Technical and Economic Potential Assessment of Pumped Storage Hydropower in Canada

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WATERPOWER CANADA

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Stantec

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GLOSSARY OF TERMS

Energy Capacity is the cumulative capacity to produce electricity over a given period of one year in terawatt-hours (TWh p.a.) of a group of power generating assets.

Feasibility Factors are the factors that would impact whether or not a project could be developed, including technical; economic; environmental; and social considerations. Details are covered in Section 4.2 Feasibility Factors.

Power Capacity is the cumulative installed capacity in gigawatts (GW) of a group of power generating assets.

Realistic Potential is the possible power and energy capacity of a group of power generating assets once feasibility factors have been considered.

Theoretical Potential is the possible power and energy capacity of a group of power generating assets without considering feasibility factors.

Units of Measure for Capacity and Energy Note that megawatts (MW) capacity or gigawatt-hours (GWh) energy storage are used as unit of measure for individual plants while the thousand times larger GW or TWh are generally used for provincial or national cumulative statistics.

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EXECUTIVE SUMMARY

WaterPower Canada is the national trade association for the hydroelectricity industry representing almost 85 GW of renewable electricity generation. In response to the Canadian federal government's commitment to achieving a net-zero emissions electricity supply by 2035 and a net-zero economy by 2050, WaterPower Canada is commissioning this research project on Pumped Storage Hydro (PSH) in Canada.

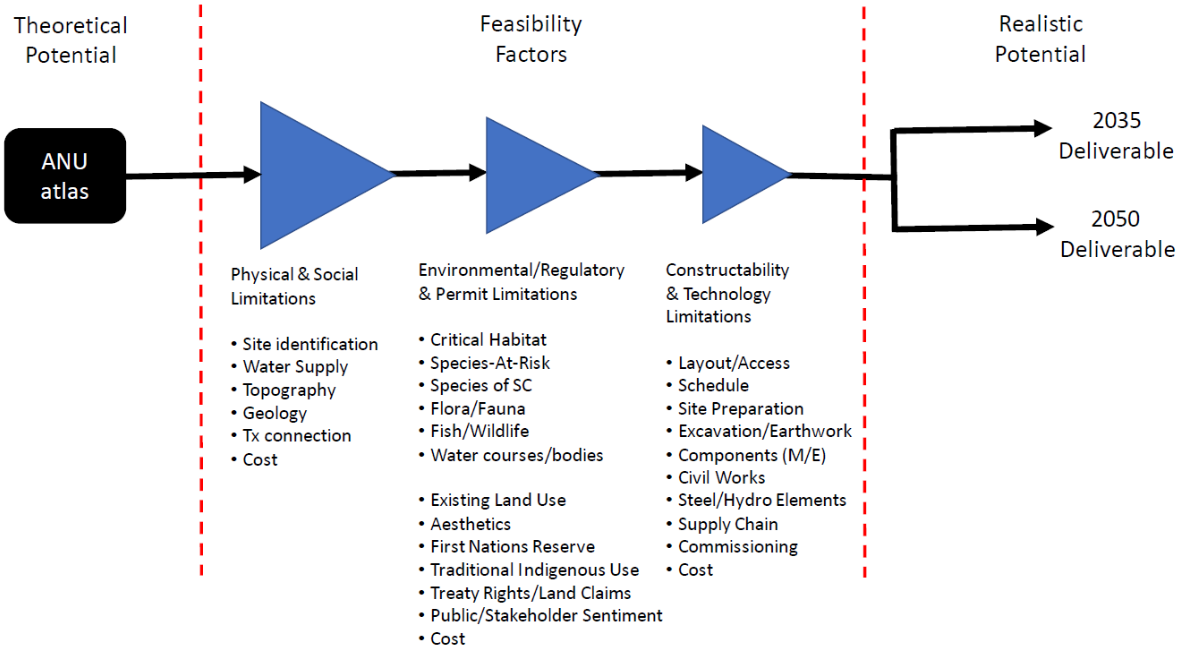
A study alliance was formed and awarded a contract by WaterPower Canada to conduct the assessment of PSH potential in Canada consisting of Stantec as study lead, the Australian National University (ANU), the Centre for Energy Advancement through Technological Innovation (CEATI) and Power Advisory (PA). This study alliance set out to address the overarching objective of the work: To assist WaterPower Canada and the industry to better understand the strategic value of PSH, along with identification of the viable potential for sites where PSH facilities might be considered in the future or are currently under development.

Section 2 provides an introduction to PSH and global historic development perspective, and Section 3 includes a summary list of known PSH projects under development.

In Section 4, the potential for further development of PSH projects is described in detail, and includes the following sequential process used as the study methodology:

- ANU's Global Pumped Hydro Atlas (Appendix B) provides for a structured, consistent, and thorough interrogation of the landscape to identify topographically suitable candidate sites. The results determine the Theoretical Potential.
- Feasibility Factors, which drive cost and the chances of a successful development are used to screen down the set of theoretical candidate sites to those that might reasonably be candidates for actual development. Feasibility Factors, when applied against the identified Theoretical Potential, will yield the Realistic Potential.
- The Realistic Potential in Canada is categorized over two timeframes, development between now and 2035, representing the immediate future and PSH development prior to 2050, representing the longer-term future. To meet the imminent need of the federal Clean Electricity Regulations by 2035, the potential sites described herein are an essential component.

From the onset of the study, the ANU data base of closed-loop sites was deemed the most comprehensive list representing the largest overall potential for PSH sites in Canada. Over 200 TW of Theoretical Potential PSH sites are identified in the atlas. Open-loop sites, sites associated with the Great Lakes and sites that accommodate abandoned mines were not identified to augment this Theoretical Potential, an approach that underestimates the potential, and therefore, is consistent with the overarching objective of the work to provide a conservative PSH potential.



The results of this process are presented in Section 5, confirming the Realistic Potential for Canadian PSH development, including categories of Medium (10% of theoretical sites in blue) and High (1% of sites in green). [1]

	Number of Sites	Total Installed Capacity (MW)	Number of Sites	Total Installed Capacity (MW)
Theoretical Potential	**116,383**	**222,796,251**		
	High		**Medium**	
	1%		**10%**	
Realistic Potential w/o Cost Adjustments	3,385	17,747,889	25,431	88,532,889
Realistic Potential after Transmission Adjustment	2,159	13,827,889	16,890	74,023,500
Realistic Potential after Transmission and Constructability Adjustment	2,073	13,449,944	16,245	71,446,389
Realistic Potential after Transmission, Constructability and Equipment Adjustment	1,168	8,293,333	11,706	61,181,167
Realistic Potential	**1,164**	**8,260,000**	**11,638**	**60,876,889**
By 2035	996	7,069,722	10,121	52,981,000
By 2050	168	1,190,278	1,517	7,895,889
Realistic Potential	**1,164**	**8,260,000**	**11,638**	**60,876,889**

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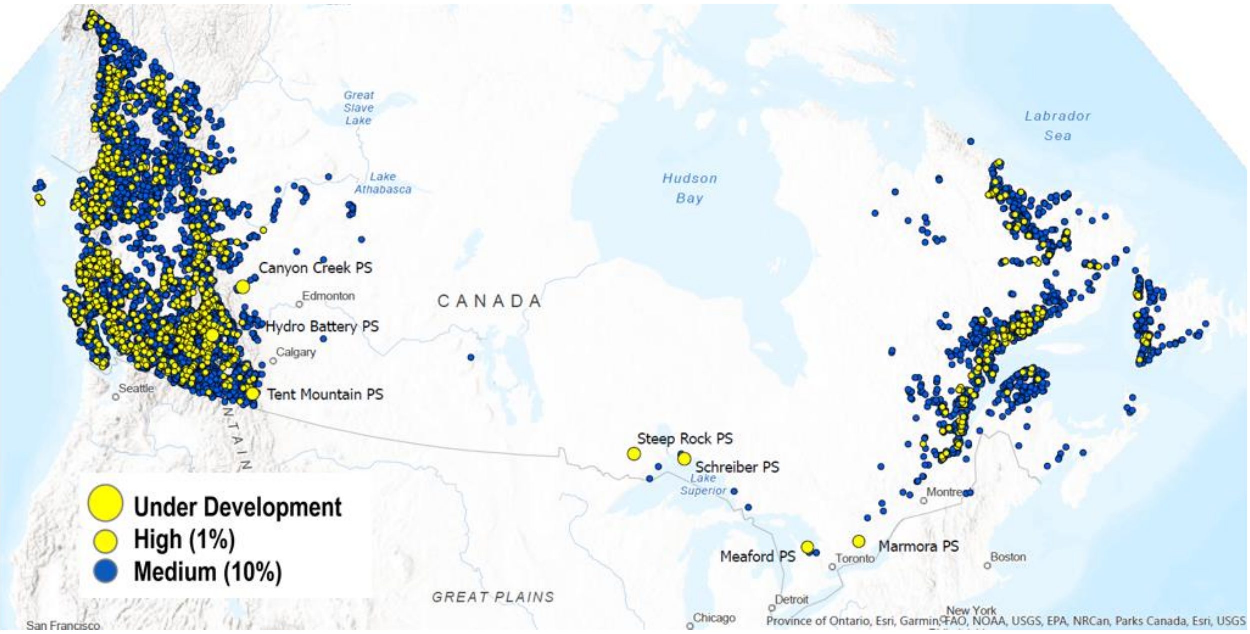
[1] In the table "Cost Adjustments" refer to those costs added to the base costs of the pumped hydro storage facility itself and are attributed to (i) transmission interconnection for the dedicated project substation and line, (ii) constructability for new construction access roads and elevated costs from adverse geotechnical site conditions, and (iii) hydraulic site conditions that may raise costs for the pump-turbine equipment.



Province of Ontario, Esri, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada, Esri, USGS

Section 6 presents insights from various market participants, including major Canadian utilities, power producers and Original Equipment Manufacturers (OEMs) that were surveyed to take the pulse of the "industry" regarding PSH. Approximately 60% of polled entities responded and were divided into the two categories: "Active Development Interest in Canada" (Yukon Energy Corp, OPG, NL Hydro) and "Not Active".

Section 7 presents in closing the study major findings, including the following:

- PSH is a mature technology that is based on conventional hydro technology. Sites with higher hydraulic head are generally more attractive because of their energy density and availability of water is a prerequisite. The technological and environmental aspects of PSH development are well refined.
- Machinery can be configured using reversible pump-turbines, ternary or quaternary arrangements, each having their own advantages, but costs favour the pump-turbine configuration. The determination of equipment configuration is based on the optimization of the needs of the power system and market opportunities.
- Sites could use existing reservoirs or natural waterbodies as storage reservoirs. Off-river, closed-loop systems offer advantages in environmental impact and operational independence, and consequently those locations were prioritized in this report. These are the only reported sites under active development in Canada and have been highlighted for their niche potential in this report.
- The characteristic of PSH to be able to respond quickly to load changes or the variability of non-dispatchable renewable generation such as wind and solar power, underscore PSH's role as stabilizing backbone of a power grids, especially as non-dispatchable renewable energy penetration is increasing.
- The international context suggests that Canada is in need of urgent action to develop PSH if a 100% renewable energy generation mix is to be attained by 2035 or even 2050
- The Theoretical Potential for PSH in Canada is for all practical purpose inexhaustible with over 100,000 identified sites and over 200,000 GW of capacity possible.

- This potential is distributed unequally throughout the country with British Columbia taking by far the largest portion followed by Quebec and Newfoundland and Labrador.
- The geographic distribution of this Theoretical Potential is also well correlated with the wind resource in the country providing the possibility of using this synergy for fully renewable and dispatchable renewable electricity generation.
- To assess the Realistic Potential the sites were screened using Feasibility Factors related to
    - Proximity to transmission assets and interconnection costs
    - Environmental and social constraints addressing potential conflict or opportunities with First Nation interests and protected lands
    - Constructability with respect to site access infrastructure and conducive ground conditions for construction
    - Suitability of the different types of machinery technology and their cost impact
- To determine the Realistic Potential an approach was employed that categorized 10% of the Theoretical Potential sites with a medium Realistic Potential and 1% with a high Realistic Potential
- The resulting cumulative high Realistic Potential across Canada amounts to over 8,000 GW[2] installed capacity at almost 1,200 site locations.
- Among those sites about 85% are realistic to be developed in the near future before 2035 based on the established time constraints for permitting of the PSH and transmission assets provided that development efforts were to commence today.
- The Realistic Potential is unequally distributed with similar countrywide patterns as the Theoretical Potential: British Columbia in the lead followed by Quebec and Newfoundland and Labrador
- The PSH sites that are actually undergoing development are highly concentrated in two provinces: Ontario and Alberta.
- Feedback from over 30 potential PSH developers around the country was solicited and responses were received from the majority.
- Among provincial utility companies no interest in developing PSH was expressed with the exception of Ontario Power Generation in Ontario. Independent power producers, oil and gas and First Nations lead the way with active development efforts.
- Generally, a sentiment of fatigue seems to prevail about PSH being heralded as projects to come soon but always in the future, and never leading to real construction investment.

Recommendations for next steps that come out of this study are as follows:

- Improve the data base for Theoretical Potential to include more sites, for example the Great Lakes as lower reservoir, the Niagara Escarpment and its proximity to Lake Ontario for example. This work is already in progress at ANU. Another option to reflect additional capacity would be the recognition of abandoned mines, where the mine could be utilized as a lower reservoir for PSH installation. Adding the Canadian territories would also complement the amount of already identified sites but hasn't commenced, yet.

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[2] It is noted that this potential is almost two orders of magnitude larger than the existing conventional hydro capacity in existence in Canada.

- Study the Canadian context with respect to additional need for transmission, hydro, wind, solar and PSH to realistically implement a renewable generation mix aligned with the time schedule for Net Zero Targets. International comparison, for example Australia as a prominent case, suggest that deployment rates for wind and solar need to accelerate by an order of magnitude which will have significant effects on the need for PSH. Note that the past is a poor predictor of the future in this case.
- Refine the Feasibility Factors in the assessment with benchmarking to actually constructed project case examples from USA and other international locations.
- Identify additional potential sites for consideration for PSH development that are defined as open-loop systems.

1. INTRODUCTION

1.1 STUDY CONTEXT

In fulfilling its mandate as a national trade association for hydropower producers in Canada, WaterPower Canada has commissioned this Technical and Economic Assessment research project to identify the potential for further development of Pumped Storage Hydro (PSH) projects to address the net-zero goals that have been identified by the Canadian federal government[3].

Accelerated retirement of fossil fuel plants, load growth from widespread electrification of transportation and mining industries, emerging crypto-currency mining and data server centers in Canada are all drivers for an increasingly secure, reliable and robust electric power grid. Hydropower has played the role of the grid's primary supply and stabilizing backbone for over a century, and with the increasing penetration of non-dispatchable renewable generation from wind and solar power, will need PSH to supplement this role.

The PSH "water battery" is uniquely versatile, proven and sustainable in that it stores unparalleled amounts of energy up to gigawatt-hour (GWh) levels over a wide range of time periods from seconds to days and longer. Depending on the prevailing need, it can serve a versatile range of purposes such as

- fulfilling scheduled short-term capacity and energy demands
- shifting load-demand imbalances
- energy arbitrage according to daily patterns of variable renewable (wind and solar) generation and consumer demand
- stabilize frequency and voltage of a power grid
- serve to stabilize the transmission system through spinning inertia.

Several PSH projects are currently in active development in Canada that will serve as enabling technology for building out a larger portion of the non-dispatchable renewable generation potential across the country. Many more are possible as Canada is blessed with a geography and climate that provides the elevation relief and a supply of available water in many locations across the country. This makes it possible to potentially develop PSH sites well beyond Canada's presently foreseen need. This research project quantifies a "Realistic Potential" of PSH by assessing the "Theoretical Potential", and then applying "Feasibility Factors" against it.

Further, the study takes the pulse of major industry stakeholders: Utilities, independent power producers, equipment suppliers, construction contractors and power system operators. Many responded to our call and are recorded in this report.

1.2 STUDY ALLIANCE

In March 2022, a study alliance was formed and awarded by WaterPower Canada to conduct the assessment of PSH potential in Canada consisting of:

- Stantec as principal investigators and study lead. Stantec employs one of the largest dedicated hydropower and pumped storage engineering groups in the world, and through its legacy firms, represent a history of more than 100 years of engineering waterpower plants.
- Australian National University (ANU), an academic institution that has demonstrated leadership, earned credibility and attracted significant research funding for the advancement of pumped storage hydro, both domestically and in a global sense.

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[3] Pertinent regulations include the Clean Electricity Regulations, formerly the Canada Clean Standard, and the Canadian Net-Zero Emissions Accountability Act.

- Centre for Energy Advancement through Technological Innovation (CEATI) as an industry organization that represents the body of knowledge from a majority of owners, service providers and equipment manufacturers active in the hydropower space in Canada and internationally.
- Power Advisory (PA) as a firm with deep understanding of the Canadian electricity markets and system operation.

The profiles of each firm are described in more detail in Appendix A.

1.3 Project Understanding

WaterPower Canada is commissioning this study in the national context of Canada’s goal to achieve a net-zero emissions electricity supply by 2035 and a net-zero economy by 2050. The study will provide underpinning through research, information compilation and intelligent interpretation that presents the value, strategic advantages and role of pumped storage hydropower (PSH) in a future decarbonized electricity supply-mix in Canada.

The overarching objective of the work is to assist WaterPower Canada and the industry to better understand the strategic value of PSH, along with identification of viable sites where PSH facilities might be considered in the future.

As the main outcome of the study is to assess the potential for the realistic development of PSH, the key to the assessment is identifying the set of actual candidate sites that could potentially be developed. The Australian National University’s team has developed a GIS-based tool to execute a structured search for pairs of potential water storage reservoirs that meet certain physical and environmental criteria as described in Appendix B. The use of this tool provides for a structured, consistent, and thorough interrogation of the landscape to identify topographically suitable candidate sites. The extensive list of sites identified by the ANU tool forms the Theoretical Potential.

Feasibility Factors, which drive cost and the chances of a successful development are used to screen down the set of theoretical candidate sites to those that might reasonably be candidates for actual development. The identified Feasibility Factors help eliminate the portion of candidates that are not likely to be implemented. The remaining set of sites from this process are considered the Realistic Potential.

The Realistic Potential in Canada is categorized over two timeframes, and by geographic region. The first envelope under consideration represents Realistic Potential for PSH development between now and 2035, representing the immediate future. The second envelope represents Realistic Potential for PSH development prior to 2050, as representing the longer-term future.

Further, major Canadian utilities, power producers and Original Equipment Manufacturers (OEMs) have been surveyed in a brief questionnaire to take the pulse of the industry regarding PSH.

2. INTRODUCTION TO PUMPED STORAGE HYDRO

2.1 HOW PUMPED STORAGE HYDRO WORKS

PSH acts as a large “water battery” as it can store energy and release it when needed. It works on the physical principle of potential hydraulic energy and its conversion into mechanical and electrical energy and vice versa of the water moving between reservoirs.

As shown in Figure 1, PSH sites require two water reservoirs with different elevations so that energy can be pumped from the lower reservoir into the upper reservoir for storage and be released back to the lower reservoir for generation. For large elevation differences between the reservoirs, the hydraulic head is increased. Therefore, more energy can be stored for the same amount of water using smaller reservoirs, smaller water conveyance conduits, and smaller physical equipment sizes, usually resulting in lower investment costs.

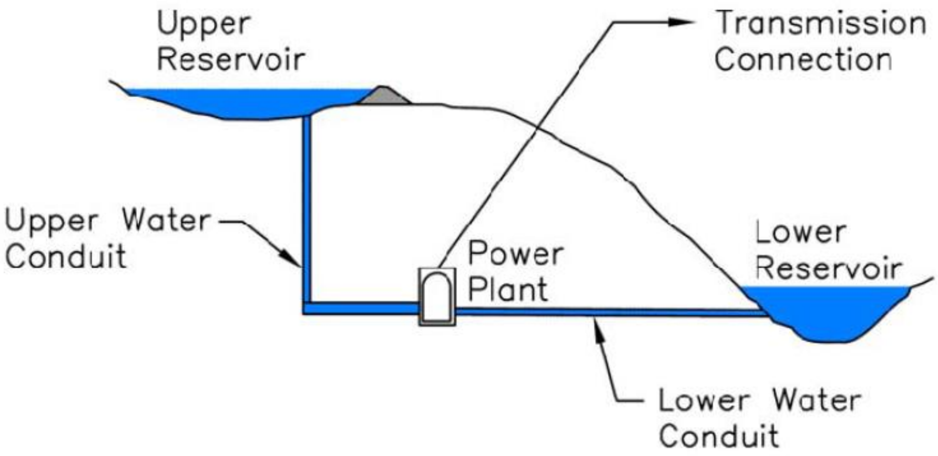


Figure 1 Typical Pumped Storage Arrangement

The two main types of PSH in use are open-loop and closed-loop systems:

- Open-loop: With either an upper or lower reservoir that is continuously connected to a naturally flowing water source such as a river.
- Closed-loop: An “off-river” site that produces power from water pumped between reservoirs without significant natural inflow.

Also referred to as “off-stream” or “off-river”, a closed-loop PSH project has two reservoirs, both not hydraulically connected with a natural waterbody and water only being diverted for initial filling and for make-up of water lost during operation due to leakage and evaporation. Closed-loop systems offer more opportunities to minimize environmental impacts than open-loop PSH due to their hydraulic isolation from the natural water bodies. They are subjected to fewer operational restrictions, and hence, more easily start, stop, reverse, and switch between pumping and generating operation modes. Output and reservoir water levels can be adjusted as needed by the power system with fewer constraints. This type of PSH is the most common type under active development in Canada, and the only type considered for this study. Strictly speaking, this approach underestimates the number of potential sites, and is therefore, conservative in answering the central question of this study: Is the potential for PSH sufficient to fill the needs of our power systems?

During periods of low power demand, typically overnight, inexpensive off-peak excess electricity produced by base load plants or intermittent renewables is used to pump water from the lower to the upper reservoir. This charges the water battery. Thereafter, the PSH facility can act as a hydroelectric power plant that generates electricity to meet peak load (demand) at premium on-peak electricity prices. The power plant consumes electricity when electricity prices are lower, and then releases water to generate electricity when the demand increases, and electricity prices are higher. It serves an energy market by time-shifting available electricity from times of surplus to times of need. This energy arbitrage constitutes the classical revenue stream and economic justification for construction of new PSH.

It should be noted that the processes of pumping and generating are not 100% efficient and less energy is generated by a given amount of water than was used to pump the same amount of water. The Round-Trip Efficiency (RTE) collects all losses from pumping and generating into a single number, and factors in inefficiencies of power transformation, the electrical pump motor and generator losses from copper and magnetization losses, their mechanical inefficiencies in bearings, seals and cooling and the hydraulic inefficiencies of pump, turbine and the conveyance water passages. In addition, water disappears from the closed-loop process through seepage and evaporation. Table 1 shows a simplified calculation of RTE for a PSH project where the total efficiency is computed as the product of the individual efficiencies that can vary widely depending on configuration and operation.

Table 1 Return-Trip Efficiency (RTE) for a Typical PSH Example

Generating	
Water Conveyance	97.50%
Turbine	95.00%
Generator Electrical	98.00%
Generating – Subtotal	90.80%
Pumping	
Water Conveyance	96.50%
Pump	94.00%
Motor Electrical	98.00%
Pumping – Subtotal	88.90%
Operational	
Evaporation Losses / Leakage	99.80%
Total RTE	**80.50%**

The hydro turbine and storage pump equipment used in PSH can have the principal configurations shown in Figure 2:

- Quaternary (4 machines): pump & motor plus turbine & generator on combined or separate shaft lines
- Ternary (3 machines): pump, motor-generator & turbine on a single shaft
- Reversible pump-turbine with motor-generator (2 machines such as the solution implemented at the OPG Pumped-Storage GS at Sir Adam Beck where the machine can be started either as generator, by way of conventional process - opening turbine blades partially to achieve Synchronous-No-Load (SNL) before closing generator breaker - or as a pump, by way of across line induction start following reversal of two of the generator power leads to achieve rotation in reverse direction).

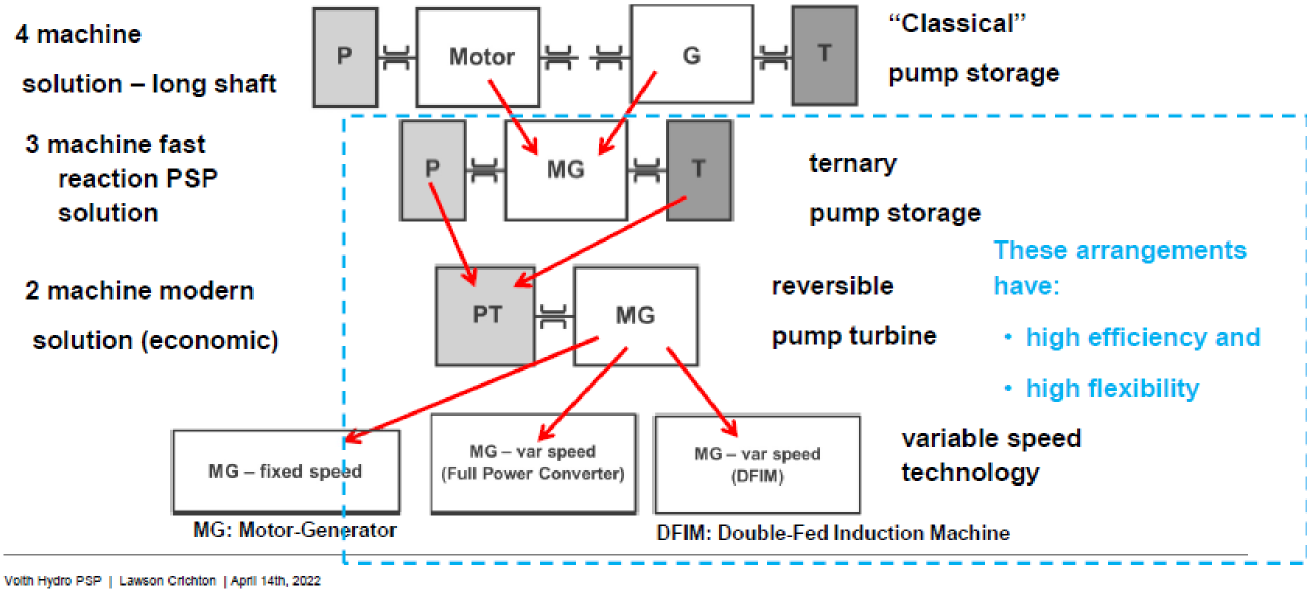
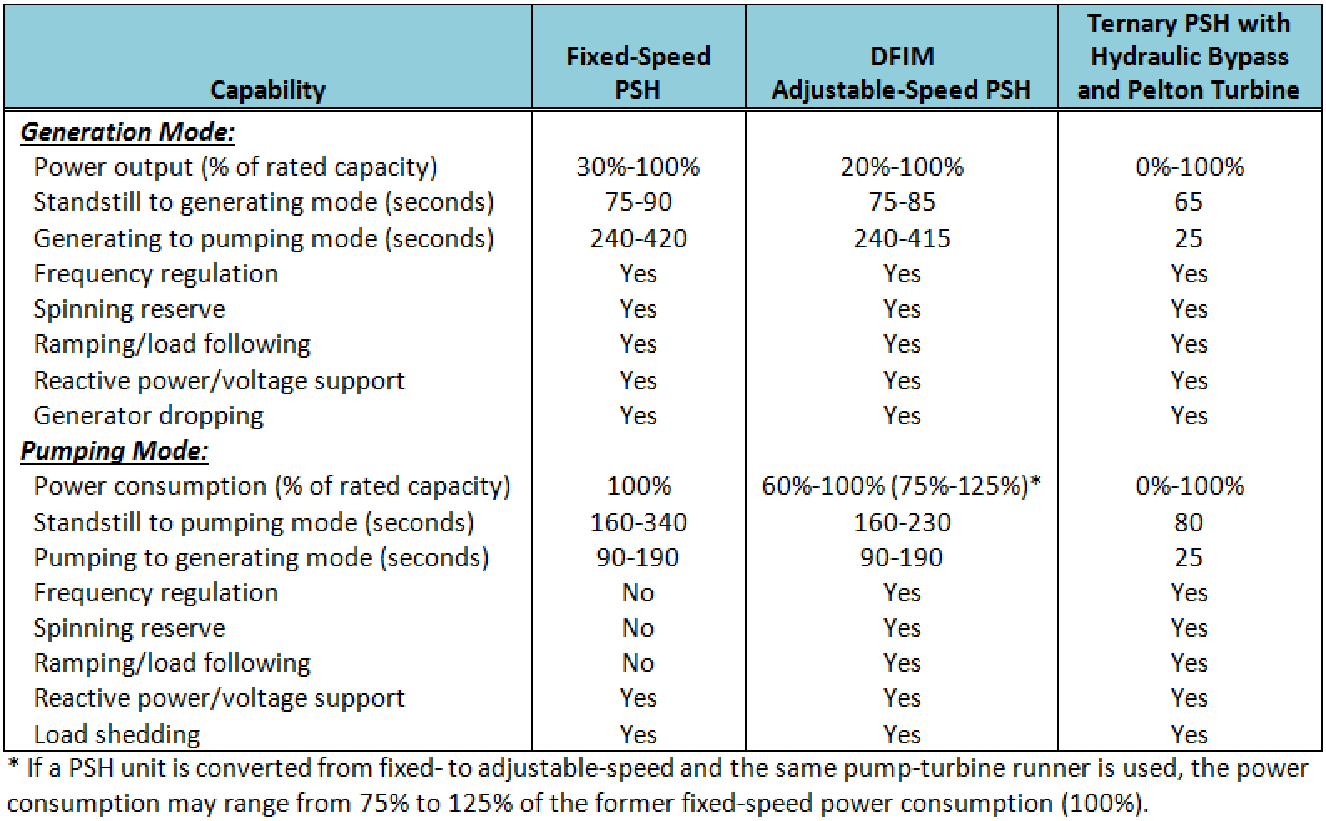


Figure 2 Conceptual Machinery Configuration in PSH (Source: Voith)

The optimum configuration of equipment is a matter of site-specific evaluation of hydraulic characteristics and operational requirements in the context of available technology, performance and costs.

Startup and mode change speed is one key performance feature of a PSH unit, and typically ranges in the order of seconds to minutes. This fast response time aligns PSH units with single cycle, gas-fired combustion turbines for speed of response, but apart from some fossil sets or nuclear fueled thermal units that are often used to serve base load and require significantly longer startup time, in the order of hours. Table 2 shows the operational capabilities that would be typical for different equipment configurations.

Table 2 Typical Operating Capabilities of Fixed Speed, DFIM[4] Adjustable and Ternary PSH



Capability	Fixed-Speed PSH	DFIM Adjustable-Speed PSH	Ternary PSH with Hydraulic Bypass and Pelton Turbine
Generation Mode:			
Power output (% of rated capacity)	30%-100%	20%-100%	0%-100%
Standstill to generating mode (seconds)	75-90	75-85	65
Generating to pumping mode (seconds)	240-420	240-415	25
Frequency regulation	Yes	Yes	Yes
Spinning reserve	Yes	Yes	Yes
Ramping/load following	Yes	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Generator dropping	Yes	Yes	Yes
Pumping Mode:			
Power consumption (% of rated capacity)	100%	60%-100% (75%-125%)*	0%-100%
Standstill to pumping mode (seconds)	160-340	160-230	80
Pumping to generating mode (seconds)	90-190	90-190	25
Frequency regulation	No	Yes	Yes
Spinning reserve	No	Yes	Yes
Ramping/load following	No	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Load shedding	Yes	Yes	Yes

* If a PSH unit is converted from fixed- to adjustable-speed and the same pump-turbine runner is used, the power consumption may range from 75% to 125% of the former fixed-speed power consumption (100%).

The ability to change modes of absorbing and releasing electricity of PSH, sometimes even both at the same time, allows PSH to also serve a Capacity Market. This market awards revenue and provides economic justification for PSH based on its ability to stabilize the power grid very quickly with respect to its voltage and frequency by adjusting PSH's level and mode of power generation/absorption. Voltage and frequency of the power system diverge from their nominal values when the instantaneous equilibrium of generation supply and load demand are out of balance. The Ancillary Services associated with having instantaneous capacity available may form other potential sources of revenue on markets in areas where they exist. This role of PSH can be considered a service to the transmission and distribution (power delivery) system where these types of services may be offered under contracted conditions.

Figure 3 demonstrates how the physical arrangement of a PSH project is closely related to the geography and climate that nature provides. Steep terrain with impermeable geological layers and a wet climate facilitates PSH's feasibility.

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[4] DFIM: Double-Fed Induction Machine

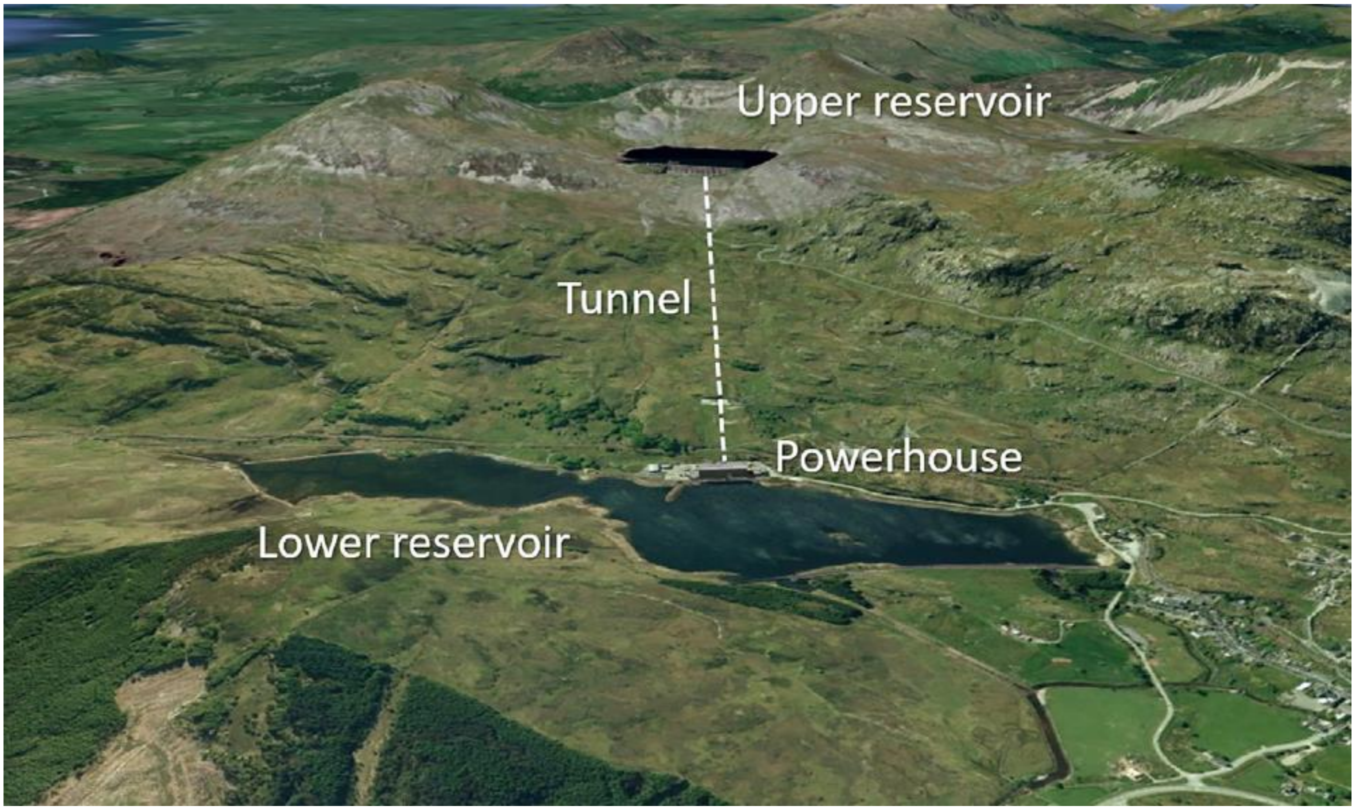

Figure 3 Physical Layout of a Closed-Loop, Off-River PSH System: Ffestiniog PSH in Wales

2.2 RETROFITTING HYDROPOWER ASSETS FOR PUMPED STORAGE HYDRO

Besides purpose-built greenfield PSH, retrofitting and modernizing existing conventional hydropower assets for pump-back capability is another opportunity for increasing the PSH fleet in Canada.

