

Article

Renewable Hydrogen Production and Geostorage Potential in Eastern Canada: A Qualitative Assessment

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Abstract

Energy storage systems, in a variety of forms and scales, contribute substantially to energy conservation while ensuring a reliable, efficient, and sustainable energy supply in modern hybrid energy systems. Storing the massive volumes of hydrogen required to meet future global supply chain demands can be achieved through geostorage in caverns in subsurface salt structures, created by controlled dissolution of the salt, and depleted hydrocarbon reservoirs. This study qualitatively but systematically assesses the potential use of geostorage solutions for large-scale energy storage in the Canadian Eastern region to support the renewables-to-hydrogen industry. The qualitative assessments indicate that the four Atlantic Provinces and Québec possess great potential for national-/international-scale hydrogen production with high-quality year-round wind resources, extensive shallow offshore seabed areas suitable for wind turbine deployment, extensive and expanding electrical grid connectivity, deep-water ports, and extensive salt deposits with structures suitable for massive geostorage. The assessment also demonstrates that integrated hydrogen production and geostorage systems can support large-scale renewable energy utilization while enhancing long-duration energy storage and grid stability. Furthermore, a portion of the waste heat generated during electrolysis, hydrogen compression, and chemical conversion processes can be utilized for district heating, greenhouse operations, compressed-air energy heat provision, and industrial applications, improving overall system efficiency and reducing fossil fuel usage and carbon-based emissions. The qualitative assessments also highlight the importance of coordinated interprovincial and federal planning to support long-term decarbonization efforts and develop sustainable, reliable geostorage-based hybrid energy systems.



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1. Introduction

Increasing global growth in energy demand across all sectors, which is still primarily met by hydrocarbon-based fuels (~80% [1]), together with the adverse influences of global warming, represent some of the most significant challenges facing the World [2], mainly driven by rapid population growth and continuing urbanization, accompanied by ongoing industrial, technological, socio-economic, and lifestyle developments worldwide [3,4]. Over the 25-year period from 2000 to 2025, for example, primary energy use rose from

$\sim 390 \times 10^{12}$ MJ to $\sim 655 \times 10^{12}$ MJ (an increase of $\sim 68\%$) globally, whereas anthropogenic carbon dioxide emissions released into the atmosphere increased from ~ 23.1 Gt to ~ 38.1 Gt (an increase of $\sim 65\%$) [5–7].

As the world's energy utilization and human-induced environmental impacts continue to rise, there is an urgent need to transition toward cleaner, more reliable, and energy-efficient systems to diminish greenhouse gas emissions and achieve long-term environmental and energy sustainability. Using renewables, emerging energy carriers (e.g., hydrogen), innovative, advanced hybrid energy technologies combined with energy storage systems (ESSs) are effective and practical solutions and support global sustainable development goals (SDGs) [8,9]. ESSs can contribute significantly to energy supply reliability and conservation by helping balance energy demand and generation, improving grid stability, facilitating the integration of renewable energy resources, and improving overall energy security across a range of residential, commercial, industrial, and utility-scale applications [10,11].

Like a hybrid electric vehicle (EV), a hybrid electrical grid must accommodate variable energy supply and demand from multiple sources. Some sources, such as nuclear power, provide steady baseload electricity to the grid; others, such as combined-cycle natural gas turbines, are designed to respond to fluctuations in demand and provide dispatchable power when needed. In contrast, renewable energy sources such as wind, solar, tidal, and certain hydroelectric systems produce variable and intermittent energy across different time scales and therefore require ESSs to ensure reliable and stable grid operation and energy delivery to end users.

Storage approaches can be classified by response time, power output, energy capacity, and duration, plus energy and power density [12,13]. Proper choices for the ongoing energy transition require careful planning and creative solutions over many scales. Regional demand also impacts storage requirements. In Europe, energy consumption is greater in winter than in summer, with less demand for interim storage, although the rising trend and intensity of heat waves in Europe with temperatures to 40°C is increasing the demand for energy for cooling [14]. The complete shutdown of the UK's Heathrow Airport on 20 March 2026, due to a fire at an electrical substation, demonstrated the lack of resilience and redundancy in critical regional and national energy infrastructure [15]. Europe's underground natural gas storage capacity is reported to be around one-third of its annual consumption, which is sufficiently large to meet peak demand during winter [16].

Battery energy storage systems (BESSs) give excellent short-term response (in a few-second range [17]). BESS farms can store energy at the +GWh scale, and power output can be designed over a huge range—from sub-MW to hundreds of MW. However, BESSs have constraints: for example, they need critical minerals/metals (such as Cu, Co, Li, and graphite) in quantities that will soon strain world supplies as electrification continues toward the reduced emissions for 2030 and net-zero emissions by 2050 goals that Canada and many other countries have agreed to. These materials are also becoming strategic resources vulnerable to global politics. This strain will increase BESS costs and generate greater environmental and political concerns relating to resource exploitation in challenging socio-political conditions.

Political manipulations of rare earth metals supply chains and economic costs have impacted industry. Batteries are relatively short-lived, highlighting that BESSs must be designed to accommodate battery replacement as their rechargeability slowly decays. Other constraints include BESSs' vulnerability to destruction, sabotage and vandalism (especially in conflict regions), fire hazards related to manufacturing defects, land use issues, and cold climate concerns. Battery fires are dangerous because they can release hazardous gases from burning materials and are difficult to extinguish. On 7 September 2026, it was reported that a battery fire in Prince Edward Island (PEI), Canada, required two weeks to

safely extinguish [18]. Finally, massive battery use means massive chemical recycling to recover metals, requiring large infrastructure investments and environmental care.

As EVs are adopted, demand increases from EVs and BESSs will compound with increased impact costs and environmental concerns. Although BESSs are a vital part of a modern grid, providing excellent short-term response, their use as a large-scale, long-duration energy storage (LDES) system is already problematic because of costs per MWh; this issue will not disappear in the foreseeable future.

To achieve grid-scale energy storage for peak flattening and ancillary services provision from off-peak excess renewable energy, the most practical solution is geostorage, especially in subsurface salt deposits with appropriate caprock and seal characteristics. Vertical caverns or horizontal galleries can be created in salt deposits through solution mining, potentially with relatively low-to-moderate environmental impact. The solutioning brine may be dispersed in the ocean following an environmental assessment of the proposed brine disposal area to ensure that the discharge does not adversely affect marine life. Dispersal rates and impact radius should be assessed and monitored during operations. Brine produced from solution-mined salt caverns is typically near saturation with respect to halite, i.e., ~26–30 wt% NaCl (~260–300 ppt) with normal marine waters at ~32–35 ppt [19]. Hydrogen and compressed-air energy storage (CAES) in caverns or in steel-cased wellbores will enable grid growth with sustained stability while servicing an emerging international-scale green hydrogen industry. Furthermore, storage technologies such as CAES systems provide essential grid services, including LDES, smoothing of inherently variable renewables, rotational inertia for frequency control, stable voltage output, and load-following capabilities.

