A 10-Year Retrospective and Prospective Assessment of Trends in Electricity Supply and Demand and Associated Water Consumption in the Great Lakes St. Lawrence Region

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Xin Shen // Civil Engineering

Jeremy Bricker // Civil Engineering

Curt Wolf // Civil Engineering

Jon W. Allan // School of Environment and Sustainability

Dan Cooper // Global CO_2 Initiative, Mechanical Engineering

Susan Fancy // Global CO_2 Initiative, Mechanical Engineering

UNIVERSITY OF MICHIGAN

GREAT LAKES ST. LAWRENCE GOVERNORS & PREMIERS

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Abbreviations

AELE
Annual Electricity Supply and Disposition Survey (Canada)

EIA
U.S. Energy Information Administration

HQT
Hydro-Québec TransÉnergie

IESO
Independent Electricity System Operator (Canada)

MISO
Midwestern Independent System Operator (U.S.)

NYISO
New York Independent System Operator

PJM
Pennsylvania-New Jersey-Maryland

SEDS
State Energy Data System

Definitions

Electricity Generation

The process of generating electric power from sources of primary energy such as wind, solar, hydropower, coal, natural gas, nuclear, or biomass. For utilities in the electric power industry, it is the stage prior to its delivery (transmission, distribution, etc.) to end users or its storage, using for example, the pumped-storage method. In this report, power plants are described in terms of their power capacity in megawatts (MW), and electricity generation is expressed as kilowatt hours (kWh).

Electricity Consumption

End-use consumption data represents the energy actually used by consumers in commercial and residential sectors. Transmission and distribution energy losses from the transfer of electricity from power plants to end users are not included, which averages around 5% in the U.S [1] , and 4.5% to 8% for Hydro-Québec's [2] and Ontario's transmission system.

Great Lakes St. Lawrence Region or "Region"

Describes the land encompassed by the States of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania and Wisconsin and the Provinces of Ontario and Québec.

Water Consumption

Powerplants use large volumes of water primarily for cooling, or to spin turbines in the case of hydroelectric powerplants, and also for other purposes. The total amount of water withdrawn from a source is defined as water withdrawal, and the amount of withdrawn water that's not returned to the original source and is lost permanently is defined as water consumption. Water consumption is the portion that is permanently lost through evaporation, transpiration, or other means. In the utility industry, water consumption rates are expressed as gallons per megawatt (MW) of power generated.

Executive Summary

The Conference of Great Lakes St. Lawrence Governors and Premiers (GSGP) is evaluating strategies to enhance the Region's economic competitiveness and appeal as a hub for future industries. It is assessing the availability and sustainability of electricity and water resources to support existing business sectors and ones anticipated to be growing in coming years such as data centers, advanced manufacturing, and others.

GSGP partnered with the University of Michigan to conduct a historical regional electricity and water assessment with future consumption projections. Publicly available data was used to summarize the past and plot the future for the Region.

Key questions that were addressed included:

- How much electricity is generated in the Region, and what is the fuel mix including renewables such as wind, hydroelectric, and solar?
- How is the Region meeting its renewable energy demand—is it through local production or by importing from other areas such as the southern United States to fulfill state-and provincial-level clean energy targets?
- Where are the major transmission lines in the Region?
- What is the net import or export of electricity into or from the Region, and what are the main sources? Is there a surplus of energy that could support the development of new industries and future growth? Which states or provinces are the largest exporters?
- Over the next decade, what are the projected changes in electricity consumption, fuel mix, and water usage under various growth and carbon scenarios?
- What are recommendations for achieving optimal outcomes in terms of electricity production, fuel mix, emissions, and water use?

Work products for this study include this report and a slide deck of key graphs and tables based upon data from authoritative sources such as EIA, IESO, HQT, MISO, PJM, and NYISO.

Overall, the study observed that with the Region's **shift from coal and nuclear to gas, solar and wind, energy production has been significantly decarbonized and uses less water, while supporting an increase in regional GDP.** The dual benefit of more efficient energy production and decreased water use offers new potential economic opportunities for the Region. Key insights from the study include:

- **The Region produces more energy than it consumes** - and has an opportunity going forward to consider the best economic usage for excess regional energy. In 2023, the Region generated 1,397 billion kWh and exported 79.3 billion kWh, or 5.7% of generation. This provides an opportunity to evaluate the Region's strategy going forward - is it better economically to continue to export and sell power, or instead fuel new industry and growth in the Region? A few examples of economic growth opportunities include data centers, high purity polysilicon manufacturing for usage in solar panels and electronics, or products that use waste carbon dioxide as a feedstock.

  To give context to this figure, in the example of a data center, center power usage can range from a few megawatts (MW) to 100 MW. Assuming a 50 MW data center and 24/7 operation, a midsize center would use 438,000,000 kWh per year, or 0.438 billion kWh. In total, the Region could immediately accommodate 181 data centers of this size without building new energy generation facilities.
- **Energy consumption for the Region over the last 10 years has been largely stable, while province and state level real GDP has grown.** Energy consumption for the Region has remained relatively flat within year to year variability, ranging from 1,262 billion kWh in 2014 to 1,213 kWh in 2023. Over the same timeframe, GDP for Ontario [3], Québec [4] , and the U.S. Great Lakes States [5] increased in the low single digit percentages annually, typically 1-4%. Net GDP gains for the decade also include a 2020 decrease in GDP from covid.
- **Significant opportunities exist for additional low to zero emission energy generation** in wind, solar, and anaerobic digestion to produce either natural gas or electricity. **For energy storage, there is also significant capacity for pumped hydro systems**, although these would need to account for complexities in siting on highly desirable shoreline, availability of supporting infrastructure and community receptivity. Pumped hydroelectric storage is a method of storing energy by using surplus electricity when available to pump water from a lower reservoir to a higher reservoir, then releasing the water through turbines to generate electricity later on. It's essentially a "water battery" that can be charged and discharged to balance electricity supply and demand.
- **The Region has conserved billions of gallons of water annually related to electricity production.** Water consumption for energy production has declined by 24% in the last 10 years, from 544 million gallons to 412 million gallons. Further reductions of up to 30% are possible with the further addition of renewable energy sources to the grid and the ongoing retirements of legacy coal plants.
- **The Region's electric system operates as a whole with considerable interstate/interprovincial, and international power flows.** The Region demonstrates a high degree of interdependence and cross-border connectivity. In 2022, Ontario exported a total of 22.4 billion kWh to Michigan and Minnesota, and Québec exported 13.6 billion kWh to New York. Within the U.S., Pennsylvania, Illinois, and Michigan exported power to surrounding states at 80.2, 36.5 and 10.8 billion kWh, respectively.

Recommendations for further study include:

- Given the Regions' net export of power and decreased water consumption, analyze the economic implications of the import and export cost differentials versus alternative use scenarios. What are the economic trade-offs and opportunity costs of selling excess power for the region instead of using it to support new industries such as data centers or high purity polysilicon manufacture? What are the potential economic multiplier effects on larger supply chains and cluster economies from these or other new industries?
- Given that carbon capture and utilization is not included in future energy demand projections from the regional transmission operators, assess the Region's economic opportunity as well as energy, land and water needs. Focus especially on industrial products that can be manufactured using waste carbon dioxide as a feedstock, such as construction materials or valuable chemicals.
- Devise strategies for the Region to harmonize electricity data for improved comparability and Regional planning.

> The Region produces more energy than it consumes - and has an opportunity going forward to consider the best economic usage for excess regional energy.

The Region's electric system operates as a whole with considerable interstate/ interprovincial, and international power flows.

Full Report

1. Historical Electricity Generation Including Fuel Mix

The total electricity generation including fuel mix was assessed for each of the eight Great Lakes States and the Provinces of Ontario and Québec, as well as for the Region as a whole for 2014-2023. Data for these calculations was obtained from the U.S. Energy Information Administration (EIA) Electricity Data Browser for the United States, and from multiple sources for Canada. Please see Appendix A for detailed descriptions of the methodology and data sources.

The 2014-2023 electricity supply fuel mix from these datasets is illustrated as stacked plots for each of the eight Great Lakes States (Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin) , as well as Ontario and Québec, and for the Region as a whole.