Advantages of a conversion over new PSH include

- Existing dam, electrical power system and transportation infrastructure provide
  - Lower environmental burden including greenhouse gas emissions as compared to a greenfield PSH project
  - Savings in construction cost compared to a greenfield PSH project
- Cost savings on support infrastructure such as maintenance equipment and personnel
- Faster schedule due to potentially reduced time needed to obtain licenses and environmental permits

The most obvious conversion approaches would be

- Add a pump-turbine to an existing plant
- Install a separate pump station to return water from the tailrace to the headpond reservoir
- Replace existing turbine-generator units with reversible pump-turbine equipment

However, these retrofit PSH facilities would be open-loop and environmental constraints on natural rivers in place for the existing conventional hydro could become an obstacle to the conversion.

2.3 REASONS FOR PUMPED STORAGE HYDRO TODAY

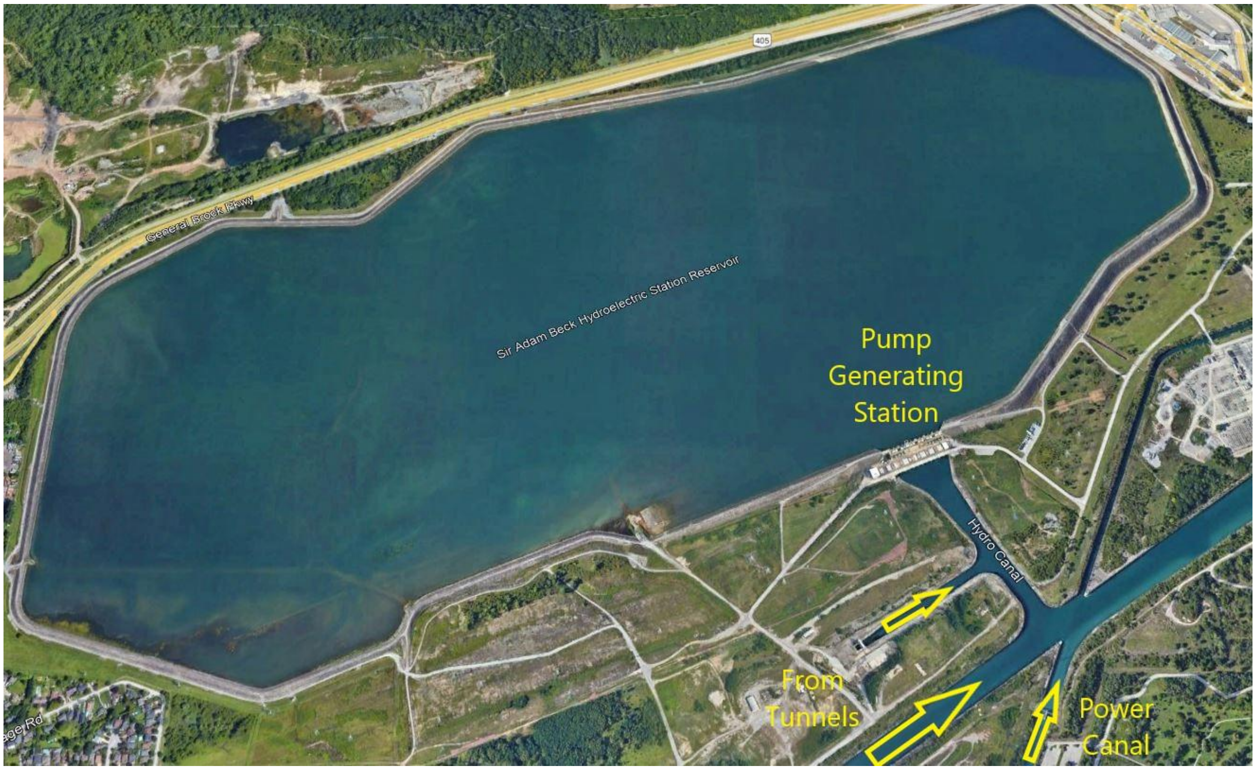

Figure 4 Sir Adam Beck Pump Generating Station in Niagara Falls, Ontario

In recent decades, wind and solar power have made great strides in contributing to a renewable generation mix alongside hydropower which has been the trusted workhorse of our electricity systems for well over a hundred years. However, the challenges of wind and solar integration lie in the variability of wind and sunlight and their inability to be reliably dispatched according to power demand. Hence, the challenge is to find a way to make electricity generated from wind and solar resources adaptable to market requirements for stability and on-demand dispatch protocols. As the percentage of wind and solar power generation grows, the unpredictable changes in weather not only affect generation capacity from non-dispatchable renewables but also increase swings in power demand. This compounds the challenges of power system stability and reliability and creates an increasing need for fast-acting energy storage to serve as a compensating mechanism. Longer-term variations over daily cycles, weeks and even seasonal changes in power demand and generation capacity are superimposed on short-term variations and create concerns over resource adequacy.

PSH offers the ability to store energy produced from non-dispatchable renewable resources when abundant or even superfluous, and to release this renewable energy back into the power system at the very moment in time when it is needed, most often during peak electricity demand. Energy arbitrage is the process of balancing the electricity between times of surplus generation and excess demand. Another function of PSH is to contribute fast-acting standby capacity as ancillary service to the power system for frequency and voltage control. These need to be kept within narrow bands of variation to satisfy the technical requirements of electricity users so electrically powered processes and devices function as intended. A combination of remuneration for arbitrage, energy and capacity markets, and any ancillary services provide potential revenue streams that constitute the economic drivers for new PSH to be constructed. All of the aforementioned benefits of deploying PSH on the electricity systems in Canada are in addition to the goal of contributing to the displacement of GHG emitting energy technologies.

Other energy storage technologies that have been deployed globally include electro-chemical batteries, flywheels, super capacitors, compressed air energy storage (CAES), thermal energy storage (TES), and hydrogen storage. Additional energy storage technologies are in various stages of technology readiness and may be prepared for commercial deployment in the near future. Each of these technologies may find their own niche in the power system, whiles others still face considerable technical or environmental challenges.

Conventional hydro reservoirs also represent an important storage technology. For example, Hydro-Quebec's existing reservoirs have an estimated live storage capacity of about 170 TWh which can in part be used to play a role similar to that of PSH.

According to the International Hydropower Association[5] (IHA), PSH represents nearly 95% of the globally installed energy storage capacity (excluding the storage capacity of conventional hydropower reservoirs). These projects not only facilitate other forms of energy production but are also among the fastest response stations on the power system. They can pump or generate at their nameplate rating or at less than full load, thereby increasing the flexibility in operational use of PSH projects for voltage and frequency regulation of the power system. Transmission congestion and overload is reduced by co-locating a pumped storage project near a wind or solar power facility. Storing wind and solar energy as pumped storage during critical times of grid congestion, allows power to service loads at a time when the congestion is reduced and or the power is needed on other parts of the system. Studies for capacity and storage sizing and location of pump storage projects can determine what percentage of the wind energy needs to be reinforced by pumped storage hydro.

It also needs to be noted that since the Sir Adam Beck II complex in Niagara completed in the 1950s, Canada has not seen any new PSH facility built for over 70 years. The Sir Adam Beck Pump Generating Station (PGS) plant associated with Sir Adam Beck II was constructed to take advantage of the Niagara Treaty water allotment and the additional water available over night. This additional stream share becomes available to be time-shifted and pumped into the reservoir to then serve the electricity market during the next days(s) when demand and market costs are higher. The reason for the hiatus in new PSH construction can be found in the abundance of conventional hydro generation in Canada that can perform in some ways the role of PSH within the limits of its permissible flow variation on a river system. These limits are largely governed by environmental considerations as well as the needs of other recreational and commercial riparian users. Also “Carbon Neutral” or “Net Zero” are only recent goals with political and societal support. With increasingly stringent water management plans, decarbonization targets for our generation mix that must eliminate fossil fast-acting gas plants and the above-mentioned advent of non-dispatchable renewables at a scale that has a real impact on our power systems, PSH has come under increasingly serious consideration.

2.4 History of Pumped Storage

The first hydro plants with pumped storage capability were built in Switzerland. The first known pumped-storage development was in Zurich, Switzerland, and operated as a hydro-mechanical storage plant until 1891. The first documented use of pumped-storage for electricity generation was at the Ruppoldingen plant in Switzerland on the Aare River in 1904. In 1929, the Rocky River pumped storage plant, the first such plant in North America, was constructed on the Housatonic River in the US State of Connecticut.

The pumps and turbines were installed as individual units. These plants did not use reversible pump-turbines that are now standard in pumped storage plants. These early pumped storage plants, with individual pumps and turbines, had high overall cycle efficiencies because pumps and turbines could be designed for maximum efficiency at the single synchronous speed of the generator/motor. However, the electrical-mechanical equipment costs for these plants, as a percentage of the total plant cost, was high due to the separate pump-motor and turbine-generator installations.

The modern pumped storage era in the US began in the mid-1960s and included Taum Sauk, Yards Creek, Muddy Run and Cabin Creek these stations were intended to primarily utilize relatively inexpensive surplus off-peak energy for pumping and return blocks of peaking power. Once in use, some of these plants were operated to take advantage of their capability to provide frequency regulation, load following and spinning reserve.

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[5] Source: IHA Hydropower Status Report 2022

Table 3 PSH Technology Summary Timeline

Year	Project Name
1849	James B. Francis Developed inward flow reaction turbine
1873	First application of movable wicket gates
1880's	Swiss develop pump back and pump storage schemes
1910's	Pump storage plants constructed in Germany Vertical shaft Francis turbines manufactured
1929	Rocky River PS Project on the Housatonic River - first PS in USA Development of wicket gates in conjunction with Francis pump-turbine
1956	TBA Hiwassee Unit 2 is a true reversible pump-turbine. Proves that a single runner can perform as a pump and turbine.
1957	Sir Adam Beck Pump Generating Station (PGS), 175MW is the only facility of its kind in Canada
1960's	Develop adjustable frequency motor starting system - overcomes the problem of pump rotor starting
1980's	US Bureau of Reclamation experiment with adjustable speed machines
1990's	Japanese manufacturers develop adjustable speed turbines
1985	World's largest PS project: Bath County VA, six unit 2,100MW
1996	First 395MVA adjustable speed machine at Ohkawachi PS project Japan, enters commercial operation
1998	Chaiara, Bulgaria; two units 864MW; highest head (2,400 feet), single stage pump/turbines
1990's	Development of Electricity markets. PS receives full compensation for ancillary services
1999	Yanbaru – Okinawa, Japan; One unit rated 30MW, first pumped storage plant to operate with sea water
2000	Goldisthal, Germany; four units (two single speed, two adjustable speed) 345 MVA each.
2003	2,400MW Guangdong pumped storage project was completed, located in Guangdong Province, China. features 8 x 300MW turbines
2012	Lake Hodges 40 MW most recent North American PSH
2022	Nant De Drance 900MW (Switzerland) pumped storage power station currently under construction. 6 Francis pump turbines.
2023	The 3,600MW Fengning pumped storage power station under construction in the Hebei Province of China will be the world's biggest pumped-storage project upon completion in 2023.

2.5 Existing Pumped Storage in Canada

As pronounced on OPG's website: While the vast bulk of Canada's pumped storage hydroelectricity potential remains untapped, the Sir Adam Beck Pump Generating Station (PGS) provides long-standing proof of the viability and value of this technology. And while it remains Canada's only operating pumped storage facility today, strong interest on the part of developers and system operators strongly suggests this won't be the case much longer.

Figure 5 Sir Adam Beck (SAB) Complex in Niagara with Pump Generating Station (PGS)

The Sir Adam Beck PGS was constructed concurrently with the Sir Adam Beck II Generating Station at Niagara Falls and went into service in 1957. It consists of a 750-acre storage reservoir, sitting at a higher elevation than the Upper Niagara River, and into which water is pumped overnight when electricity demand is low. The reservoir requires about eight hours to fill, and this water is then released during periods of high demand. The PGS has six generating units and capacity to displace up to 600 MW of what would otherwise often be peaking fossil fuel generation, over eight hours.

In 2017, Ontario Power Generation completed a $60-million refurbishment of the reservoir, which increased its storage capacity and is expected to extend its operating life for another 50 years. The Sir Adam Beck PGS enables Ontario Power Generation to more efficiently use of the water available to it for power production under the Niagara Diversion Treaty of 1950, which also ensures sufficient flows to safeguard other values such as the spectacular beauty of the falls themselves.

2.6 Pumped Storage in the Global Context

Worldwide, PSH is the most widespread electric energy storage system in use on bulk power, high voltage power networks. Today, pumped hydro storage systems account for nearly 95% of designated energy storage capacity (153 GW, equivalent to about 2% of total power capacity worldwide), while electro-chemical battery storage systems total around 4 GW[12]. Pumped storage is a mature technology with a proven track record and is represented by many large and small projects ranging from less than 10 MW to over 3,000 MW.

A significant and growing portion of the hydroelectric generation capacity worldwide is devoted to pump storage projects that are designed not only to enable significant growth of wind and solar but to also provide power during peak loads, during grid stress events and provide other key reliability attributes - frequency control, voltage support, load following and spinning reserve.

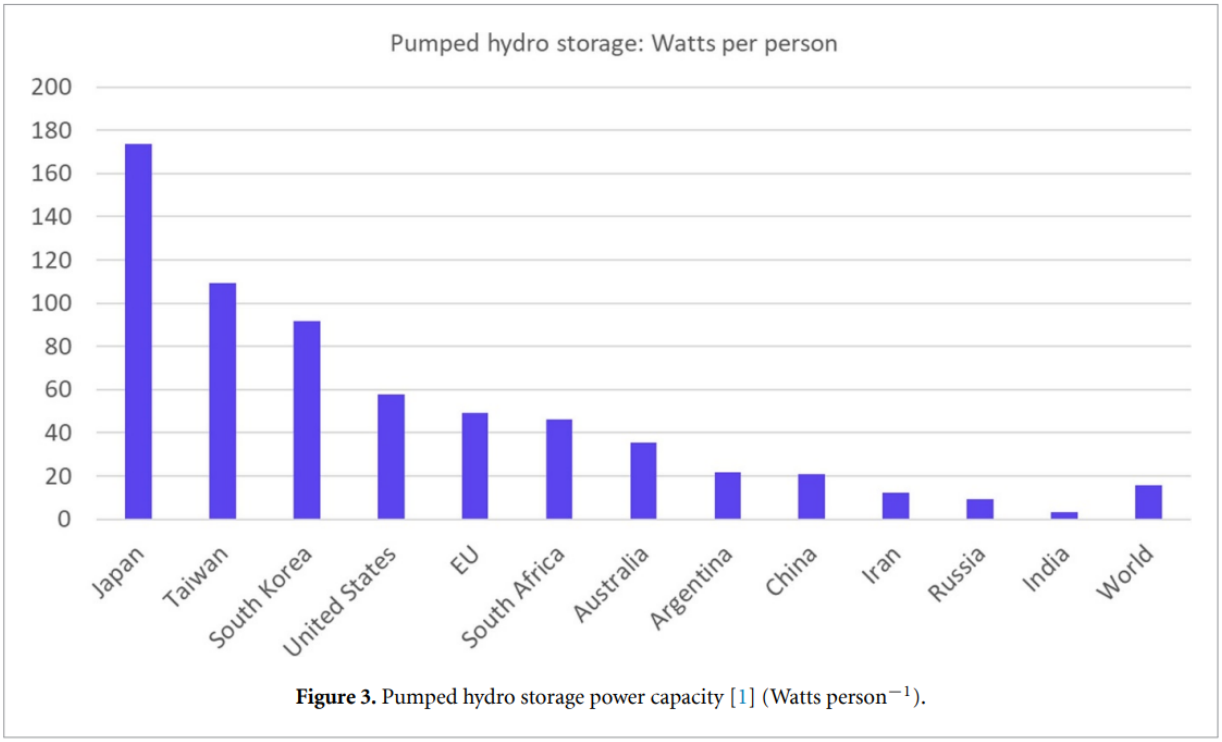

Figure 6 A Review of Current PSH by Region [Blakers, Stocks 2021]

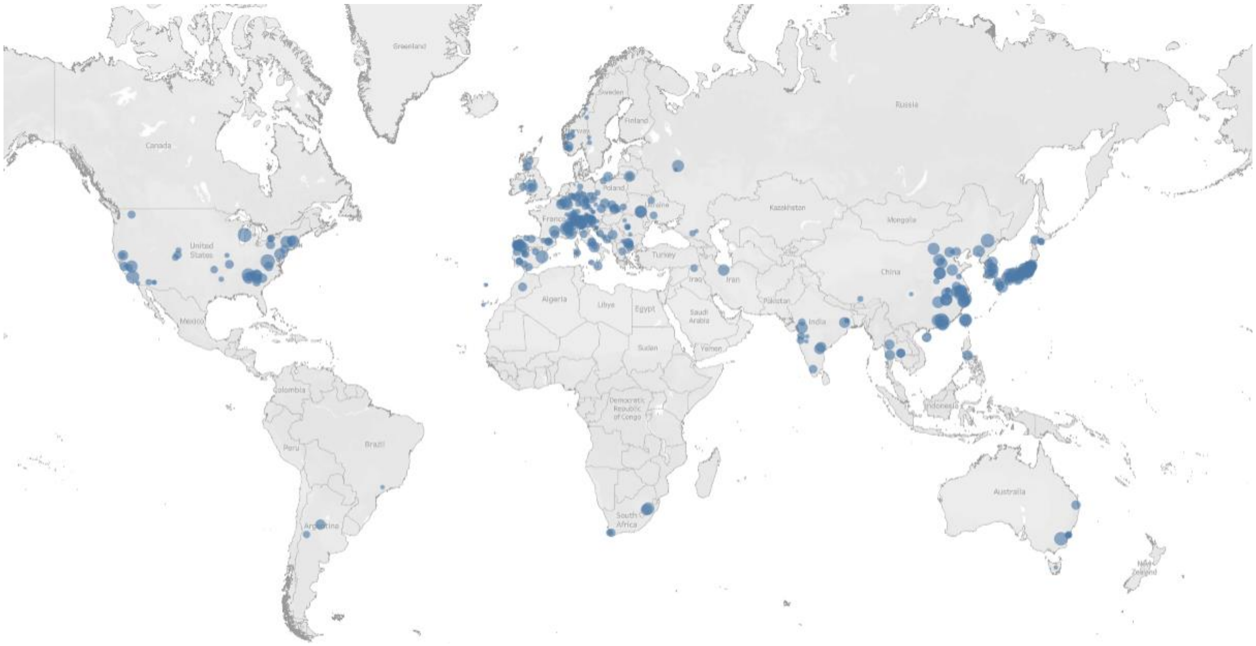

Figure 7 Map of Operational PSH Plants around the World [IHA, 2022]

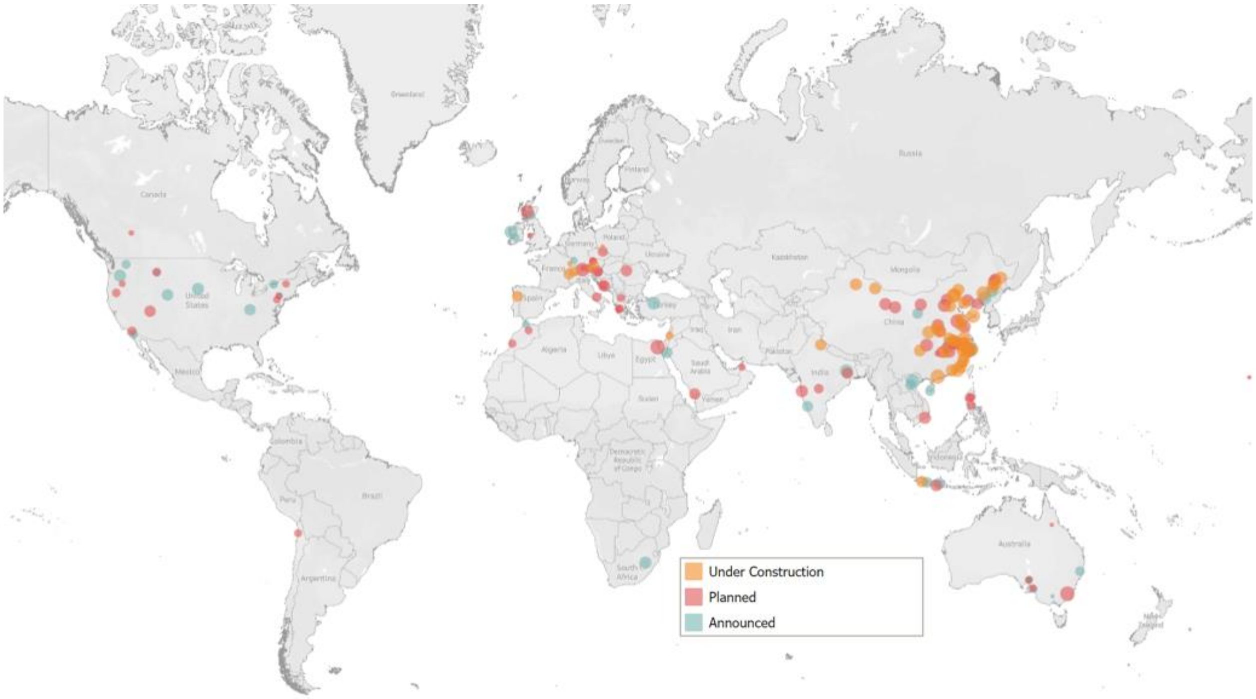

Figure 8 Map of Planned, Announced and Under Construction PSH Plants around the World [IHA, 2022]

Per capacity statistics published annually by IRENA[6], “2021 was a strong year for the energy transition – the world added almost 257 gigawatts (GW) of renewables, increasing the stock of renewable power by 9.1 per cent and contributing to an unprecedented 81 per cent of global power additions.”

Table 4: Renewable Installed Capacity in the World and in Canada

Worldwide Renewable Installed Capacity in GW	**2020**	**2021**	**New in 2021**
Wind	732	825	93 (36.3%)
Solar	717	849	132 (51.7%)
Hydro	1,335	1,360	25 (9.7%)
Other Renewables	24	30	6 (2.3%)
Total	2,807	3,064	257 (100%)

Canadian Renewable Installed Capacity in GW	**2020**	**2021**	**New in 2021**
Wind	14	14	677 MW[7] (29.4%)

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[6] Downloaded January 23, 2023 from International Renewable Energy Agency: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_RE_Capacity_Statistics_2022.pdf?rev=460f190dea15442eba8373d9625341ae

[7] All numbers in GW except new installations in Canada for reasons of resolution. 1 GW equals 1,000 MW

Solar	3	4	288 MW (12.5%)
Hydro	81	83	1,336 MW (58.1%)
Other Renewables	2	2	(1) MW (0.0%)
Total	101	103	2,300 MW (100%)

Wind and solar energy are globally following a trend that will make them the predominant generation form which generally must be paired with storage systems to support grid stability, thus providing a strong driver for PSH. Canada may be on a somewhat different trajectory because the strong presence of conventional hydro and its associated storage temper the global trend. Here a lesser need for PSH installations prevails than is the case globally but in Canada wind and solar are making also an increasing contribution to the generation mix.

A study published by ANU in 2021 identified 616,000 potential PSH sites globally that are outside the bounds of protected and urban areas. These sites have an enormous, combined potential that is orders of magnitude higher than required to support large penetration of wind and solar power into the generation mix according to ANU's analysis.

The sites are widely distributed across the world as seen below in Figure 9. Lowest cost sites are shown in red and sites with twice the capital cost are shown in yellow.

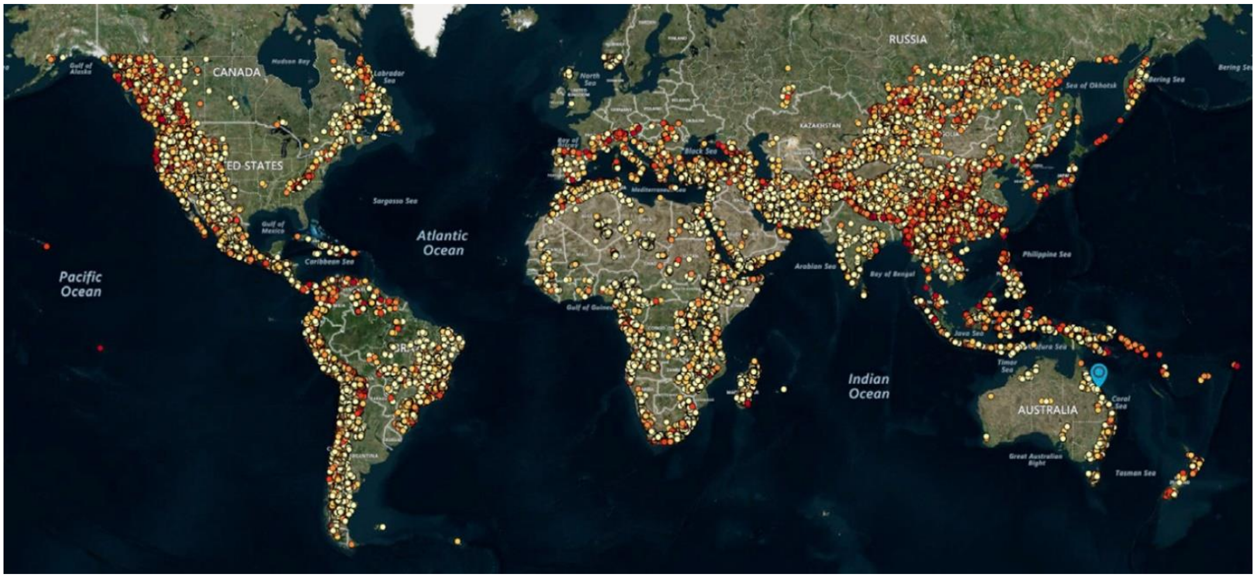


Figure 9 Distribution of 150GWh-18h-Storage Closed-Loop PSH Sites Identified in [Stocks 2021]

This same study states that global electricity production must approximately triple for there to be complete elimination of fossil fuels from the energy sector. This tripling of energy production may cause per capita electricity consumption to reach about 20 MWh per person, per year[5], or 20 GWh per million people to reach 100% renewable energy. This means deployment rates of solar, wind, hydro and other renewable technologies will need to grow by a factor of 20 to eliminate fossil fuels by 2050. To have enough energy storage capacity to supply one day of storage, storage energy and power of about 500 TWh and 20 TW will be needed[5]. Less than 1% of the total found storage capacity from this study has to be captured to reach 100% renewable energy production globally.

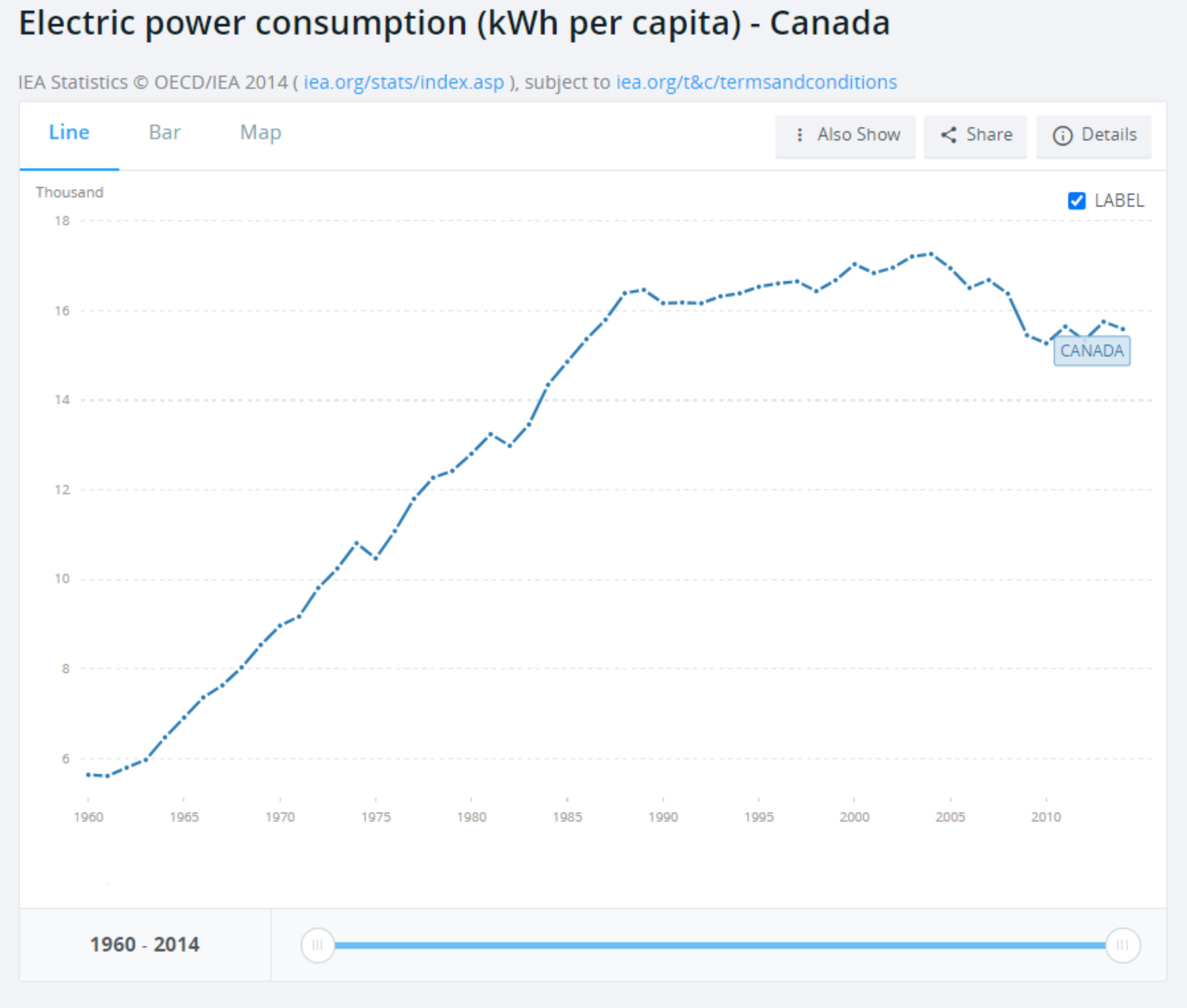
If we consider the data presented in Figure 10 for Canada and the expected electrification trends advance decarbonization, then the electricity demand in 2050 could reach 20 MWh per person or around 1,000 TWh for a population of 50 million people. If we assume the hypothetical scenario that half of this demand will be covered by dispatchable Net-Zero-compatible generation, conventional hydropower primarily, then the other half needs to be provided by non-dispatchable wind and solar.

Table 5 calculates what this would mean for wind and solar deployment if they split the additionally required demand half and half. Under this scenario over 70 GW of wind power 190 GW of solar power were needed which means an addition of about four times the existing wind capacity and over fifty times the existing solar capacity. Thus, in annual numbers about 2 GW of wind power and 6.4 GW of solar power would need to be added each year. Such a scenario would have a dramatic effect on energy markets and the requirement for additional PSH.

From the analysis that ANU has conducted for other countries that target a 100% renewable energy system, in general terms 2 to 3 kW of storage power per person has been shown to be required. On this basis Canada would need 100 GW of storage power before 2050 which could be spread over conventional hydropower, PSH, batteries and demand management (which acts like storage). Since Canada has a different generation mix and the correlations between wind and solar resource availability in relation to load peaks is also different - electric winter heating that is already prevalent in some hydro-rich provinces and may increase throughout Canada with the progress of decarbonization – one must expect different PSH requirements. Nonetheless, completing detailed power system and load forecast analyses for the Canadian provinces would not fundamentally change the primary conclusion that deployment of PSH will be needed to keep up with the expected installation of wind and solar.

Table 5: Hypothetical Scenario of Meeting Energy Demand by 2050 Purely from Renewable Sources

Needed Electricity in 2050	1,000	TWh
Conventional Hydro Power		
Installed Capacity in 2021	83	GW
Contribution	50%	of Needed Energy
	500	TWh
Capacity Factor	60%	
Total Capacity Contribution	95	GW
Additional Capacity Contribution	12	
	15%	of Existing
Needed yearly installation	0.4	GW per year
Wind Power		
Installed Capacity in 2021	14	GW
Contribution	25%	of Needed Energy
	250	TWh
Capacity Factor	40%	
Total Capacity Contribution	71	GW
Additional Capacity Contribution	57	
	399%	of Existing
Needed yearly installation	2.0	GW per year
Solar Power		
Installed Capacity in 2021	4	GW
Contribution	25%	of Needed Energy
	250	TWh
Capacity Factor	15%	
Total Capacity Contribution	190	GW
Additional Capacity Contribution	187	
	5141%	of Existing
Needed yearly installation	6.4	GW per year



Electric power consumption (kWh per capita) - Canada

IEA Statistics © OECD/IEA 2014 (iea.org/stats/index.asp), subject to iea.org/t&c/termsandconditions

Figure 10 Per Capita Energy Consumption in Canada[8]

2.7 Pumped Storage and Grid Stability

2.7.1 Power System Response without PSH

In February 2021, a burst of arctic air dropped Texas temperatures below freezing overnight. By the morning, energy demand rose to 71GW in response to turning on heating systems to combat the cold weather. Texas power plants were only able to supply 51GW of power and ended up having to shed load to prevent a grid collapse.

This undersupply of power left more than 10 million people without electricity at its peak and left some without power for several days. State officials determined that 246 people died for reasons related to the freeze and power grid failure yet outside experts believe the number is much higher than reported.

A number of causal factors have been identified as attributing to this event. The grid and power systems were not properly winterized despite warnings of needing further protection from the cold after a similar, but less

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[8] https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?end=2014&locations=CA&start=1960&view=chart

catastrophic, event in 2011. Texas operates on a deregulated power grid that is used to extreme heats, but the infrastructure is ill-equipped to operate in the extreme cold. Since Texas' power grid is a deregulated market, companies are always trying to bring the cheapest power to customers which can come at the expense for investment in reliable infrastructure systems.

Storage capabilities from PSH would have made a vital difference in preventing these blackouts if sufficient storage energy were available to bridge over the cold wave or until measures to reduce demand could have been put in place. One main cause of this undersupply was due to a drop in natural gas production, which lowered pressure in the pipelines and limited the amount of power produced by natural gas plants. Having firm generation, from an available PSH installation that is ready to supply power on demand regardless of external factors has proven to benefit communities during blackouts.

In Texas there were no conventional hydropower or PSH generation available to save the day as can be seen outlined in Figure 11.