The energy transition will benefit from the stability and services that large-capacity energy storage technologies bring. As renewables become a greater part of energy sources on the road to grid decarbonization, massive storage becomes an essential design component. Hydrogen production and distribution as a means of storing and distributing green energy and fuels continues to be viewed as an important part of the energy transition.

The estimate of global hydrogen storage by 2050 is several hundred billion cubic metres (bcm), dependent on future hydrogen demand and the assumed share of hydrogen requiring storage. Estimates consist of ~580 bcm under an IEA-based scenario and ~670 bcm under an IRENA-based scenario [20]. A large-scale energy storage medium is necessary to accommodate high levels of variable energy sources in electrical power grids. Furthermore, green hydrogen requires electricity produced by renewables for electrolysis, but 20–30% of input energy is lost as low-grade heat. Storing hydrogen consumes another 15% as the unused heat of compression is spilled [21]. Large heat losses represent an opportunity to develop advanced, hybrid energy systems to use and store excess heat. Potentially, in CAES technology, stored heat can be used to heat compressed air entering air engines to produce power, thereby reducing the amount of energy lost in hydrogen production and compression processes.

This qualitative study aims to respond to the following research question: Does the Canadian Eastern region (CER) have sufficient and appropriate potential to produce and store hydrogen at a large-scale using renewables and transport it nationally and internationally for a variety of applications? Therefore, the primary contributions of the present study to addressing the identified knowledge gaps are summarized as follows:

- Systematically and qualitatively assess renewable energy resources, particularly wind resources, bathymetry, and the distribution of salt structures in Eastern Canada to evaluate their potential for large-scale hydrogen production and storage for national/international uses.

- Descriptively examine and compare various potential large-scale energy storage alternatives for implementing LDES solutions in the CER.
- Qualitatively discuss waste heat recovery from different hydrogen production processes for use in diverse applications in the CER.
- Propose potential locations for hydrogen hubs in Eastern Canada based on several key criteria.

2. Study Area Characteristics

Emerging advanced hybrid energy systems, consisting of primary energy production integrated with energy storage facilities, require reliable geostorage solutions. Favourable regional wind conditions, geographic disposition, and geological strata can support large-scale green hydrogen production projects in the CER. Massive renewable energy resources—particularly wind energy—are available in this region, creating opportunities for energy storage and the utilization of low-grade heat to enhance the value of hydrogen production, storage, and transportation.

Canada's Atlantic Provinces—Newfoundland and Labrador (NL), Nova Scotia (NS), New Brunswick (NB), and PEI—together with the Province of Québec (QC), shown in Figure 1, are appropriately positioned for hydrogen production and transportation at a national/international scale. The Gulf of St. Lawrence and the Canadian Atlantic coastlines possess some of the best year-round wind conditions in Canada (Figure 2) [22,23], along with an extensive shallow littoral or continental shelf suitable for large offshore wind turbine arrays, direct access to national/international shipping routes, strong electric grid connectivity, and vast subsurface hydrogen storage potential in salt deposits.



Figure 1. Map illustrating the Eastern part of Canada. The red dotted line indicates the boundary of Eastern Canada.

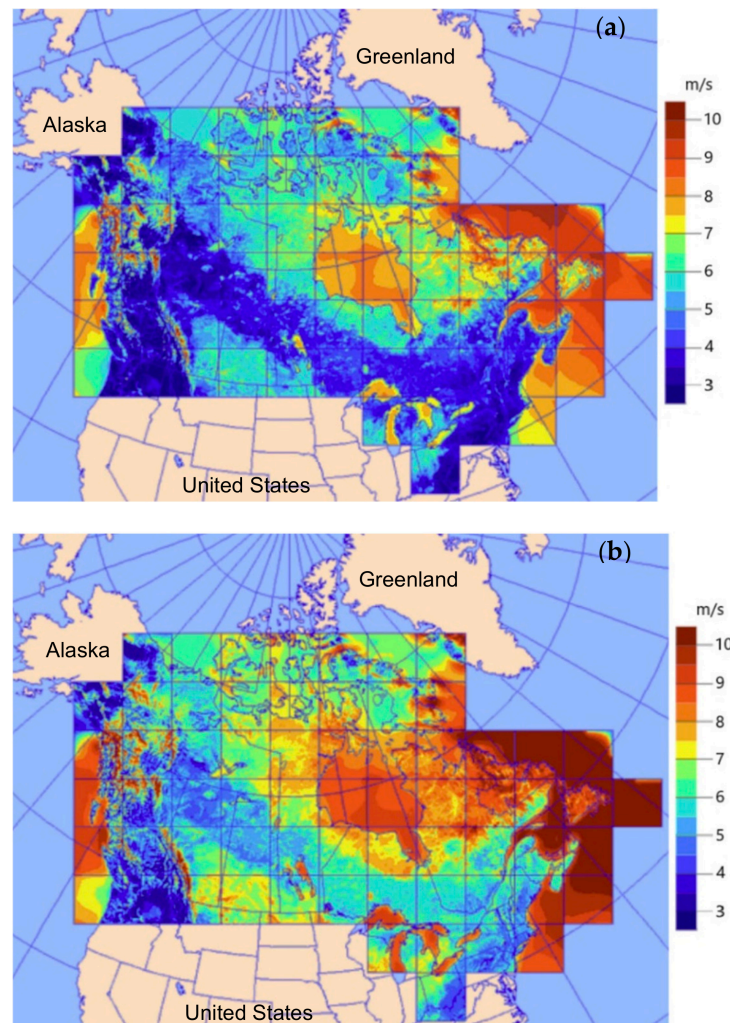


Figure 2. Yearly average wind speed at altitudes of (a) 30 m and (b) 80 m above ground level in Canada (modified from [24]). These two maps are used only as preliminary regional indicators.

Electric power grids in the CER, which still partially rely on fossil fuels for electricity generation—mainly in NS (~70%), NB (~32%), and NL (~2.6%)—are gradually decarbonizing through the integration of renewable energy resources and increasing electrification demands, particularly from the transportation sector. Table 1 presents the contribution of various energy sources to electricity generation in the CER in 2023 as an example.