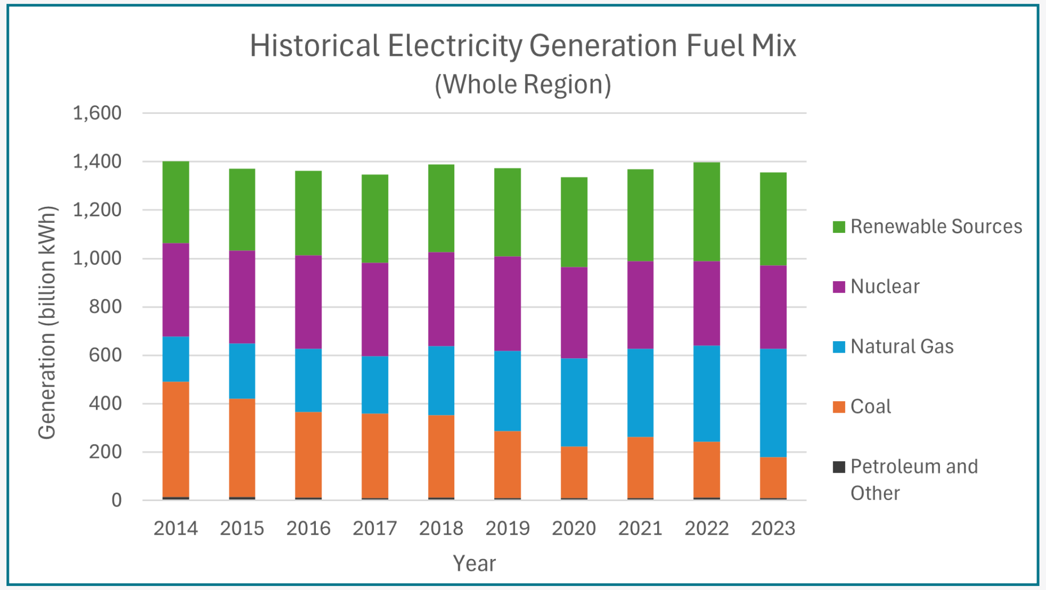


Figure 1. Historical Electricity Generation Including Fuel Mix for the Region. This figure shows the total amount of energy generated for the Region for 2014-2023. Each major fuel source is shown in a different color, illustrating its share within the bar for each year. The electricity consumption of the eight Great Lakes States was obtained from the U.S. Energy Information Administration, and for Ontario and Québec Provinces is from the Canada's Energy Future 2023 Independent Electricity System Operator data.

2. Historical Electricity Consumption

The electricity consumption was evaluated for each of the eight Great Lakes States, the Provinces of Ontario and Québec, as well as for the Region as a whole for 2014-2023. Data for these calculations was obtained from the EIA's State Energy Data System (SEDS): 1960–2022 for the United States, For Canada, data from Ontario's Independent Electricity System Operator (IESO) and Hydro-Québec TransÉnergie (HQT) was used. Please see Appendix B for detailed descriptions of the methodology and data sources.

The results of historical electricity consumption are illustrated by a time series figure showing the changes in each state or province from 2014 to 2023, along with a stacked plot that shows the total electricity consumption of the region and the shares contributed by each area. All data is shown in the related data table.

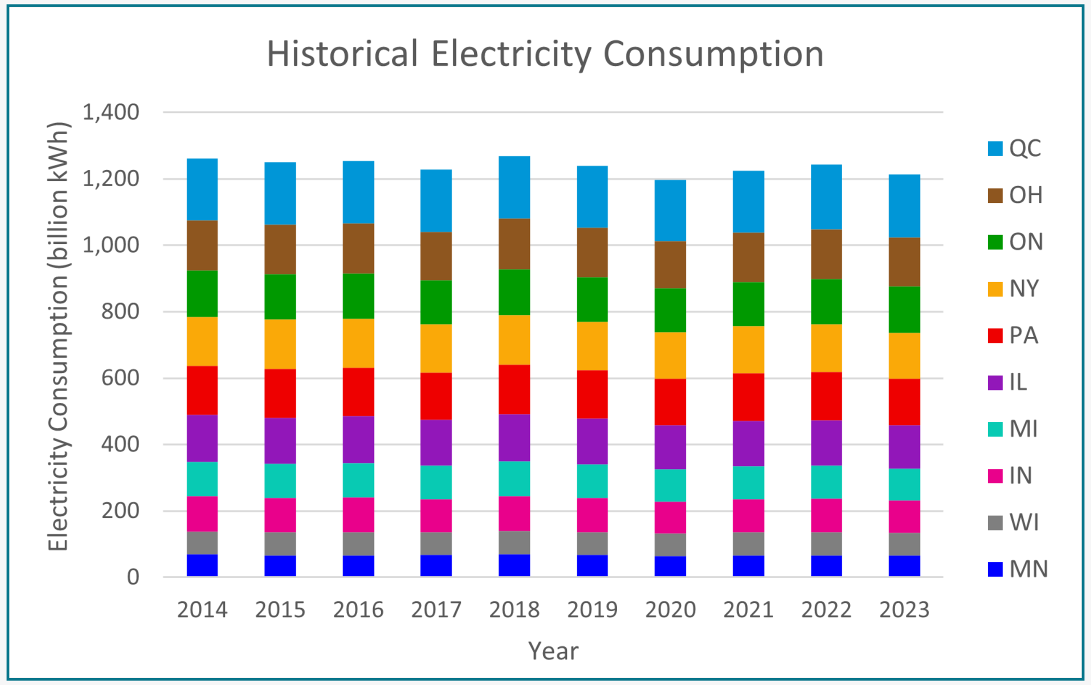


Figure 2. Historical Electricity Consumption by State or Province for the Region. This figure shows total consumption for 2014-2023. Each state and province is shown in a different color, illustrating its share within the bar for each year across the Region. The electricity consumption of the eight Great Lakes States was obtained from the U.S. Energy Information Administration, and for Ontario and Québec is from Canada's Energy Future 2023 Independent Electricity System Operator data.

3. Historical Water Consumption for Electricity Generation

The amount of water consumed for electricity generation was summarized for each of the eight Great Lakes States, and the Provinces of Ontario and Québec, as well as for the Region as a whole for 2014-2024. Please see Appendix C for details on the methodology used to make calculations and data sources.

Electricity generation in the Region has historically relied heavily on water-intensive processes tied to fossil fuels and nuclear power. Coal-fired power plants, for instance, withdraw immense amounts of water for cooling and consume significant portions through evaporation. Natural gas plants are less water-intensive but still require substantial withdrawals. Nuclear power plants also demand large volumes of water for cooling and contribute to thermal pollution risks. While oil plays a minor role in electricity generation in the Region, it remains a significant consumer of water resources in the broader energy system.

The Region exported a net excess energy of 79.3 billion kWh in 2022, or 5.7% of generation

Previous reliance on thermoelectric power generation placed considerable stress on the region's freshwater resources which is now decreasing. For example, coal plant closures in Michigan since 2015 have reduced water use for electricity generation by 40%, while Illinois saw an 82% drop in coal-related water withdrawals between 2005 and 2014 [6]. Similarly, Ontario's complete phaseout of coal by 2014 eliminated daily withdrawals of nearly 26 billion gallons of water [7]. These examples highlight substantial water savings as the Region transitions away from traditional fossil fuels.

As renewable energy capacity grows across the region and fuel types change, the pressure on freshwater resources is expected to further decline significantly. Replacing coal with natural gas powerplants cuts total water withdrawals by 10,500 gallons per MWh and consumption by 260 gallons per MWh [8]. Solar photovoltaic (PV) and wind energy are even more efficient: their water intensity is just 1–2% of coal or gas, requiring negligible water for operation beyond minimal panel or turbine maintenance [9].

Hydropower, while renewable, presents a more complex picture due to potential water losses from reservoir evaporation.

The results of historical water consumption are illustrated by a time series figure showing the changes in each state, Ontario and Québec from 2014 to 2023, along with a stacked plot that shows the total electricity consumption of the Region and the shares contributed by each state and province. All data is shown in the related data table.

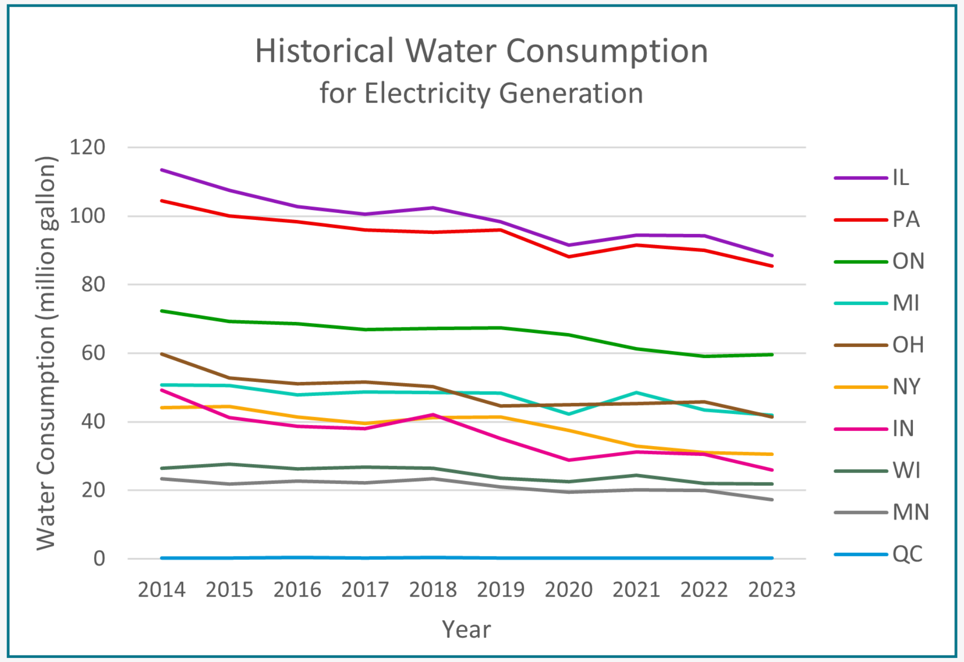


Figure 3A. Time Series of Historical Water Consumption for Electricity Generation in the Region (2014–2023). Each state and province is shown in a different color, with lines depicting the trend over the past 10 years. The water consumption totals were calculated by applying standard water consumption coefficients for each type of fuel mix to the historical electricity consumption represented by Figure 2.