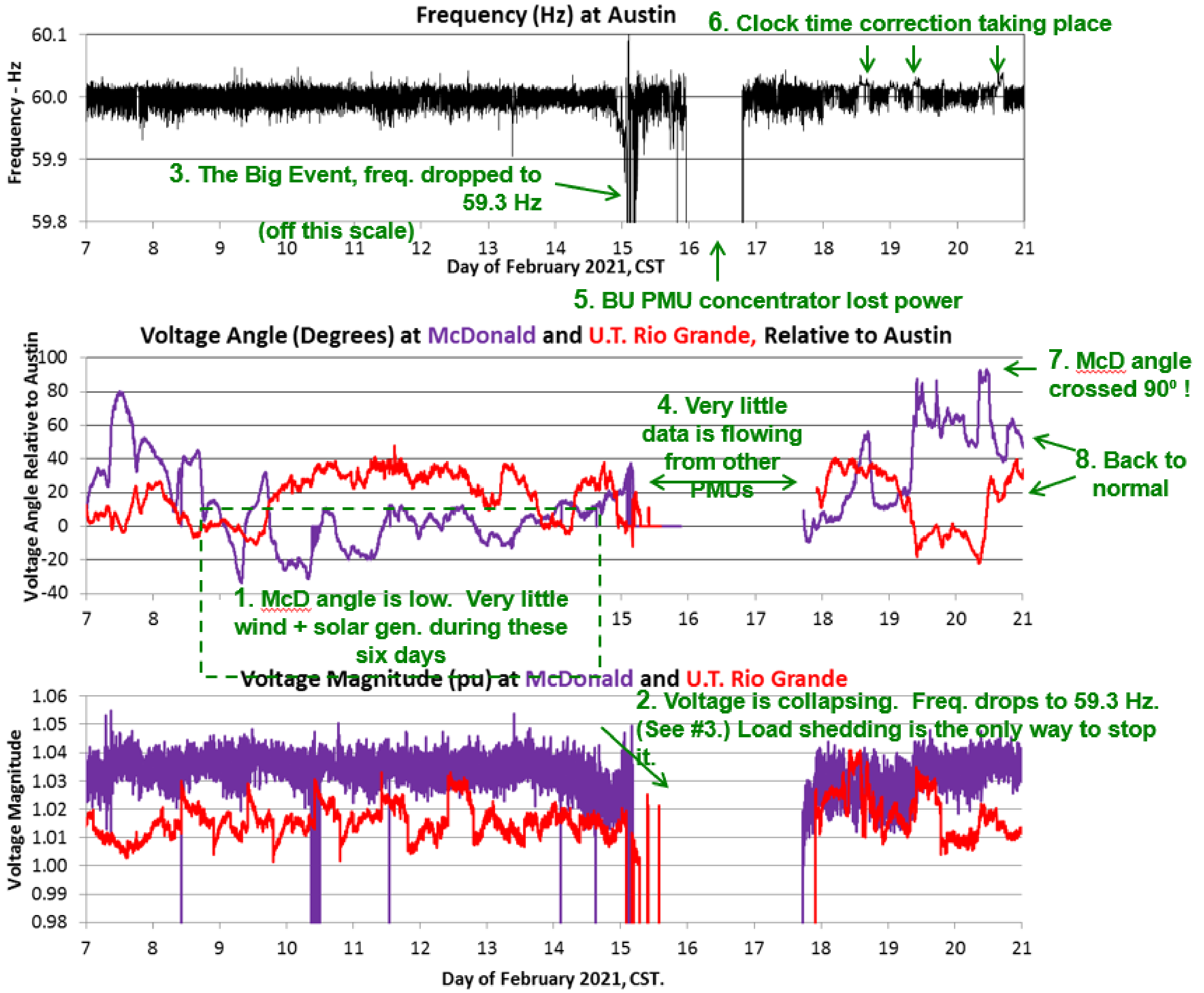
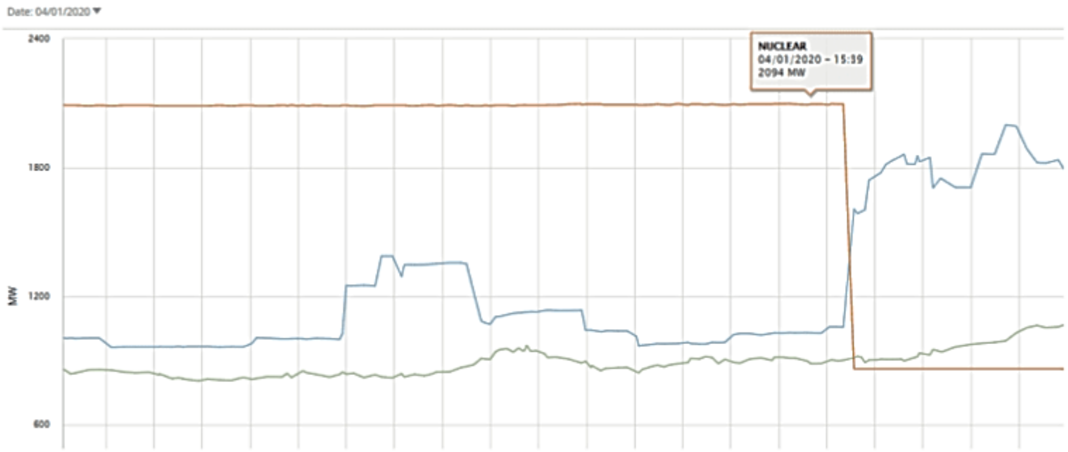


Figure 11 Frequency, Phase Angle and Voltage during Texas Blackout in February 2021

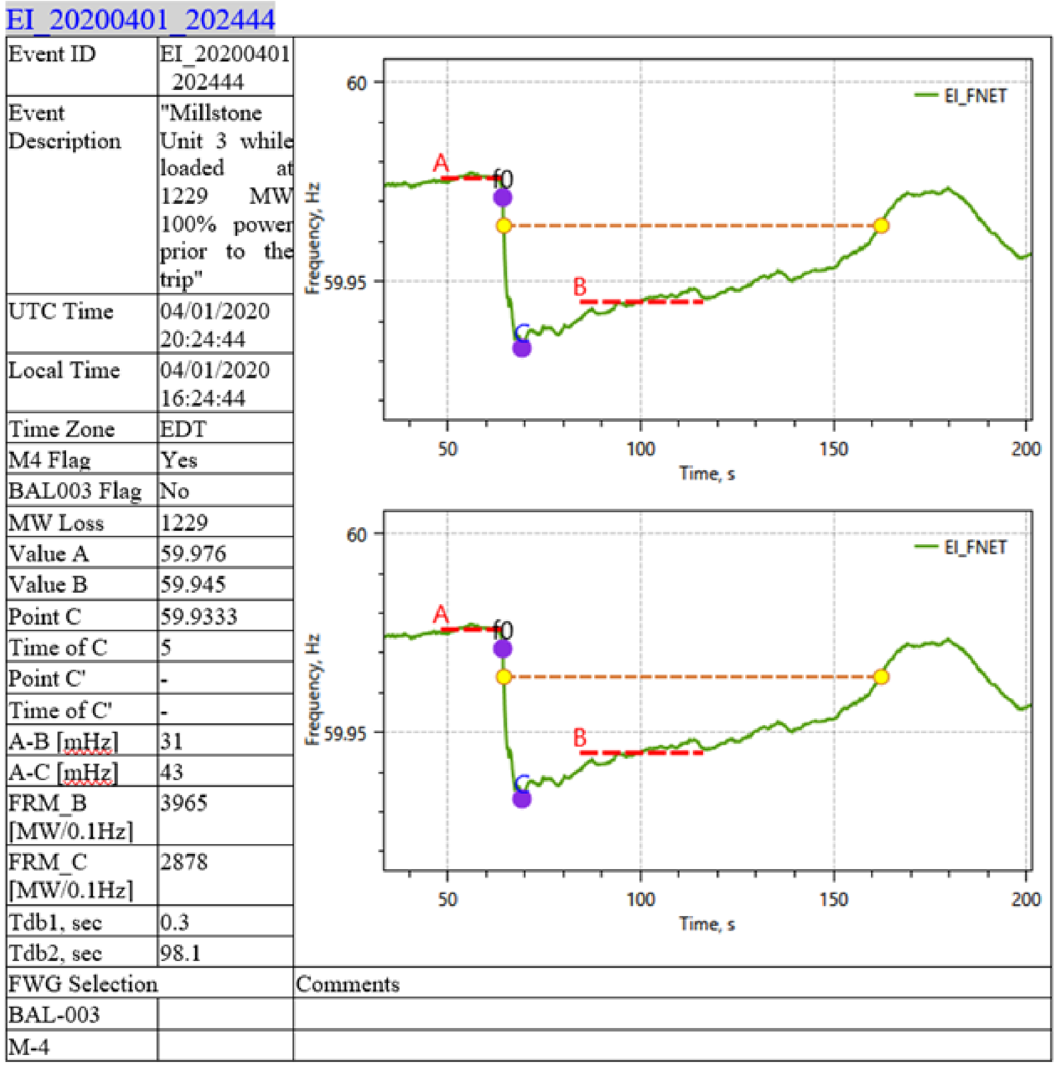
2.7.2 Power System Response with PSH

At 4:15pm on April 1, 2020, a fault in the switchyard of a New England nuclear plant caused the plant to trip offline. Despite the loss of over 1,200 MW of power, the equivalent of nearly half a million homes, the lights throughout the region didn't even flicker. The conventional hydropower fleet with fast regulating capabilities on the New England grid were certainly of assistance. However, only because the region's two PSH facilities (Bear Swamp and Northfield Mountain) instantly generated power was it possible to make up the shortfall.

Instead of a shortfall leaving hundreds of thousands of households without power, to most citizens in New England, nothing happened. Only power system engineers saw the details in Figure 12.



ISO New England Fuel Mix Graph 4/1/20



EI_20200401_202444

Event ID	EI_20200401 202444
Event Description	"Millstone Unit 3 while loaded at 1229 MW 100% power prior to the trip"
UTC Time	04/01/2020 20:24:44
Local Time	04/01/2020 16:24:44
Time Zone	EDT
M4 Flag	Yes
BAL003 Flag	No
MW Loss	1229
Value A	59.976
Value B	59.945
Point C	59.9333
Time of C	5
Point C'	-
Time of C'	-
A-B [mHz]	31
A-C [mHz]	43
FRM_B [MW/0.1Hz]	3965
FRM_C [MW/0.1Hz]	2878
Tdb1, sec	0.3
Tdb2, sec	98.1

FWG Selection		Comments
BAL-003		
M-4		

Figure 12 “Non-Event” in New England when 1,200 MW Dropped off the Grid in April 2020[9]

2.8 Storage Technologies in Comparison

Conventional hydropower reservoirs play a big role in grid scale storage in regions where hydropower is abundant and in some markets that are interconnected with these regions. However, the development of new conventional hydropower facilities with reservoir storage is facing many constraints, potential sites are few and generally far from load centers and PSH as well as other storage technologies are essential to allow the integration of wind and solar generation in the context of growing demand.

Besides PSH, other technologies compete for the storage market, yet with other technical, environmental and cost attributes. These are summarized in Table 6 for a 100MW/0.4GWh and for a 1,000MW/10GWh storage facility.

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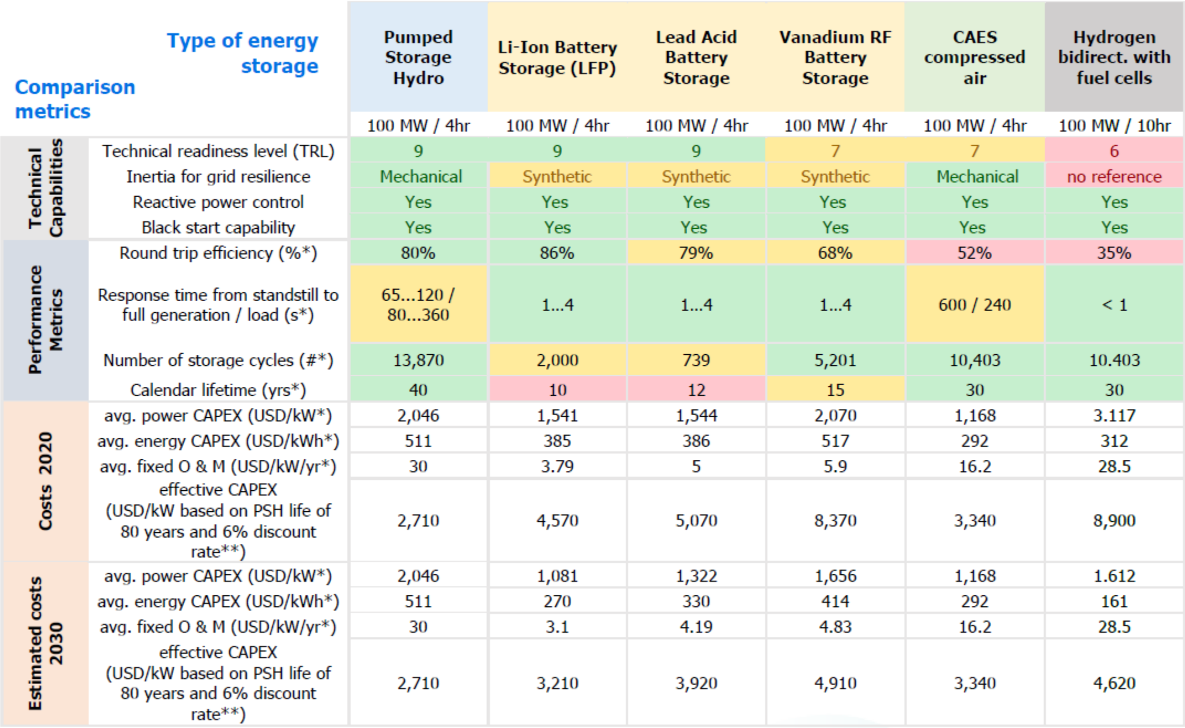
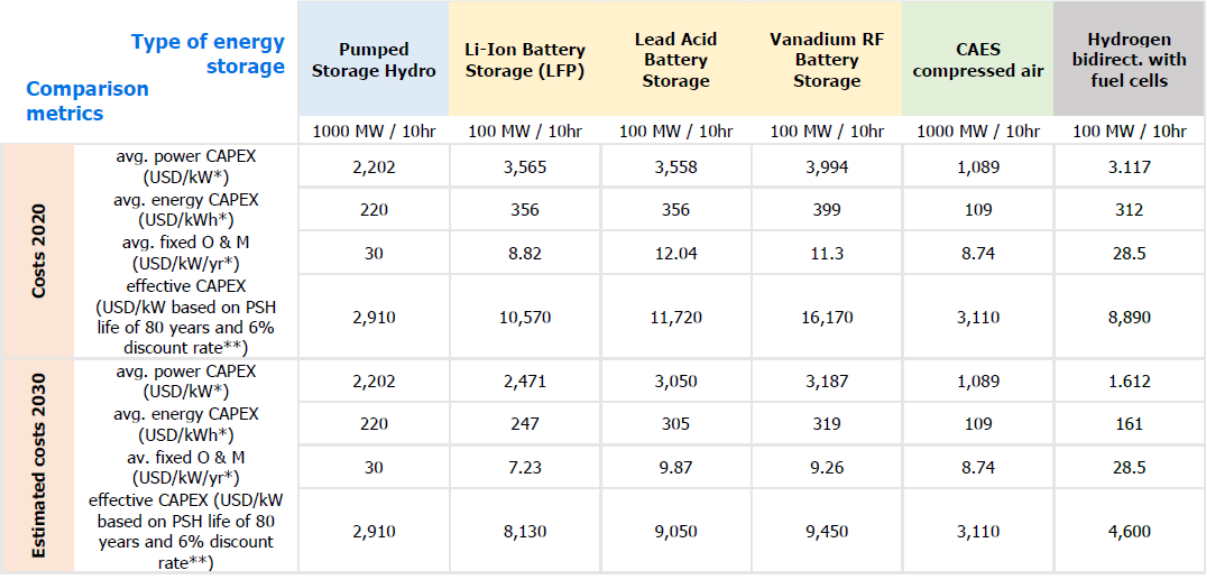
[9] NERC FNET/FRAT event plot the event starting frequency was 59.976 Hz and lowest frequency was 59.9333 Hz. the lowest local frequency response was 59.84 Hz

Table 6 Attributes of Different Storage Technologies for 100MW/0.4GWh and 1000MW/10GWh



Comparison metrics	Type of energy storage	Pumped Storage Hydro	Li-Ion Battery Storage (LFP)	Lead Acid Battery Storage	Vanadium RF Battery Storage	CAES compressed air	Hydrogen bidirect. with fuel cells
		100 MW / 4hr	100 MW / 4hr	100 MW / 4hr	100 MW / 4hr	100 MW / 4hr	100 MW / 10hr
Technical Capabilities	Technical readiness level (TRL)	9	9	9	7	7	6
	Inertia for grid resilience	Mechanical	Synthetic	Synthetic	Synthetic	Mechanical	no reference
	Reactive power control	Yes	Yes	Yes	Yes	Yes	Yes
	Black start capability	Yes	Yes	Yes	Yes	Yes	Yes
Performance Metrics	Round trip efficiency (%*)	80%	86%	79%	68%	52%	35%
	Response time from standstill to full generation / load (s*)	65…120 / 80…360	1…4	1…4	1…4	600 / 240	< 1
	Number of storage cycles (#*)	13,870	2,000	739	5,201	10,403	10.403
	Calendar lifetime (yrs*)	40	10	12	15	30	30
Costs 2020	avg. power CAPEX (USD/kW*)	2,046	1,541	1,544	2,070	1,168	3.117
	avg. energy CAPEX (USD/kWh*)	511	385	386	517	292	312
	avg. fixed O & M (USD/kW/yr*)	30	3.79	5	5.9	16.2	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,710	4,570	5,070	8,370	3,340	8,900
Estimated costs 2030	avg. power CAPEX (USD/kW*)	2,046	1,081	1,322	1,656	1,168	1.612
	avg. energy CAPEX (USD/kWh*)	511	270	330	414	292	161
	avg. fixed O & M (USD/kW/yr*)	30	3.1	4.19	4.83	16.2	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,710	3,210	3,920	4,910	3,340	4,620



Comparison metrics	Type of energy storage	Pumped Storage Hydro	Li-Ion Battery Storage (LFP)	Lead Acid Battery Storage	Vanadium RF Battery Storage	CAES compressed air	Hydrogen bidirect. with fuel cells
		1000 MW / 10hr	100 MW / 10hr	100 MW / 10hr	100 MW / 10hr	1000 MW / 10hr	100 MW / 10hr
Costs 2020	avg. power CAPEX (USD/kW*)	2,202	3,565	3,558	3,994	1,089	3.117
	avg. energy CAPEX (USD/kWh*)	220	356	356	399	109	312
	avg. fixed O & M (USD/kW/yr*)	30	8.82	12.04	11.3	8.74	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,910	10,570	11,720	16,170	3,110	8,890
Estimated costs 2030	avg. power CAPEX (USD/kW*)	2,202	2,471	3,050	3,187	1,089	1.612
	avg. energy CAPEX (USD/kWh*)	220	247	305	319	109	161
	av. fixed O & M (USD/kW/yr*)	30	7.23	9.87	9.26	8.74	28.5
	effective CAPEX (USD/kW based on PSH life of 80 years and 6% discount rate**)	2,910	8,130	9,050	9,450	3,110	4,600

* Source: US DOE, 2020 Grid Energy Storage Technology Cost and Performance Assessment
** Estimation based on the value of initial investment at end of lifetime including the replacement cost at every end of life period.

PSH is not only the most mature and proven technology among the contenders but also emerges as most cost effective for the larger sites (with the exception of CAES which has never been built at scale).

3. PUMPED STORAGE PROJECTS UNDER DEVELOPMENT

Known activity in development of PSH sites across Canada is limited to few provinces as shown in Table 7. The total cumulative installed capacity is just over 7,000 MW and a total of 107 GWh energy storage, or a tiny fraction of the practical potential identified.

Some of these sites are in the early development stage of project initiation while others appear construction ready as soon as environmental permits, interconnection agreements and investment decisions are confirmed. With the exception of one project in the initiation stage in British Columbia that is meant to serve the Alberta market, all sites are either in Alberta or Ontario where the power market is conducive to PSH developments.

Ontario features the largest amount of known PSH under development among the provinces. Steep Rock PSH, Schreiber PSH, Meaford PSH and Marmora PSH are all being positioned for consideration by the IESO for assessment of their merit to the Ontario power grid.

Table 7 Known PSH Projects under Development[10]

Name	Province	Head [m]	Installed Capacity [MW]	Energy Storage [GWh]
Canyon Creek PS	AB	500	75	3
Meaford PS	ON	180	1,000	8
Marmora PS	ON	260	400	2
Schreiber PS	ON	155	333	2
Steep Rock PS	ON	130	900	6
Tent Mountain PS	AB	300	320	2
Hydro Battery PS	BC	1,285	4,000	84
Total			7,028	107

In addition, Yukon Energy Corp has Moon Lake PSH on their list of potential future projects without specifying the ratings for this project.

The fact that so many PSH projects are under active development across several provinces and with substantial amounts of development efforts and investment attests to energy companies believing in the merit of the technology.

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[10] Note that throughout the development process the head, capacity and energy storage values may change with progress in planning, definition and implementation of a project.

4. POTENTIAL FOR FURTHER DEVELOPMENT OF PUMPED STORAGE PROJECTS

The purpose of this study is to document that great potential for further development of PSH exists in Canada and to identify the regions of the country that have higher potential.

Stantec's approach to undertaking the study and delivering the intended work product involves four steps:

- Theoretical Potential: Identification of a body of candidate PSH development sites considering all of Canada using a structured search tool and Stantec's knowledge and contacts in the Canadian hydropower industry.
- Feasibility Factors: Identification of factors that transform the established theoretical potential into a set of projects as a result of assessment and filtering for various conditions or considerations that would reduce the likelihood of project constructability. Appendix D gives further descriptions how the Feasibility Factors were applied. Some sites may be attractive for reasons that have not been identified in the study and that could override the filtering exercise such as strong community interest, transmission being built closer to the site for other reasons, calls for market supply to address resource adequacy or specific grid requirements.
- Realistic Potential: Application of successively restrictive screening criteria, the above Feasibility Factors, to reduce the number of candidate sites, with an objective to balance the number of identified sites with an eye toward geographic diversity, which may imply differing criteria for differing areas of the country to obtain an inventory of sites that is balanced across the country. The end result will identify sites that show promise for successful development and execution, including their relative importance in the process.
- Interpretation and Presentation: Interactively working with WaterPower Canada and industry leaders to understand, describe and report the technologies, factors and strategic implications that will have emerged from the previous step to arrive at a feasible set of PSH sites across Canadian geographies.

The following sub-sections describe each step in more detail and, in particular, discuss those Feasibility Factors that were found to be relevant.

4.1 THEORETICAL POTENTIAL

Identification of the Theoretical Potential is largely based on prior work done by the Australian National University (ANU). The data is publicly available in the form of GIS maps but bringing ANU into the study alliance has yielded the benefit of access to the underlying data base and algorithms for adaptation to the Canadian context.

ANU has developed a holistic methodology which relates PSH to population centers, the wind resource and the solar resource. The advantage of this approach is that PSH is clearly seen in relation to the technology that it will support, and work best in collaboration with solar and wind.

The ANU Atlas is unique in its scope, but it needs to be clearly stated that it is not comprehensive in that certain sites are not mapped. The sites in Canada that were omitted in the atlas include:

- Sites North of the 60th Parallel in Yukon, Northwest Territories and Nunavut
- Sites around the Great Lakes that are strictly speaking not closed loop sites because of their connection to a natural waterbody as lower reservoir
- Sites at abandoned mine sites where a potential reservoir does not show up in the mapped topography

However, showing fewer sites than theoretically available is not considered a major drawback in the context of the objective of the study to show a conservative set of potential sites available for development.

Figure 13 shows a sample of the ANU Global PSH Atlas for the Canadian geography with concentration of attractive sites towards the Rocky Mountains and in Atlantic Canada.

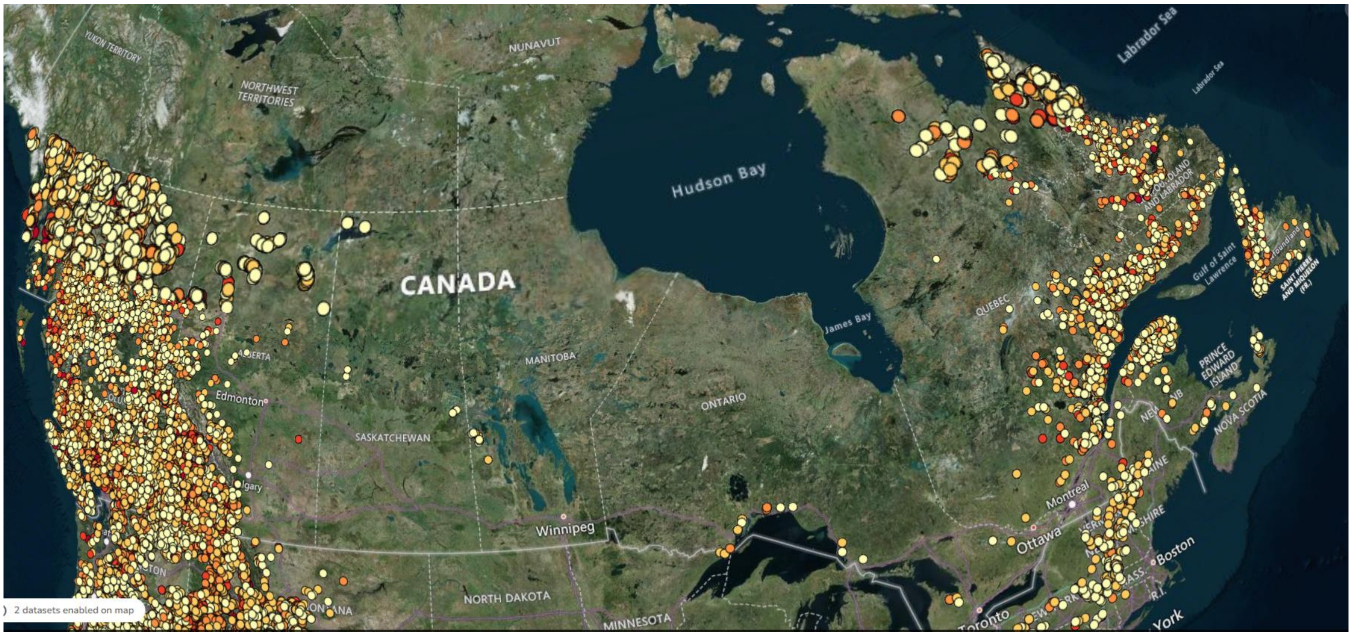


Figure 13 Canadian Window into Global PSH Atlas from ANU

Sites are classified with the redder dots indicating superior sites.

4.1.1 Use of GIS Tools

ArcGIS Pro is the application used in this study to explore, visualize and analyze data. The software supports data visualization and advanced analysis. ArcGIS Pro is the latest professional GIS application released by ESRI. The Near tool, part of the ArcGIS Pro Intersect Analysis tool package was used to calculate distances from related datasets like provincial transmission lines and the Canadian road and highway network. The tool produces an attribute table relating both feature classes and will provide the exact distance from one feature class to another. The tool can also determine the closest line from a point if there are multiple lines in a feature class. The Intersect Analysis tool was used to relate geographic areas in Canada to potential PSH sites.

- ArcGIS was used to connect each province’s transmission network to potential PSH sites in the province. The Near tool was used to determine the distance from transmission lines to each potential PSH site. Each site found the closest transmission line that could support the required load, i.e., a line of adequate voltage level for the power rating of the site, and connection to the corresponding provincial power system.
- Finding the distance to roads was necessary to determine the accessibility of potential sites to deliver materials and equipment. The National Road Network for Canada, provided by the Federal Government's Open Data portal, was used to find the distance from potential sites to the nearest road to determine the extra cost needed to access the site by vehicle.
- The original GIS Analysis from the ANU study avoided built-up cities and protected areas like national parks in their analysis. The database used to determine this information was the Canadian Protected and Conserved Areas Database (CPCAD). The available geospatial data contained national reporting for protected areas obtained from Canadian Environmental Sustainability Indicators (CESI), Federal Sustainable Development Strategy (FSDS) progress reports and Canadian Protected Areas Status Reports. The protected areas included conservation areas, national parks, wildlife habitat areas, old growth management areas, proposed biodiversity reserves, and Sea to Sky wildland zones. All protected lands were considered to equally increase the timeline the PSH project. Land of indigenous concern were treated in a separate step (see below).

- Used an available GIS layer shared by the Canadian government to determine rock quality at each site. Sites were filtered using the Intersect Analysis tool to determine between Canadian Shield geology or softer rock at the site.
- ArcGIS Pro was used to find potential sites that were within Indigenous reserve boundaries. Upstream and downstream sites were intersected with the GIS layer to determine sites that are on Indigenous land and therefore not a viable location for PSH development to err on the conservative side regarding Realistic Potential.
- The Near tool was used to determine areas with an abundance of permafrost. Used the resource titled “All Sites Permafrost, Atlas of Canada, 5th Edition”. Filtered for continuous and extensive discontinuous permafrost with low to medium ground ice content.

4.2 FEASIBILITY FACTORS

The following Feasibility Factors were explicitly used to filter the Theoretical Potential:

- Transmission Costs and Constraints
- Environmental, Social and Governance (ESG) Constraints
- Constructability Costs
- Technology Costs

Two very important feasibility factors which must be considered when determining where a pumped storage plant could be implemented are: First, having the site geography and water resources necessary that lend itself to being a reasonable site for the plant, its storage reservoir and hydraulic resources, and second, perhaps just as important, having the excess power and associated infrastructure necessary to actually power the pumps themselves.

PSH plants can be some of the largest localized load centers depending on the plants total power output/input that can only be placed in a location on the grid that has the capacity to absorb generation output and supply pump power. Nor would it make any sense to build a large load center in an area where providing the power input is excessively expensive where the plant could not differentiate itself from peak and nominal prices of energy such that the plant is not able to perform economic benefits in addition to its function.

Further elaboration of the Feasibility Factors can be found in Table 5.

Table 5 Feasibility factors/consideration for successful pumped storage hydro schemes

Characteristic	Preferred Situation	Rationale
Head	Maximum differential	Minimizes costs, reservoir size, tunnel diameters, powerhouse dimensions, and equipment size
Length of water conduits	Minimum total length	Minimizes costs and project footprint
Topography	Varied topography	Allows for reservoir construction with minimal excavation or embankments
Geology	Sound, unfractured, consistent, limited faulting	Limits reservoir leakage and foundation preparation requirements; provides suitable local construction materials
Power capacity	Maximum megawatts	Increases revenue potential
Energy storage potential	Maximum MWh	Increases revenue potential and operational flexibility
Construction	Simple access, standard duration	Minimizes costs
Water availability	Plentiful, available, and nearby	Reduces costs and risk exposure for filling and replenishment water
Environmental, regulatory, and land use	Closed loop, limited environ./reg. exposure, desirable land ownership	Reduces costs, risk exposure, permitting requirements, and development duration
Transmission	Nearby and available transmission capacity	Reduces potential costs of new T-lines and/or grid upgrades
Power marketing	Large spreads, suitable partnership opportunities, multiple offtakers	Increases revenue potential and ease of marketing; reduces risk exposure

4.2.1 Transmission Constraints

4.2.1.1 General Transmission Considerations

Transmission systems are critically important to integrate renewables and pumped storage hydro into the electric power system. Favourable sites for renewable energy sources and pumped storage hydro may be far away from load centers and from suitable transmission infrastructure. As well, sites for renewables may not be close to sites for pumped storage hydro. Upgrades to existing transmission facilities and new transmission facilities may be required to accommodate pumped storage and renewables. Power system studies will identify the specific transmission requirements to interconnect and support pump storage and renewables.

The North American bulk power system is made up of four major electric networks, termed Interconnections, as shown in Figure 14. Each Interconnection is a synchronous system within itself but is asynchronous as compared to its neighboring Interconnections. The bulk power system is also divided into several regional reliability councils. The Canadian electrical grids are divided by provinces due to the provincial governments historically having responsibility for power transmission. Most of the provinces and territories are still regulated industries, except for Alberta and Ontario, which were de-regulated. British Columbia and Alberta are part of the Western Interconnection of North America and the Western Electricity coordinating Council (WECC). Saskatchewan and Manitoba are part of the Eastern Interconnection of North America and the Midwest Reliability Organization (MRO). Ontario, Quebec, New Brunswick, and Nova Scotia are part of the Northeast Power Coordinating Council (NPCC). Prince Edward Island and Newfoundland are not part of any of the regional electrical reliability councils. Ontario, New Brunswick, Nova Scotia, and Prince Edward Island are part of the Eastern Interconnection. Quebec is asynchronous to all other jurisdictions except mainland Labrador and forms its own Interconnection. The island of Newfoundland is also asynchronous to other jurisdictions and forms the Island Interconnected System.

Figure 14 shows the synchronous interconnections in North America and the regional electric reliability councils. While NL has not signed on with NERC, the Island of Newfoundland is connected to Labrador with a 900-MW Labrador - Island Link and Newfoundland is connected to Nova Scotia with the 500-MW Maritime Link. The interconnection in the Canadian territories in the North (YK, NT & NU) are not relevant in this study because no Theoretical Potential has been identified there by ANU.