Table 1. Different energy sources for electricity generation in the CER in 2023 (data extracted from [25]). Here, “Other” includes categories that are not listed.

Province	Petroleum	Coal	Natural Gas	Nuclear	Hydro	Wind	Solar	Biomass	Other
NB	7.2%	9.3%	15.2%	34.2%	25.5%	4.8%	<0.1%	3.8%	-
NL	2.0%	-	0.6%	-	97.0%	0.4%	<0.1%	<0.1%	-
NS	8.3%	40.2%	21.3%	-	10.7%	15.2%	1.1%	3.2%	-
PEI	0.8%	-	-	-	-	82.9%	3.0%	0.6%	*
QC	0.2%	-	<0.1%	-	93.9%	5.0%	<0.1%	0.7%	<0.1%

* In PEI, wind, solar, and biomass sources account for ~86.5% of on-island electricity generation. This province is also an electricity importer, meeting ~70% of its 2023 electricity demand through submarine cables from NB [26].

3. Methodology

This study is based on a qualitative and descriptive but systematic approach. The assessment procedure used in this study for the CER is as follows:

- Describe the characteristics of the study area (Eastern Canada), such as wind conditions, geographical characteristics, salt deposits with potential structures for developing storage caverns through dissolution, and the contribution of different energy sources to electricity generation in 2023 (as an illustrative example).
- Qualitatively identify the rationale for developing renewable hydrogen in Eastern Canada, specifically in the Gulf of St. Lawrence and Atlantic littoral regions, by synthesizing wind profiles, bathymetric data, and salt characteristics.
- Qualitatively assess the potential for recovering low-grade waste heat from hydrogen-related processes, such as electrolysis, compression, liquefaction, and conversion, for use in diverse applications.
- Qualitatively, and to a limited extent quantitatively, examine hydrogen storage in solution-mined salt caverns considering various parameters at a large scale in the CER, specifically within the salt structures of the Gulf of St. Lawrence.
- Qualitatively assess the potential risks, environmental issues, sustainability considerations, and environmental regulations associated with large-scale hydrogen storage in caverns created in salt structures.
- Qualitatively evaluate the relationship between wind power and large-scale hydrogen production, as well as between large-scale hydrogen geostorage and CAES, to support LDES applications.
- Identify the key criteria for proposing potential locations for hydrogen hubs in the CER.

4. Siting Renewable Hydrogen Production in Canada

In March 2024, Canada signed a “Memorandum of Understanding” [27] to advance the 2022 “Joint Declaration of Intent” with Germany to foster green hydrogen development to meet German needs [28]. It is anticipated that such large-scale hydrogen production will also provide energy storage services to many other nations as an international hydrogen supply chain emerges. Given the significant seasonal variation in solar energy availability in Canada, the limited geographical applicability of tidal energy, and the current relatively advanced development of hydroelectric power facilities, wind energy represents a particularly promising option for advancing a green hydrogen industry capable of producing, storing, and distributing large amounts of carbon-free energy in the form of hydrogen (H_2) or hydrogen-derived molecules (e.g., NH_3 and CH_4).

In Canada, the use of solar energy must contend with its counter-cyclical nature: during winter, solar radiation is weakest when energy demand is highest. Additionally, in many coastal regions of Canada (e.g., the Atlantic Provinces), fall and winter months experience the greatest cloud cover, further amplifying the counter-cyclical challenge associated with solar energy generation.

Wind is the other viable renewable energy option, and the development of wind power requires optimal siting for an integrated, large-scale wind-to-hydrogen energy production and storage economy. The Gulf of St. Lawrence and Atlantic littoral regions represent some of the most favourable areas in Canada for national-/international-scale green hydrogen generation for the following reasons:

- The average wind profile is among the best in Canada.
- Maximum wind velocities are generally lower in the Gulf of St. Lawrence than along the open Atlantic coast, resulting in reduced wind curtailment while still maintaining a remarkable annual wind profile.

- Wave heights in the Gulf of St. Lawrence are generally more moderate than those along the open Atlantic littoral, which may positively influence siting decisions.
- Extensive littoral areas have water depths of less than 40 m, particularly in the south-western portion of the Gulf of St. Lawrence.
- No iceberg risk exists in these areas, although winter surface drift ice remains an operational issue in the Gulf of St. Lawrence.
- Diapiric salt structures suitable for product (e.g., hydrogen and other molecules) and energy storage, such as CAES, are available both onshore and offshore.
- Direct marine access exists for national/international product transshipment.
- Direct access to the St. Lawrence Seaway is available, providing access to a serviced population exceeding 100 million people and enabling bulk product distribution as far west as Duluth, Minnesota, in the US.
- A highly skilled human infrastructure exists with companies, technologists, and engineers available in the Atlantic Provinces because of the established offshore oil and gas industry.
- Strong connectivity exists to the regionally integrated North American Eastern Inter-connection grid and the adjacent Québec power grid.
- Supportive LDES capacity exists through hydroelectric dams in QC and NL, enhancing grid stability and ensuring a reliable green energy supply to both the electrical grid and industrial sectors.

Of particular interest are the littoral regions surrounding Îles de la Madeleine and PEI, which have open exposure to the prevailing northwesterly winds. In these regions, several thousand square kilometres of offshore areas have water depths of less than 40 m (Figure 3). These conditions facilitate the installation of multiple offshore wind turbine projects in areas that do not interfere with heavily travelled shipping lanes in the Gulf of St. Lawrence, while also avoiding the more severe Atlantic storms and wave conditions—should these become development constraints. Similar favourable locations within the Gulf may also exist off the west coast of Newfoundland and within the Northumberland Strait between PEI and NS.



Figure 3. Bathymetry of the Gulf of St. Lawrence (modified from [29,30]).

As an example, the average wind profile at an altitude of 10 m above ground level for the Îles de la Madeleine airport, located in the Magdalen Islands, QC, is shown in Figure 4. The Îles de la Madeleine are centrally situated within the Gulf and are relatively low-lying; therefore, offshore wind turbines located around the islands can capture high-quality wind from any direction with minimal ground-effect turbulence. Although commercial wind turbine designs vary, electric power generation generally begins at wind speeds of $\sim 2.5\text{--}5\text{ m/s}$, reaches rated capacity at $\sim 10\text{--}15\text{ m/s}$, and maintains full rated output until the cut-off wind speed, which typically ranges from 20 to 30 m/s (commonly $\sim 25\text{ m/s}$), at which point turbines shut down for safety reasons [31]. Analysis of meteorological data indicates that strong winter winds are co-cyclical with regional energy demand, meaning that greater wind energy is available during periods of highest energy consumption.