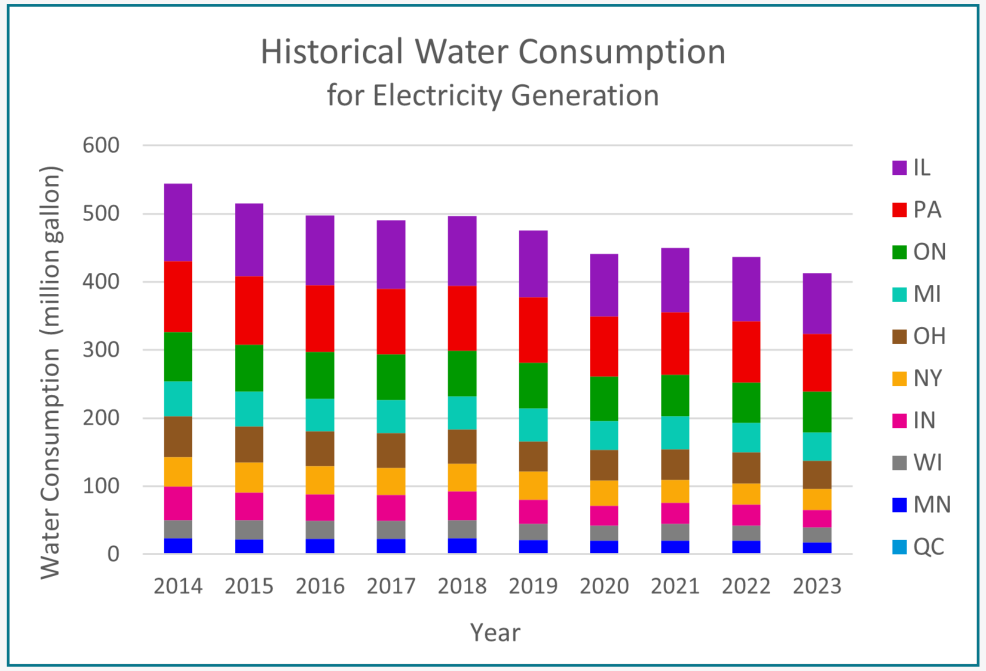


Figure 3B. Time Series of Historical Water Consumption for Electricity Generation in the Region (2014–2023). Each state and province is shown in a different color, with lines depicting the trend over the past 10 years. The water consumption totals were calculated by applying standard water consumption coefficients for each type of fuel mix to the historical electricity consumption represented by Figure 2.

4. International Electricity Transmission: Imports and Exports

The location and quantity of electricity generated in each state and province was summarized, based on data from EIA, HQT, and IESO, including the amount of electricity exported and its destinations, as well as the amount of electricity imported. Additionally, major transmission lines in the region were identified. Please see Appendix D for a description of the datasets used and methodology.

The topline result using these 2022 datasets showed that the Region had total generation of approximately 1.35 billion kWh and energy usage of 1.2 billion kWh, or 0.15 billion kWh which represents 11% excess generation. Note that this is not usable excess generation, as there are transmission and distribution losses which range from a few percent to 8% depending upon the location. **The Region exported a net excess energy of 79.3 billion kWh in 2022, or 5.7% of generation which is represented in Figures 4B and 4C.**

Table 4 presents the total inbound and outbound for the Region as a whole. By subtracting outbound from inbound, it is found that the Region net exported 79.3 billion kWh of electricity in 2022.

Inbound	Outbound	Inbound - Outbound
91.5	170.8	-79.3

Table 4. Total Inbound and Outbound Electricity for the Great Lakes Region (2022)

The net inbound—either interstate/interprovincial or international—for each state or province was calculated by subtracting exports from imports. The resulting net inbound values may be positive or negative: a positive value indicates that more electricity flowed into the state or province than flowed out (i.e., net import), whereas a negative value indicates a net export of electricity from the state or province during the year. The total net inbound for each state or province was calculated by summing these two values. The net inbound values for each state and province were cross-checked against the difference between local electricity generation and consumption for the corresponding year. The results were consistent within a reasonable margin of error, indicating that the data compiled are reasonably reliable.

In 2022, Ontario exported a total of 22.4 billion kWh to Michigan and Minnesota, and Québec exported 13.6 billion kWh to New York. Within the U.S., Pennsylvania, Illinois, and Michigan act as key energy exporters to surrounding states at 80.2, 36.5 and 10.8 billion kWh, respectively.

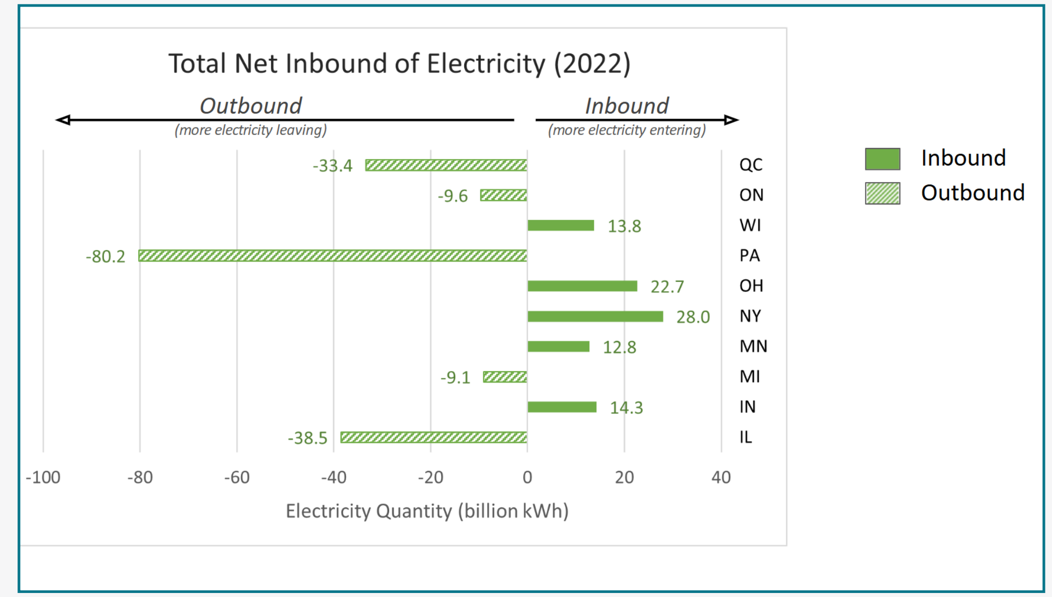


Figure 4A. Net Inbound Electricity by State and Province The y-axis represents the different states or provinces, and the x-axis shows the values of total net inbound electricity in billion kWh labeled on each bar. The "net inbound" is calculated as inbound minus outbound electricity for each state or province, and the values can be either positive or negative. Bars on the right side of the figure have positive values, indicating that more electricity flowed into the corresponding region on the y-axis than flowed out (i.e., net import). Bars on the left side of the figure have negative values, indicating that more electricity flowed out of the corresponding region on the y-axis than flowed in (i.e., net export).