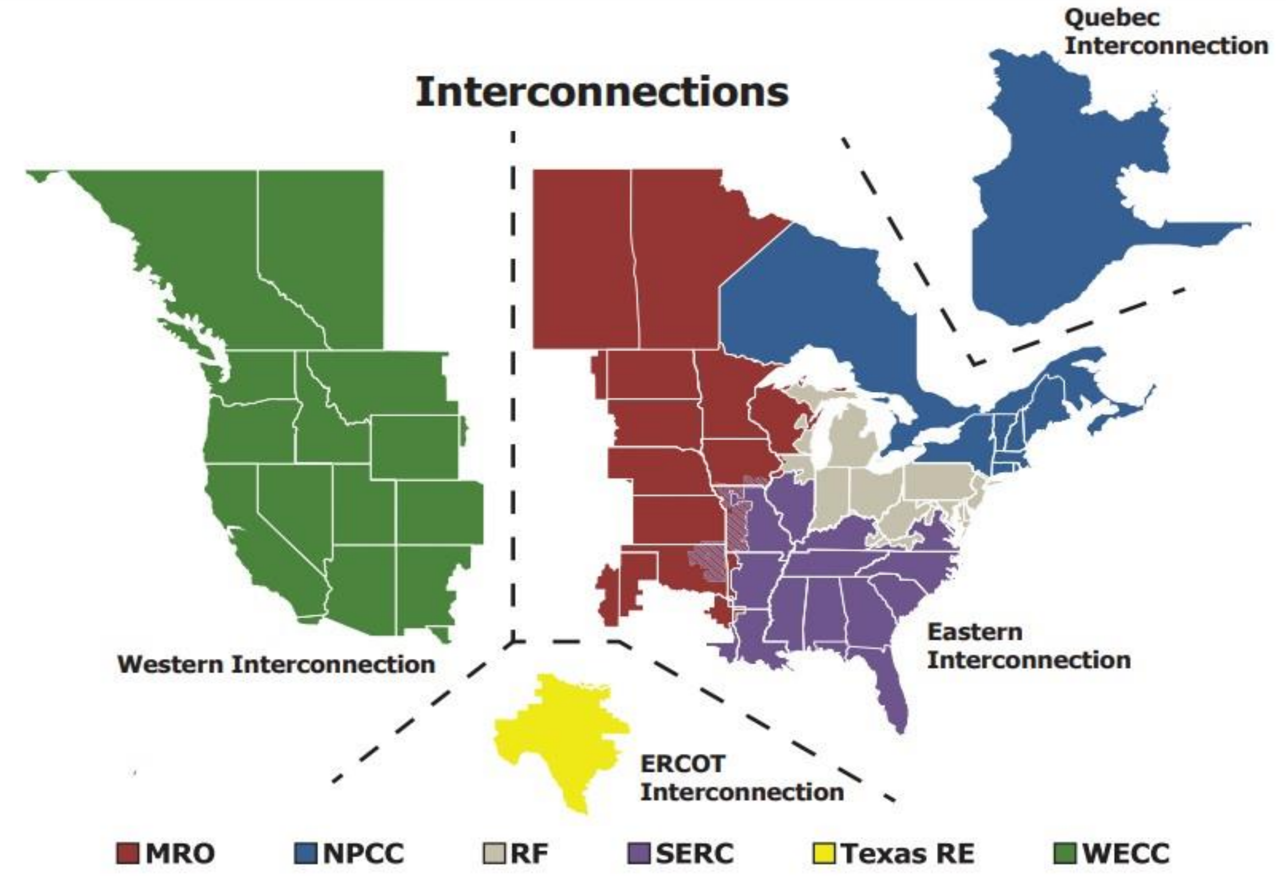
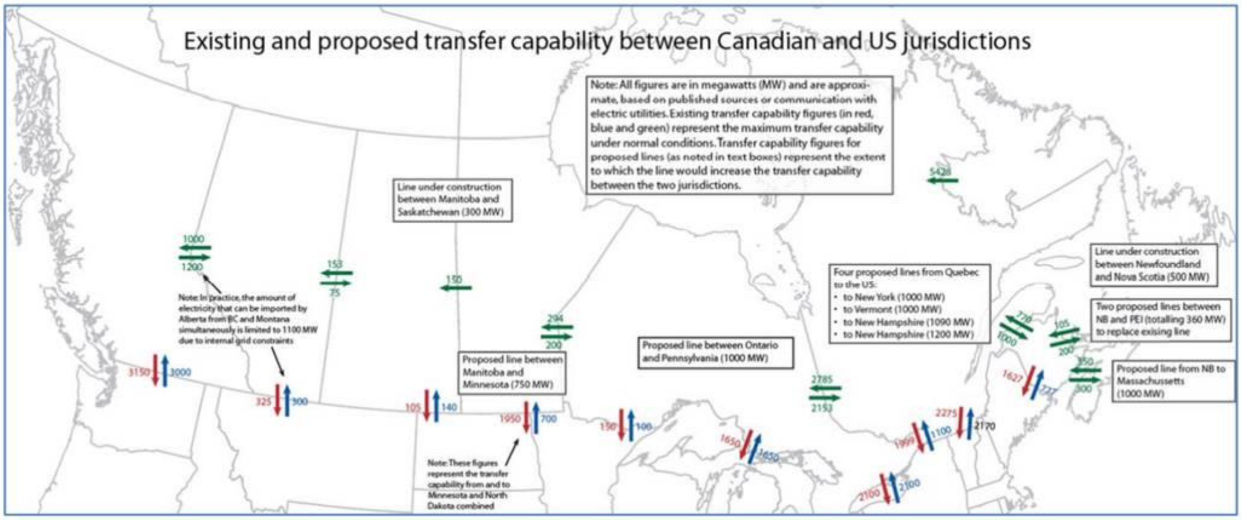


Figure 14 North American Interconnections and Reliability Councils [11]

Figure 15 shows the transfer capability of existing transmission infrastructure between the provinces and from Canada to the United States. Interconnection requests and approval from both power system operators and transmission owners is required to be able to connect to existing transmission infrastructure.


Existing and proposed transfer capability between Canadian and US jurisdictions

Note: All figures are in megawatts (MW) and are approximate, based on published sources or communication with electric utilities. Existing transfer capability figures (in red, blue and green) represent the maximum transfer capability under normal conditions. Transfer capability figures for proposed lines (as noted in text boxes) represent the extent to which the line would increase the transfer capability between the two jurisdictions.

Line under construction between Manitoba and Saskatchewan (300 MW)

Note: In practice, the amount of electricity that can be imported by Alberta from BC and Montana simultaneously is limited to 1100 MW due to internal grid constraints

Proposed line between Manitoba and Minnesota (750 MW)

Note: These figures represent the transfer capability from and to Minnesota and North Dakota combined

Proposed line between Ontario and Pennsylvania (1000 MW)

Four proposed lines from Quebec to the US:
- to New York (1000 MW)
- to Vermont (1000 MW)
- to New Hampshire (1090 MW)
- to New Hampshire (1200 MW)

Line under construction between Newfoundland and Nova Scotia (500 MW)

Two proposed lines between NB and PEI (totalling 360 MW) to replace exising line

Proposed line from NB to Massachussetts (1000 MW)

Figure 15 Existing and Proposed Transfer Capability between Canadian and US Jurisdictions [12]

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[11] https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/NERC%20Interconnections.pdf

[12] Report of the Standing Committee on Natural Resources on Strategic Electricity Interties (page 8), December 2017. rnnrrp07-e.pdf (ourcommons.ca)

4.2.1.2 *Application of Feasibility Factor Transmission*

To apply a feasibility factor related to costs of transmission line construction and interconnection, a simplistic approach was adopted to be able to deal with the substantial number of theoretically possible PSH sites. This approach assigned a required line voltage according to the installed PSH capacity and derived costs from this line voltage and the distance to the nearest line as shown in Table 8. One substation is assumed per proposed pump storage facility in this analysis.

Table 8 Interconnection Costs

Installed PSH Capacity [MW]	Nominal Line Voltage [kV]	Line Construction Cost [CAD/km]	Substation Cost [CAD]
65	69	$1,100,000	$7,500,000
140	115	$1,200,000	$8,300,000
600	230	$1,400,000	$11,000,000
1000	345	$2,200,000	$16,000,000
2000	500	$2,800,000	$23,000,000
3700	735	$3,200,000	$47,000,000

Factors that would need to be considered for a specific site to refine the analysis include:

- Costs will be dependent on jurisdiction and terrain of the transmission line.
- The line capacities will be dependent on the conductor selected and the length of the line. Surge impedance loading impacts the amount of power that can be transmitted on a line and is related to the length of the line. The capacities in Table 8 can be assumed for a line length of approximately 100 km, with greater power capacities for shorter lines and lower power capacities for longer lines.
- Only single circuit lines have been considered in this analysis, for simplicity.

Transmission projects can have long project timelines from initiation of feasibilities studies to commercial operation/in-service date. The following factors will contribute to the project timeline:Table 9

- Number of jurisdictions/regulatory bodies
- Terrain complexity
- Remoteness
- Number of impacted private landowners
- Environmental issues along the route
- Length of line
- Indigenous relations
- Number of navigable waterways

In Canada, energy infrastructure projects involving overhead transmission lines generally require entering an environmental assessment (EA) process before advancing to permitting and development stages. Based on the current Federal, Provincial and Territorial EA legislation and regulatory regimes of Canada, EA processes and associated timelines vary by jurisdiction and the Project location, duration, and type. Proponents will be required to conduct baseline data collection and Indigenous and public engagement as part of the EA process and to support the development of regulatory filings. Site specific factors and consultation concerns can also impact the length of time required to collect baseline data and conduct engagement programs. The average timeline for baseline data collection, engagement, and the development and submission of regulatory filings is approximated to be 3 years for studies and 5 years for environmental assessment. With this estimate, the potential sites can be developed within the 2035 window of opportunity for Net Zero Targets.

Generally, transmission projects can be completed from commencement of studies to commissioning within approximately 10 years; however, in future it is anticipated that consultation and permitting requirements will become more complex and will likely extend project timelines.

For the sole purpose of providing a quantifiable factor in the analysis and given two project timelines of 2035 and 2050, it was assumed that projects with transmission lines less than 500 km could be completed by 2035 and project with lines greater than 500 km could be completed by 2050, as shown in Table 9 Projected Project Timeline based on Line LengthTable 9.

Table 9 Projected Project Timeline based on Line Length

Transmission Line Length (km)	Projected Project Timeline
Less than 500	**By 2035**
Greater than 500	**By 2050**

4.2.2 Environmental, Social and Governance Considerations

4.2.2.1 General ESG Considerations

Environmental and social factors along with issues related to organizational governance, can play significant roles in determining the feasibility of a development. The importance of environmental factors is due to the fact that potential sites have existing ecosystem function and key physical factors that support that function. The environment at a proposed site may possess components that may be negatively impacted by the activities associated with the development or may in turn have components which may negatively impact one or more phases of the proposed development. These potential negative interactions are constraints that need to be considered.

For the purposes of this study, the relative potential impact of development on valued environmental components at each location that was considered. The uniqueness and importance of the ecological function of a potential location will vary. Typically, the more disturbed (previously developed) an area is, the less likelihood there is of that location having significant environmental features requiring preservation and the less likely that development will cause significant new impacts.

Within each province, there are species and their associated habitat that are ascribed different levels of protection under regulation. Additionally, there are federally listed species (and their habitat) which are protected by regulations. The potential or confirmed presence of these species and habitat at a proposed site would warrant more detailed assessments with the potential to impose either partial or total exclusion of the site as a candidate. The option may also exist for the anticipated impact to these species and their habitat to be offset. Any offsetting plan would be developed in conjunction with the relevant regulatory authority(ies).

Existing water courses and waterbodies will not be utilized as reservoirs for the proposed developments as they are not included in the Theoretical Potential data base. However, filling make-up water may be drawn from them. How the reservoirs interact with waterbodies and water courses with their fish communities and fish habitat and the potential impacts to water quality and quantity will be critical environmental components to be considered during the screening study.

Specific environmental features may include:

- Presence of critical habitat

- Areas of special Concern
- Occurrence of Species at Risk (SAR)
- Flora and fauna
- Fish and Fish habitat
- Water courses and Waterbodies

Social factors are of comparable significance to those of the physical environment. In fact, these social factors have proven to be critical constraints especially with large-scale developments involving new or less popular technologies.

For any proposed location, the existing land uses and the potential impact on these uses by the development will be issues of considerable significance. Areas with high recreational and or heritage value will be more severely impacted than more remote low-use areas. Proposed development in areas which are popular for recreation or have high aesthetic value are more likely to face strong, organized opposition by stakeholders and members of the public. There are also social factors which are not necessarily associated with location-specific issues, but rather arise from higher-level prevailing perspectives or conditions. These may include public sentiment associated with aspects such as the sustainability or ethicality of the procurement methods of certain components. Fluctuating supply and demand as well as geopolitical issues are also social factors which may impact development despite not being location specific.

Indigenous engagement and protection of indigenous rights are regulated by Canada's Constitution Act, Section 35, federal law as well as provincial and territorial legislation. Indigenous rights under federal law were further strengthened in 2021 by the passage of the United Nations Declaration on the Rights of Indigenous Peoples Act (UNDRIP Act). The location of any proposed site within the boundaries of indigenous traditional land (disputed, ceded or unceded) will require varying levels of engagement. Where a proposed site impinges on sacred areas or other areas that may be of special significance to indigenous communities this may partially or completely disqualify the site. There are numerous ongoing legal cases related to indigenous land claims across Canada. Typically, a location which is under legal dispute or previously been the cause of conflict would be less desirable for development. Indian Reserves, specified by the federal *Indian Act,* are areas which are federally owned, but are set aside for First Nations (an indigenous people), after contract with the Canadian Crown. These reserves are surveyed areas with defined boundaries.

Each province has its own legislation related to the use of water resources. Such legislation covers issues such as equitable sharing of the resource among users. The existing water resource users and the potential impact of development will need to be taken into consideration.

Specific social issues may include:

- Existing land use
- Water Resource Use
- Aesthetics
- Traditional indigenous Uses
- First Nation Reserve
- Land claims/treaty rights
- Public and stakeholder sentiment (anticipated degree of opposition)

In order to complete the environmental and social feasibility screening, environmental and social data from each of the identified sites was collected and reviewed. Existing federal, provincial or regional databases were consulted. Available interactive GIS resources were also examined. Indigenous treaty boundaries, traditional territory maps and land claim archives were consulted.

In addition to the physical environmental and social issues noted above, the relevant provincial and federal regulatory processes that will be applicable to each site will also be considered, as these can have significant impacts on both cost and schedule of any proposed development. All provinces have environmental assessment and permitting processes which are required for hydro development and operation. Depending on the location and potential impacts, federal assessment and permitting may also be required. The greater the anticipated impact to the existing physical and social environment, and if the project capacity exceeds the 200-MW trigger in the federal Impact Assessment Act, the more detailed and complex the regulatory processes will likely be. The complexity of regulatory processes may vary among provinces even for similar developments. In reviewing the proposed sites for realistic feasibility, the ease of permitting was factored in and applied as part of the screening.

The organizational governance of any proponent of a PSH project, as well as the levels of governments responsible for approvals, advocate agencies and constructors will have to credibly earn the social license with host communities and stakeholders. This necessitates to not only adhere to prevailing standards, laws and regulations but to present a reasonable level of transparency, to operate in an ethical manner, to solicit early and regular stakeholder input and to be a conduit that seeks to function for the common good, in this case the striving to reduce GHG emissions.

4.2.2.2 Application of ESG Feasibility Factors

The intent of the screening of potential development locations was to:

1. Eliminate sites that were considered unlikely/impossible to develop because of ESG issues considered to be so significant or contentious that it would be difficult to justify any effort in their pursuit. These were considered ‘No-Go’ sites.
2. Identify sites that would likely have more complex or prolonged permitting processes, due to potential ESG issues, with this prolonged permitting process delaying their development until closer to 2050.
3. Identify sites that would likely have simpler/shorter permitting processes, due to potential ESG issues which may be more commonplace, less significant or less contentious, with these shorter permitting processes allowing their development sometime between the present and 2035.

The following feasibility factors were applied:

1. First Nation Reserve Lands

   First Nation Reserves lie within legally surveyed boundaries, are federally owned, set aside for First Nation band use, and administered by the Chief(s) and Council(s) of the specified band(s). Any proposed use of reserve land would meet numerous legal and social hurdles which would be very difficult to overcome. Therefore, where potential sites which encroached on Reserve Lands, they were eliminated from further consideration.

2. Protected Lands

   Lands may be protected by different levels of government for several reasons. Federal, provincial and municipal governments may accord different levels of significance and protection to lands. These lands may have ecological, geographical, cultural or social significance. For the purpose of this study, protected lands, such as National Parks, have been excluded.

For the purposes of the study, potential sites that were neither First Nation Reserves nor on protected lands were considered to be subject to a shorter, less difficult permitting process, with better chances of being developed between the present and 2035. Sites on First Nations reserves were considered infeasible but those on protected lands potentially feasible, subject to a longer permitting process which generally made then infeasible for cost reasons. While these high-level screening factors were applied, it should be noted that any proposed project would likely be subject to a provincial and/or federal environmental assessment process which would identify the site-specific impacts that would need to be addressed prior to the issue of any permits.

4.2.3 Constructability

4.2.3.1 General Constructability Considerations

The development of a PSH project involves many construction activities covering several different disciplines. Construction approaches are developed from very early in the project planning stages, for example, in contracting method to be used, in construction staging, for sourcing appropriate local materials and ways to mitigate access, foundation, and geotechnical risk.

The unique site considerations and constructability factors associated with a potential pumped storage site have significant effects on its feasibility, and detailed studies and analysis will be required to confirm the feasibility of any given potential project. These specific activities are beyond the scope of this screening study. Conversely, this study will identify prospective locations where further detailed investigations, analyses, and studies can be undertaken to better define their individual feasibility.

Constructability analyses assist in identifying and quantifying risk through cost estimating and scheduling to establish Commercial Operation Date through technical and economic feasibility.

Site considerations and constructability have a major influence on the feasibility of a project. Constructability considerations pertain to an understanding of the constraints to scope and schedule and the costs of implementation. These constraints must consider input from all stakeholders.

We note the importance of a predictable environmental assessment process, the need to have realistic cost and schedule estimates (working backwards from a preordained in-service date may not be good practice).

The simplifications applied in this feasibility screening study, on review, must be refined and added to. At the refinement stage it is important to select sites for practicality and permitting criteria. The constructability factors may be refined with stakeholders in conjunction with the environmental factors. Sites need to be LIDAR surveyed and examined by competent engineers and contractors.

The importance of completed design work, experienced contractors, available skilled and productive workforce, and an effective supply chain are paramount for safety and efficiency.

Efficiency and reliability objectives must be set and met in practice. Merely because a project meets economic hurdles and can abate CO2 is not sufficient in itself, but the project must be planned properly, which can only be accomplished when permits and procurement proactively anticipate the sequencing of construction stages to get to commercial operation quickly - refer to An Action Plan for Solving our Climate Crisis Now | Speed & Scale (speedandscale.com). Prudent action starts with a comprehensive understanding of all the project phases and constraints.

4.2.3.2 Application of Feasibility Factor Constructability

A staged approach is always employed in hydroelectric design to permit risk identification, mitigation and appropriate layout and particularly geological understanding which will drive the construction methods and planning. To parse out site specific acceptability in our GIS in order to aid ranking from a constructability viewpoint, Stantec applied resultant cost multipliers or Go/No Go gates for the following:

- Presence or lack of permafrost – No Go decision implemented. Avoidance of permafrost areas is a key consideration in our GIS model. Permafrost excludes a great landmass in Canada's north. The head and thus energy storage potential in these areas is however limited.
- Road access, rail and proximity, hard rock – Cost increments applied. PSH projects involve transportation of very large amounts of materials and equipment, and rail access is likely preferred, however road networks are effective and particularly in areas where mining or logging infrastructure is already invested.

For rock surrounding the conveyance system and the underground powerhouse and caverns, a cost increment was applied in stronger rock for excavation effort, and this was applied for sites within the Canadian Shield. For each site that is identified, assessment and investigation of local geotechnical conditions will be necessary since these conditions are highly site specific and will be required for any major civil project execution.

4.2.4 Suitable Technology

4.2.4.1 General Technology Considerations

Hydraulic turbomachinery, hydro turbines and storage pumps, above a relatively small threshold size are custom designed for the hydraulic site conditions of head and flow. This custom design results in a wide variety of turbine types and configurations that have cost impacts on the project from the following main factors:

- Hydraulic head and variation thereof
- Power capacity requirements
- Operational requirements including number of units

Other elements, such as pump-turbine, or turbine and pump selection is usually undertaken during the detailed scope discussion.

Costs depend on selection of the shaft speed(s) and generator voltage which impact the size and costs of each motor and generator. It is noted that this selection is not independent of the hydraulic design mentioned above. Station step-up transformer costs are also somewhat impacted by this selection.

The selection of number of units also has cost implications and balance the operational needs with the initial capital costs through the quantity and size of individual pieces of equipment in the power train as well as balance of plant.

The setting of the hydraulic machines in elevation relative to ground and water levels affects civil costs. It addresses operational needs to protect against cavitation damage and impacts costs for excavation and powerhouse civil construction. A decision to construct the associated powerhouse above ground or underground will also influence costs. However, the decision can be one that aids in reducing other social implications.

Each site has its own complexities which deserves careful engineering analysis of hydraulic conditions, site arrangement and operational objectives to select the most appropriate technology for the site.

4.2.4.2 Application of Feasibility Factor Technology

To explicitly address the cost impact of technology selection in the feasibility screening a single predominant factor has been identified in the hydraulic head. At a threshold number of 500 m the reversible pump turbine which is the technology of choice for cost effective implementation of PSH becomes infeasible and a Francis-type reaction machine is no longer feasible in most cases and needs to make way to a Pelton-type impulse turbine. Inherently, impulse machines cannot reverse the flow direction from generating to pumping (a jet in free air cannot be reversed) and a multi-stage pump is typically required in pumping mode. In addition to this change in prime mover configuration, the costs associated with electrical equipment, hydraulic manifolds and balance of plant installation and construction increase substantially. In a high-level estimate a factor of 1.6 has been applied to the base costs of a reversible pump-turbine installation.

4.2.5 Energy Storage Potential

There is no specific rule for energy storage capability with respect to feasibility. However, Stantec’s experience is that developers and generation entities expect eight or more hours of continuous operation in the generating mode from a grid scale pumped storage hydropower project. In a few cases, developers may have been searching for as little as four hours, but to Stantec’s knowledge, such projects have not been developed. By comparison, grid scale battery storage projects have historically offered a one to two hours of continuous operation at rated capacity, but this is rapidly increasing as battery technology advances.

To provide an indication of the upper limit of battery capacity and storage, the Gateway project in San Diego, California, USA is designed to have a discharge capacity of 250 MW and a storage of between 1 to 1.5 GWh (4 to 6 hours of continuous operation). Source: pv-magazine.com, Aug 20, 2020.

Storage expressed in hours of continuous generation implies a relationship with the rated generation capacity of the facility. Grid scale pumped storage hydro projects generally have capacities more than 100 MW, although there is one facility in southern California USA with a nominal rating of 40 MW. This would imply that a discharge cycle of as little as 320 MWh might be an extreme lower limit on feasible grid scale PSH. The case cited here was an addition to an existing upper / lower reservoir combination and might not be generally indicative of the lower limit feasibility energy storage.

The desired amount of energy storage from a grid-scale closed-loop pumped storage hydro project is dependent upon the characteristics of the time-of-day energy value, grid reliability and the prevailing quantity and load profile of non-dispatchable capacity. It is difficult to generalize, but in wide area screening studies, Stantec had often used as an initial starting point a desired capacity of 500 MW with eight hours of continuous generation (4 GWh storage). The volume of water needed to support storage is naturally dependent upon the vertical distance between upper and lower reservoir. If the intent is to identify candidate sites in a screening study, then the process would be to establish the viable amount of water that could be stored within the upper and lower reservoir, and considering the vertical differential and a reasonable efficiency, determine the potential energy of specific candidate sites.

Hard feasibility criteria in terms of capacity and electrical energy per cycle or minimum generation time at full capacity have not been used in the assessment of the Realistic Potential but are implicit in the parametric cost equations used.

4.3 REALISTIC POTENTIAL

Determining the cumulative Realistic Potential, defined by WaterPower Canada as the possible power and energy capacity at a given site once feasibility factors have been considered, is a matter of applying the Feasibility Factors as a filter to the Theoretical Potential.

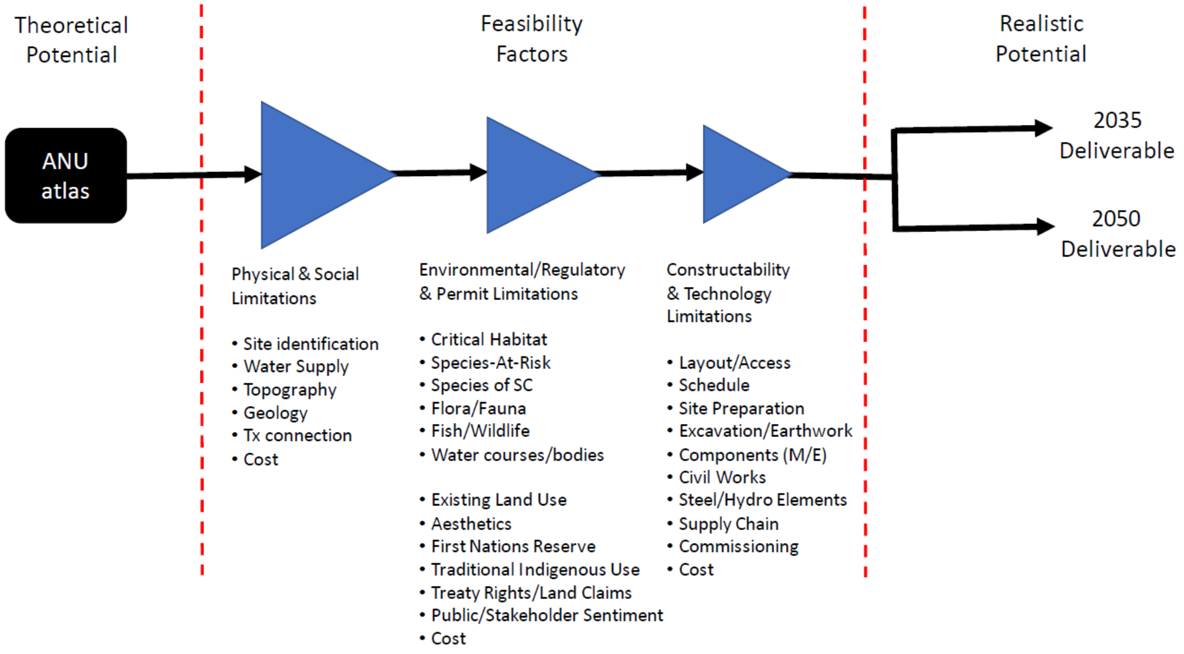


Figure 16 Flow Chart from Theoretical to Realistic Potential

In its simplest form the filtering process consists of determining the value to the system, and hence ratepayers, of each project by applying the Feasibility Factors and comparing then that value to a benchmark cost in each jurisdiction across Canada.

To temper this mechanistic approach Stantec has also engaged with major provincial and private hydroelectricity producers to discuss and assess their current approaches to fleet-wide investment. Discussions with First Nation groups, regulators and other stakeholders would reveal how opportunities in PSH development could contribute to the future clean, reliable and resilient grid.

4.4 INTERPRETATION OF RESULTS

The Realistic Potential of pumped storage hydro is quantifiable. Bounding the Realistic Potential to simply the revenue of the finished plants would be a mistake though, and a broader consideration must enter the intelligent discussion of findings. Below we highlight some of the items which would be considered in the discussion:

- Firming up non-dispatchable renewable energy sources and support their continued growth and penetration
- Making use of non-utilized baseload generation to assume pump load during off peak hours, preventing plant shutdowns, lowering start/stop costs, reducing unnecessary fuel loss and improving efficiency.
- Realize revenue from sale of energy, capacity and ancillary services
- Enable electrification of other industries
- Building capacity in host communities
- Opportunity for engaging Indigenous communities in partnership
- Carbon offsets and trading
- Local construction jobs
- New employment for skilled labour, specialists and support staff
- Taxes paid at municipal, provincial and federal level
- Benefit to supporting industries
- Local investment opportunities.

5. STUDY RESULTS WITH COMMENTARY

5.1 THEORETICAL POTENTIAL

Closed-loop type of PSH is the most common type under active development in Canada, and the only type considered for this study. Strictly speaking, this approach underestimates the number of potential sites, and is therefore, conservative in answering the central question of this study: Is the potential for PSH sufficient to fill the needs of our power systems?

5.1.1 Canada-Wide Theoretical Potential

Figure 17 shows a map of Canada with the Theoretical Potential sites indicated. The total count of sites amounts to well over 100,000 with a cumulative theoretical capacity of over 200 TW (200,000 GW), over 2000 times the existing installed capacity of conventional hydro in our country.

Clearly, this merely reflects the abundance of the country’s opportunity in fresh waterbodies and topographical relief. It constitutes an immense potential well beyond what Canada would ever require to be installed. And note that this immense resource is not equally distributed among the provinces but there is some potential everywhere except for Prince Edward Island. Further, the ANU data base does not include PSH sites North of Sixty in Nunavut, Yukon and Northwest Territories.

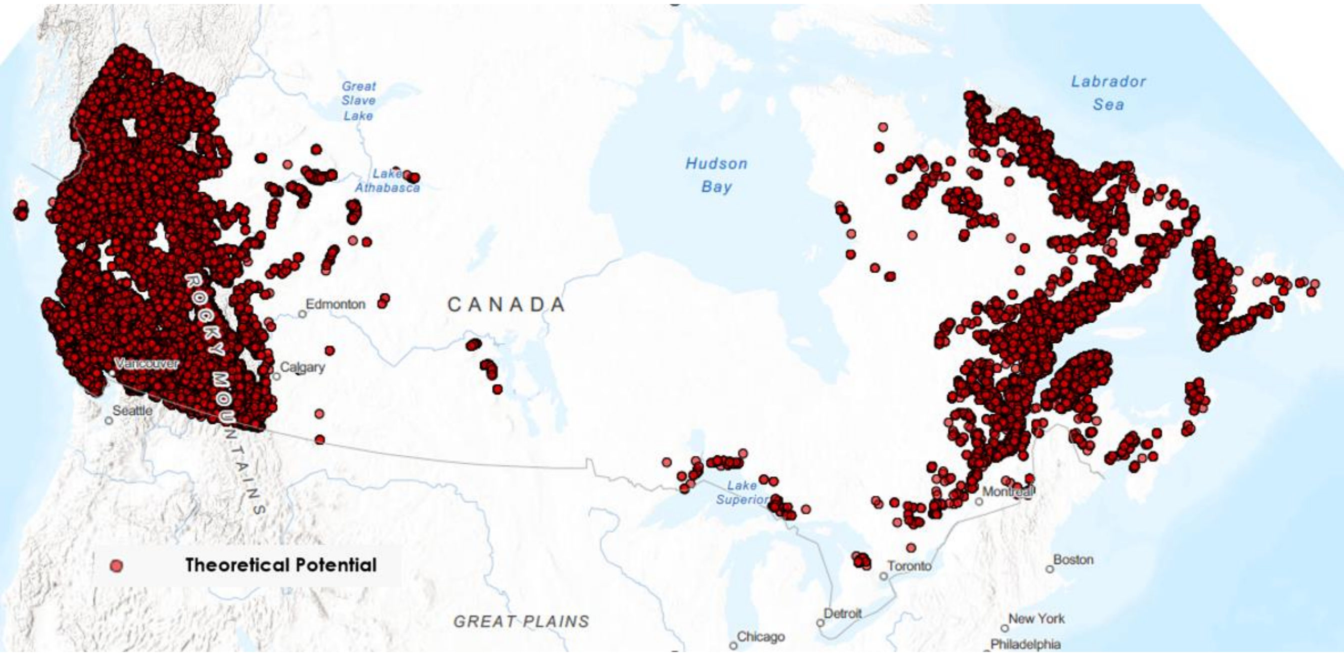


Figure 17 Distribution of Theoretical Potential PSH Sites in Canada

Figure 18 shows how unequal the distribution among regions within Canada is in terms of “Province, Number of Sites and Percentage of Total Sites“. British Columbia takes the vast lion share due to the Rocky Mountains with over 80% of sites followed by Quebec (10%) and Newfoundland and Labrador (6%) with their costal mountains and then Alberta (2%) on the dry side of the Rocky Mountains. Saskatchewan, Manitoba, Ontario, New Brunswick and Nova Scotia each take only insignificant site counts by comparison.

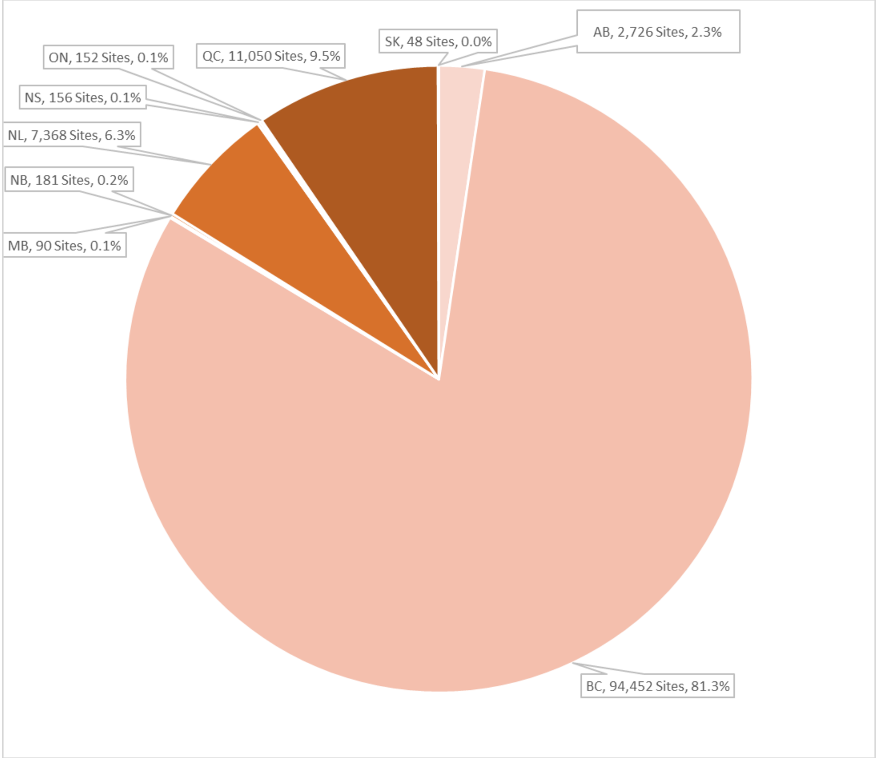


Figure 18 Breakdown of Theoretical Potential PSH Sites by Province

Figure 19 demonstrates the strong correlation between identified PSH sites and where a strong wind resource prevails in Canada. This correlation would suggest that a natural affinity between wind power facilities that can produce a high capacity factor with PSH facilities that can firm up this generation with their storage capability, a combination that could result in a 100% renewable electricity supply mix with good load following capability. Deeper technological and economic analyses would be worthwhile to investigate the specific synergies in a multi-technology economic assessment. However, even without these studies it would seem compelling that these synergies exist in many locations across Canada.

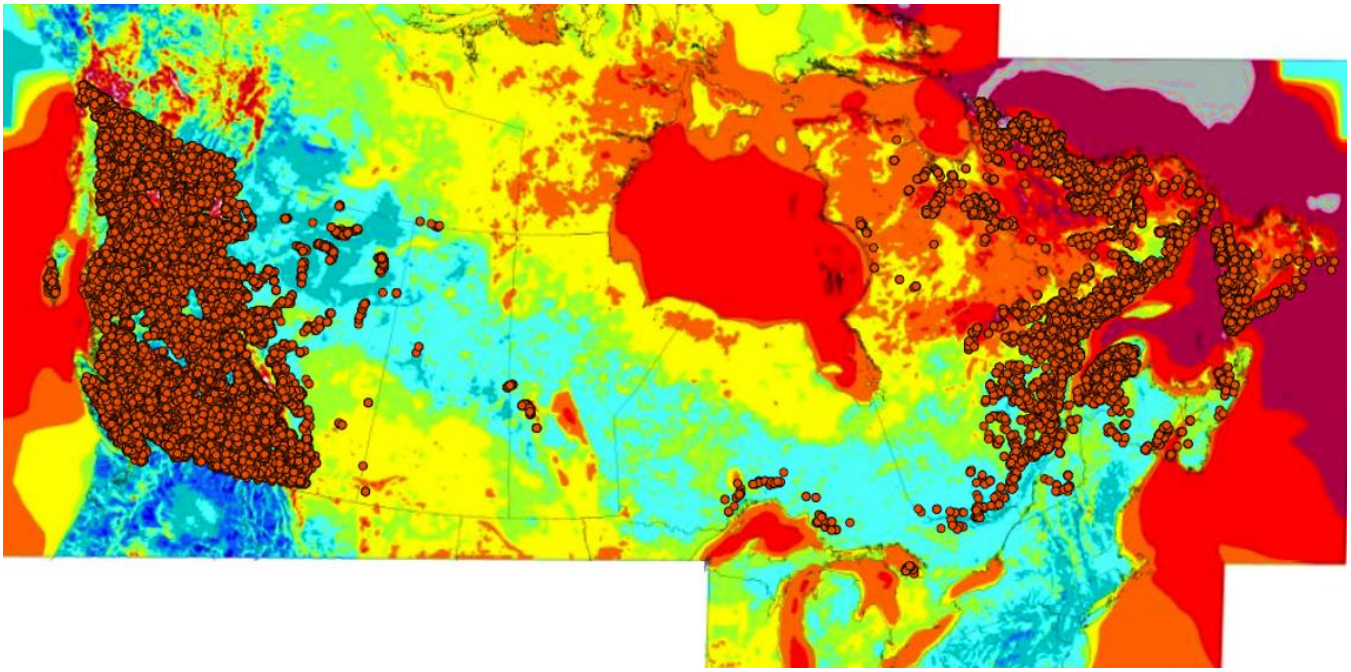


Figure 19 Theoretical Potential PSH Sites and Wind Resource in Canada (darker red means stronger winds)

5.1.2 Newfoundland and Labrador Theoretical Potential

In Atlantic Canada, Newfoundland and Labrador has, with 7,368 sites, the strongest Theoretical Potential, as seen in Figure 20.