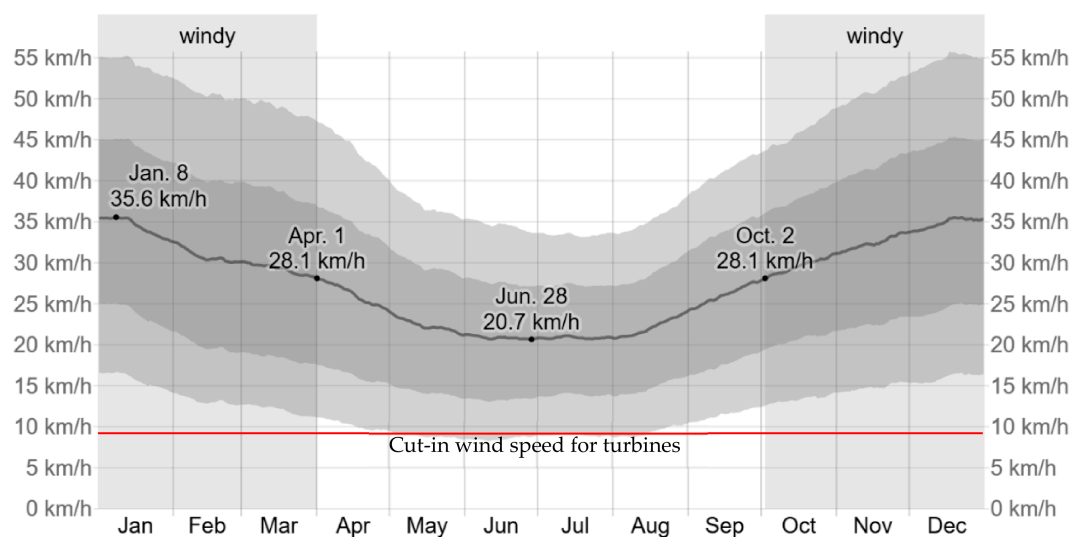


Figure 4. Average wind profile at an altitude of 10 m above ground level measured at the Îles-de-la-Madeleine Airport in the Magdalen Islands, QC, Canada [32]. This wind profile is utilized only as a preliminary regional indicator.

The islands are underlain by significant Paleozoic salt dome structures in which caverns capable of providing substantial storage capacity can be developed. These structures are highly valuable not only as secure pressurized storage sites for hydrogen and derivative products, but also for CAES systems that can help accommodate large inputs of green wind power into the regional electrical grid. The Atlantic littoral also possesses significant wind power potential; however, severe storms and large waves may constrain turbine placement and design. Note that not all salt is created “equal,” and subsurface characterization is required and is discussed below.

5. Heat Losses

Electrolysis for hydrogen production will take place in onshore facilities, and the locations of these facilities may improve overall project efficiency. The energy required to break the bonds in $2\cdot(\text{H-O-H})$ into $2\cdot\text{H}_2 + \text{O}_2$ is reasonably well understood, and conversion efficiency is generally $\sim 75\%$; the energy losses are primarily released as low-grade heat from the electrolyzers, while the stored energy is retained in the form of H_2 [33]. If hydrogen is stored and shipped, it must be compressed and possibly liquefied for marine transport, resulting in the generation of additional large quantities of low-grade heat. If hydrogen is converted into more easily transported energy carriers (e.g., NH_3 , CH_4 , CH_3OH , and C_6H_{12}), further energy losses will occur during the conversion processes. It should also be noted that safety considerations related to hydrogen embrittlement, storage, transportation,

and operational activities, plus infrastructure reliability, must be carefully addressed to minimize potential hazards, equipment failures, and environmental risks.

Hydrogen production and transshipment facilities can be positioned near urban centres, industrial sites, and ports to take advantage of the available low-grade heat. As a simple example, locating such facilities near dimensional lumber or pulp-and-paper manufacturing sites would allow large quantities of low-grade heat to be utilized for kiln drying and industrial process heating.

For the overall hydrogen production and shipping process, low-grade heat losses likely account for between 30% and 50% of the electrical energy input [34], depending on the type of electrolysis used, whether hydrogen compression to ~20 MPa is required, whether liquefaction to cryogenic conditions is needed, and whether additional molecular conversion processes are employed. Some of this heat could potentially be utilized to generate electricity through an Organic Rankine Cycle (ORC) system, particularly the heat generated during compression, which may reach sufficiently high temperatures (e.g., >200 °C) to make ORC technology economically viable. However, ORC efficiency strongly depends on the temperature of the waste heat recovered from the compression process, and additional capital expenditures are associated with heat exchangers and the development of ORC systems.

The subject of improving efficiency through the planned co-use of waste heat has received increasing attention and has been well addressed in the recent literature, for example, in [35]. If electrolysis, compression, and conversion processes are located near larger urban centres, for example, Saint John, NB, or Halifax, NS, obvious applications for waste heat include district heating and various industrial processes. In rural settings, greenhouse operations require heating and drying, as well as electrical energy for lighting and ventilation systems. In cold climates, greenhouse operations during winter and shoulder seasons may require an approximate electrical-to-thermal energy ratio of 1:4; however, during summer, the demand for heating becomes minimal unless substantial product dehydration activities are undertaken. Seasonal variations consistently present challenges related to energy availability, storage, and utilization. Careful assessment of these issues can lead to system designs that reduce the impacts of weather-related seasonality.

Co-generation of electrical power using ORC technology may provide additional value; because CAES systems are required to integrate large-scale variable wind power into the electrical grid, further benefits may be achieved by utilizing waste heat in CAES expansion systems for electricity generation. CAES expansion turbines require heating of the air input to prevent icing during expansion stages, and nearby heat sources, potentially combined with thermal energy storage technologies, may enable additional electricity generation. Similar opportunities for the utilization of low-grade heat exist in many other applications, including nuclear power plants, combined-cycle natural gas power plants, and diesel-electric power systems, where exhaust heat can provide substantial value, particularly in remote cold-climate regions. The seasonal nature of thermal energy demand is characteristic of Canadian energy systems, and this cyclic behaviour presents challenges in identifying effective and efficient applications for low-grade thermal energy.