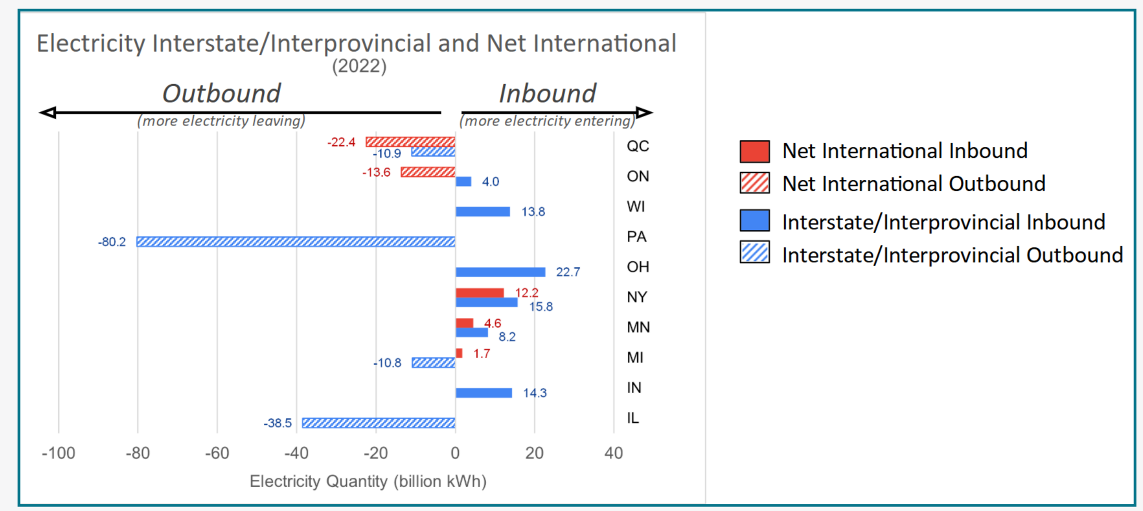
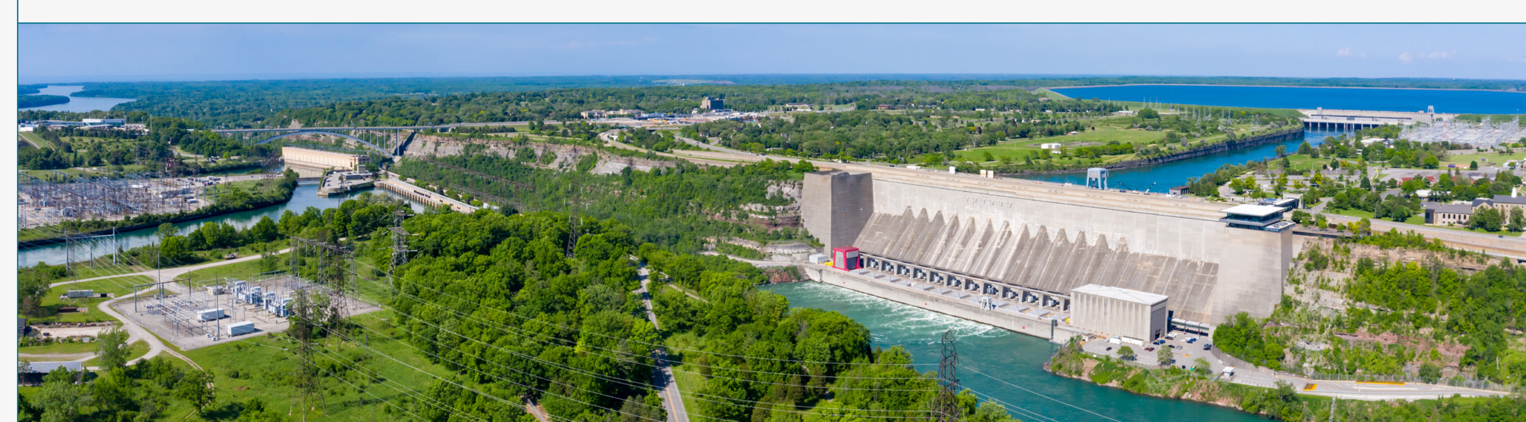


Figure 4B. Electricity Interstate/ Interprovincial and Net International Similar to Figure 4A presents the "total net inbound" electricity flows, but broken down into interstate/ interprovincial (shown in blue) and international (shown in red) components. The y-axis represents the different regions, and the x-axis shows the values of total net inbound electricity with specific numbers labeled on each bar. As in Figure 4A, the values on the bars can be either positive or negative: bars on the right side of the figure have positive values, indicating that more electricity flowed into the corresponding region on the y-axis than flowed out (i.e., net import); bars on the left side have negative values, indicating that more electricity flowed out of the corresponding region on the y-axis than flowed in (i.e., net export). Since interstate/interprovincial and international net inbound flows are calculated separately, some states or provinces — such as Ontario — may simultaneously show a positive net interstate/interprovincial flow (inbound) and a negative net international flow (outbound). This indicates that Ontario imported electricity from other Canadian provinces, while exporting more electricity to U.S. states than it imported from other provinces.



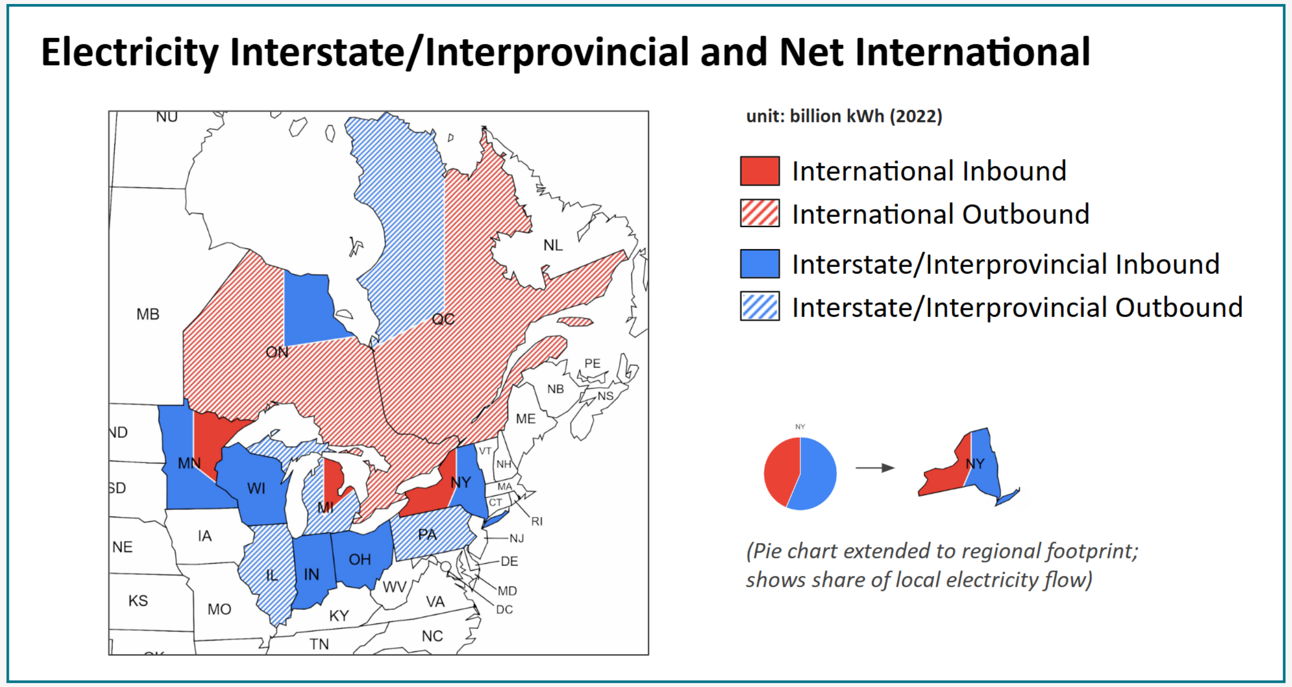


Figure 4C. Spatial Map of Inbound and Outbound Electricity Flows This map illustrates the spatial pattern of net inbound and outbound electricity flows for each state and province, both interstate/interprovincial (domestic) and net international. The region demonstrates a high degree of interdependence and cross-border connectivity for international electricity flows. Ontario and Québec are significant sources of outbound electricity to the United States, contributing to inbound flows for Minnesota, Michigan and New York that totaled 36 billion kWh in 2022. Within the United States, Pennsylvania, Illinois, and Michigan act as key energy suppliers, sending outbound electricity to surrounding states at 80.2 kWh, 36.5 kWh, and 10.8 kWh respectively. For Ontario and Québec data, the electricity flow direction and sources can be identified, but for U.S. states' interstate electricity flow the direction or source is not known.