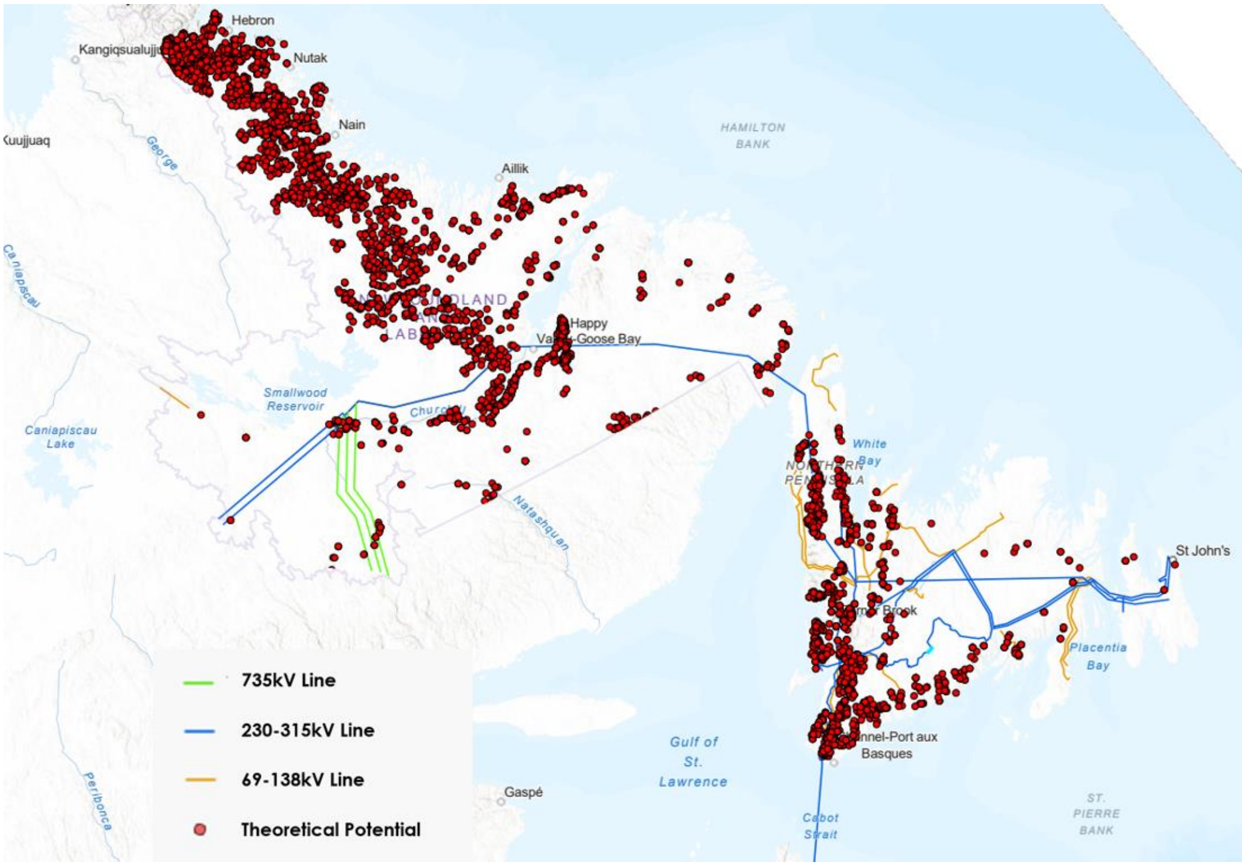


Figure 20 Distribution of Theoretical Potential PSH Sites in Newfoundland and Labrador

5.1.3 Theoretical Potential in Maritime Provinces: Nova Scotia, New Brunswick and Prince Edward Island

Throughout the Maritime Provinces, Nova Scotia and New Brunswick host hundreds of sites while PEI none as identified in Table 10:

Table 10 Theoretical Sites in Atlantic Canada

Province	Number of Sites
Nova Scotia	156
New Brunswick	181
Prince Edward Island	0
Total	337

The distribution of sites with the strongest Theoretical Potential is shown in Figure 21.

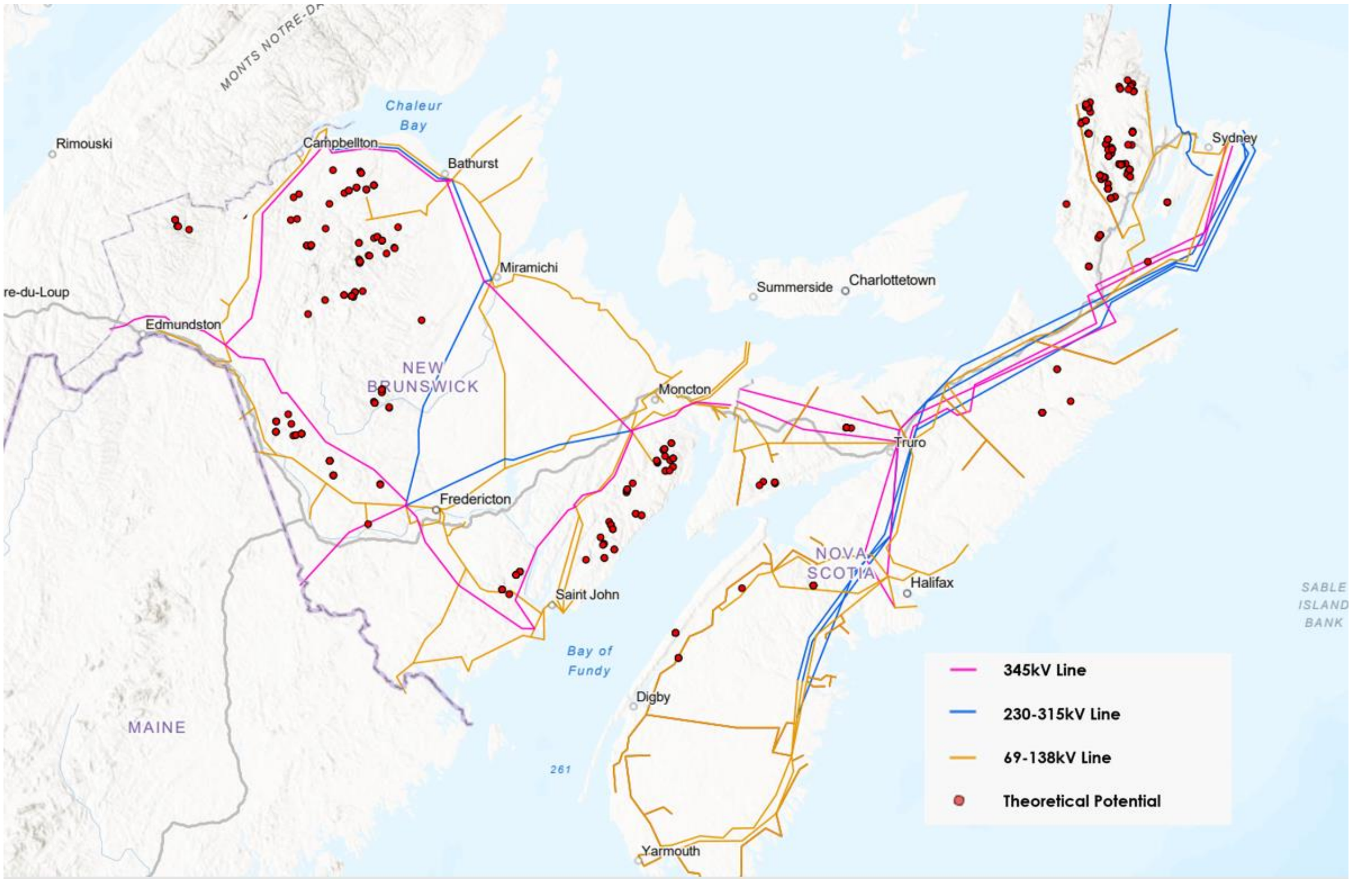


Figure 21 Distribution of Theoretical Potential PSH Sites in Nova Scotia and New Brunswick

5.1.4 Quebec Theoretical Potential

Throughout Quebec, 11,050 sites are identified, only second to British Columbia. Figure 22 shows the distribution of sites with the strongest Theoretical Potential.

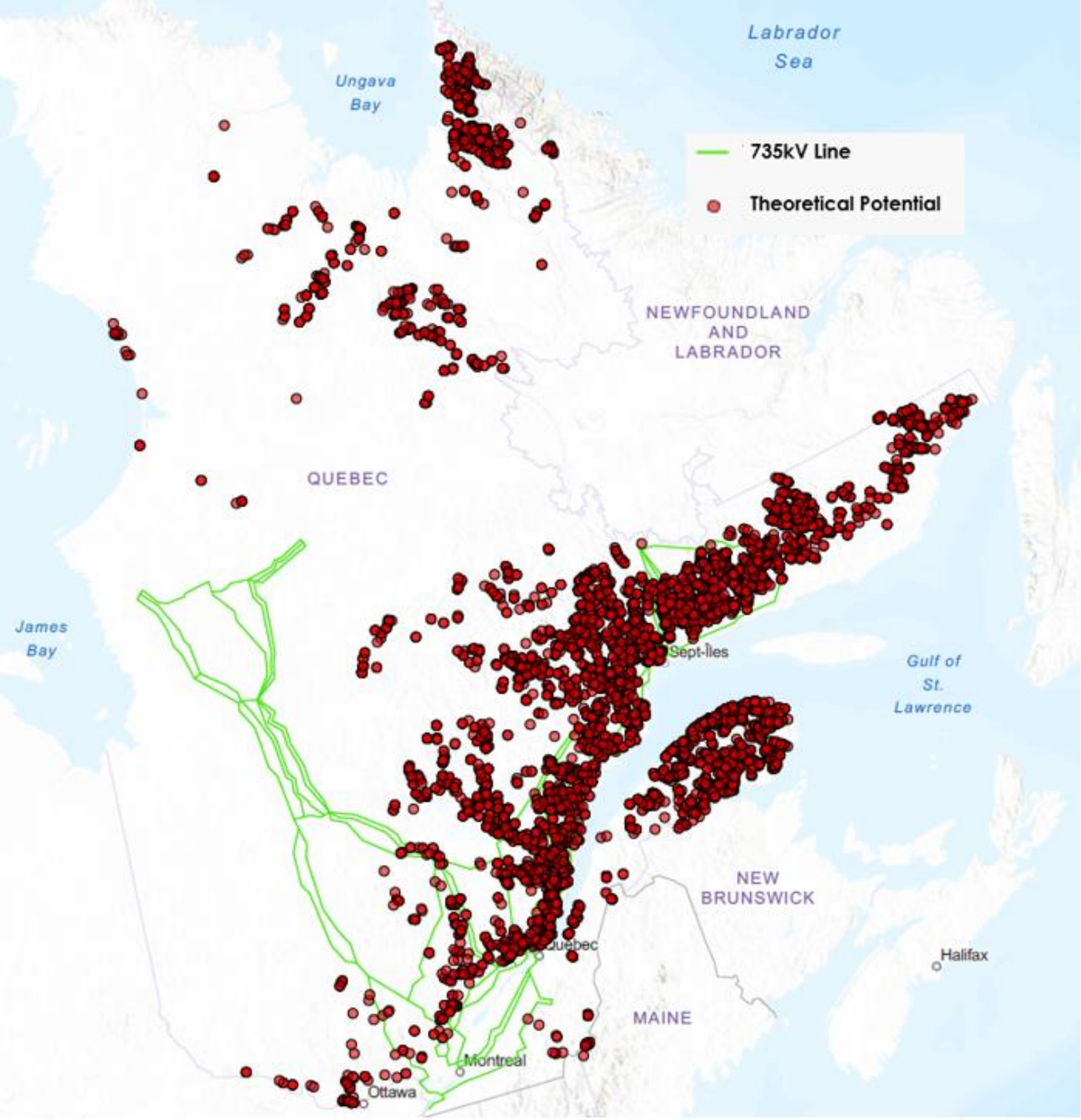


Figure 22 Distribution of Theoretical Potential PSH Sites in Quebec

5.1.5 Ontario Theoretical Potential

Throughout Ontario 152 sites are identified, a small percentage of the Theoretical Potential in Canada but still respectable as an absolute number. Figure 23 shows the distribution of sites with the strongest Theoretical Potential.

With Marmora PSH, Meaford PSH, Schreiber PSH and Steep Rock PSH either under development or under consideration in the province, there is evidence of the strong interest for advancing PSH projects in Ontario.

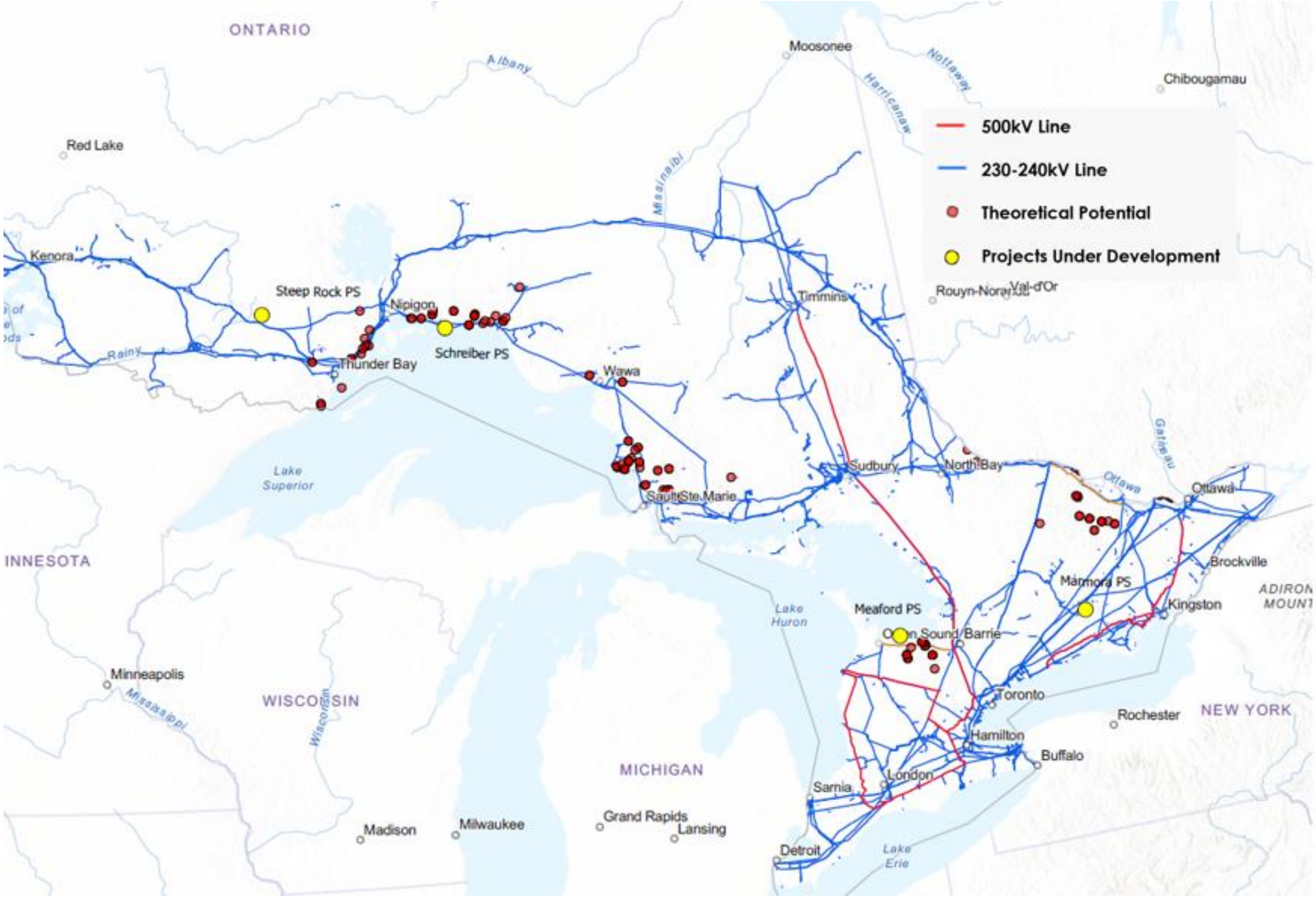


Figure 23 Distribution of Theoretical Potential PSH Sites in Ontario

5.1.6 Prairies Theoretical Potential: Saskatchewan and Manitoba

In the prairie provinces Manitoba features 90 Theoretical Potential sites and Saskatchewan 48. The topography and relative dry climate do not provide significant opportunity in this region. Figure 24 shows the distribution of the relatively sparse set of identified sites with the strongest Theoretical Potential.

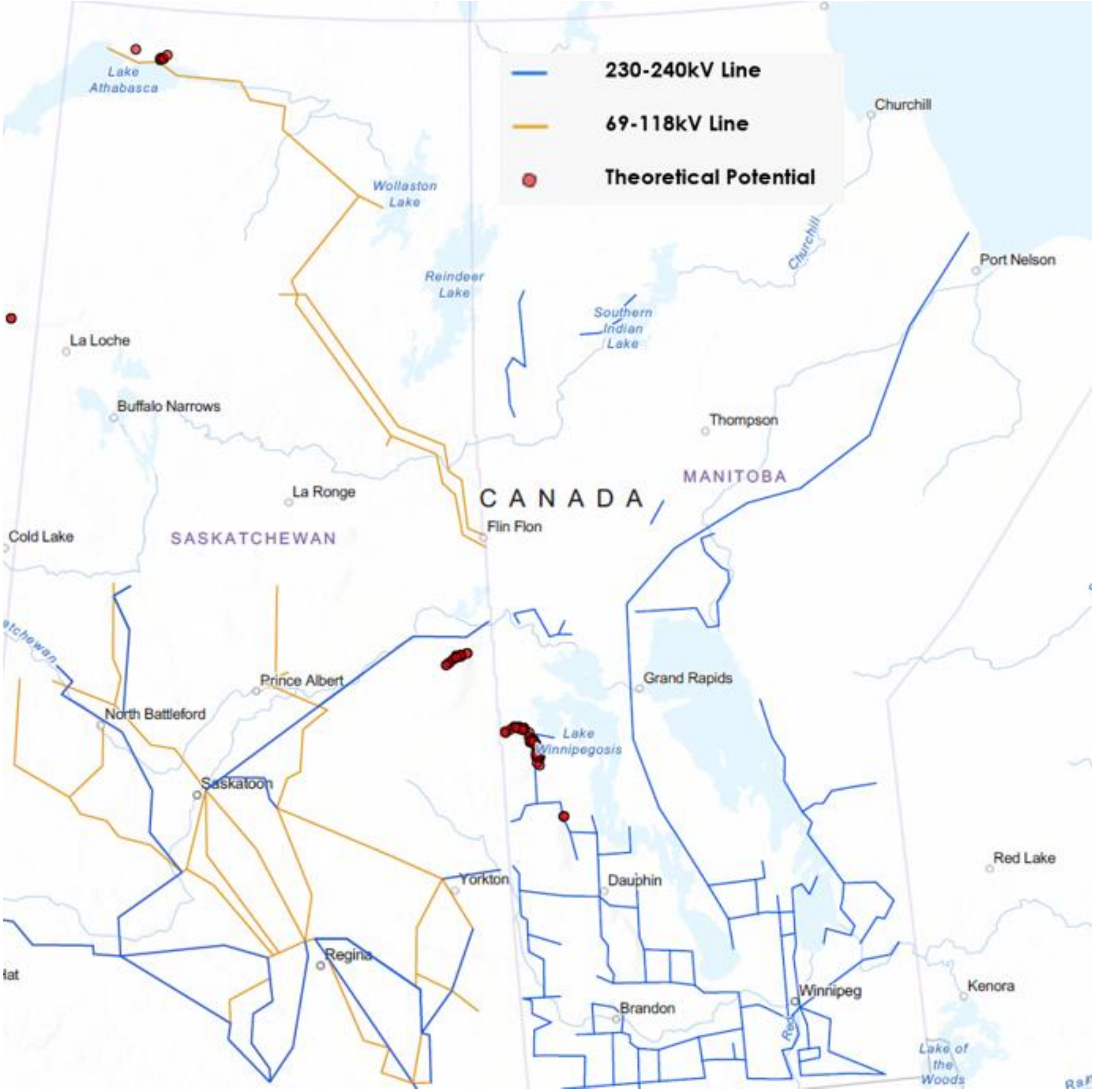


Figure 24 *Distribution of Theoretical Potential PSH Sites in Prairies*

5.1.7 Alberta Theoretical Potential

Alberta with about 2,700 sites is one of the provinces with a relatively high incidence of Theoretical Potential. Figure 25 shows where the sites with the strongest Theoretical Potential are located.

With Canyon Creek PSH and Tent Mountain PSH under development in the province and Revelstoke PSH being just across the provincial border in British Columbia there is evidence that PSH is not only theoretically possible but already being advanced through investment in project initiation or definition efforts.

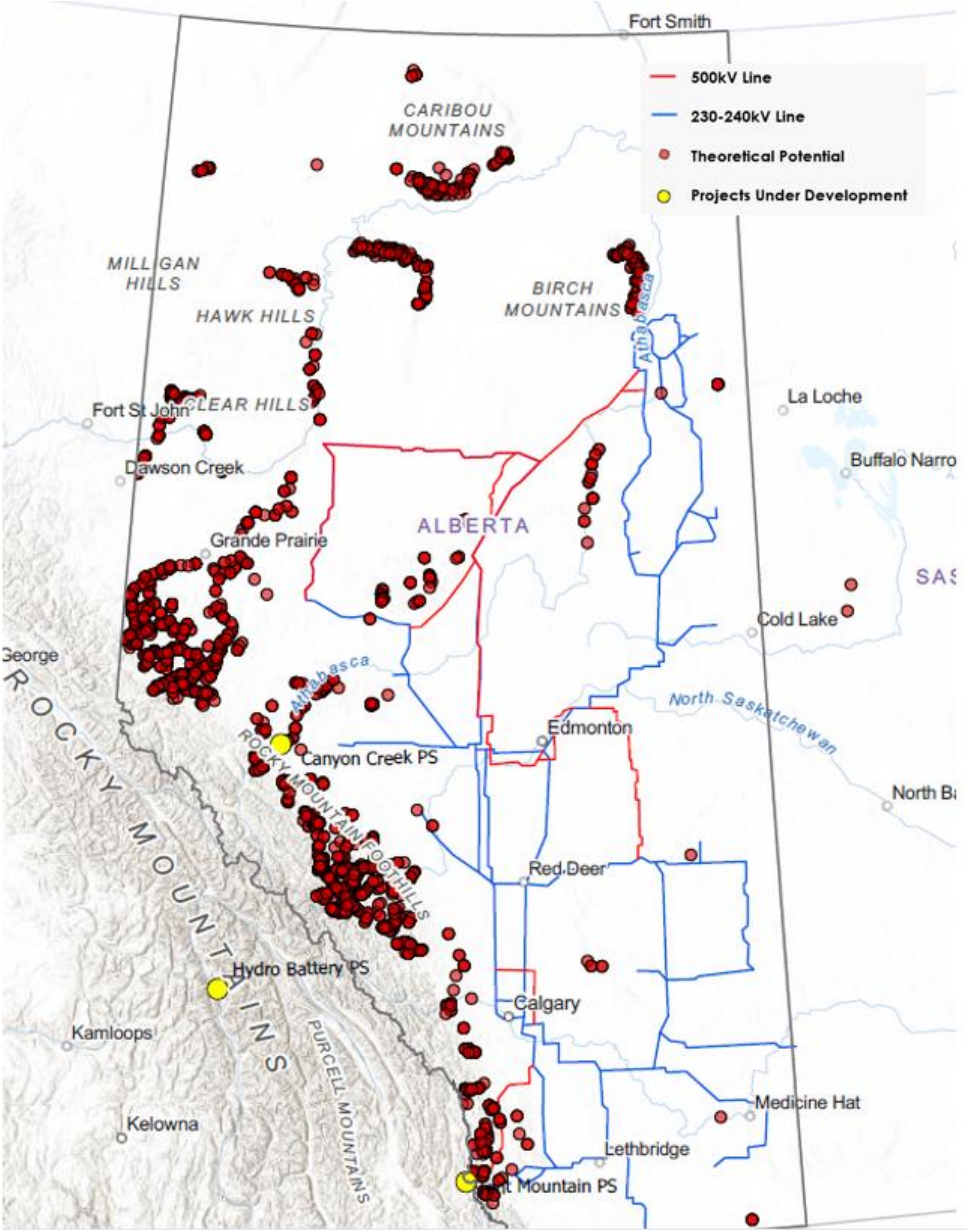


Figure 25 Distribution of Theoretical Potential PSH Sites in Alberta

5.1.8 British Columbia Theoretical Potential

British Columbia is blessed with high mountains and wet air masses coming off the Pacific Ocean. Consequently, there is an abundance of Theoretically Potential sites. The opportunity here shows in Figure 26 over 94,000 sites.

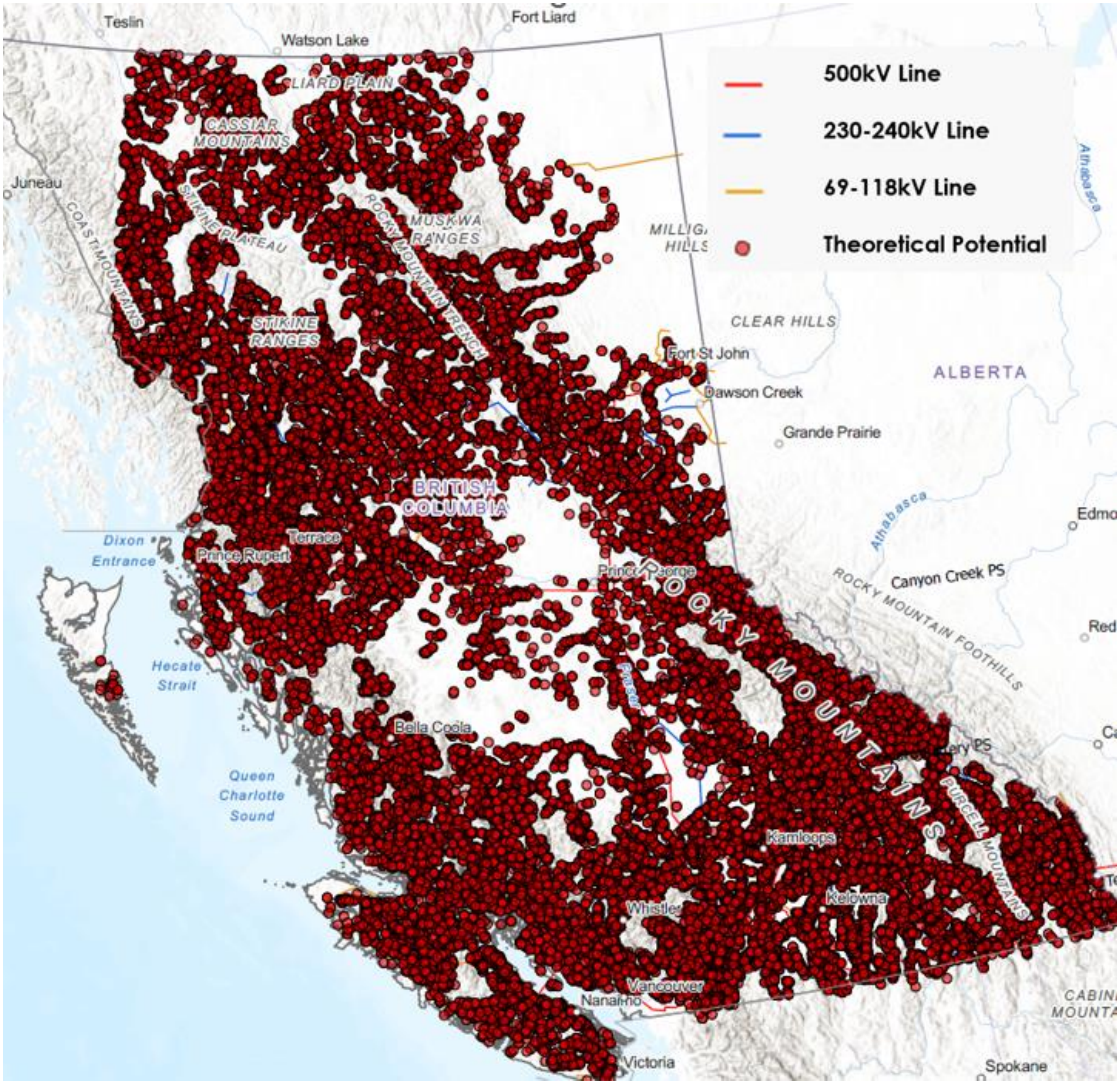


Figure 26 Distribution of Theoretical Potential PSH Sites in British Columbia

5.1.9 North of Sixty Theoretical Potential: Yukon, Northwest Territories and Nunavut

The ANU data base does not include PSH sites North of Sixty. Even though population centers are few, there may still be value in researching sites in future studies, particularly as mining developments precipitate advancement of sites such as the Moon Lake PSH noted as a potential future project by Yukon Energy Corp.

5.2 Realistic Potential

5.2.1 Canada-Wide Realistic Potential

To determine the Realistic Potential the approach is to use the Feasibility Factors discussed in Sections 3.3.1 to 3.3.4 - namely Transmission, ESG, Constructability and Technology – to adjust the costs.

Of the Theoretical Potential sites 89% have been filtered out as not being sufficiently attractive for Realistic Potential development. The remaining sites are classified into High and Medium Realistic Potential with the following classification:

- High Realistic Potential: The top 1% of Canada-wide Theoretical potential sites at this level
- Medium Realistic Potential: The next best sites amounting to 10% of sites

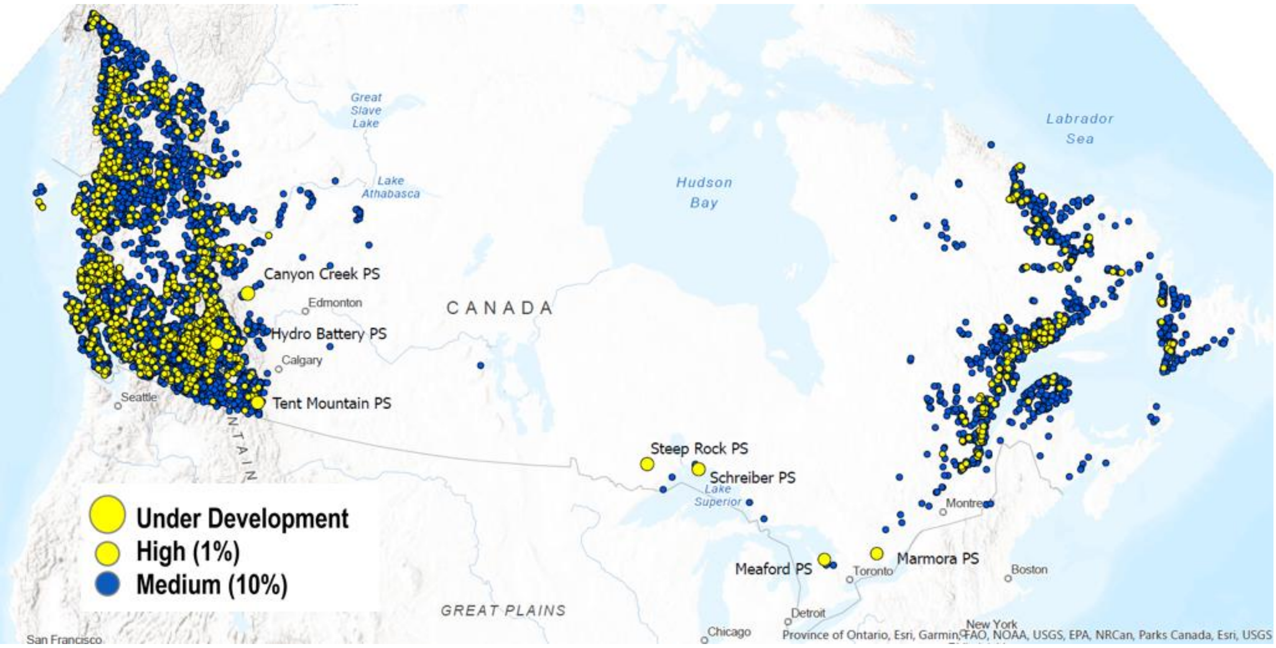
The distribution pattern of sites across Canada is analogous to the distribution of the Theoretical Potential shown in Figure 18. Most sites are still in the high mountains of British Columbia and the higher topography in the Atlantic region.

The resulting cumulative high Realistic Potential across Canada amounts to over 8 TW installed capacity at almost 1,200 site locations. In Table 11 it is shown how the over 116,000 Theoretical Potential sites are gradually filtered down through application of the Feasibility Factors into sites of high and medium Realistic Potential. Among those about 85% are realistic to be developed in the near future before 2035 based on the established time constraints for permitting of the PSH and transmission assets provided that development efforts were to commence today.

Table 11: Progressive Filtering of the Theoretical Potential

	Number of Sites	Total Installed Capacity (MW)	Number of Sites	Total Installed Capacity (MW)
Theoretical Potential	**116,383**	**222,796,251**		
	High		**Medium**	
	1%		**10%**	
Realistic Potential w/o Cost Adjustments	3,385	17,747,889	25,431	88,532,889
Realistic Potential after Transmission Adjustment	2,159	13,827,889	16,890	74,023,500
Realistic Potential after Transmission and Constructability Adjustment	2,073	13,449,944	16,245	71,446,389
Realistic Potential after Transmission, Constructability and Equipment Adjustment	1,168	8,293,333	11,706	61,181,167
Realistic Potential	**1,164**	**8,260,000**	**11,638**	**60,876,889**
By 2035	996	7,069,722	10,121	52,981,000
By 2050	168	1,190,278	1,517	7,895,889
Realistic Potential	**1,164**	**8,260,000**	**11,638**	**60,876,889**

Figure 27 shows the distribution of high and medium Realistic Potential PSH sites across Canada.