6. Hydrogen Storage Scale

Storing hydrogen in solution-mined caverns within the salt structures of the Gulf of St. Lawrence is necessary for large-scale accumulation, process supply, and product shipment. Assuming a cavern depth of 1000–1200 m, the maximum and minimum storage pressures are estimated at ~20 MPa and ~5 MPa [36,37], respectively. The actual operating pressures and injection rates depend on stability analysis involving cavern geometry, roof span, depth to the top of the cavern, potential for salt creep, and the risk of fracturing or breaching the

cavern walls due to over-pressurization. The maximum allowable pressure is generally a governmental regulatory issue and is typically limited to ~80% to ~85% of the least principal in situ stress at the top of the cavern [38], a value that must be measured by the project proponent. The minimum operating pressure depends on geomechanical analyses intended to ensure the long-term stability of the cavern with minimal salt sloughing and no risk of upward roof caving. This requires careful selection of the maximum probable cavern diameter and an optimal roof geometry generated during the solution-mining process.

Figure 5 exhibits the distribution of Paleozoic and Mesozoic onshore and offshore subsurface salt deposits in the CER. Figure 6 schematically illustrates a simplified solution-mined cavern for gas storage (e.g., hydrogen or compressed-air). Past and present subsurface extraction of salt through conventional mining (e.g., Malagash and Pugwash) and solution mining (e.g., Amherst) provide data on the characteristics and properties of salt deposits. For example, based on studies of the depths of salt structures formed from salt deposits in and around the Magdalen Islands in the Gulf of St. Lawrence, these salt structures have been identified at depths ranging from ~30 m to ~1000 m [39].

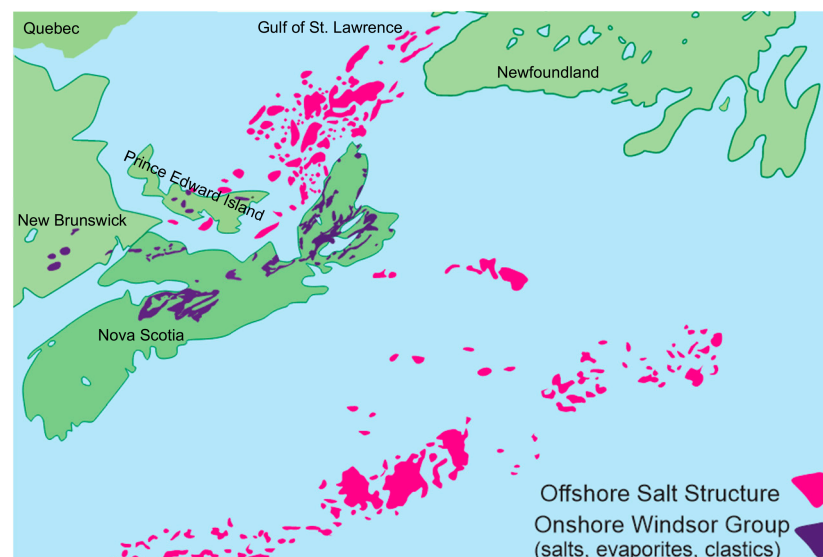


Figure 5. Subsurface salt structures of Paleozoic and Mesozoic age, onshore and offshore in the CER.

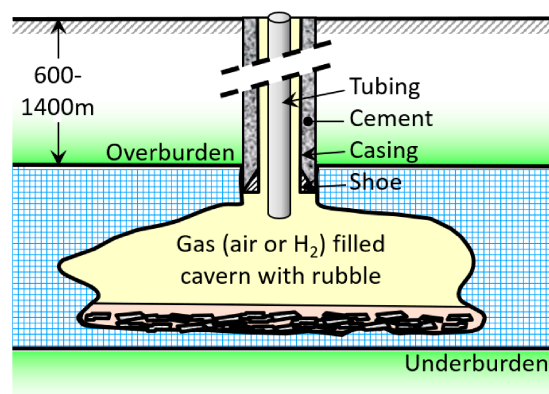


Figure 6. Schematic illustration of a simplified solution-mined cavern for storing gas.

Consider, as an illustrative example, one cubic metre of cavern storage volume at a temperature of 20 °C (293.15 K). To determine the effective working density of hydrogen in

a 1 m³ cavern operating between pressures of 5 MPa and 20 MPa, the real-gas equation, which accounts for compressibility at elevated pressures, is used [40]:

$$\rho = \frac{P}{Z \cdot R_{spec} \cdot T} \quad (1)$$

where ρ is the density, P is the pressure, T is the temperature (in Kelvin), Z is the compressibility factor which accounts for deviations from ideal-gas behaviour and is defined as the ratio of real volume of the gas at specified pressure and temperature to ideal volume of the gas at specified pressure and temperature [41]—and R_{spec} is the specific gas constant, which is given by

$$R_{spec} = \frac{R}{M} \quad (2)$$

where R is the universal gas constant (8.314 J/mol·K) and M is the molar mass of gas (2.016 × 10^{−3} kg/mol for hydrogen). Therefore,

$$R_{spec} = \frac{8.314}{2.016 \times 10^{-3}} = 4124 \text{ J/kg·K}$$

At elevated pressures, hydrogen exhibits real-gas behaviour and becomes less compressible than predicted by the ideal-gas law, resulting in compressibility factors greater than unity ($Z > 1$). At 20 °C, the compressibility factors (Z) at 5 MPa and 20 MPa are estimated to be 1.031 and 1.116 [42], respectively.

Using Equation (1), the hydrogen densities at the two operating pressures are

$$P = 5 \text{ MPa: } \rho = \frac{5 \times 10^6}{1.031 \times 4124 \times 293.15} \approx 4.02 \text{ kg/m}^3$$

$$P = 20 \text{ MPa: } \rho = \frac{20 \times 10^6}{1.116 \times 4124 \times 293.15} \approx 14.82 \text{ kg/m}^3$$

The effective working density ($\Delta\rho$) of hydrogen is then calculated as

$$\Delta\rho = \rho_{at \ 20 \text{ MPa}} - \rho_{at \ 5 \text{ MPa}} \quad (3)$$

Thus,

$$\Delta\rho = 14.82 - 4.02 = 10.8 \text{ kg/m}^3 \approx 11 \text{ kg/m}^3$$

Therefore, the effective working density of hydrogen is ~11 kg/m³ of cavern storage volume when operating between 5 MPa and 20 MPa.