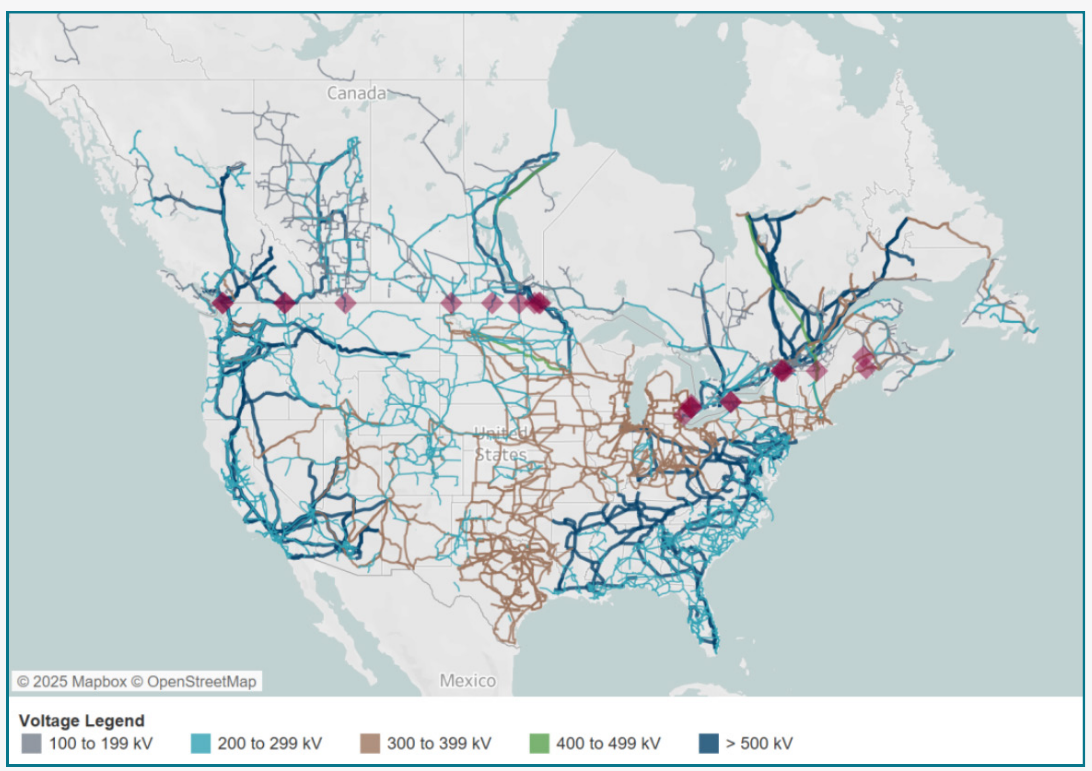


Figure 4D. Map of Major Transmission Lines for Canada and the U.S. The map illustrating the major transmission lines is from figure "International Power Lines and the Canada–U.S. Grid", published in an article by the Canada Energy Regulator (CER) [10]. In the map, major transmission lines are represented according to their voltage levels (kV), with higher-voltage lines indicating greater transmission capacity and regional significance.

5. Future Projection of Electricity Consumption for the Region

Projected changes in electricity consumption were summarized for high (3.29%), medium (2.60%), and low GDP growth (1.99%) scenarios for 2025-2035. The consumption projections were created using electric grid regional transmission operator data from NYISO, MISO, PJM, IESO, and HQT (operators coordinate regional power flows). Since the total Region-wide consumption projections exhibit notable linearity, the average annual growth rate for each scenario was calculated to provide a more direct quantification and comparison. Please see Appendix E for further information about the methodology.

The results of the future projection of electricity consumption are illustrated by a time series figure for the Region under three consumption growth scenarios. Data is shown in the related data table.

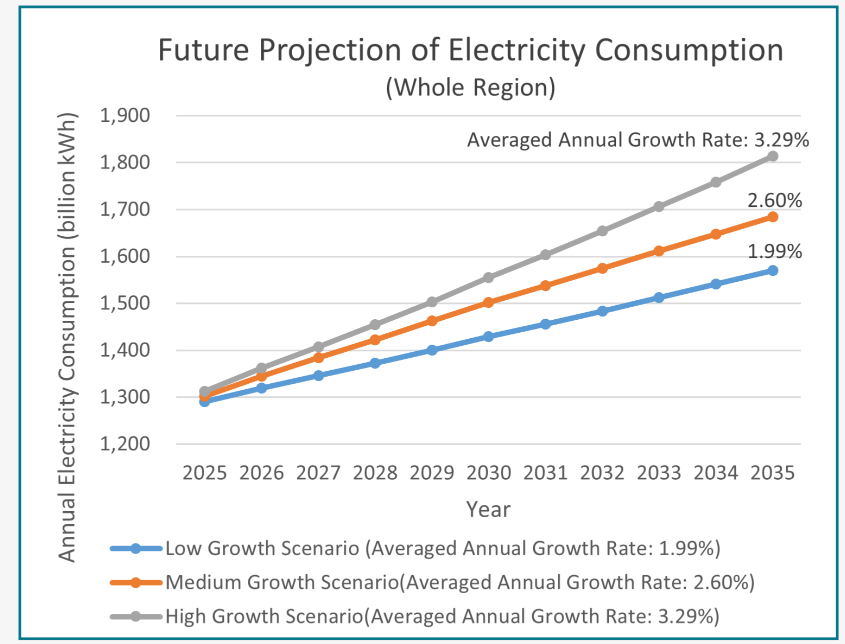


Figure 5. Future Projection of Electricity Consumption Includes electricity exported for consumption outside of the Region. Datasets used from the U.S. and Canada were from regional transmission operators and harmonized to represent the Region's geographical footprint. The average annual growth rate of each scenario is obtained by first calculating the year-over-year growth, and then taking the average of these annual growth rates over the 10-year period.

6. Future Projection of Electricity Generation Fuel Mix for the Region

Projected changes in fuel mix were forecast under high, medium and low carbon scenarios to meet projected electricity consumption scenarios for 2025-2035 for the Region. Renewable energy and net zero goals for each state and province are reflected in the low, medium and high carbon scenarios. Note that although the definition of "carbon scenarios" may vary across projections from different states or provinces, their main characteristics are the proportion of renewable energy and the level of carbon emissions. For example, low carbon scenarios have higher proportions of clean energy sources such as hydro or solar.

Energy generation fuel mix projections were created using regional transmission operator data for Canada and the United States. Please see Appendix F for further information on the methodology that was used.

The results of the future projection of the electricity generation fuel mix are illustrated as stacked plots showing the share of each fuel source for the entire region under low-carbon, medium-carbon, and high-carbon scenarios. Data is shown in the related data table.

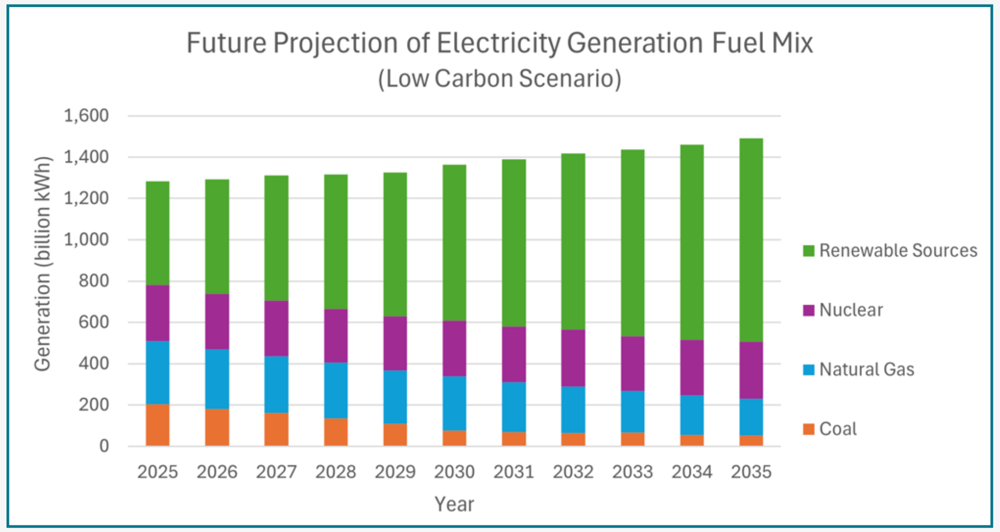


Figure 6A. Future Projection of Electricity Generation Fuel Mix - Low Carbon Scenario Represents a future projection of electricity generation fuel mix under the low-carbon scenario for the Region. Each major fuel source is shown in a different color, illustrating its share within the bar for each year throughout the next decade.