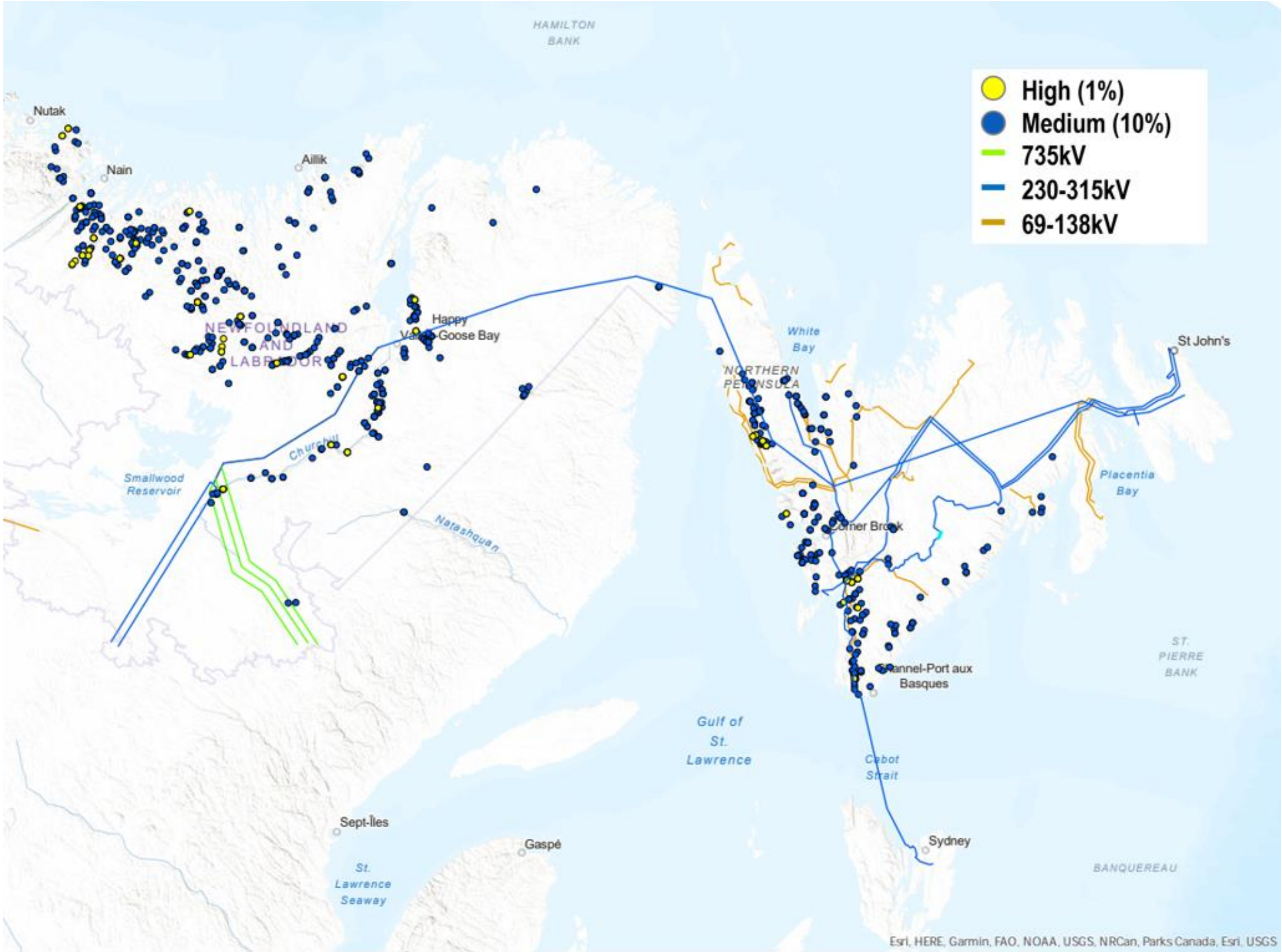
Province of Ontario, Esri, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada, Esri, USGS

Figure 27 *Distribution of Realistic Potential PSH Sites in Canada*

5.2.2 Newfoundland and Labrador Realistic Potential

Figure 28 shows a substantial Realistic Potential that exists in Newfoundland and Labrador. The sites are primarily located on the western island and in Labrador where mountainous terrain provides for hydraulic head, and therefore, high energy density in the water. This makes construction costs on a per-installed-capacity attractive even factoring in the long distances of some sites to existing transmission.

An augmenting factor for the Realistic Potential in Newfoundland and Labrador is the recent international agreement for export of hydrogen to Europe which is not yet factored in. This recent development could set the stage for significant renewable energy growth potential in the in the region and prove to be a substantial opportunity in the renewable energy storage sector for Canada.



Esri, HERE, Garmin, FAO, NOAA, USGS, NRCan, Parks Canada, Esri, USGS

Figure 28 Realistic Potential in Newfoundland and Labrador

5.2.3 Realistic Potential in Maritime Provinces: Nova Scotia, New Brunswick and Prince Edward Island

Figure 29 shows the Realistic Potential in the Maritime Provinces. Few sites remain with a concentration in Cape Breton in Nova Scotia and along the Bay of Fundy in New Brunswick. If ocean renewable tidal power plants emerge in the future, these sites could become even more valuable to firm up this non-dispatchable generation form but as of present electricity production from the ocean is negligible.

Nova Scotia is thermal generation dominated, and New Brunswick has a large nuclear component in their generation mix. In both cases, load following capabilities are limited making PSH potentially more valuable in the future. PEI shows no potential for PSH, even though non-dispatchable wind generation is a strong contributor to power generation in that province. Consideration for increasing access to PSH resources on the mainland by way of underwater cable interties could be further explored to help stabilize the electricity system on the island.

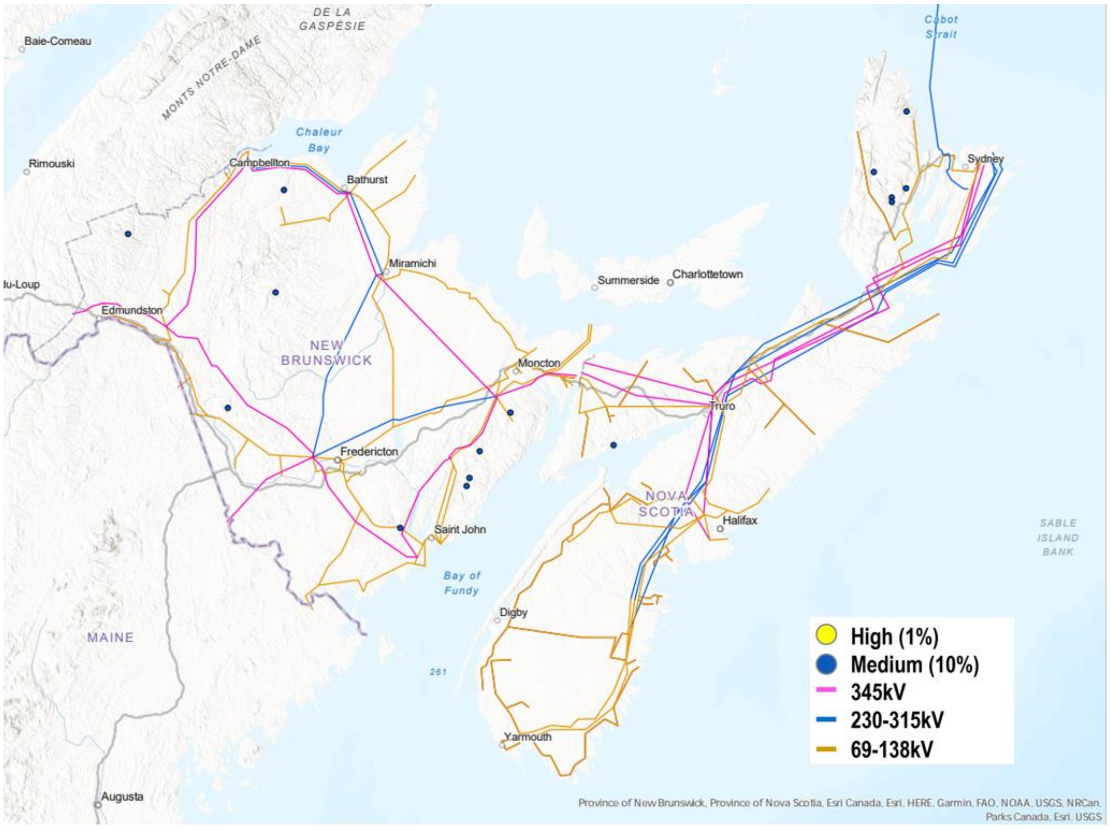


Figure 29 Realistic Potential in Nova Scotia and New Brunswick

5.2.4 Quebec Realistic Potential

Quebec shows a large number of Realistic Potential PSH sites but also has an abundance of conventional hydro power with large storage reservoirs in the province.

Sites are generally spread along the St. Lawrence River and its gulf. The locations in the Matane region of Quebec are conveniently co-located with existing large non-dispatchable wind power facilities. Cross-border exports into the New England states of the USA are already a factor in Quebec's energy policy and may encourage future PSH development. With the development of green hydrogen also under consideration throughout this region, PSH could play a vital role in the synthesis of these renewable energy sources.

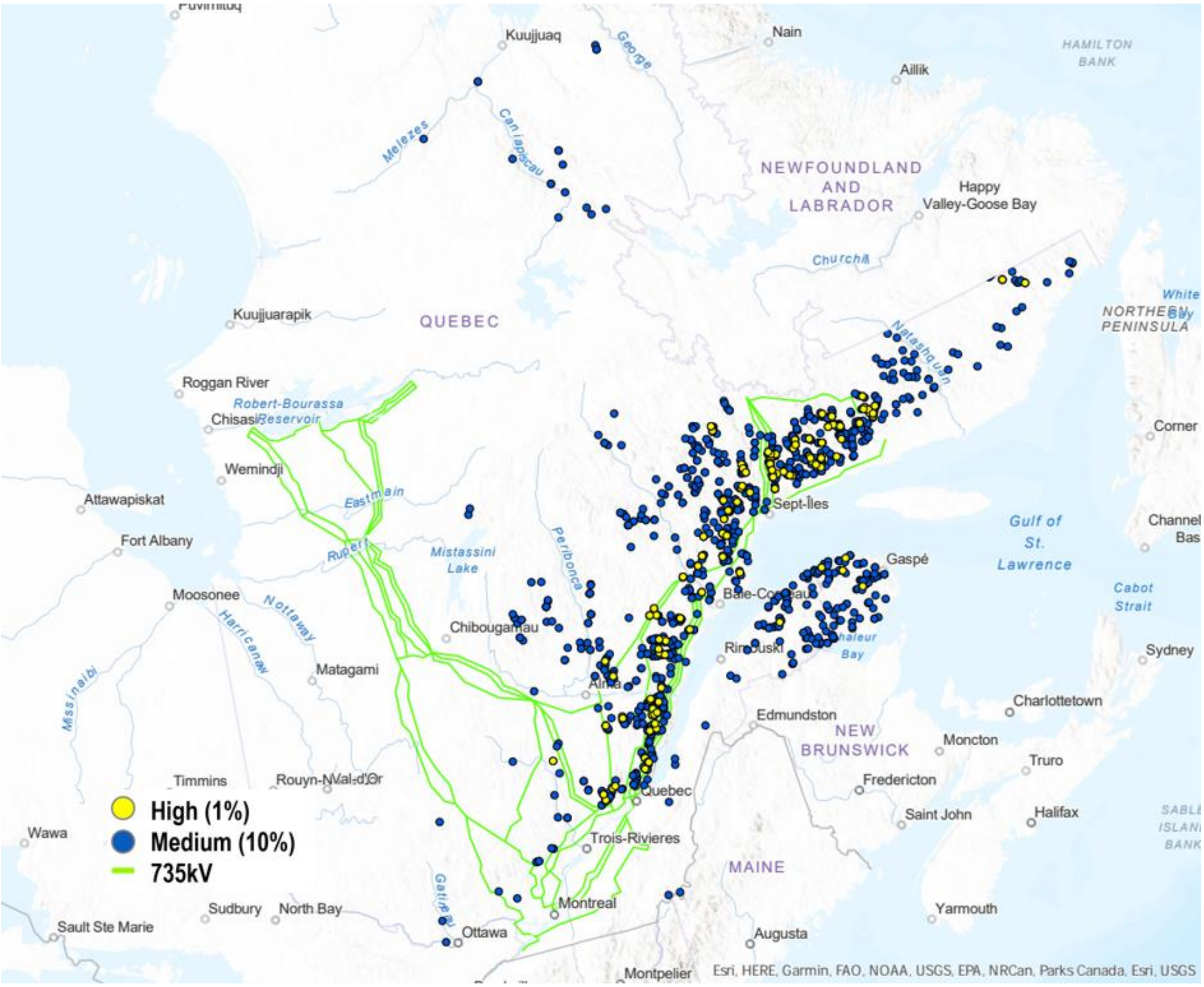


Figure 30 *Realistic Potential in Quebec*

5.2.5 Ontario Realistic Potential

Figure 31 shows a scatter of sites North of Superior, in the Blue Highlands and along the Quebec border. Generally, however, there are few attractive sites to be found in this province. Sites not linked to natural topographic features, such as PSH using a mine excavation for a reservoir are not being detected by the methodology that is underlying this study. Steep Rock PSH and Marmora PSH are examples of such sites which are under development and document that a site may become more attractive under certain beneficial niche circumstances. A lower reservoir being one of the Great Lakes, such as Meaford PSH, is by definition not identified in the Theoretical Potential because this involves a natural waterbody and makes the site open loop.

A generation mix heavy on nuclear in Ontario along with a program that promotes further Small Modular Reactors (SMRs) as well as wind and solar development may shift the power system needs to further enhance attractiveness of PSH in Ontario in the future.

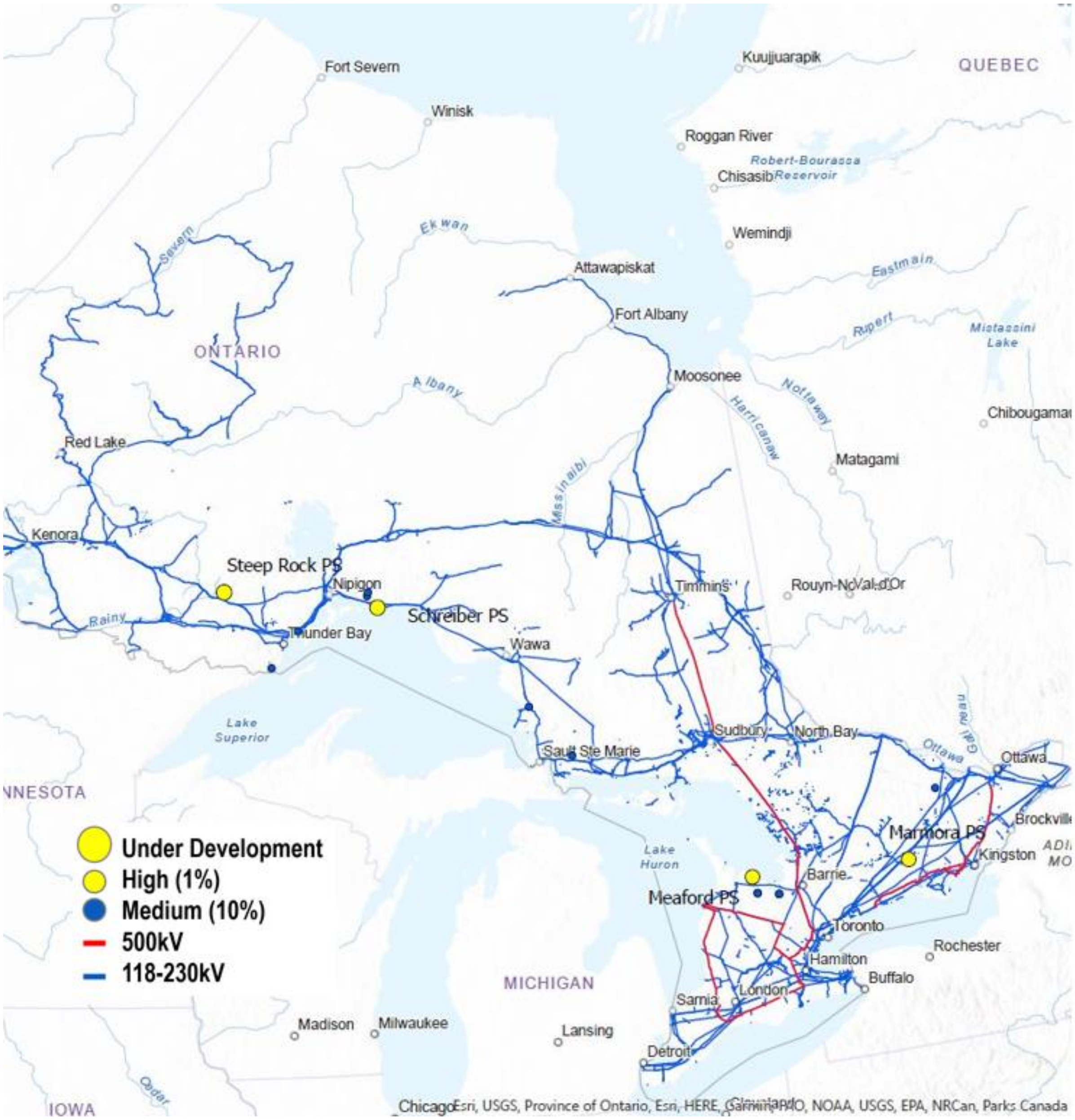


Figure 31 Realistic Potential in Ontario

5.2.6 Prairies Realistic Potential: Saskatchewan and Manitoba

In Figure 32 it can be seen that only one site in the provinces of Saskatchewan and Manitoba could be attractive in the Canadian context. The combination of relatively flat terrain and dry climates is not favourable to PSH with the exception of an isolated site of medium realistic potential near Lake Winnipegosis.

Manitoba with its generation mix dominated by conventional hydro is less likely to develop into a climate that welcomes PSH than Saskatchewan with its thermal and wind power facilities.

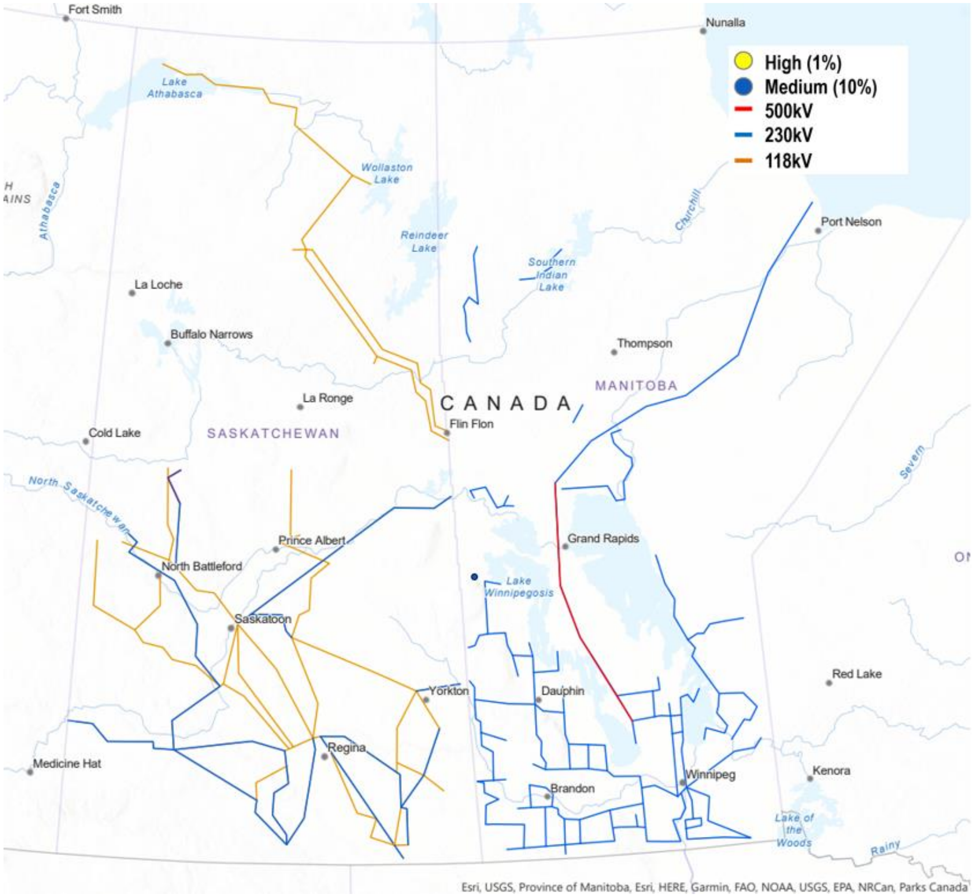


Figure 32 *Realistic Potential in Prairies*

5.2.7 Alberta Realistic Potential

Alberta is among the most attractive locations for PSH development as seen in Figure 33.

PSH sites are abundantly clustered around various hilly terrains and in the foothills of the Rocky Mountains, although not as favoured by terrain and water availability as neighbouring British Columbia.

A slow-acting thermal-dominated generation mix is conducive to development of PSH, which several known development sites in and around the province attested to as well.

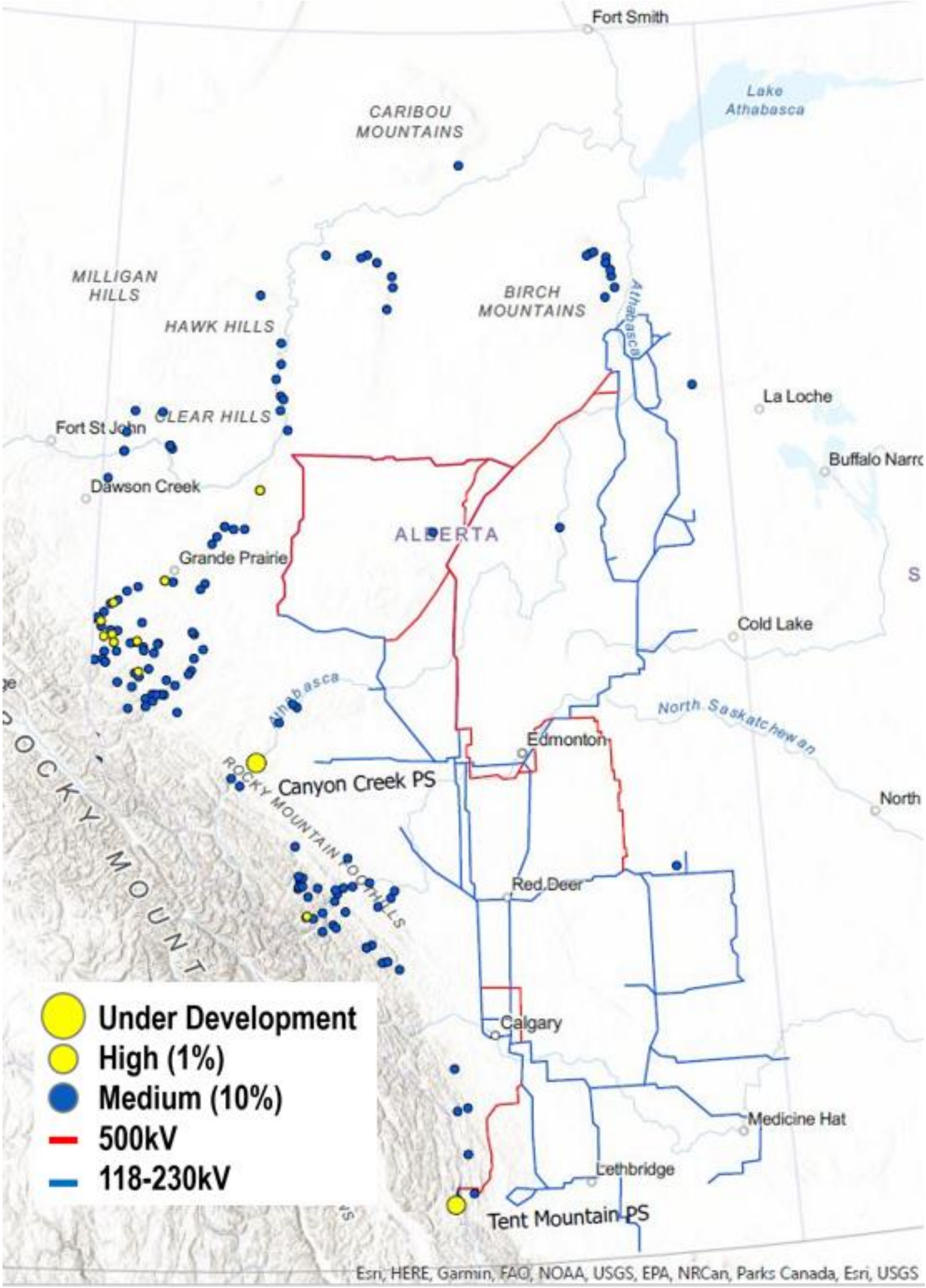


Figure 33 Realistic Potential in Alberta

5.2.8 British Columbia Realistic Potential

British Columbia maintains its top position for sites in Canada also in the Realistic Potential category with most sites being located here.

By cost alone Figure 34 shows sites on its Pacific islands, along the Rocky Mountains and into the interior to the Alberta Border, from the Washington Border in the south all the way to the very north of the province at the Alaska Border.

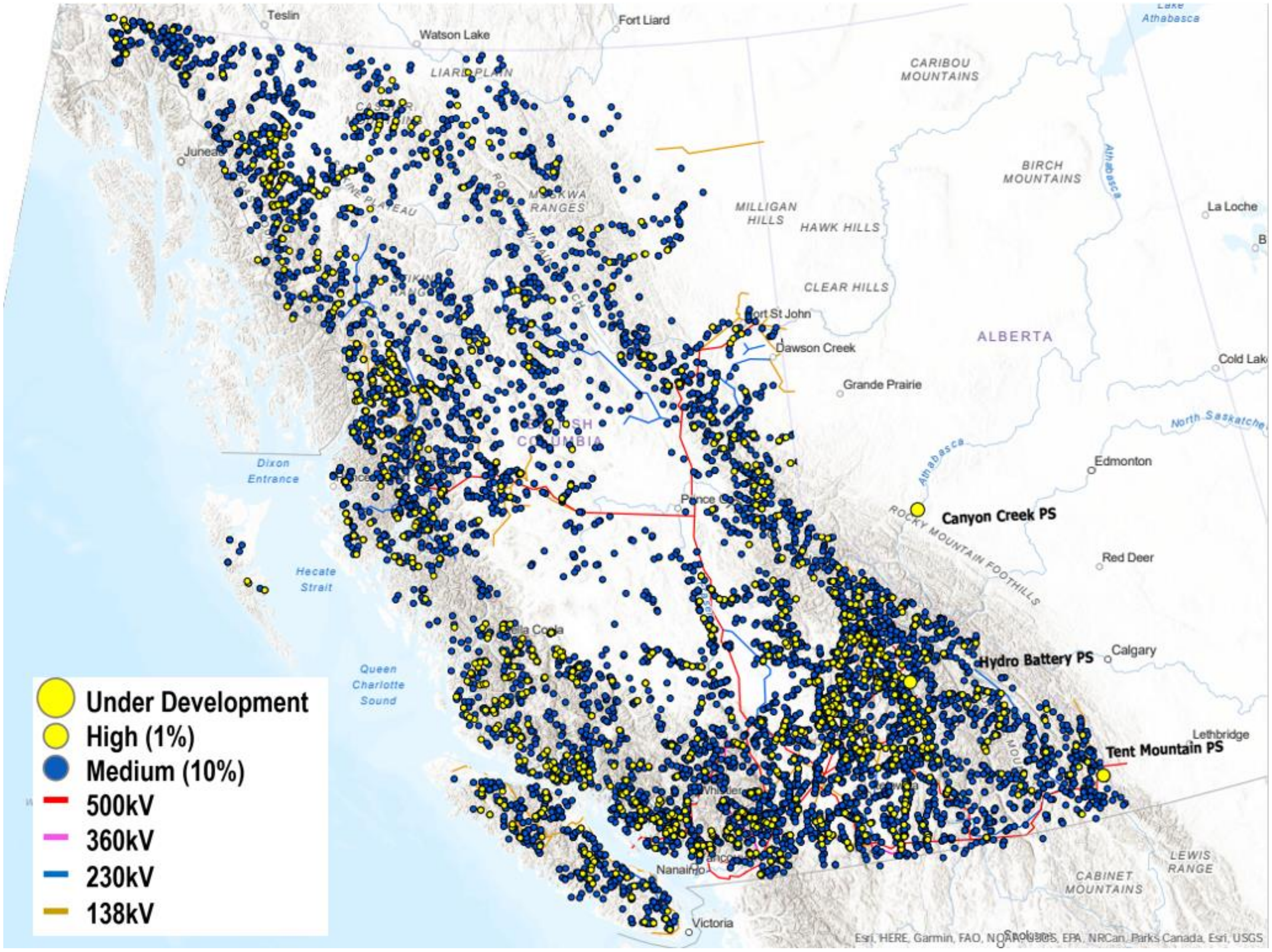


Figure 34 Realistic Potential in British Columbia

6. INSIGHTS FROM MARKET PARTICIPANTS

Our outreach included over 30 firms with about 60% response rate to the questionnaire regarding their activities in the PSH space (see Appendix E). This section summarizes the feedback received in two categories: Firms that do not actively participate in PSH development and active developers.

6.1 UTILITIES THAT ARE NOT CURRENTLY LOOKING INTO PUMPED STORAGE HYDROPOWER

Brookfield Renewable Canada does not plan to participate in the Pumped Storage Hydro Market in Canada and do not have any Canadian PSH projects under consideration. Reasons stated included the perception of major regulatory hurdles that make PSH projects risky, uncertain and at best, quite lengthy. PSH projects are also very capital-intensive and power markets offer insufficient valuation of long-term storage. Actions that the government could do to encourage PSH projects would be to have faster approval processes and fewer regulatory hurdles, as well as tax incentives and more attractive funding considerations. Finally, Brookfield would also be interested in proper valuation of pumped storage, including Renewable Energy Credits (RECs) and the advantages it brings to grid stability and the integration of further intermittent renewables.

Other utilities provided short responses, as they do not have any PSH projects in the works mostly due to the economics. They also added that they are not intending on developing PSH soon. Those utilities were Fortis BC, Manitoba Hydro, Newfoundland and Labrador Hydro, Columbia Power, Nelson Hydro and SaskPower. Nelson Hydro did add that they are a small municipal utility, which makes pumped storage too costly for a small power producer.

A utility that wished to remain anonymous mentioned that they have studied potential PSH project opportunities and found that the obstacles were the difficulty of putting into perspective the analysis of the local environmental impacts of a PSH in relation to the need to promote the use of renewable energy. The industry is turning to solar and wind because the environmental impacts seem more acceptable than hydro, but this still involves major constraints in the management of power and energy and as is most often the case, the responsibility for oversight in managing the balance of the electricity system falls to the system or market operator. Firm capacity will be a major limiting factor on the penetration of variable renewable energy sources in the future. Regulators and government entities will need to understand the importance of the relationship between firm capacity and reliability and ensure the proper balance is in place.

6.2 UTILITIES THAT ARE CURRENTLY LOOKING INTO PUMPED STORAGE HYDROPOWER

Yukon Energy has a PSH project in Yukon included as part of their 10-year resource plan. The project is Moon Lake PSH. The resource plan is publicly available on their public website. Due to time and resources, Yukon Energy was unable to provide additional project details.

Newfoundland Labrador Hydro responded that in the past, they had never considered PSH as an option to increase their capacity due to cost. However, in 2023, they will be investigating pumped storage further as a resource option, likely for both existing assets and potential future hydro projects. Given the high preponderance of potential wind sites along the northeastern shoreline of Labrador, it would seem that this investigation will yield good results.

Ontario Power Generation has studied potential project opportunities and is actively engaged in the development of a PSH project. Currently in the initiation phase, the Marmora PSH Project would have a 400-MW output, and 2 GWh capacity, with around 65 MW of minimum output. OPG has a 50:50 ownership of the project shared with Northland Power Inc. This project is located adjacent the town of Marmora, Ontario, 2 km south-east of the

Marmora town center, which is roughly halfway between Toronto & Ottawa. This project has a closed-loop system using an abandoned iron-ore mine void as the lower reservoir and reshaping the above ground mine spoil pile into the upper reservoir. It would connect to the existing Hydro One 230KV corridor located around 10km north of Marmora. The head varies; penstock is around 260 meters vertical drop. The portion of the value for their firm that would be spent in Canada would be more than 70%.

The Marmora Project would have multiple positive impacts to both, the Canadian and Ontario economy:

- Due to the ongoing IESO Gate 2 review of this project; the direct economic impact and cost to store / generate electricity cannot be shared at the present time
- Unlike other storage technologies most of the construction cost is reinvested in Canadian companies and the Canadian workforce.
- The Project transforms a crown liability for mine rehabilitation (as the Marmora mine was abandoned in 1978 prior to mine closure rehabilitation requirements) and transforms this into an environmentally positive long life (>90 years) clean energy storage asset for Ontario.
- The Project enables further decarbonization of the Canadian economy by storing excess clean energy during periods of excess generation; and generating electricity during higher value periods reducing the demand for peak gas generation
- Tertiary benefits for tourism and the local economy have been estimated at up to $35M per year

Ontario Power Generation foresees on the electrical power transmission side that the location of the Marmora PSH Project is not directly constrained. The ongoing electrification of the economy will create new bottlenecks and will subsequently alter the electricity demand curves that need to be considered when investing in generation projects. For the environmental, social, and regulatory side, there are no specific obstacles in this regard for the Marmora project beyond those that are expected and reasonable. As the Marmora PSH project is a closed-loop system and repurposes an abandoned mine-site; there are minimal to no negative impact on fisheries, waterways, wildlife, agriculture, tourism, flora or fauna. The local community is supportive to rejuvenate the local economy and repurpose an abandoned mine. First Nations engagement continues and is generally supportive. There are no specific obstacles regarding constructability beyond those expected of a typical generation project. The location of the project has a wide catchment for labour; and is adjacent a major highway. Short term threats relate to supply chain constraints and inflationary pressures. There are no specific obstacles concerning suitable technology; any technology that can improve efficiency and operational reliability improves the business case. There are no specific issues regarding energy storage potential. The contracting of long-life high capital cost assets can be difficult when compared to shorter life or GHG emitting assets. The system operators may use processes to compare assets that are not well suited for assessing the value of PSH. This can be problematic to justify the capital investment. The fair assessment of PSH can be difficult as the overall services provided can be undervalued; PSH can provide more than just capacity with opportunities to provide an additional measure of grid services, such as operating reserve; Automated Generation Control (AGC), and voltage regulation. Considering only benefits to the hydro ratepayers, rather than the overall benefits to the taxpayer or the overall Ontario economy, stymies innovative approaches such as the Marmora PSH project, which is transforming an abandoned mine, and thereby, reduces the Crown's (taxpayer's) potential liability to remediate the property. It would be beneficial if the overall value to the province was more broadly considered when assessing PSH projects.

Transmission would benefit by a more progressive forward-looking plan and investment associated with increased electrification ensuring generation assets have increased transparency on expected future transmission capacity. Transmission approvals and construction seems to lag the demand for clean energy generation / storage. Development of a national strategy to improve transmission assets, and in a manner to better facilitate connection by PSH facilities along with variable renewable energy resources could expedite achieving net zero targets. From the perspective of power markets, a review of the approach for considering long life capital assets could emphasize the value of PSH compared to other technologies.

The Independent Electricity System Operator (IESO), located in the province of Ontario, has studied potential PSH project opportunities, and is having active discussions for the following PSH projects: Marmora, Meaford and Schreiber, with a combined capacity of approximately 1,800 MW. They are all at Gate 2 of the unsolicited proposal evaluation process. Note that the IESO does not own assets and negotiates contracts with developers to design, build, commission and operate the facilities. The portion of the value for their firm that would be spent in Canada is 100%. In general, the two biggest impediments to advancing PSH are CAPEX cost and length of time required to develop these facilities. The IESO believes that government funding and more active involvement of the Canada Infrastructure Bank might help advance PSH projects in a more expeditious manner.