For example, for a cavern with an operational storage volume of ~10⁶ m³, the usable hydrogen that can be stored and withdrawn for shipment or industrial use can be determined by

$$m_{working} = \Delta\rho_{working} \cdot V_{storage} \quad (4)$$

Thus,

$$m_{working} \approx 11 \times 10^6 \approx 11,000 \text{ tonnes}$$

This storage scale can be compared with the carrying capacity of marine hydrogen transport vessels. For a cryogenic liquid hydrogen carrier operating at ~20 K and near atmospheric pressure, the density of liquid hydrogen is ~71 kg/m³. A large-scale carrier, for example, may have a storage capacity of ~200,000 m³. Hence, using Equation (4), a single shipment could transport ~14,200 tonnes of hydrogen. The required underground

hydrogen storage volume for operation between pressure limits of 20 and 5 MPa can be calculated as

$$V_{cavern} = \frac{m_{carrier}}{\Delta\rho_{working}} \quad (5)$$

Therefore,

$$V_{cavern} = \frac{\sim 14.2 \times 10^6}{\sim 11} \approx 1.3 \times 10^6 \text{ m}^3$$

The rate at which this volume of hydrogen can be produced depends on the output capacity of electrolyzers. Additional electrical power is also required for staged hydrogen compression and liquefaction to cryogenic temperatures, processes that generate substantial quantities of waste heat.

The design of wind turbine arrays and electrolyzer systems determines the filling rate of the storage caverns, including engineering constraints and economic considerations associated with operational downtime and risk management. As underground storage capacity can substantially exceed cooling and shipping capacities, a built-in storage buffer can be developed to mitigate the impacts of prolonged operational interruptions at relatively low additional cost. It is likely that at least two caverns, each with a sufficiently large storage volume, are required. From a facility risk-management perspective, two sufficiently large caverns are generally preferable to a single larger cavern. For larger hydrogen production facilities, the number of storage caverns can be increased to accommodate strategic hydrogen reserves. It is important to note that salt deposits are not uniform in their geological and geomechanical characteristics. Therefore, detailed characterization, site-specific analyses, and comprehensive risk assessments of promising salt formations are essential for evaluating their integrity, long-term stability, and suitability for hydrogen geostorage while also addressing potential environmental risks and sustainability considerations.

Several potential risks must be considered when evaluating salt deposits with structures for hydrogen storage, including hydrogen reactivity with impurities and residual minerals, salt movement or creep closure rates, microbial activity, and caprock integrity. Additionally, hydrogen leakage through existing fractures, faults, or improperly sealed wells can compromise storage efficiency and raise environmental and safety concerns [43]. Geomechanical changes resulting from cyclic hydrogen injection and withdrawal can alter stress distributions within the storage salt deposits and surrounding rock mass, potentially affecting cavern stability [44]. Uncertainties associated with the long-term behaviour of hydrogen under subsurface conditions, including its interactions with geological materials and microorganisms, also require careful investigation [45]. Furthermore, variations in temperature and pressure during storage operations may influence cavern integrity and storage capacity over time. Consequently, detailed geological, geochemical, and geomechanical studies, supported by monitoring and risk management strategies, are required before large-scale hydrogen geostorage projects can be implemented safely and effectively.

Regulatory and environmental issues must also be carefully considered, including brine disposal, impacts on marine ecosystems, hazards of groundwater contamination, and challenges related to offshore infrastructure deployment. The disposal of large volumes of concentrated brine produced during solution mining and its uncontrolled discharge can increase local salinity, alter seawater chemistry, and adversely affect benthic organisms and other sensitive marine ecosystems [46]. Therefore, environmentally responsible brine management strategies, including controlled discharge in accordance with environmental regulations or recovery of commercial salt products through evaporation and processing, should be considered to minimize environmental impacts and improve resource utilization. Offshore construction and operational activities may also disturb marine ecosystems through seabed excavation, sediment resuspension, underwater noise generated during

drilling and installation, and temporary habitat modification, all of which require appropriate mitigation measures and environmental monitoring [47].

Groundwater protection is another critical consideration. Although salt caverns are typically located a few hundred metres below potable aquifers and are separated by low-permeability geological formations, maintaining well integrity throughout the project life cycle is essential to prevent unintended hydrogen migration or brine leakage [48]. Consequently, comprehensive site characterization, well integrity testing, continuous pressure and groundwater monitoring, and risk-based environmental management plans should be implemented before and during operation. Furthermore, offshore hydrogen geostorage projects must comply with national and international environmental regulations governing offshore resource development, marine environmental protection, and subsurface energy storage. Accordingly, comprehensive environmental impact assessments, long-term environmental monitoring programs, emergency response plans, and stakeholder engagement should be incorporated into project development to ensure environmental protection and sustainability, regulatory compliance, and public acceptance of offshore hydrogen storage facilities.

7. Wind Energy Storage

Electrolysis requires a stable direct current supply, whereas wind power is inherently intermittent and variable. Therefore, two factors are essential for large-scale hydrogen production: extensive grid interconnections and large-scale energy storage, particularly LDES. Connection to a large electrical grid allows excess wind-generated electricity beyond the stable operating requirements of electrolyzers to be dispatched to other consumers, while also enabling the grid to compensate for temporary shortfalls in wind power generation when needed. The greater the transmission and interconnection capacity, the stronger the stabilizing effect on wind power integration. However, energy storage is also required to ensure a stable long-term electricity supply for electrolysis, particularly when hydrogen production demand represents a substantial fraction of grid capacity (e.g., higher than 10%) and when the penetration of wind energy into the grid becomes significant (e.g., over 30–40%). Potential storage options include hydrogen to fuel turbines or fuel cells, pumped hydro, batteries, and CAES. Among these options, CAES is argued here to be the most suitable solution for large-scale LDES applications in Eastern Canada.

It should be noted that, in practical operation, grid-forming power electronic converters, fast-response ESSs, and grid ancillary services are expected to collectively support frequency regulation, transient stability, and real-time load balancing within integrated onshore and offshore wind-electrolyzer systems. Grid-forming converters can provide synthetic inertia and voltage support, thereby enhancing dynamic stability under high penetration of inverter-based resources. Fast-acting ESSs can absorb short-term fluctuations in wind power output and smooth rapid variations in electrolyzer demand, ensuring continuous and stable operation. Additionally, participation in ancillary service markets and coordinated control strategies at the system level enable real-time balancing between generation and demand, reducing curtailment and maintaining grid reliability.

Utilizing a portion of the produced hydrogen for grid stabilization is technically feasible; however, because hydrogen and hydrogen-derived products are expected to have substantial economic value, consuming them to stabilize grid demand may not be the most efficient approach. Direct storage of renewable energy is generally more efficient. Moreover, ESSs allows the intermittent portion of wind power generation to be captured and stored for later release as stable, conditioned alternating current (AC) electricity.