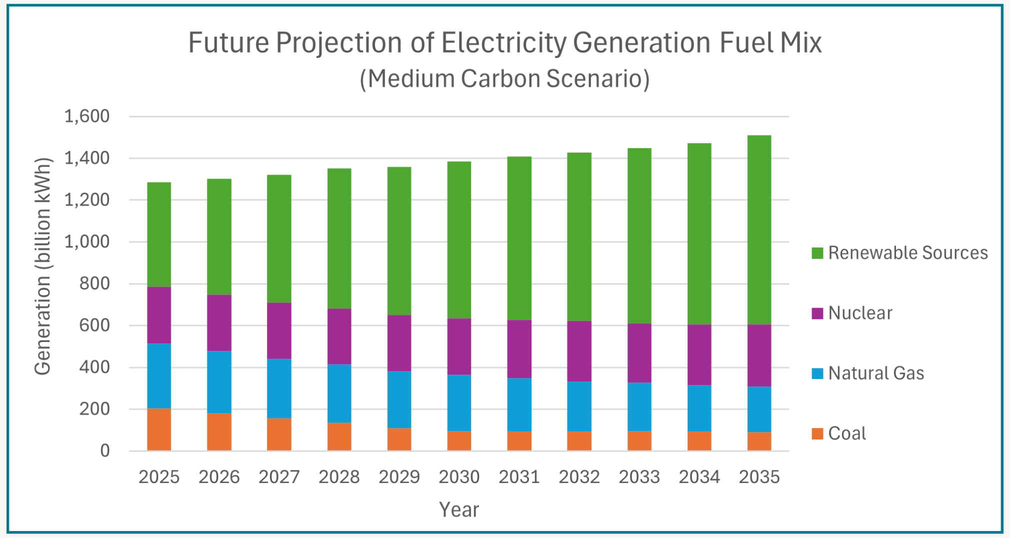


Figure 6B. Future Projection of Electricity Generation Fuel Mix - Medium Carbon Scenario Represents a future projection of electricity generation fuel mix under the medium-carbon scenario for the Region. Each major fuel source is shown in a different color, illustrating its share within the bar for each year throughout the next decade.

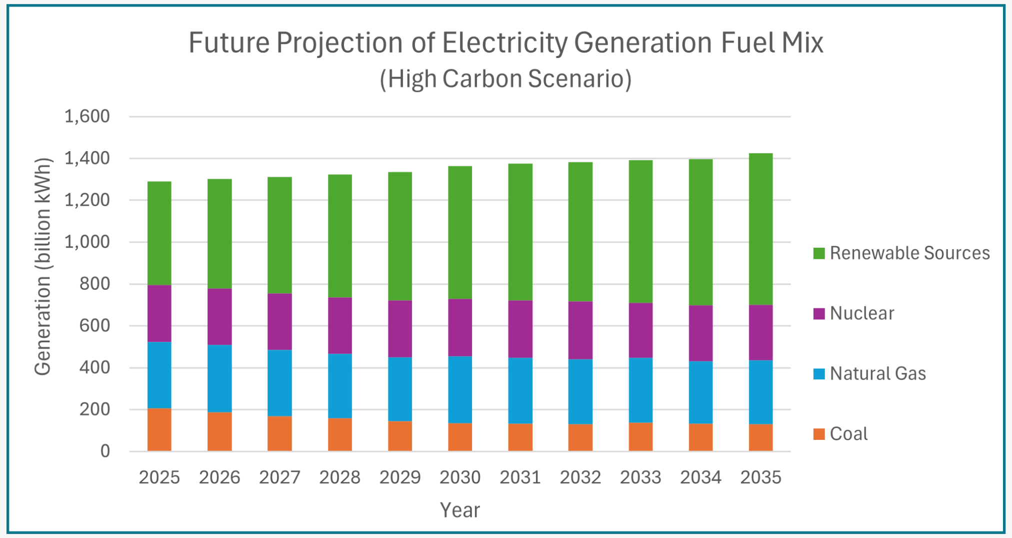


Figure 6C. Future Projection of Electricity Generation Fuel Mix - High Carbon Scenario Represents a future projection of the electricity generation fuel mix under the high-carbon scenario for the Region. Each major fuel source is shown in a different color, illustrating its share within the bar for each year throughout the next decade.

There is theoretically significant potential for future offshore wind electric power generation in the Region. However, this has so far proven to be of little interest to the public and in some cases the public has been outright hostile to the notion of this commercial use of the Great Lakes shoreline or bottomlands. While offshore wind may pair well with pumped hydro storage (please see Appendix C), siting issues and associated public pushback on both of these technologies still loom large. Shorelines in general have priorities for residents, tourists and wildlife preservation.

7. Future Projection of Water Consumption for Electricity Generation for the Region

The projected water use for the Region was summarized for generating electricity under the low, medium and high carbon scenarios for the region as a whole for 2025-2035 that are described in Section 6 above.

This study assumed that there will be no significant technological breakthroughs in electricity generation over the next decades that would lead to large changes in water consumption. Based on the projected electricity generation fuel mix for each carbon scenario in Section 6, the future projection of water consumption for electricity generation under low-carbon, medium-carbon, and high-carbon scenarios is made using the same water consumption coefficients as those in Section 3.

The results of the future projection of the water consumption for electricity generation are illustrated as stacked plots showing the share of each fuel source for the Region under low-carbon, medium-carbon, and high-carbon scenarios. All data is shown in the related data table.

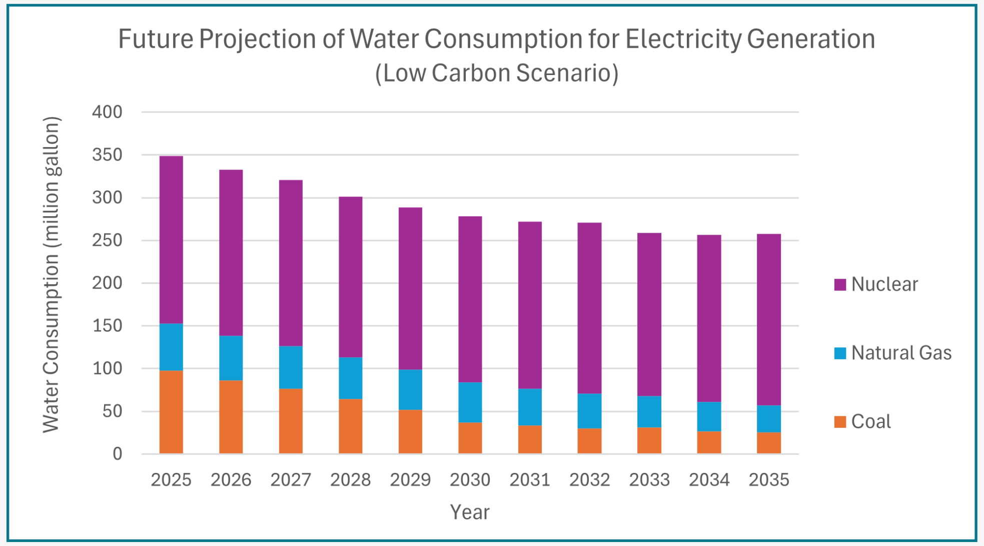


Figure 7A. Future Projection of Water Consumption for Electricity Generation - Low Carbon Scenario Represents a future projection of the water consumption for electricity generation under the low-carbon scenario for the Region. Each major fuel source is shown in a different color, illustrating its share within the bar for each year throughout the next decade.

The Region has conserved billions of gallons of water annually related to electricity production

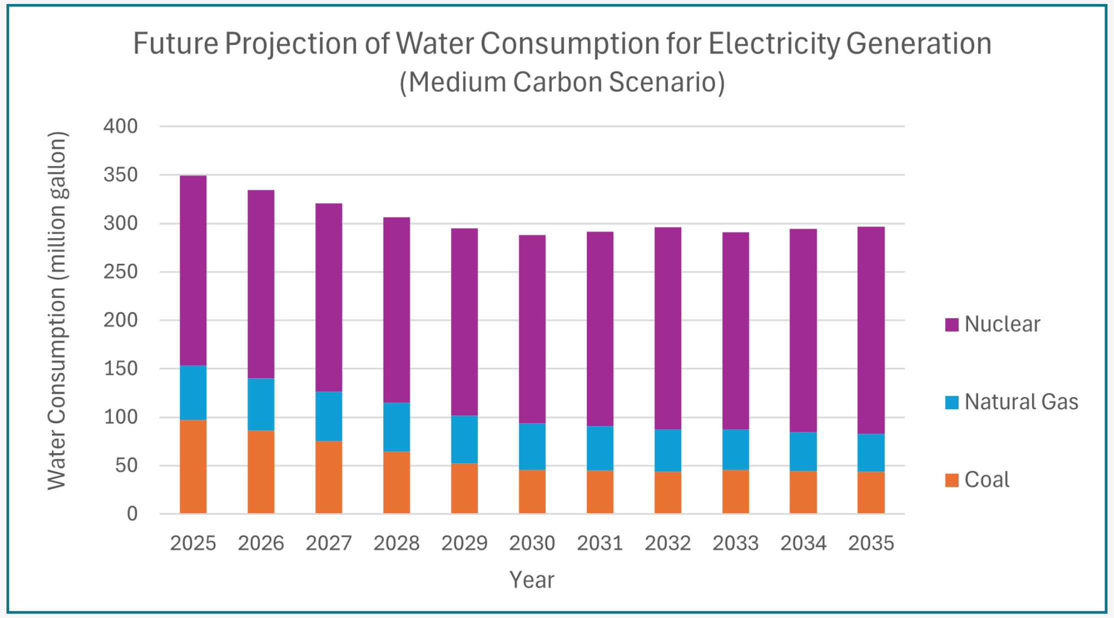


Figure 7B. Future Projection of Water Consumption for Electricity Generation - Medium Carbon Scenario Represents a future projection of the water consumption for electricity generation under the medium-carbon scenario for the Region. Each major fuel source is shown in a different color, illustrating its share within the bar for each year throughout the next decade.

