3.88	3	4.83	3	14.32	8	13.80	10	4.45	7
Coal	0.32	0	-	0	-	0	0.32	0	5.79	9
Solar	2.81	2	0.11	0	-	0	0.75	1	0.01	0
Other	5.24	4	2.37	2	1.59	1	-	0	0.58	1
Total Region	103.09	86	127.03	82	213.16	113	146.87	107	66.33	106
Net Imports	16.78	14	26.97	18	-24.95	-13	-9.60	-7	-3.59	-6
Total Generation	119.87		154.00		188.22		137.27		62.74	
Pumping Load	1.78		1.33		-		-		-	
Net Energy	118.09		152.67		188.22		137.27		62.74	

Table 20: Regional Renewables Curtailment (%) by Case

Case	Technology	NE	NY	QC	ON	AT
C1	Solar	1.43	0.06	0	0	0
	Wind, Onshore	6.53	0.23	0	0	0
	Wind, Offshore	0.5	0.13	0	0	0
	Wind Total	**1.39**	**0.19**	**0**	**0**	**0**
	Renewable Total	**1.39**	**0.17**	**0**	**0**	**0**
C2	Solar	0.1	0	0	0	0
	Wind, Onshore	0.28	0.03	0	0	0
	Wind, Offshore	0.03	0.01	0	0	0
	Wind Total	**0.07**	**0.03**	**0**	**0**	**0**
	Renewable Total	**0.08**	**0.02**	**0**	**0**	**0**
C3	Solar	1.39	0	0	0	0
	Wind, Onshore	6.5	0.02	0	0	0
	Wind, Offshore	0.51	0	0	0	0
	Wind Total	**1.39**	**0.01**	**0**	**0**	**0**
	Renewable Total	**1.39**	**0.01**	**0**	**0**	**0**
C4	Solar	0.01	0	0	0	0
	Wind, Onshore	0.01	0	0	0	0
	Wind, Offshore	0	0	0	0	0
	Wind Total	**0**	**0**	**0**	**0**	**0**
	Renewable Total	**0**	**0**	**0**	**0**	**0**

Table 21: Interregional Power Transfers (GWh) by Case

Region	Interconnect	Transmission Expansion	Gross Exports (GWh) One-Way Trade	Gross Exports (GWh) Two-Way Trade	Gross Imports (GWh) One-Way Trade	Gross Imports (GWh) Two-Way Trade	Net Exports (GWh) One-Way Trade	Net Exports (GWh) Two-Way Trade
NE	NY	No	6,349	6,007	1,718	1,610	4,631	4,396
		Yes	9,921	6,395	292	383	9,628	6,012
	QC	No	0	4,630	18,642	17,422	-18,642	-12,792
		Yes	0	5,075	18,174	16,998	-18,174	-11,922
	AT	No	0	0	4,277	4,086	-4,277	-4,086
		Yes	0	0	9,634	9,426	-9,634	-9,426
	Total	**No**	**6,349**	**10,637**	**24,638**	**23,119**	**-18,288**	**-12,482**
		Yes	**9,921**	**11,470**	**28,100**	**26,806**	**-18,179**	**-15,336**
NY	NE	No	1,718	1,610	6,349	6,007	-4,631	-4,396
		Yes	292	383	9,921	6,395	-9,628	-6,012
	QC	No	0	3,170	21,340	19,925	-21,340	-16,756
		Yes	0	1,154	36,104	33,341	-36,104	-32,186
	ON	No	0	0	2,455	2,306	-2,455	-2,306
		Yes	0	0	1,069	991	-1,069	-991
	Total	**No**	**1,718**	**4,780**	**30,145**	**28,238**	**-28,427**	**-23,458**
		Yes	**292**	**1,537**	**47,094**	**40,727**	**-46,801**	**-39,189**
QC	NE	No	18,642	17,422	0	4,630	18,642	12,792
		Yes	18,174	16,998	0	5,075	18,174	11,922
	NY	No	21,340	19,925	0	3,170	21,340	16,756
		Yes	36,104	33,341	0	1,154	36,104	32,186
	ON	No	14,874	14,807	1,365	1,372	13,509	13,435
		Yes	32,133	31,867	219	171	31,914	31,696
	AT	No	663	875	28,780	29,130	-28,117	-28,255
		Yes	882	914	29,223	29,291	-28,341	-28,377
	Total	**No**	**55,519**	**53,029**	**30,145**	**38,301**	**25,374**	**14,728**
		Yes	**87,292**	**83,119**	**29,442**	**35,692**	**57,850**	**47,427**
ON	NY	No	2,455	2,306	0	0	2,455	2,306
		Yes	1,069	991	0	0	1,069	991
	QC	No	1,365	1,372	14,874	14,807	-13,509	-13,435
		Yes	219	171	32,133	31,867	-31,914	-31,696
	Total	**No**	**3,820**	**3,677**	**14,874**	**14,807**	**-11,054**	**-11,129**
		Yes	**1,288**	**1,162**	**32,133**	**31,867**	**-30,845**	**-30,705**
AT	NE	No	4,277	4,086	0	0	4,277	4,086
		Yes	9,634	9,426	0	0	9,634	9,426
	QC	No	28,780	29,130	663	875	28,117	28,255
		Yes	29,223	29,291	882	914	28,341	28,377
	Total	**No**	**33,057**	**33,216**	**663**	**875**	**32,395**	**32,341**
		Yes	**38,857**	**38,717**	**882**	**914**	**37,975**	**37,803**
Total Gross Trade		**No**	**100,465**	**105,339**				
		Yes	**137,650**	**136,005**				

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