Implementation of pumped hydro storage at the gigawatt scale for extended durations (e.g., 16 h at rated output or longer at partial load) will require either modification of existing

hydroelectric facilities to accommodate pumped storage operations or the development of new greenfield projects involving hydro reservoir construction. The latter option may be difficult to implement in NS, NB, and PEI because of geographical, environmental, and social considerations. Modification of existing facilities may be more feasible if the electrical grids of the Atlantic Provinces and QC become more strongly integrated. The extensive hydro reservoirs within the Manicouagan and Duplessis hydro development watersheds in eastern QC, north of the St. Lawrence Estuary, may offer opportunities for large-scale pumped hydro storage integration. However, significant challenges remain, including transmission distances, infrastructure costs, jurisdictional considerations, and grid management complexities. Consequently, pumped hydro storage alone is unlikely to provide sufficient energy storage capacity for an international-scale hydrogen production and export industry.

BESSs are most suitable for rapid response applications and short-duration energy storage over periods up to several hours. However, the high cost of batteries on a per-MWh basis limits their suitability for LDES applications. Additionally, concerns related to critical mineral supply chains, environmental impacts, fire hazards, security risks, and end-of-life recycling remain important issues. Within an integrated grid system, batteries play an essential role in providing fast demand-response services; however, they lack stabilizing rotational inertia and are less suitable for large-scale LDES applications.

The parallel development of additional underground caverns for CAES during periods of excess wind power generation represents one of the most promising approaches for achieving the massive storage capacities required. Such storage capacity would not only support the hydrogen industry but would also smooth renewable energy variability and stabilize long-duration electricity supply, thereby facilitating grid decarbonization. This capability would support the retirement of coal-fired power plants and reduce reliance on natural gas power generation for balancing supply-demand fluctuations.

As an example, a CAES cavern with a constant operational volume of $\sim 10^6 \text{ m}^3$ operating between pressure limits of 5 MPa and 20 MPa can theoretically store on the order of 5–10 GWh of energy, depending on the thermodynamic assumptions and overall system efficiency. If the air is assumed to remain at a constant temperature (i.e., an isothermal process), the work (W_{iso}) associated with expansion from 20 MPa to 5 MPa can be computed as

$$W_{iso} = P_{max} V \ln \left(\frac{P_{max}}{P_{min}} \right) \quad (6)$$

Thus,

$$W_{iso} = (20 \times 10^6) (10^6) \ln \left(\frac{20 \times 10^6}{5 \times 10^6} \right) \approx 2.8 \times 10^{13} \text{ J} \approx 7.8 \text{ GWh}$$

The above value represents the ideal isothermal expansion work. To determine the actual electrical energy that can be delivered, several factors, including turbomachinery efficiency, heat transfer limitations, pressure losses, and other system losses, must be considered.

A typical salt deposit can accommodate multiple caverns within salt diapirs and salt sheets, including combinations of hydrogen storage caverns and CAES caverns. Where diapiric salt structures are favourable, vertical caverns can be developed through dissolution; alternatively, modern horizontal drilling and solution-mining technologies can enable the construction of elongated horizontal caverns within bedded salt deposits. Horizontal galleries offer several advantages for both hydrogen and CAES applications because large working volumes can be achieved with smaller cavern diameters, thereby enhancing geomechanical stability.

For example, a horizontal gallery ~1000 m in length (L) and 35–40 m in diameter (D) can provide an operational storage volume on the order of 10^6 m^3 , based on the following calculation:

$$V_{\text{gallery}} = \frac{\pi D^2}{4} L \quad (7)$$

$$\text{For } D = 35 \text{ m : } V_{\text{gallery},35} = \frac{\pi(35)^2}{4} 1000 \approx 0.96 \times 10^6 \text{ m}^3$$

$$\text{For } D = 40 \text{ m : } V_{\text{gallery},40} = \frac{\pi(40)^2}{4} 1000 \approx 1.26 \times 10^6 \text{ m}^3$$

Thus,

$$V_{\text{gallery}} \approx (0.96 \text{ to } 1.26) \times 10^6 \text{ m}^3 \approx 10^6 \text{ m}^3$$

Such caverns could potentially be spaced laterally at intervals of 100–125 m. The approximate number of caverns per square kilometer (N) are

$$\text{For } 100 \text{ m : } N = 10 \text{ caverns/km}^2 \Rightarrow V_{\text{km}^2} = 10(10^6) = 10^7 \text{ m}^3/\text{km}^2$$

$$\text{For } 125 \text{ m : } N = 6.4 \text{ caverns/km}^2 \Rightarrow V_{\text{km}^2} = 6.4(10^6) = 0.64 \times 10^7 \text{ m}^3/\text{km}^2$$

Thus, the potential storage capacity could approach $\sim 10^7 \text{ m}^3$ per square kilometer. For CAES applications, using Equation (6) and assuming a constant cavern volume and ideal isothermal expansion from 20 MPa to 5 MPa, this storage volume could theoretically provide ~77 GWh per square kilometer of expansion work. The actual electrical energy that can be delivered would depend on operating conditions and the overall system efficiency.

Estimated costs per MWh of energy storage for CAES systems developed in solution-mined salt caverns are generally lower than those for BESSs [49], although some batteries remain necessary in integrated grids for short-term response and demand-smoothing services. As an overall economic comparison, CAES can provide lower capital expenditure per unit of stored energy as well as lower levelized storage expenses than BESSs for large-scale, long-duration applications, mainly because the storage capacity is provided using relatively low-cost and long-life underground caverns [50,51]. However, the economic viability of CAES is highly site-specific and depends on factors such as geological conditions (e.g., the depth, thickness, purity, and geomechanical suitability of salt formation), cavern development costs, and system configuration, which directly affect infrastructure costs. In addition, conventional CAES systems may require supplementary heat sources, often natural gas, whereas advanced adiabatic CAES designs incorporate thermal energy storage to improve efficiency and reduce emissions. Nevertheless, the deployment of CAES is geographically constrained to regions with suitable subsurface geological formations [52,53].

CAES is particularly well-suited for LDES applications, and the number, size, and location of caverns required must ultimately be determined through detailed analyses of energy system deployment (e.g., wind turbines), meteorological conditions, project scale, and grid requirements. Generally, the round-trip efficiency of CAES systems ranges from ~40% to ~70% [54], depending on the system design and the extent of thermal energy recovery. Conventional diabatic CAES systems typically exhibit lower round-trip efficiencies (about 40–55%) because a significant portion of the compression heat is lost and external fuel is required during expansion [55]. In contrast, advanced adiabatic CAES systems can achieve efficiencies of up to ~70% through the recovery and reuse of compression heat [56]. Although CAES has lower round-trip efficiencies than pumped hydro and BESSs, it offers significant advantages for large-scale LDES owing to its relatively low energy storage costs, its capacity to store substantial amounts of energy in suitable

geological formations, its security against sabotage or vandalism, its fire safety, and its minimal need for critical minerals and metals.