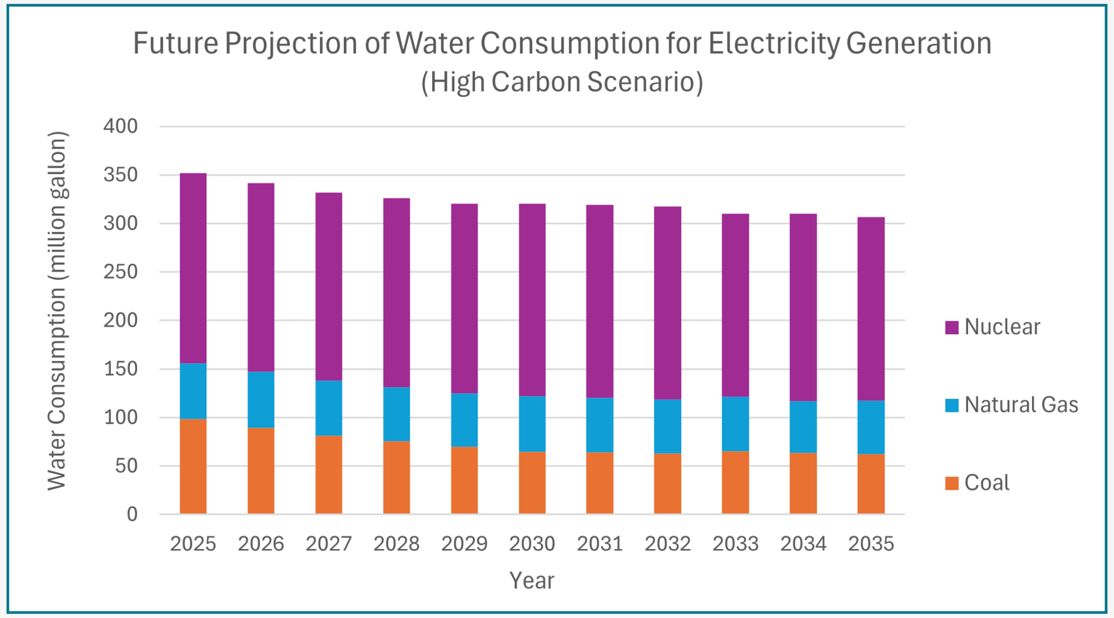


Figure 7C. Future Projection of Water Consumption for Electricity Generation - High Carbon Scenario Represents a future projection of the water consumption for electricity generation under the high-carbon scenario for the Region. Each major fuel source is shown in a different color, illustrating its share within the bar for each year throughout the next decade.

Appendices

To answer the questions in this study, historical data for electricity consumption and generation fuel mix were collected from individual state and provincial datasets, while future projections of electricity consumption and fuel mix were obtained from regional transmission operator (RTO) data. This is primarily because most projections are only available at the operator level, not at the state or provincial level. Note that electricity generation does not account for transmission and distribution line losses, which is a few percent for any given region.

For water, state level historical electricity consumption and fuel mix was used to estimate total water usage for each state and province as well as the region as a whole. More details on each set of calculations are below.

Appendix A: Historical Electricity Generation & Fuel Mix Methodology

A.1 Historical Fuel Mix Methodology and Datasets

The fuel mix data for the Great Lakes States was sourced from EIA through its interactive dataset: Electricity Data Browser [11]. This dataset provides a consolidated and structured version of all tables relevant to "Energy Consumption by Electric Power Sector" in the SEDS dataset [12]. The raw data originates from EIA survey form EIA-923, Power Plant Operations Report and predecessor forms.

The fuel mix data for Ontario and Québec from 2014 to 2021 was obtained from Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050 [13] [14] and cross-validated using the Annual Electricity Supply and Disposition Survey (AELE) [15] [16]. The fuel mix data for Ontario in 2022 and 2023 is obtained from IESO's energy output charts in the Annual Review of 2022 and 2023 [17]. Similarly, the fuel mix data for Québec in these years is sourced from the Energy Sources and Sales in 2022/2023 charts in HQT's Annual Report 2022 [18] and 2023 [19].

There were significant inconsistencies in the datasets for Canada (see Appendix 1). Therefore, in this report the main source was Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050 and Operator-level annual reports published by IESO and HQT (please see Appendix 1 for more detail) to adjust and refine the final data table.

A.2 Challenges with Canada's Historical Fuel Mix Data

The lack of a single authoritative data source for Canada and the absence of a unified validation process introduced challenges in assembling a consistent historical electricity generation fuel mix dataset for Ontario and Québec. This was addressed by the following:

- Due to differences in fuel source classifications between the two countries' datasets, a harmonization of fuel sources was performed, primarily by aggregating subcategories of renewable energy and other distributed power generation. Additionally, due to discrepancies in fuel source classifications, the fuel mix categories in the operator-reported data for Ontario and Québec lack separate entries for petroleum and natural gas in 2022 and 2023. In short, the way Canada categorizes energy sources doesn't always match how United States sources categorize them, so this report adjusts the data to make it comparable.
- To address this, corrections are applied using data from the Energy Fact Book 2024-2025 [20], published by Natural Resources Canada. Specifically, the Provincial Electricity Generation by Source 2022 tables are used to determine the proportion of electricity generation attributed to petroleum and natural gas in Ontario and Québec. These proportions are then multiplied by the initial total electricity generation reported by the respective operators for 2022 or 2023 to estimate the corresponding values. The estimated petroleum and natural gas contributions are subsequently added to the total generation for each respective year, and the corrected electricity generation value is used as the total electricity generation for that year.

As further background on Canada, a unified and reliable data source, or a sufficiently authoritative institution to collect and validate all data (similar to the EIA in the U.S.), is lacking for historical electricity generation fuel mix data in Canada. During the process of compiling historical fuel mix data for this study, we identified four statistical reports from different institutions that included the necessary fuel source categories and time periods of interest:

1. National Inventory Report from The Environment and Climate Change Canada [21].
2. Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050 [13] [14].
3. Annual Electricity Supply and Disposition Survey (AELE) [15] [16].
4. Operator-level annual reports published by IESO and HQT [17] [18] [19].

However, the values reported for each fuel source and year exhibited significant discrepancies, making cross-verification difficult. Even if some potential sources of error, such as rounding, could be deemed acceptable, there remains a lack of a widely recognized reference or baseline dataset to guide data selection, comparison, and validation. Furthermore, these institutions operate in parallel rather than in a hierarchical manner, preventing the prioritization of one dataset over another based on the reliability of statistical methodologies.

The lack of a single authoritative data source and the absence of a unified validation process introduced challenges in assembling a consistent historical electricity generation fuel mix dataset for Canada. This report recommends integrated, harmonized electricity generation and fuel mix datasets for Canada to help the Region with future energy planning.

A.3 Classification Overlap Issues in Canada's AELE Dataset

Some of Canada's datasets suffer from classification overlap. Generally, we expect datasets for a specific object to be mutually exclusive and collectively exhaustive. However, in the case of the third dataset AELE, the boundaries of its fuel source classification are unclear: upon reviewing the specific definitions and scopes [22], we found that there is overlap between categories (e.g., Category 5.1.1 and 6.1). This inherent flaw made this dataset completely unusable for this report, although we still included AELE as one of the data sources for the fuel mix.

Appendix B: Historical Energy Consumption Methodology

The electricity consumption of the eight Great Lakes States for 2014–2022 was obtained from the U.S. Energy Information Administration's (EIA) State Energy Data System (SEDS): 1960–2022 dataset [12]. Notably, the term "energy" in the dataset's "Total Energy Consumption" tables refers to primary energy, not specifically electricity. Therefore, electricity consumption corresponds to the table "Electricity Sales to Ultimate Customers" within the dataset. The 2023 electricity consumption was obtained from the SEDS: 2023 Updates dataset, which explicitly provides this information in the table "Electricity Consumption Estimates, 2023."[23]

For Canada, Ontario's electricity consumption was obtained from the province's power system operator, the Independent Electricity System Operator (IESO), which provides the "Historical Consumption Overview" [24]. Similarly, Québec's electricity consumption was obtained from its power system operator, Hydro-Québec TransÉnergie (HQT), which provides the "History of Electricity Demand in Québec" [25]. HQT's statistical data only cover the period from 2019 onward. Therefore, for the years 2014–2018, the 2019 values were used as proxies.