7. CLOSING

The conclusions that follow from the assessment presented in this report are:

- PSH is a mature technology that is based on conventional hydro technology. Sites with higher hydraulic head are generally more attractive because of their energy density and availability of water is a prerequisite. The technological and environmental aspects of PSH development are well refined.
- Machinery can be configured using reversible pump-turbines, ternary or quaternary arrangements, each having their own advantages, but costs favour the pump-turbine. The determination of equipment configuration is based on the optimization of the needs of the power system and market opportunities.
- Sites could use existing reservoirs or natural waterbodies as storage reservoirs. However, off-river, closed-loop systems offer advantages in environmental impact and operational independence.
- The characteristic of PSH to be able to respond quickly to load changes or the variability of non-dispatchable renewable generation such as wind and solar power, underscore PSH's role as stabilizing backbone of a power grids, especially as non-dispatchable renewable energy penetration is increasing.
- The international context suggests that Canada needs urgent action to develop PSH if a 100% renewable energy generation mix is to be attained by 2035 or even 2050.
- In certain regions of Canada, where development of green hydrogen is being considered, alignment of this technology with PSH and sources of variable renewable energy could be synthesized to provide an overall benefit to the Canadian energy portfolio of the future.
- The Theoretical Potential for PSH in Canada is for all practical purpose inexhaustible with over 100,000 identified sites and over 200 TW (200,000 GW) of capacity possible.
- This potential is distributed unequally throughout the country with British Columbia taking by far the largest portion followed by Quebec and Newfoundland and Labrador.
- The geographic distribution of this Theoretical Potential is also well correlated with the wind resource in the country providing the possibility of using this synergy for fully renewable and dispatchable renewable electricity generation.
- To assess the Realistic Potential the sites were screened using Feasibility Factors related to:
    - Proximity to transmission and interconnection costs
    - Environmental and social constraints addressing potential conflict with First Nation interests and protected lands
    - Constructability with respect to site access infrastructure and conducive ground conditions for construction
    - Suitability of the different types of machinery technology and their cost impact
- To determine the Realistic Potential an approach was employed that categorized 10% of the Theoretical Potential sites with a medium Realistic Potential and 1% with a high Realistic Potential
- The resulting cumulative high Realistic Potential across Canada amounts to over 8 TW (8,000 GW) installed capacity at almost 1,200 site locations.
- Among those sites about 85% are realistic to be developed in the near future before 2035 based on the established time constraints for permitting of the PSH and transmission assets provided that development efforts were to commence today.
- The Realistic Potential is unequally distributed with similar countrywide patterns as the Theoretical Potential: British Columbia in the lead followed by Quebec and Newfoundland and Labrador
- The PSH sites currently undergoing actual development are highly concentrated in two provinces: Ontario and Alberta.

- Feedback from over 30 potential PSH developers around the country was solicited and responses were received from the majority.
- Among provincial utility companies no interest in developing PSH was expressed with the exception of Ontario Power Generation in Ontario. Independent power producers, oil and gas and First Nations lead the way with active development efforts.
- Generally, a sentiment of fatigue seems to prevail about PSH being heralded as projects to come soon but always in the future, and never leading to real construction investment.

Recommendations that come out of this study are as follows:

- Improve the data base for Theoretical Potential to include more sites. As an example, the Great Lakes could be used to serve as a lower reservoir. With the Niagara Escarpment and its proximity to Lake Ontario, there could be many, yet unidentified, sites. This work is already in progress at ANU. Adding the Canadian territories would also complement the amount of already identified sites but hasn’t commenced, yet. Further, abandoned mine sites could be evaluated throughout Canada to assess if the mine could serve as lower reservoir, given suitable conditions in place to construct an upper reservoir.
- Study the Canadian context with respect to additional need for transmission, hydro, wind, solar and PSH to realistically implement a renewable generation mix aligned with the time schedule for Net Zero Targets. International comparison suggests that deployment rates for renewable energy sources need to accelerate by an order of magnitude which will have significant effects on the future need for PSH. Note that the past is a poor predictor of the future in this case.
- Refine the Feasibility Factors in the assessment with benchmarking to actually constructed project case examples from USA and other international locations.
- Identify additional potential sites for consideration for PSH development that are defined as open-loop systems.

8. ACKNOWLEDGEMENT

The study team listed in Appendix F acknowledges the guidance and leadership provided by WaterPower Canada and its consultants.

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9. REFERENCES

[1] Ontario Power Generation, “Refurbishing the Pump Storage Reservoir”, https://www.opg.com/strengthening-the-economy/our-projects/niagara-pump-reservoir/

[2] Ontario Pumped Storage, “About the Project”, https://www.ontariopumpedstorage.com/about/

[3] International Hydropower Association, “Pumped Hydro - Refurbishing the Pump Storage Reservoir”, https://www.hydropower.org/factsheets/pumped-storage#:~:text=The%20International%20Hydropower%20Association%20(IHA)%20estimates%20that%20pumped%20hydro%20projects,600%2C000%20identified%20off%2Driver%20sites.

[4] International Renewable Energy Agency, “Innovative Operation of Pumped Hydropower”, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Innovative_PHS_operation_2020.pdf

[5] Andrew Blakers, “A Review of Pumped Hydro Energy Storage”, https://iopscience.iop.org/article/10.1088/2516-1083/abeb5b/pdf

[6] International Hydropower Association, “Pumped Storage Tracking Tool”, https://www.hydropower.org/hydropower-pumped-storage-tool

[7] International Hydropower Association, “Pumped Hydro - Water Batteries for Solar and Wind Power”, https://www.hydropower.org/factsheets/pumped-storage

[8] Pacific Northwest National Laboratory, “Open or Closed: Pumped Storage Hydropower is on the Rise”, https://www.pnnl.gov/news-media/open-or-closed-pumped-storage-hydropower-rise

[9] Ontario Pumped Storage, “A Clean, Quiet, Renewable Opportunity”, https://www.ontariopumpedstorage.com/about/pumped-storage-101/#:~:text=Pumped%20storage%20hydro%20power%20represents%20nearly%2095%20per,has%20been%20utilized%20for%20more%20than%20a%20century

[10] Government of Canada, “Canada Invests Over $960-Million in Renewable Energy and Grid Modernization Projects”,https://www.canada.ca/en/natural-resources-canada/news/2021/06/canada-invests-over-960-million-in-renewable-energy-and-grid-modernization-projects.html

[11] Pumped Storage Hydropower International Forum, “Innovative Pumped Storage Hydropower Configurations and Uses”, *61432192836f8d346bc2928e_IFPSH - Innovative PSH Configurations & Uses_ 15 Sept.pdf (website-files.com)

[12] International Energy Agency, “Battery storage is (almost) ready to play the flexibility game”, https://www.iea.org/commentaries/battery-storage-is-almost-ready-to-play-the-flexibility-game

[13] Matthew Stocks, Ryan Stocks, Bin Lu, Cheng Cheng, Andrew Blakers, “Global Atlas of Closed-Loop Pumped Hydro Energy Storage”

[14] MWH, “Report on Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest”

[15] Pumped Storage Hydropower Capabilities and Costs, Pumped Storage Hydropower International Forum, Capabilities, Costs & Innovation Working Group, September 2021

[16] 130.01GW pumped storage capacity globally in 2021 https://www.statista.com/statistics/1304113/pumped-storage-hydropower-capacity-worldwide/)

[17] Technology Maturity “A review of technology innovations for Pumped Storage Hydropower, https://publications.anl.gov/anlpubs/2022/05/175341.pdf

[18] Andrew Blakers, Matthew Stocks, Bin Lu and Cheng Cheng "A review of pumped hydro energy storage", 25 March 2021

[19] Batteries get hyped, but pumped hydro provides the vast majority of long-term energy storage essential for renewable power – here's how it works

[20] Bin Lu, Andrew Blakers, Matthew Stocks, Cheng Cheng, Anna Nadolny, "A zero-carbon, reliable and affordable energy future in Australia", Energy, Volume 220, 2021

[21] *A. Blakers, M. Stocks, B. Lu, C. Cheng and R. Stocks, "Pathway to 100% Renewable Electricity," IEEE Journal of Photovoltaics, vol. 9, no. 6, pp. 1828-1833, 2019*

- Andrew Blakers, Bin Lu, Matthew Stocks, '100% renewable electricity in Australia', Energy, vol. 133, pp. 471-482, 2017

APPENDIX A

APPENDIX A – CORPORATE PROFILES OF STUDY ALLIANCE

1.STANTEC OVERVIEW

The Stantec community unites approximately 25,000 employees working in over 400 locations across six continents. We collaborate across disciplines and industries to bring environmental, energy, water, buildings, and infrastructure projects to life. Our work, from initial project planning and permitting through to design, construction, commissioning, maintenance, decommissioning, and remediation—begins at the intersection of community, creativity, and client relationships.

For over a 100 years Stantec has engineered waterpower plants in our legacy firms MWH and Harza, names that continue to command respect for trailblazing leadership in their day. Today we employ over 650 dedicated waterpower professionals in our worldwide operation that is led from headquarters in Canada and is represented in every province.

As a province with particular strength in both, the manufacture of hydro equipment and as the home of North America's largest hydropower producer, Quebec is also home to Stantec for over 60 years. With over 1,500 employees in 14 offices throughout the province, our team has completed thousands of engineering and urban design projects and won numerous awards and distinctions that celebrate our creativity and excellence. Our firm is ranked in the Top 5 engineering consulting services in the province and our expertise covers the following sectors:

- **Buildings**
- **Transportation Infrastructure**
- **Urban Infrastructure**
- **Energy & Resources**
- **Environmental Services**
- **Water & Wastewater Engineering**

No.1

Most Sustainable Firm in North America (Corporate Knights, 2021)

No.3

Top 10 Global Design Firms in Power – Hydro Plant (ENR, 2021)

No.4

Top 15 Global Design Firms in Dams & Reservoirs (ENR, 2020)

No.9

Top 200 Global Environmental Firms (ENR, 2021)

No.12

Top 150 Global Design Firms (ENR, 2021)

No.15

Top 25 Global Design Firms in Power - Transmission & Distr. (ENR, 2021)

Stantec is a key player for the design of major infrastructure projects: Waterpower, schools, hospitals, roads, bridges, water treatment plants, telecommunications networks, power substations and distribution networks, etc. Throughout the year, we have developed a deep understanding of the needs of Canadians and play an integral role of advising public and private organizations.

We care about the communities we serve—because they're our communities too. This allows us to assess what's needed and connect our expertise with appreciation to nuances and envision what's never been considered, to bring together diverse perspectives so we can collaborate toward a shared success. We are designers, engineers, scientists, and project managers, innovating together at the intersection of community, creativity, and client relationships. Balancing these priorities results in projects that advance the quality of life in communities across the globe.

We believe sustainable design can defy expectations and propel our communities into the future. We are helping clients realize the full potential of their projects in terms of life cycle cost, energy efficiency, carbon reduction, and human health and wellness. Informed by data and grounded in the market, we design to support human resilience, health, and wellness while delivering value through life cycle cost analysis and reduction of energy and carbon use.

Our core values unite us as a firm. Our commitment to the health and safety of our people and to being ethical underpins everything we do. They drive our actions and are embedded in our delivery and account management philosophy.

We Put People First. People are at the heart of everything we do. That's why we listen to the needs of our clients and their people. It's why we define fulfilling careers for our people, allowing us to discover, develop and retain the best in their fields. For WaterPower Canada, this means we put your team first, too. We focus on their needs and prioritize health, safety, security, and the environment in all our projects.

We Do What is Right. We approach every project as a partnership because our work creates a lasting impact. Integrity guides what we do, which means we make the right choice even when it's the tough choice. For WaterPower Canada, this means we will be a trusted advisor, willing to be a strong voice advocating for responsibility and accountability.

We Are Better Together. When smart, passionate, creative people come together, real possibilities are unleashed. Diverse perspectives will create extraordinary results. We draw on the wide breadth of project expense to build the right team for each project; because when we work together, no problem is too large or complex.

We Are Driven to Achieve. We believe that transformation, in our work and in ourselves, is truly possible. We're defined by our entrepreneurial spirit and the pursuit of not only what's next, but what's best, bringing imagination and determination to every challenge. We deliver the excellence that propels us and our clients to success. For WaterPower Canada, this means talented, committed, focused teams and repeatedly successful projects.

1.1 SUSTAINABILITY

Stantec is committed to being a leader and model of **sustainability** by doing business in a way that meets the needs of the present while contributing to an environmentally, socially, and economically sustainable future. This commitment is at the heart of how Stantec operates and how it delivers solutions to our clients and is vital to the long-term success in achieving its vision. Stantec integrates sustainability into our overall operations and everyday practice by:

- Implementing best industry, employee, and vendor practices to reduce resource use, waste, and emissions while increasing efficiency and effectiveness.
- Fostering an understanding of sustainability at all levels of the organization in ways that are both personally and professionally relevant.
- Embracing an accountable and transparent governance and leadership structure that integrates sustainability considerations into all our business decisions.
- Reporting on our sustainability performance and achievements.

No.5

Ranked fifth most sustainable corporation in the world (2021 Corporate Knights Global 100)

No.1

Ranked most sustainable corporation in North America (2021 Corporate Knights Global 100)

Net Zero

Carbon Neutral by 2022, then net zero by 2030 (Our Operational Pledge)

1.2INCLUSION & DIVERSITY

Embracing **Inclusion and Diversity (I&D)** is part of our commitment to build an inclusive workplace that not only empowers and inspires—but also attracts and nurtures the very best talent from all over the world. Stantec has implemented a board diversity policy that ensures that the profiles of senior management and board members provide the necessary range of perspectives, experience, and expertise required to achieve effective stewardship. The Corporate Governance and Compensation Committee is responsible for assessing Stantec's progress against this policy's objectives. Stantec puts a focus on diversity in our top leadership. We believe that representation matters, and when top leadership is diverse, it brings about innovation and inspiration to our diverse colleagues, clients, and communities. Currently, 38% of Stantec's board members are women, 38% of our C-Suite are women, and 25% of our C-Suite are women of colour.

Canada's Best Employers

2020 Forbes

World's Best Employers

2020 Forbes

America's Best Employers for Women

2020 Forbes

Gender Equality Index

1.3HYDROPOWER EXPERIENCE

Stantec has been providing engineering services to customers in North America and around the world since 1920. Our client base for hydropower and dams includes for decades among others the largest utilities in Canada and the United States, including:

- BC Hydro
- Yukon Energy Corp.
- Northwest Territories Power Corp.
- Manitoba Hydro
- SaskPower
- Ontario Power Generation
- Hydro Quebec
- Nova Scotia Power
- NL Hydro / Nalcor
- Fortis BC
- United States Army Corps of Engineers
- United States Bureau of Reclamation

In 2020, Stantec celebrated 100 years of experience in the planning, design, and construction of dam and hydropower projects. Throughout our history, Stantec has been rated within in the top hydropower firms globally. Our offerings range from feasibility studies to design and construction of new dams and hydropower plants as well as preparing designs for upgrades and modernization of existing facilities. We have the specialized experience and depth of expertise to apply the latest technologies and design innovations to projects, while delivering cost-efficient, safe, and reliable long-term operations.

Figure 2 Rocky Mountain Project

1.4 STANTEC PUMP STORAGE SERVICES

Stantec, is a global leader in pumped storage and stands alone in North America, with our full range of engineering and environmental services from concept planning to implementation of projects ranging in capacity from 40 to 3,000 MW as well as complementing the life cycle with rehabilitation services. Our firm is shaping the industry by embracing cutting-edge technology and utilizing our engineers' hands-on experience in all phases of the project lifecycle and sharing our expertise in industry associations. Our work integrates advances in design, technology, materials, fabrication methods, and controls. These advances significantly improve efficiency, performance, operation, and project flexibility. Adjustable and variable speed technology enables greater savings in overall system production costs, provides larger amounts of various operating reserves, and delivers more value to the power system. Stantec has developed a global footprint in pumped storage from over 55 years of experience working with our international clients. Table1 shows the wide range of pump storage services that we are providing, and Section 2.2 shows sample project profiles.

Stantec's services in pumped storage include site selection, feasibility studies, licensing, and construction management. These activities address a whole spectrum of issues relating to the need for power, technical feasibility, environmental acceptability, economic and financial soundness and regulatory and permit approvals. Stantec's design activities are a culmination of the project planning services. Stantec has one of the largest staff of pumped storage specialists in the international consulting field.

We specialize in all features of pumped storage projects:

- Power Generation Equipment Design Parameters and Specifications – Pump turbines, generator-motors, substations
- Plant Systems – Auxiliary power, communication, mechanical, and electrical balance of plant systems
- Water Conveyance Structures – Tunnels, pipelines, penstocks, and analysis using 3D fluid dynamics calculations
- Storage Facilities – Dams, spillways, intakes, 3D finite element modeling analysis
- Foundations – Foundation and materials testing, geotechnical investigations and treatment, rock mechanics
- High-Voltage Transmission – Switchyards, gas insulated switch gear (GIS), control facilities

16,000+ MW of Constructed New Pumped Storage

14,500 MW of Upgrades

100,000+ MW Studied

Since 1920, Stantec has designed hundreds of new dam and hydropower projects globally, producing clean reliable energy and water storage solutions for millions of people around the world.

Our first-class reputation has been earned by delivering projects in 35 countries on six continents and includes some of the largest and most complex projects at the time of their implementation.

Stantec is focused on providing sustainable solutions for our clients and society, whether through the construction of new facilities or improving the safety, reliability, and efficiency of existing projects.

Our sustainable and economic solutions minimize the impact

We have developed a global footprint in pumped storage working with our international clients. These projects range in installed capacity from 40 MW to 2,100 MW.

1960s-1980s

Seneca, USA, 380MW

Mingtan, Taiwan, 1650MW

Rocky Mountain, USA, 848MW

Yang Yang Korea, 1000MW

1990s-1980s

Guide for EPRI-Planning and Evaluation of pumped storage Projects

Guide for EPRI-Adjustable Speed Pumped Storage

Blue Diamond, USA, 400MW

Tianhuangping, China, 1800MW

Togbai, China, 1200MW

Guangzhou, China, 1200MW

Sanchung Korea, 700MW

Chair, Bulgaria, 864MW

Bhumibol, Thailand, 170MW

Parsa, Israel, 800MW

2000s-2010s

Northfield Mountain, USA, 1080MW

Pumped Storage and Wind Integration Study for BPA, USA

Castaic Upgrading, USA, 1,247MW

Shandong Taian, China, 1000MW

Fairfield, USA, 640MW

Lima, South Africa, 1,500MW

Mormon Flat, USA, 60 MW

Mt. Elbert Condition Assessment, USA, 200MW

Raccoon Mountain, USA, 1,530MW

Riverbank, Canada,

Ongoing

Canyon Creek, Canada, 75MW

Steep Rock, Canada, 400-800MW

Rocky Mountain, USA, 1,095MW

Eagle Mountain, USA, 1,300MW

Hurricane Cliffs, USA, 300MW

Mulqueeney Ranch, USA, 200-400MW

Mokelumne, USA, 400MW

Yards Creek, USA, 501MW

Gregory Country, USA, 1800MW

Lake Hodges, CA, USA, 40MW

2. AUSTRALIAN NATIONAL UNIVERSITY

The Australian National University (ANU) founded in 1946 is Australia's highest ranked University. ANU has been engaged in renewable energy research and teaching for 50 years. ANU is a world-leading university in Australia’s capital. Excellence is embedded in their approach to research and education. Notable recent contributions include the Global Atlas of Off-River Pumped Storage Hydro (Appendix B).

3. CENTRE FOR ENERGY ADVANCEMENT THROUGH TECHNOLOGICAL INNOVATION (CEATI)

The corporate mission of CEATI is to provide leadership in developing applied technology solutions for the electricity industry on a collaborative basis with over 150 utilities participating from more than 18 countries.

CEATI is a user-driven technology solution exchange and development program for utilities. The CEATI program model was built to combine inter-utility information exchange and informal benchmarking with the development of practical projects yielding results that have an immediate benefit for our participants. Projects are initiated on issues raised by participating organizations and are designed to result in practical deliverables. As all projects are sub-contracted to outside firms, CEATI is not bound to work with a single research organization. This provides greater flexibility such that all projects are undertaken by the most appropriate firms and industry recognized experts, including those entities participating in the program.

With over 30 years of experience in technology development, CEATI International’s roots date back to 1891 with the founding of the Canadian Electric Association (CEA). Today, CEATI continues to grow, capitalizing on working relationships with a global network of technology providers and expert groups. Over the last 5 years CEATI has expanded steadily to serve utility industry participants through 22 focused programs. CEATI participants now represent utilities throughout the world. This diversity contributes to the strength of CEATI programs and brings value directly to participants who are integral to the success of this user-driven program.

CEATI’s Generation Program consists of the Asset Management, Dam Safety, Hydropower Operations & Planning, Hydraulic Plant Life, Thermal Generation, and Strategic Options for Integrating Emerging Technologies and Distributed Energy Interest Groups.

4. POWER ADVISORY

Power Advisory (PA) offers extensive experience in North American electricity markets. Services include:

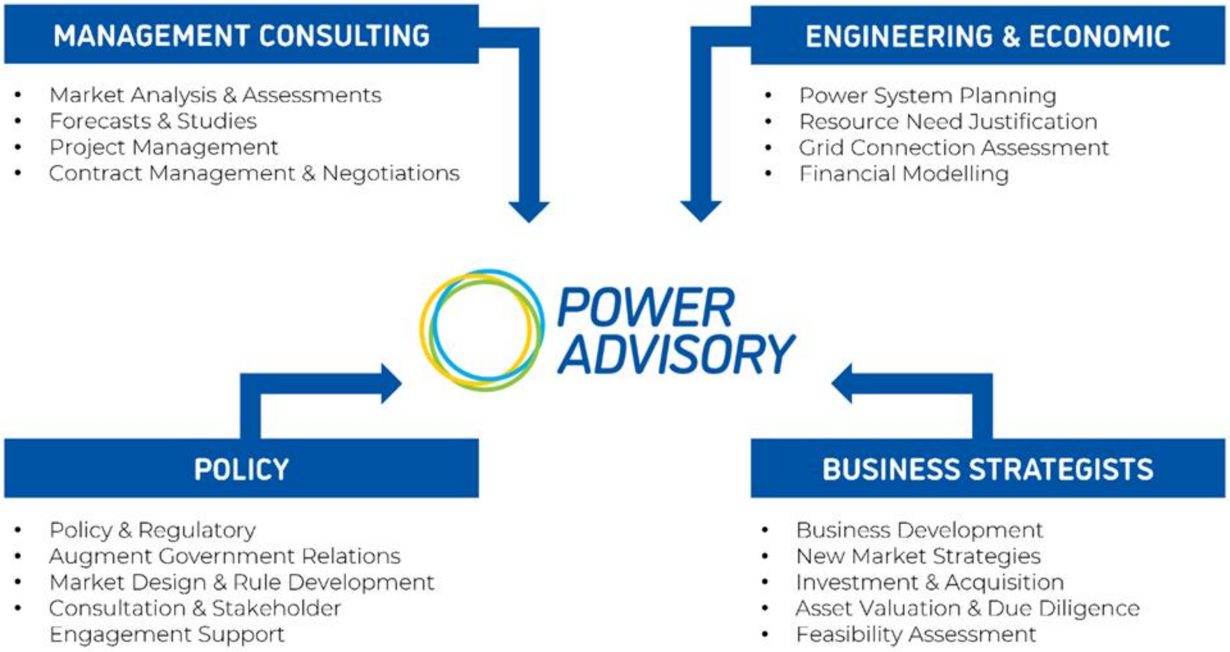


Figure 1 Power Advisory Services

Power Advisory's market assessments are robust and reflect a deep understanding of the power system, market design, and investment climate. Furthermore, Power Advisory is regularly called upon by clients to critically assess project economics and evaluate the reasonableness of their underlying assumptions in both wholesale and regulated markets.

Power Advisory's advice is based on an understanding of fundamental economic drivers as shaped by electricity market structures, electricity market design, project development, and associated commercial and financing agreements, regulatory frameworks, and market behaviour. Their consulting services are provided by seasoned electricity sector professionals who offer a wide breadth and significant depth of industry knowledge. this experience and knowledge, combined with a detailed understanding of market fundamentals, yields the strategic insights provide clients with market advice that enhances project value and mitigates project risk.

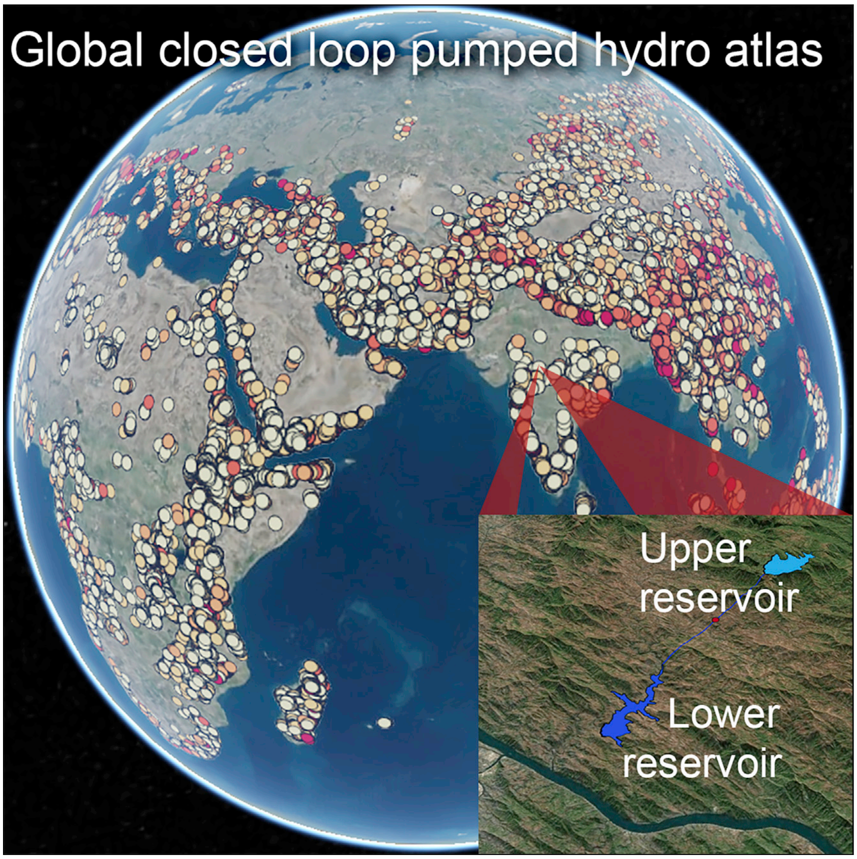
APPENDIX B

Joule

CellPress

Article

Global Atlas of Closed-Loop Pumped Hydro Energy Storage



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HIGHLIGHTS

Closed-loop, off-river pumped hydro increases potential for electrical storage

GIS analysis was used to assess the global closed-loop hydro resource

616,000 potential sites identified with combined storage potential of 23,000 TWh

Wide distribution of sites can support large future fractions of wind and solar

Wind turbines and solar photovoltaic (PV) collectors comprise two thirds of new generation capacity but require storage to support large fractions in electricity grids. Pumped hydro energy storage is by far the largest, lowest cost, and most technically mature electrical storage technology. Closed-loop pumped hydro storage located away from rivers (“off-river”) overcomes the problem of finding suitable sites. GIS analysis ranging has identified 616,000 individual systems, demonstrating that storage is not a constraint to wind and PV deployment.

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CellPress

Joule

Article

Global Atlas of Closed-Loop Pumped Hydro Energy Storage

Matthew Stocks,[1,2,*] Ryan Stocks,[1] Bin Lu,[1] Cheng Cheng,[1] and Andrew Blakers[1]

SUMMARY

The difficulty of finding suitable sites for dams on rivers, including the associated environmental challenges, has caused many analysts to assume that pumped hydro energy storage has limited further opportunities to support variable renewable generation. Closed-loop, off-river pumped hydro energy storage overcomes many of the barriers. Small (square km) upper reservoirs are typically located in hilly country away from rivers, and water is circulated indefinitely between an upper and lower reservoir. GIS analysis of high resolution global digital elevation models was used to determine economically feasible closed-loop scheme locations outside protected and urban areas. This search identified 616,000 potential storage sites with an enormous combined storage potential of 23,000 TWh. This is two orders of magnitude more than required to support large fractions of renewable electricity, allowing flexible site selection. Importantly, the resource is widely distributed to effectively support large-scale solar and wind deployment for electrical grid decarbonization.

INTRODUCTION

Solar photovoltaic modules (PV) and wind turbines are now the largest and second largest sources of net new electricity generation capacity, respectively, with 97 GW of solar PV and 59 GW of wind installed in 2019.[1] The economics of these technologies have reached the point where they are now the lowest cost sources of electricity generation in many regions, resulting in expectations of continued growth. These sources of generation are variable in nature—the amounts of energy delivered depends on the amount of wind and solar insolation available.

Energy storage will be necessary to support large fractions of wind and solar PV penetration in electricity networks. Studies at a world wide[2,3] and country-level scale[4–8] have identified that storage will be key to managing a future grid with very high penetration of variable renewables. Storage technologies in these studies include batteries, power to gas (hydrogen or methane), thermal storage, and pumped hydro energy storage.

Pumped hydro energy storage is a form of potential energy storage. A system comprises two reservoirs at different elevations connected by either pipes or tunnels. The difference in elevation is called the "head." When providing electricity to the electricity network, water flows from the upper reservoir to the lower reservoir along the pipes or tunnels through a turbine connected to a generator, much like a conventional hydroelectricity generation scheme. However, when there is an excess of electricity available, water is pumped from the lower reservoir to the upper reservoir. The pump can be a separate unit or, as is often the case, the turbine/generator is reversible and acts as the pump/motor.

Context & Scale

Wind turbines and solar photovoltaic (PV) collectors dominate new electricity capacity additions. Wind and solar PV are variable generators requiring storage to support large fractions of total generation. Pumped hydro energy storage is the largest, lowest cost, and most technically mature electrical storage technology. However, new river-based hydroelectric systems face substantial social and environmental opposition, and sites are scarce, leading to an assumption that pumped hydro has similar limited potential.

Closed-loop pumped hydro storage located away from rivers ("off-river") overcomes the problem of finding suitable sites. We have undertaken a thorough global analysis identifying 616,000 systems, available on a free government online platform. This immense pumped hydro resource demonstrates that low cost energy storage is not a constraint to wind and PV deployment for most of the world. Understanding this helps overcome a key barrier to continued deployment of variable renewables.

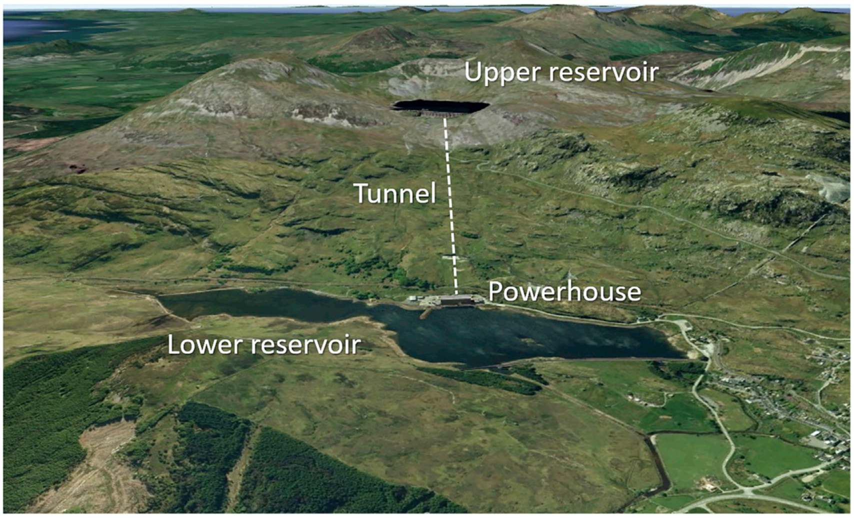

Figure 1. An Example of a Closed-Loop, Off-River Pumped Hydro Storage System: Ffestiniog Power Station in Wales

The scheme comprises high head and small reservoirs. Background image from Google Earth.

Pumped hydro energy storage was originally developed to manage the difference between the daily cycle of electricity demand and the baseload requirements for coal and nuclear generators: Energy was used to pump water when electricity demand was low at night, and water was then released to generate electricity during the day. Consequently, pumped hydro is currently the largest source of electrical energy storage with more than 95% of the world's electricity storage power (GW) capacity and 99% of the storage energy (GWh). Despite this, many studies considering high fractions of renewable energy in future electrical systems ignore pumped hydro storage.[3,5] Others assume no growth in pumped hydro energy storage[2] or limit the growth in pumped hydro to the scale of the conventional hydroelectricity resource. The topography requirements of conventional pumped hydro are often cited as a reason for the need to develop other storage technologies.[9,10]

A closed-loop, ''off-river'' pumped hydro overcomes these constraints. The upper reservoir for these schemes is located high in hilly areas rather than in a river valley. Closed-loop schemes recycle water between the two reservoirs; that is, the water is cycled between the upper and lower reservoirs during operation with no aim to capture water in the upper reservoir for additional power generation. Water consumption is only required to replace the difference between evaporation and seepage, and rainfall. The reservoirs are also typically small, of the order of tens to hundreds of hectares. Locating upper reservoirs away from rivers and the small area of the reservoirs greatly reduces the environmental impact. It also minimizes the need to manage large flood events, which substantially reduces construction cost. Since most of the world's land surface is not near a river, there are vastly more potential areas for off-river compared with on-river pumped hydro systems.

The Ffestiniog Power Station, as shown in Figure 1, is an exemplar for closed-loop, off-river systems. This site has good head (300 m), low separation keeping tunnels short (1.3 km), small reservoir areas (10 and 30 Ha) and limited upper reservoir catchment (160 Ha). It is designed purely for energy storage with no rivers dammed for power generation (as usually associated with conventional hydro schemes). Raccoon Mountain pumped hydro schemes in the United States is another example

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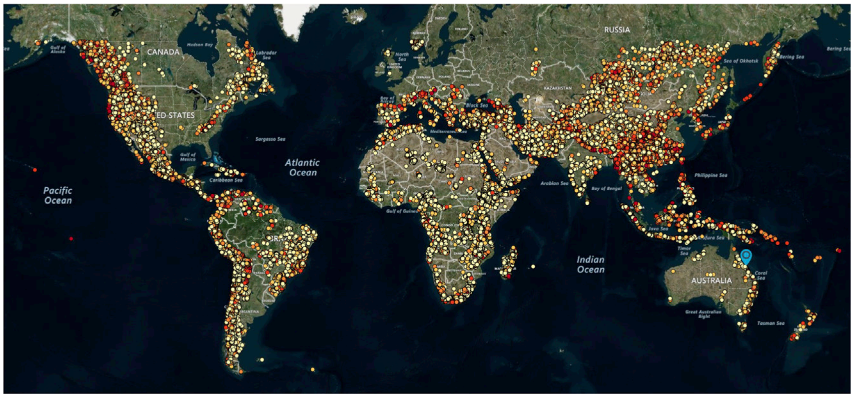

Figure 2. Distribution of Large 150 GWh 18 h Storage Closed-Loop Pumped Hydro Storage Sites Identified in this Study

Lowest costs sites are shown in red with yellow representing sites with twice the capital cost. Similar regional distributions occur with smaller sized schemes but with larger numbers of sites. Image credit: Data61 hosting and Bing Map background.

of a closed-loop, off-river schemes with no intent to capture additional water for energy.