Finally, large-scale CAES not only stabilizes electricity supply to electrolyzers but also contributes rotational inertia and frequency regulation support to the electrical grid. This capability would facilitate greater penetration of renewable energy into the grid, thereby supporting the final stages of electricity-sector decarbonization in the Atlantic Provinces and in neighbouring electricity markets receiving stabilized renewable power exports.

Figure 7 depicts the proposed hydrogen hubs in Eastern Canada. These potential hub locations were identified based on several key criteria, including proximity to transportation networks and existing infrastructure, proximity to potential hydrogen consumers, access to deep-water ports, and the availability of suitable geological storage sites, such as depleted/abandoned hydrocarbon reservoirs and salt formations. These criteria were selected through multifaceted investigations to minimize associated costs and risks and ensure compliance with applicable regulations.

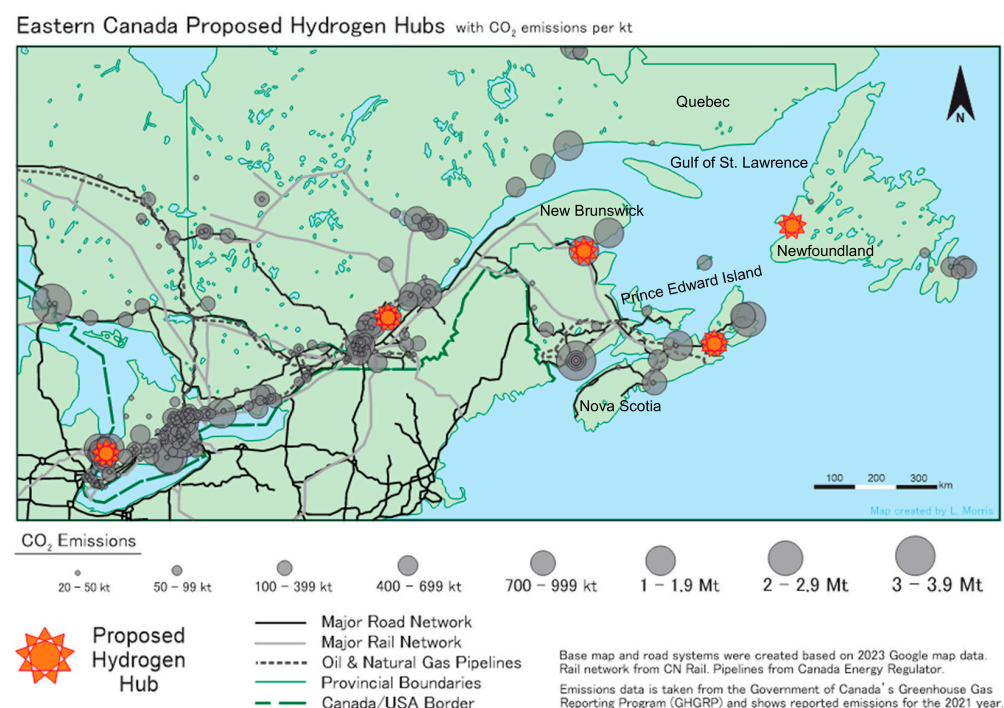


Figure 7. Proposed hydrogen hubs in Eastern Canada (modified from [57]).

8. Conclusions and Future Research Prospects

In this study, the use of geostorage solutions for large-scale energy storage in Eastern Canada was qualitatively but systematically assessed, considering the region's significant wind energy potential, extensive subsurface salt structures, and ice-free deep-water ports that can support the renewables-to-hydrogen industry. The primary outcomes of this qualitative assessment are summarized as follows:

- The four Atlantic Provinces and Québec are suitably positioned for national/international-scale hydrogen production, potentially at a large scale. The Gulf of St. Lawrence and Atlantic continental margin possess some of the best year-round wind resources in Canada, extensive shallow littoral zones suitable for large offshore wind turbine arrays, direct access to national/international shipping routes, strong grid connectivity, and relatively substantial subsurface hydrogen storage potential within extensive salt deposits.

- Salt cavern storage of compressed air can provide operational stability not only for electrolyzer arrays but also for the regional electrical grid, thereby supporting further grid decarbonization as an additional benefit of the hydrogen industry.
- Electrolysis, hydrogen compression, and chemical conversion processes can generate substantial quantities of waste heat. Locating hydrogen production facilities near urban centres can provide opportunities for district heating, greenhouse operations, and various industrial applications. Such integration can improve overall system efficiency while reducing the use of fossil fuels, thereby lowering air pollution and atmospheric CO₂ emissions.
- Relatively strong electrical grid interconnections, a highly educated workforce with extensive marine technology experience, deep-water port facilities, and direct ocean access are available throughout the region.
- Interprovincial planning and federal government coordination will be necessary to fully develop these promising regional advantages in support of Canadian and international emissions-reduction targets. Hydrogen can serve not only as a clean fuel and energy carrier but also as carbon-free feedstock for many industrial processes, the least of which is green ammonia for global agricultural applications.

This qualitative study contributes to a better understanding of large-scale hydrogen production using renewable energy sources, particularly wind energy, together with geo-storage technologies for large-scale energy storage. These hybrid systems can help reduce fossil fuel consumption while supporting long-term decarbonization and sustainability goals.

The following future studies are proposed:

- Model and analyze salt structures to develop cavern scenarios in Eastern Canada and to establish the techno-economic and environmental performance and effectiveness.
- Conduct a detailed evaluation of the geological, geochemical, and geomechanical characteristics of the selected salt caverns.
- Assess the life-cycle impacts and potentially critical risks associated with a selected salt cavern location in the Gulf of St. Lawrence region, perhaps one onshore and one offshore.

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Abbreviations

bcm	billion cubic metres
BESSs	Battery Energy Storage Systems

CAES	Compressed-Air Energy Storage
CER	Canadian Eastern Region
ESSs	Energy Storage Systems
EV	Electric Vehicle
LDES	Long-Duration Energy Storage
NB	New Brunswick
NL	Newfoundland and Labrador
NS	Nova Scotia
ORC	Organic Rankine Cycle
PEI	Prince Edward Island
QC	Québec
SDGs	Sustainable Development Goals

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