Appendix C: Water Consumption Methodology

Consumptive use data for various power generation types was taken from the March 2002 EPRI report titled Water & Sustainability (Volume 3): U.S. Water Consumption for Power Production- The Next Half Century to evaluate water use in power generation across different cooling scenarios. The figures given in this report are consistent with various other sources evaluated. This report applies conservative assumptions for each cooling configuration—such as once-through, closed-cycle, and dry cooling systems—to account for variations in water withdrawal and consumption rates.

Fuel Source	Coal	Petroleum	Natural Gas	Nuclear	Renewable Sources	Other
Gallon/MWh	480	480	180	720	0	0

Table C. Water Consumption Coefficients for Water Consumption Calculations

Appendix D: Net Electricity Import And Export Methodology

The location and quantity of electricity generated in each state and province was summarized, based on data from EIA, HQT, and IESO, including the amount of electricity exported and its destinations, as well as the amount of electricity imported.

D1. International Electricity Imports and Exports between Canada and the United States

To calculate international electricity imports and exports, as well as the net interstate flow of electricity, the raw dataset 2022 data was used. For the Great Lakes States, the SEDS dataset [26] was used, which is the foundation for the State Energy Consumption Estimates (1960 Through 2022) report [27].

The international and interprovincial electricity imports and exports of Ontario were obtained from the Table of Annual Imports and Exports by Jurisdiction provided by IESO [28]. The international and interprovincial electricity imports and exports of Québec were obtained from the Annual Report 2022 [18], incorporating data from the chart of Energy Sources and Sales in 2022 and the chart of Breakdown of Sales Outside Québec in 2022 by Market, provided by HQT. Additionally, as the source of "imports" in the HQT report is not specified and its reported value is lower than the 2022 exports to Québec recorded by IESO, it is assumed that these imports originate entirely from Ontario and are therefore classified as interprovincial imports.

D2. Interstate Electricity Import and Export for Great Lakes States and SEDS Data Issues

Data for the net interstate flow of electricity for the Great Lakes states in 2022 was also sourced from the

SEDS dataset [26]. For U.S. states, this study initially used the State Energy Consumption Estimates (1960 Through 2022) report [27] available in the SEDS report archives [29] - specifically Table C1, Energy consumption overview: estimates by energy source and end-use sector, 2022. The original values reported in trillion Btu were converted into trillion kWh to align with the unit convention used throughout this study.

However, it was later discovered that the interstate electricity flow values for Pennsylvania and Illinois appeared abnormally high—so much so that the reported net exports exceeded the difference between their electricity generation and in-state consumption in the same year, which is physically implausible.

By cross-validating the converted values from the SEDS report [27] with those extracted directly from the raw dataset [26], we found that all eight Great Lakes states exhibited similarly erroneous interstate flow values. The ratio of raw dataset values to reported values was consistently around 0.35–0.41, while the conversion factor we used from trillion Btu to trillion kWh was 0.293. This consistency suggests a systematic mismatch, likely caused by misinterpretation during unit conversion—potentially due to Btu values being mistakenly treated as if they were already in kWh before conversion.

Therefore, due to errors in the SEDS summary report, it was necessary to download and use the complete original dataset and filter the relevant data categories based on the Data Series Names (MSN), including: (1) ELEXP: Electricity exported from the United States; (2) ELIMP: Electricity imported into the United States; (3) ELISP: Net interstate flow of electricity. Information from that dataset is presented in this report.

Appendix E: Future Projection Of Electricity Consumption For The Region

Projected changes in electricity consumption were summarized for high (3.29%), medium (2.60%), and low GDP growth (1.99%) scenarios for 2025-2035.

The consumption projections were created using electric grid regional transmission operator data (operators coordinate regional power flows). Future energy projection reports of all relevant operators in the Region were used (NYISO, MISO, PJM, IESO, and HQT) including: NYISO 2024 Power Trends [30][31], MISO 2024 Load Forecast and Process Enhancements Workshop [32], PJM Transmission Planning for PJM's Future Load and Generation [33], IESO's Annual Planning Outlook [34] and Hydro-Québec's Action Plan 2035 [35].

All operator reports, except for HQT, include projections for high, medium (or reference), and low consumption growth scenarios, allowing for direct summation to estimate the consumption for the Region for each scenario. HQT's 2022-2035 projection provides only one scenario, so the same projection data is applied to all three scenarios and combined with other operators' projections.

For Great Lakes states projections, since the operational footprints of MISO and PJM cover states outside of the Region of interest in this study, the projected consumption derived at the operator scale is higher than the projected consumption at the specific state scale. To make the Regional projections accurate and meaningful, the consumption projections from MISO and PJM to include only the states of interest in this study:

1. First, we identified which states of interest belong to which operators: MISO (Illinois excluding Chicago, Indiana, Michigan, Minnesota, Wisconsin); PJM (Pennsylvania, Ohio, plus the city of Chicago).
2. We assumed that the share of consumption from these states in each operator's total consumption will remain unchanged from 2023 (the latest data available) through the projected 2035 end date. The operator's annual total consumption is calculated by summing up the real-time data [36] provided by the EIA over the entire year. (The annual consumption of Chicago city in 2023 [37] was excluded from MISO's total and added to PJM's total to reflect its reassignment.)
3. Therefore, although the consumption projections are available only at the operator level, we can isolate the state-level data by using the "share" method to extract data for each state from the total.

Although the U.S. Department of Energy also provides state-scale consumption projections [38] [39], the reports from these operators are considered to be more detailed and tailored to local conditions, which justifies their selection.

Since the total Region-wide consumption projections exhibit notable linearity, the averaged annual growth rate for each scenario is calculated to provide a more direct quantification and comparison. This index is introduced to more intuitively present and compare the growth rates across different scenarios. Specifically, for each scenario, the year-over-year growth rate is calculated for every year in the 10-year period (each year relative to the previous one), and then the average of these 10 values is taken to obtain the averaged annual growth rate.

The study team notes that although data centers and some advanced manufacturing are included in future projections, none of the operator reports addressed the future demand for energy related to carbon capture and utilization (CCUS). CCUS is an emerging industry, and the number of projects and manufacturing plants using waste carbon dioxide as a feedstock to manufacture sustainable products such as chemicals and concrete in the U.S. is still small but expected to grow, especially by the mid 2030's.

Appendix F: Future Pojection Of Electricity Generation Fuel Mix Projection Methodology

Projected changes in fuel mix were forecast under a high, medium and low carbon scenario to meet each of the projected electricity consumption scenarios for 2025-2035. Renewable energy and net zero goals for each state and province are reflected in the low, medium and high carbon scenarios. Although the definition of "carbon scenarios" may vary across projections from different states or provinces, their main characteristics are the proportion of renewable energy and the level of carbon emissions.

The energy generation fuel mix projections were created using regional transmission operator datasets. The data for the eight Great Lakes States was sourced from the EIA's Annual Energy Outlook 2023 [40], table "Electric Power Projections by Electricity Market Module Region". An interactive dataset [41] based on this report provides a more streamlined data extraction process.

To ensure the accuracy and meaningfulness of the projections, the same method that was used to calculate electricity consumption projections was replicated for the fuel mix projections and was based on each state's share of total consumption within its respective operator.

The generation fuel mix for Ontario and Québec is sourced from Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050 [13] [14]. Similarly, this report does not define the "high, medium, and low carbon scenarios" in exactly the same way but instead aligns them with the "Current Measures Scenario," "Canada Net-Zero Scenario," and "Global Net-Zero Scenario," which differ based on the pace of global climate action [42].

Similar to Appendix A, due to differences in fuel source classification between the two countries' datasets, certain fuel source categories were adjusted to integrate data from each state and province into a unified regional dataset. For example, "Uranium" is categorized under "Nuclear", and subcategories of renewable energy are aggregated.

Appendix G: Pumped Hydro Storage

Pumped hydro storage (PHS) holds significant potential in the Region as a renewable energy storage solution, leveraging the region's topography and existing infrastructure to balance grid stability amid growing wind and solar adoption.

For example, the Ludington Pumped Storage Plant, operational since 1973, exemplifies this potential. With its 2,172 MW capacity, it stores energy by moving water between Lake Michigan and an upper reservoir. However, barriers to new projects include environmental concerns—such as habitat disruption and shoreline erosion—as seen with Ludington's historical impacts on fisheries and land use. Regulatory complexity further hampers development: multi-agency permitting processes can span a decade, deterring investment despite federal government (FERC) licensing reforms. Opposition from tribes and environmental groups, coupled with high upfront costs, have stalled projects. While the Region has identified nearly 1,000 potential PHS sites, only one small facility has been built in the U.S. since 1995, underscoring the limited near-term prospects for significant capacity expansion.

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