Resource assessments are an important component of understanding the potential role of a technology in the energy mix. This work is the first global assessment of closed-loop, off-river pumped hydro energy storage opportunities. Suitable locations for closed-loop, off-river pumped hydro energy storage depend critically on the local topography. We have developed algorithms for efficiently identifying potential reservoir locations and pairing reservoirs to simulate closed-loop, off-river pumped hydro sites for a range of scheme sizes. A cost model is then applied to determine if the characteristics of the reservoir pair meet a minimum economic standard. All sites that meet the criteria are then ranked into cost classes A through E (with E double the capital cost of A) and three-dimensional (3D) visualization developed.

RESULTS

Our analysis has identified 616,818 low cost closed-loop, off-river pumped hydro energy storage sites with a combined storage potential of 23.1 million GWh. The capacity is the sum of the energy storage from non-overlapping reservoir pairs with the larger storage capacity given priority over smaller capacity pairs to avoid double counting locations with different energy storage. This resource is widely distributed across the world as exemplified by the 150 GWh sites shown in Figure 2. A table with the identified resources for each country is provided in the Supplemental Information.

The 3D visualization of one potential closed-loop, off-river site is presented in Figure 3. This is a 50 GWh, 18 h storage site that could nominally maintain 2.8 Gigawatts (GW) of power output for 18 h. The lower reservoir is visualized in dark blue in the foreground and the upper reservoir in light blue. Neither reservoir has significant catchment area, and both are located away from the major local watercourse visible in the foreground. A combination of high head, low separation of the reservoirs, and low dam wall volumes result in relatively low capital cost.

Zoomable 3D visualization of all 616,000 sites in the global atlas (such as those illustrated in Figure 3) is hosted on the Australian government's renewable energy

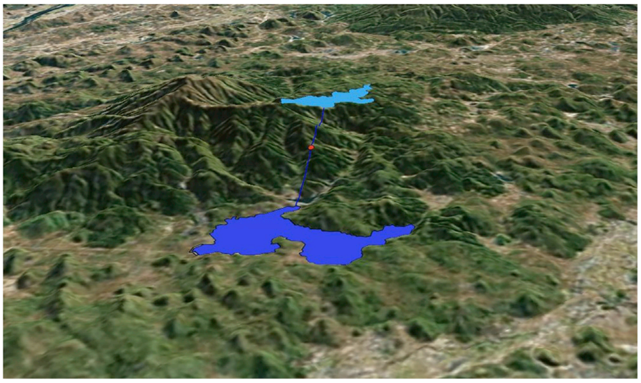

Figure 3. 3D Visualization of a Class A, Off-River Pumped Hydro Site in Southern China.
Image credit: Data61 hosting and Bing Map background.

mapping infrastructure website.[11] Included in the visualization of each site is the reservoir shape, the dam walls, and a notional tunnel route between the reservoirs. Detailed "pop-up" information for the site is available by selecting the reservoir or the connecting tunnel.

The pumped hydro resource is well distributed at a regional and sub-regional level to support variable renewable energy deployment. The pumped hydro storage capacity resource per million people for the UN geo sub-regions is shown in Figure 4. The target value of 20 GWh per million people[8] is the storage required to support 100% renewable electricity for a grid dominated by variable renewables over a wide geographical region in a high-energy-consuming developed country (Australia). Every UN sub-region, except for Micronesia, Northern and Western Europe, and Western Africa has more than 1,000 GWh of storage capacity per million people.

The contributions of the 616,000 sites to the total resource is displayed in Figure 5. Schemes were simulated with storage capacities of 2, 5, 15, 50, and 150 GWh and power to operate for either 6 or 18 h at full capacity.

The cumulative capacity of the schemes contributing to the total off-river resource are categorized by site characteristics and approximate capital cost. Estimation of the cost is discussed in detail in the Supplemental Infromation. In summary, the estimated cost of possible systems is arranged in bands from lowest to highest and the five best bands are displayed in published data (A to E, with cost-class A being the lowest and best). Several key trends emerge from these data. Larger systems contribute more to the total capacity than smaller systems resulting in an average capacity across all schemes of 40 GWh. The distribution of sites across the cost classes changes with increased storage capacity with classes A and B containing the largest proportion of 150 GWh sites, while classes D and E dominate the smaller 2, 5, and 15 GWh systems.

DISCUSSION

Global Pumped Hydro Resource

The immense closed-loop pumped hydro resource identified in this study demonstrates that availability of low-cost large-scale storage is not a limitation on the wide deployment of variable renewable energy generation.

The total global storage capacity of 23 million GWh is 300 times larger than the world's average electricity production of 0.07 million GWh per day.[12] Pumped hydro

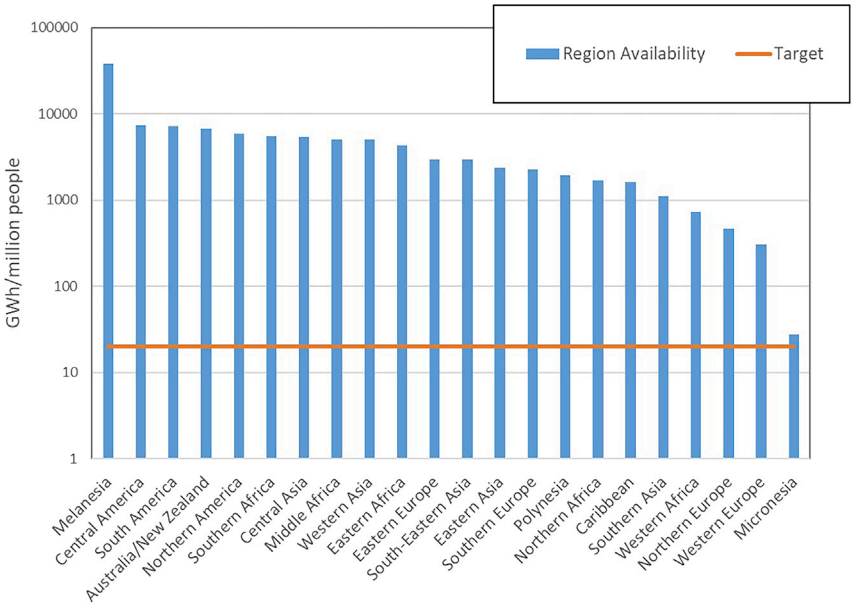

Figure 4. Off-River Pumped Hydro Resource Per Capita for UN Geo Sub-Regions.
The target of 20 GWh per 1 million/people can support a 100% renewable system.

energy storage will primarily be used for medium term storage (hours to weeks) to support variable wind and solar PV electricity generation. It is expected that pumped hydro supporting a system dominated by solar PV will cycle daily (~350 cycles per year), while storage over several days to a week may be needed to support typical wind cycles (50–100 cycles per year). This suggests a total storage requirement of the order of 1% of the annual energy demand, which means that significantly less than 1% of the sites in the atlas need to be developed to support 100% renewable electricity.

More than 70% of the world's population lives in the " sun belt" between 35° N and 35° S.[13] In this region, the monthly solar resource varies by less than a factor of two between summer and winter. Furthermore, in this range of latitudes, the number of cooling days typically exceeds the number of heating days,[14] indicating that electricity loads will be greater in summer when the solar contribution is higher. The need for a significant seasonal storage is therefore expected to be low for the majority of the world's population.

Low to moderate penetration of wind and solar PVs in electricity networks can be largely treated as a small perturbation on the system resulting in less demand needing to be met by other generation sources. The point where difficulties start to arise in an isolated electricity system is usually reported to be in the range of 20% to 50%.[15,16] Flexible demand and generation, and sharing supply and reserves across larger regions with transmission all support balancing supply and demand at these levels.[17] More than 40% has been managed with these approaches in regions within larger grids, including South Australia,[18] which is part of the larger Australian national electricity market, and Denmark,[19] within the larger European market.

The quantum of storage required is substantially reduced for large regions of connected network, allowing sharing of wind and solar resources over larger areas. The national electricity market in Australia provides electricity for most of the

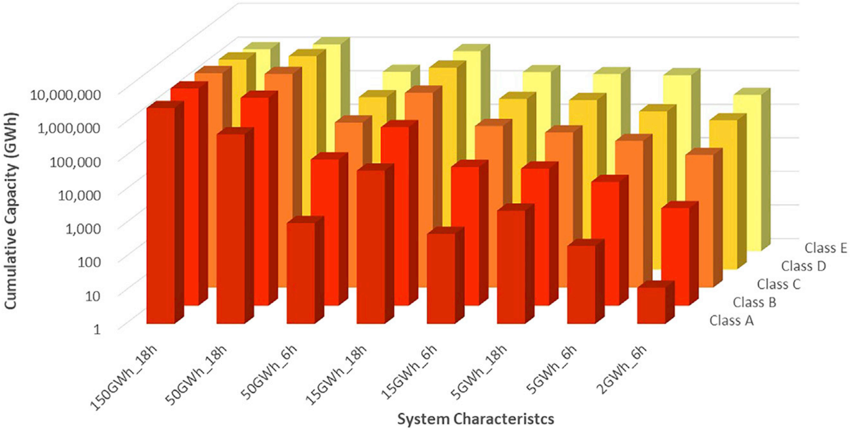

Figure 5. Cumulative Capacity of the Schemes Contributing to the Total Off-River Resource Sorted by Economic Class and Capacity

Australian population. The transmission network extends for more than 3,000 km North-South. Blakers et al.[8] found that if this system, with annual demand of 205 TWh, was dominated by variable wind and PV generation, the required storage is 400–500 GWh, which is about 20 GWh per million people. Australia is a developed country with a high per capita level of electricity consumption. This quantity of storage corresponds to 80% of average daily demand. Extrapolated to a world in which 9 billion people have similar levels of electricity consumption to Australia, the required storage is of the order of 180,000 GWh. Again, this is less than 1% of the identified closed-loop pumped hydro storage resource.

The present work is restricted to greenfield off-river sites. Brownfield sites comprising existing reservoirs and old mining sites have not yet been included. Therefore, the scale of the economically viable pumped hydro resource will be greater than modeled here. There are significant potential cost savings associated with using existing reservoirs, as has been proposed for some projects. While global databases of large reservoirs do exist,[20] examination of the use of these reservoirs show that less than 25% have hydroelectricity production as their primary use. Other uses include irrigation, drinking water, and transport, which all have potential conflicts with energy production. A significant advantage of developing off-river greenfield schemes is that energy storage would be the sole priority.

The maximum head used in this study is limited to 800 m as outlined in the Methodology. There are additional opportunities with higher head. 800 m corresponds to the upper limit for reversible Francis turbines,[21] which is the dominant turbine technology. Higher heads require ternary equipment with separate multistage pumps, usually in combination with impact turbines, such as pelton designs. These schemes require custom engineering beyond the scope of this analysis.

Seawater-based pumped hydro schemes are excluded from this work. In these schemes, the ocean is the lower reservoir, which would reduce the lower reservoir cost, and saltwater is used as the working fluid. There has been one such scheme developed, the experimental 30 MW scheme in Okinawa in Japan, which operated for 17 years from 1999 to 2016.[22] There are proposals for sea water schemes, for example in Chile[23] and Australia,[22] but there are significant environmental and engineering challenges to overcome. Turbine costs are likely to be high because vending companies may apply an engineering uncertainty premium. Additionally, land use conflicts could be significant, because hilly regions adjacent to the sea are relatively uncommon and are often socially or environmentally sensitive.

Distribution of Pumped Hydro Resource

The distribution of pumped hydro sites identified indicates that there is adequate storage available in most sub-regions to support high fractions of variable renewables. Most UN sub-regions had more than 1,000 GWh of storage potential per million people, which is approximately two orders of magnitude more than the 20 GWh target.[8]

The location of pumped hydro resources identified in this work depends on the local topography. An initial requirement is a minimum altitude for the upper reservoir. Areas with maximum altitudes above sea level of less than 100 m, such as many small island states and some coastal countries like Gambia, Qatar, and Netherlands, have no attractive potential pumped hydro resource.

The second requirement is sufficient local height differences to enable potential energy storage. While altitude often indicates resource potential, large areas of central Australia, Africa, North America, and Europe have significant altitude (>400 m), but few sites were identified because the landmass is flat with low slope. Paraguay and Uruguay are examples of countries with some areas of moderate elevation but insufficient slope. Generally, the best regions correspond well with major mountain ranges, such as the Andes in South America, Rockies in North America, and Himalayas in Asia, all well endowed with sites. Less prominent ranges of moderate heights, such as the Appalachians in the western United States and the Great Dividing Range in Australia, also offer enough height difference for a high density of sites.

Some sub-regions, such as Northern and Eastern Europe, had lower per capita resources. However, these regions are part of the larger European electricity market, which includes Western and Southern Europe, which have much better topography. The European transmission network allows sharing of electricity resources across Europe. The per capita resource for the four UN sub-regions of Europe is more than 2,700 GWh per million people. Micronesia, which represents less than 0.01% of the world's population, is the only UN region with inadequate pumped hydro resource and is instead likely to be dependent on batteries or hydrogen for electricity storage.

Large-area electricity networks with high levels of wind and PV need less storage than smaller networks, because adverse local weather is smoothed out. Sharing of resources within and between regions reduces combined generation and demand variability, which in turn reduces reserve provisions. Supergrid proposals connecting Asia or connecting northern Europe with southern Europe and northern Africa are likely to support efficient storage development.

It should be noted that this study was undertaken remotely without any on-site verification. Only areas of high urban density[24] and designated protected areas[25] were excluded. Local environmental, cultural, hydrological, economic, or geotechnical aspects may prevent use of some sites or affect their engineering suitability. However, many locations have several similar alternative sites in the local proximity.

Capital Cost of Storage

The scale of the identified resource is two orders of magnitude greater than required to support widespread deployment of variable renewables. This allows for very selective development of sites. In most regions, this enables a focus on the lowest capital cost (class A and B sites) for practical implementation. Detailed information on the calculation of capital costs is presented in the methodology section. In this section, general trends and their implication for distribution of sites are discussed.

The capital cost of an off-river pumped hydro system can be approximately divided into capital costs associated with generating power ($/GW) and those associated with the capital cost of energy storage ($/GWh). Capital costs associated with power comprise the water conveyance, machine hall, pump/turbine, generator, and substation. The capital costs associated with storing energy comprise the two reservoirs. The capital costs for power (GW) and energy storage (GWh) can be sized independently resulting in an associated storage time, which is the ratio of these two components in the scheme. In this work, we considered 6 h of storage, which aligns well with storage for the peak generation of solar PV modules, or 18 h, which some co-authors found optimal for a large fully integrated network.[8]

Compared with a river-based hydro scheme, a closed-loop, off-river pumped hydro systems has an important advantage: The upper reservoir can be located near a hilltop rather than in a river valley, which substantially increases the height difference ("head") between the reservoirs and hence the available potential energy. Generally, a large head is preferred. For example, for otherwise identical systems, doubling the head halves the water storage requirement for the required energy storage target, and substantially reduces the required size and cost of the turbines and tunnels for a given power output. The principal cost of building a reservoir is the cost of moving rock to form the dam walls. The dam walls are assumed to be composed of local rock constructed in the form of a wall with a slope (width to height) of 3:1 on both the upstream and downstream sides. Doubling the height of the wall increases the volume and cost of the wall per unit length by approximately a factor of 4. Doubling the wall height also increases the required length of the wall, by an amount determined by the local geography. On the other hand, doubling the height of the wall increases the volume of impounded water, typically faster than the square but slower than the cube of the wall height, depending on the local geography. The water-to-rock ratio is the ratio of the volume of impounded water to the volume of required rock and is the principal figure of merit for an off-river reservoir. The economics of sites generally improves with larger wall height and hence storage volume as seen in Figure 5. Small storages (2–15 GWh) generally fall into higher cost classes (D and E), while large storages (50 and 150 GWh) have more even distribution between cost classes.

In our study, head can vary by a factor of eight (100 m to 800 m), while the water-to-rock ratio can vary by a factor of more than one hundred, resulting in potential differences in storage costs for the systems analyzed of three orders of magnitude.

A system with relatively short storage times (e.g., 6 h at full power), and therefore higher power, are more expensive than the same system with lower power (e.g., 18 h at full power), because the cost of building the reservoirs is the same, but the power components are larger.

Batteries are currently able to compete with pumped hydro storage for high power applications with short term storage (minutes to an hour or so). However, for storage of hours to days, the levelized cost of storage (LCOS) for closed-loop, off-river pumped hydro is the lowest of the current electrical energy storage technologies and is expected to be lowest for at least several decades as discussed in the later cost section.

Water and Environmental Impact

A challenge for development of pumped hydro energy storage facilities has been the association with traditional river-based hydroelectric power schemes with large energy storages on rivers and the associated construction and environmental challenges.[26] Other studies[27] raise conflicts with alternative water use, such as agriculture and town water supply as limits to the opportunities for pumped hydro, and focus on upgrading existing reservoirs for conversion to pumped hydro systems. The National Hydropower Association[28] recognized the growing opportunity for pumped hydro, but considered that environmental aspects are limiting the opportunity for new river-based pumped hydro schemes in the United States.

In contrast, the water impact of closed-loop, off-river pumped hydro is expected to be small. Unlike conventional hydro, which generates energy by passing captured water through the turbine only once, closed-loop cycling in pumped hydro schemes result in stored water being used of the order of 100 times per year. For a typical head around 400 m, 1 GWh of energy storage requires approximately 1 Gigalitre (GL) of water storage, as shown in Equation 1.

Developing around 1% of the identified resource, as suggested in the earlier discussion, would require a world-wide storage of around 200,000 GL. If developed over the next twenty years as we transition to low carbon electricity networks, the annual withdrawal would be only 10,000 GL per annum. This is a tiny fraction of the world's annual water withdrawal of around 3,000,000 GL.[29] Ongoing operation would need to replace the difference between evaporation and rainfall, and water availability would be an important consideration when developing any particular site.

Shifting to renewable electricity is likely to reduce total water withdrawals. According to the UN Food and Agriculture Organization data,[29] 90% of total industrial water withdrawal in the United States is cooling water for thermal based power generation, which would be eliminated with future fossil fuel phase out. Analysis of Australia's electricity system indicated that a 100% renewable electricity system supported by pumped hydro would use much less water than the current thermal dominated system.[30] Most of the water use would be to replace evaporation from reservoirs.

Environmental impact of closed-loop pumped hydro is expected to be modest. The GIS analysis for the atlas already excludes reservoirs that would impinge on sites in the World Protected Area Database.[25] The footprint required averages 6 Ha of combined reservoir area per GWh of storage. Using the aforementioned figure of 20 GWh per million people[8] for the required storage to support 100% renewable electricity, this equates to only 1.2 square meters per person—smaller than an average bathtub.

Another perspective to understand the scale of the area requirement for pumped hydro energy storage is to compare to the land needed for the associated generation. A solar farm with a daily output of 1 GWh requires an area of land that is about 300 Ha (assuming 18% efficient modules, a capacity factor of 16%, and a module packing density of 50%). Thus, the area required for storing that energy (6 hectares per GWh) is 50 times smaller than the associated solar farm. In summary, finding enough land for off-river pumped hydro reservoirs is unlikely to be a major problem in most regions.

Prospective off-river pumped hydro storage sites vary from tens to hundreds of hectares, much smaller than typical on-river hydro energy reservoirs. Tunnels and underground power stations, as assumed in the costing methodology, can be used in preference to penstocks to minimize other surface impacts. The 2 GW, 350 GWh Snowy 2.0 scheme in Australia, presently under construction within the Kosciusko National Park World Heritage area to support Australia's rapid deployment of wind and solar, includes 27 km of tunnels and underground power station to minimize environment damage.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Requests for further information should be directed to the Lead Contact, Matthew Stocks (matthew.stocks@anu.edu.au)

Materials Availability

No materials were generated in this study.

Data and Code Availability

The global atlas output data are hosted on the Australian Renewable Energy Mapping Infrastructure[11]. The code used for identifying sites is open source and available on Github[31].

Site Identification

Potential closed-loop pumped hydro locations were identified by simulating reservoirs in the landscape and evaluating if there was another suitable reservoir nearby to form a pair. The approach used to identify prospective reservoir location builds on the "dry gully" approach described by a subset of co-authors in Lu[32]. This work expands the single reservoir search algorithms to pair upper and lower reservoirs for pumped hydro schemes and, importantly, includes costs for ranking sites. Significant speed improvements have been achieved through optimization of the algorithms and moving to a machine compiled language. This enables a global search to be undertaken in practical time frames. The code is freely available and open source[31].

Reservoir analysis used the 1 arcsecond digital elevation data from the NASA Space Shuttle Radar Topography Mission[33]. This datum has 30 m spatial resolution at the equator and has 1 m height resolution. The 14,281 land-based 1 degree by 1-degree digital elevation tiles were filled to remove local depressions. These tiles covered the region between 60° N and 56° S and encompassed more than 99.7% of the world's population.

Increased processing speed has eliminated the need for the initial filtering of prospective regions that was described in in Lu[32]. Instead, every potential reservoir across all the land-based tiles were identified according to the search criteria. Initially, a virtual stream network with a minimum 10 Ha catchment was developed and potential dam locations to be simulated identified at 10 m height intervals along the streams. A maximum reservoir depth was determined as the lower limit of 100 m or an overlap of defined exclusions zones. In this analysis, this comprised the World Database of Protected Areas[25] and regions of high urban density[24]. Characteristics of the reservoirs were then determined for water depths varying in 10 m increments to this maximum depth.

Boundaries that were common to the area of the reservoir and the flow catchment were assumed to be the center of the reservoir dam wall. The volume of an earth wall rock filled core dam with a batter of 3:1, freeboard of 1.5 m and crest width of 10 m were determined from the digital elevation model. The material for the dam wall is assumed to be excavated from within the reservoir area and partly contributes to the final water storage volume. Reservoirs with at least one GL of water storage and a stored water to dam volume ratio greater three are retained for further analysis.

Reservoirs were then analyzed as potential upper reservoirs. We explored a range of energy storage sizes of 2, 5, 15, 50, and 150 GWh. Every potential reservoir with a height difference (head) of 100 to 800 m below the target reservoir and with a height difference to separation ratio more than 0.03 (3% slope) were considered as a potential lower reservoir. The head range was based on the typical operating range for reversible Francis turbines[21]. The approximate water depth for the upper and lower reservoirs required was then determined for the target energy storage, for example, 5 GWh, by interpolating the reservoir data. Every pair of reservoirs was then ranked using the interpolated data according to the cost calculation described in the later cost section.

This rough ranking was then used for the final detailed analysis. The highest ranked pair was reanalyzed, adjusting the water depth of both reservoirs until the target energy storage was achieved. The cost of the pumped hydro scheme for that reservoir pair was then determined. Any pair in the rough ranking that contained or overlapped either of these reservoirs was then removed from the list, and the process was repeated for the next highest ranked reservoir pair. This ensured no reservoir was used more than once in the resource assessment for a given storage capacity.

Capital Cost of Storage

The economic feasibility of sites was evaluated to determine inclusion in the database using the approach described below. Further details of the parameterization of the costs are available in the Supplemental Information.

There are two largely independent components to the cost of a pumped hydro system: The reservoirs used for storing water and the power conversion system, which includes the powerhouse (pump/turbine/generator) water conveyance and switchyards. The cost of connecting from the local switchyard to the transmission network is not included as the distance to the nearest appropriate transmission will depend on the local network and will change over time. Schemes closer to existing transmission will be more attractive unless new transmission is being built to support new renewable energy generation, for example. As part of an earlier project, a cost model was developed with hydro engineering consultants using detailed spatial analysis of a range of sites. Cost fitting parameters were then determined for the cost analysis in this work as outlined below. Details of the parameterization are provided in the Supplemental Information. Costs are reported in US$. The available energy, E, stored in the upper reservoir is given by

$$E(MWh) = \frac{f\eta\rho VgH}{3.6x10^9} \quad \text{(Equation 1)}$$

where f is the fraction of the reservoir which is usable (85%); η is the turbine conversion efficiency (90%); ρ is the density of water (1,000 kgm^{-3}); V is the upper reservoir volume in m^3; g is the acceleration due to gravity (9.8 ms^{-2}); and H is the hydraulic head in m.

The cost of the energy storage component of the system is primary due to the cost of forming the dam wall, which in turn is proportional to the volume of the dam wall, R.

$$Energystoragecost\left(\frac{\$}{MWh}\right) \cong 4.8x10^5 * \frac{CR}{VH} \quad \text{(Equation 2)}$$

Here C = \$168 is the average total cost of the reservoir construction in \$/m^3 of earth moved. The lowest energy storage cost is achieved in reservoir pairs with large head and large water-to-rock (V/R) ratios for the target storage capacity.

The relationships for the power component costs comprises two components—tunnel and powerhouse—which have a complex relationship with the characteristics of the site. These fitted relationships were determined by varying the detailed cost model inputs.

A tunnel is assumed for the water conveyance between the reservoirs, because a tunnel is generally more economical for larger schemes and less dependent on route choice. The tunnel comprises of a vertical shaft, whose cost is proportional to the power of the scheme, P, in MW and a horizontal component, which also depends on the separation between the closest points of the reservoirs, S (m) and the head, H (m).

$$Tunnelcost(\$) \cong (66,000P + 17,000,000) + S(1280P + 210,000)H^{-0.54} \quad \text{(Equation 3)}$$

The cost of the vertical and horizontal component scales with power as the tunnel size is proportional to power and slightly less than the inverse square root of head as the cross-sectional area of the tunnel changes proportionally.

The powerhouse cost comprises the civil, mechanical, and electrical costs. The powerhouse is assumed to be excavated. Civil costs include the excavation of the machine and transformer halls, and tunnels for vehicle access and electrical access. Mechanical includes the pump turbines and motor generators, including commissioning. There are assumed to be two turbines up to 800 MW power, but then additional turbines are added for higher power. These components fit the relationship below across the range of heads and power of interest.

$$Powerhouse\ cost\ (\$) = \$63,500,000 * H^{-0.5}P^{0.75} \quad \text{(Equation 4)}$$

This results in a general trend of lower costs for increased head, while powerhouse costs increase less than linearly with power due to lower turbine and construction costs per MW for larger schemes. The cost model described in this study benchmarked within 5% of an independent study of pumped hydro capital costs by Entura[34] with the Aud\$680M Entura reference site costing Aud\$710M in the model reported here.

Sites are then classified using this ranking as A-class through E class. Sites with ranking below E class are discarded. An A-class site corresponds to US\$530,000 per MW for the power components and US\$47,000 per MWh of storage components. An A-class site with 6 h of storage would then have a total system capital cost per MW of US\$810,000 while an 18-h storage site would cost \$1,366,000. An 800 MW system with 5 GWh of storage would, therefore, need to have a cost below US\$660 million to be rated as class A. B-class through E class are 25% increments in costs above the A-Class site, with E class sites therefore costing approximately double that of A-Class sites.

Levelized cost is a widely used method to compare the costs of energy technologies over their lifetime. The LCOS can be calculated from

$$Levelised\ cost\ of\ storage = \frac{\sum_i^{Life}\frac{Costs_i}{(1+r)^i}}{\sum_i^{Life}\frac{Energy_i}{(1+r)^i}} = \frac{\sum_i^{Life} Capex + \frac{O\&M_i + Loss_i}{(1+r)^i}}{\sum_i^{Life}\frac{Energy_i}{(1+r)^i}} \quad \text{(Equation 5)}$$

Table 1. Levelized Costs Calculation Assumptions

Factors	Value	Units (Notes)
Real Discount Rate	5%	
Life	60	Years
Fixed O&M	$8,210	/MW/year
Variable O&M	$0.3	/MWh (pumping and gen)
Periodic O&M	$112,000	(year 20 and 40)
Pump/Gen Efficiency	81%	
Energy Cost (E.g. Solar PPA)	$40	/MWh
Energy	300	cycles per annum

Maintenance costs, lifetime, and efficiency from Akhil et al.

Here, Capex is the initial capital cost, O&M is operation and maintenance and Loss is the energy loss due to inefficiencies of the pumping/generation cycle.

The LCOS for an A-class site with 6 h of storage is US$40/MWh based on the assumptions in Table 1. Furthermore, the penalty for requiring a lowest ranking site compared with an excellent site would only result in an increase of the LCOS by around 60% from $40/MWh to $64/MWh if used for daily balancing of solar. An A-class site with 18 h of storage would need to complete the equivalent of 170 cycles per year to have a similar LCOS.

Capital cost is the dominant contributions to levelized cost varying from 60% for class A sites to 75% for class E. Given the long project life and capital component, the LCOS is very sensitive to the discount rate with a 1% increase in discount rate leading to a 10%–12% increase in levelized cost across the classes.

The levelized cost of battery storage is currently significantly higher and expected to remain so for the foreseeable future. Lazard's analysis shows in the range $US108 to US$222 of for 4 h of storage in the wholesale market[35]. Schmidt et al[36] examine historic costs of electrical storage technologies and apply learning rate analysis to project future prices. They forecast a battery capital cost reduction of 45% to 60% by 2040 relative to 2020 resulting in levelized costs of storage higher than pumped hydro. Batteries have some advantages over pumped hydro storage, including relatively fast construction cycles, modularity and very rapid power response. These storage technologies are highly complementary in a system dominated by wind and solar.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2020.11.015.

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AUTHOR CONTRIBUTIONS

Conceptualization: M.S., A.B., and B.L.; Methodology: M.S., B.L., and R.S.; Software, Data Curation and Visualization: M.S. and R.S.; Investigation M.S., C.C., and B.L.; Writing – Original Draft: M.S.; Writing – Reviewing and Editing: M.S., C.C., A.B., and B.L.; Funding Acquisition: A.B. and M.S.

DECLARATION OF INTERESTS

The authors have no competing interests to declare.

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REFERENCES

1. International Renewable Energy Agency (2020). Renewable capacity statistics 2020. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf.
2. Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A.F., Goodman, S.C., Chapman, W.E., Cameron, M.A., Bozonnat, C., Chobadi, L., Clonts, H.A., Enevoldsen, P., et al. (2017). 100% Clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule *1*, 108–121.
3. Pleßmann, G., Erdmann, M., Hlusiak, M., and Breyer, C. (2014). Global energy storage demand for a 100% renewable electricity supply. Energy Procedia *46*, 22–31.
4. Gulagi, A., Bogdanov, D., and Breyer, C. (2017). The demand for storage technologies in energy transition pathways Towards 100% renewable energy for India. Energy Procedia *135*, 37–50.
5. Grossmann, W.D., Grossmann, I., and Steininger, K.W. (2014). Solar electricity generation across large geographic areas, Part II: A Pan American energy system based on solar. Renew. Sustain. Energy Rev. *32*, 983–993.
6. Esteban, M., Zhang, Q., and Utama, A. (2012). Estimation of the energy storage requirement of a future 100% renewable energy system in Japan. Energy Policy *47*, 22–31.
7. 100 per cent renewables study – modelling outcomes, . https://thebrightfutureproject.weebly.com/uploads/2/7/1/4/27148779/100-percent-renewables-study-modelling-outcomes-report.pdf.
8. Blakers, A., Lu, B., and Stocks, M. (2017). 100% Renewable electricity in Australia. Energy *133*, 471–482.
9. Fyke, A. (2019). The fall and rise of gravity storage technologies. Joule *3*, 625–630.
10. Ziegler, M.S., Mueller, J.M., Pereira, G.D., Song, J., Ferrara, M., Chiang, Y.M., and Trancik, J.E. (2019). Storage requirements and costs of shaping renewable energy Toward grid decarbonization. Joule *3*, 2134–2153.
11. Australian Renewable Energy Mapping Infrastructure (2019). ANU STORES Worldwide. https://nationalmap.gov.au/renewables/#share=s-oDPMo1jDBBtwBNhD.
12. International Energy Agency (2018). World Energy Statistics 2018. https://doi.org/10.1787/world_energy_stats-2018-en.
13. Center for International Earth Science Information Network, C.C.U. (2018). Gridded population of the world (GPW), v4: population count, v4.11. https://doi.org/10.7927/H4JW8BX5.
14. Mistry, M. (2018). Cooling Degree days and Heating degree days. http://www.energy-a.eu/cooling-degree-days-and-heating-degree-days/.
15. GE Energy (2010). Western wind and solar integration study. https://doi.org/10.2172/981991.
16. United States Department of Energy (2008). 20% wind energy by 2030 increasing wind energy's contribution to U.S. Electricity supply. https://permanent.access.gpo.gov/lps106317/41869.pdf.
17. Denholm, P., Ela, E., Kirby, B., and Milligan, M. (2010). Role of Energy Storage with Renewable Electricity Generation. https://doi.org/10.2172/972169.
18. Australian Energy Market Operator (2017). South Australian Generation Forecasts (Australian Energy Market Operator). http://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/SA_Advisory/2017/2017-South-Australian-Generation-Forecast.pdf.
19. International Energy Agency (2018). Electricity Information Statistics 2018 (International Energy Agency). https://webstore.iea.org/electricity-information-2018.
20. Lehner, B., Reidy Liermann, C., Revenga, C., Vorosmarty, C., Fekete, B., Crouzet, P., Doll, P., Endejan, M., Frenken, K., Magome, J., et al. (2011). Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. https://doi.org/10.7927/H4N877QK.
21. Meier, R.F.L., Loos, V., Engels, K., and Thomas Beyer, J.K. (2012). A comparison of advanced pumped storage equipment drivers in the US and Europe. Hydrovision. https://doi.org/10.7927/H4N877QK.
22. Australian Renewable Energy Agency (2017). Cultana pumped hydro project knowledge sharing report. https://arena.gov.au/assets/2017/09/Cultana-Pumped-Hydro-Project-_Public-FINAL-150917.pdf.
23. Marcher, Th., Bauer, S., Allende, M., and Mathiesen, C. (2015). Valhalla – innovative pumped hydro storage facilities in Chile: challenges from a rock mechanical point of view. Geomech. Tunn *8*, 387–393.
24. Wang, P., Huang, C., Brown de Colstoun, E.C., Tilton, J.C., and Tan, B. (2017) Global Human Built-Up and Settlement Extent (HBASE) Dataset From Landsat 10.7927/H4DN434S.
25. UNEP-WCMC; IUCN (2019). The World Database on Protected Areas. (April 2019). http://www.protectedplanet.net/.
26. Yang, C.-J., and Jackson, R.B. (2011). Opportunities and barriers to pumped-hydro energy storage in the United States. Renew. Sustain. Energy Rev. *15*, 839–844.
27. Pérez-Díaz, J.I., Chazarra, M., García-González, J., Cavazzini, G., and Stoppato, A. (2015). Trends and challenges in the operation of pumped-storage hydropower plants. Renew. Sustain. Energy Rev. *44*, 767–784.
28. National Hydropower Association (2014). Challenges and Opportunities for New Pumped Storage Development (National

Hydropower Association). https://www.hydro.org/wp-content/uploads/2017/08/NHA_PumpedStorage_071212b1.pdf.

29. Food and Agriculture Organisation of the United Nations. (2019) AQUASTAT. http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

30. Nadolny, A., Stocks, M., and Blakers, A. (2018). An analysis of potential STORES environmental and water consumption impacts (The Australian Renewable Energy Agency). http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en.

31. RE100Group (2019). GitHub: PHES Searching. https://github.com/re100group/phes_searching.

32. Lu, B., Stocks, M., Blakers, A., and Anderson, K. (2018). Geographic information system algorithms to locate prospective sites for pumped hydro energy storage. Appl. Energy *222*, 300–312.

33. Earth Resources Observation And Science (EROS) Center. (2017). *Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global* [Data set]. U.S. Geological Survey. https://doi.org/10.5066/F7PR7TFT

34. Entura. (2018). Pumped hydro cost modelling. https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Inputs-Assumptions-Methodologies/2019/Report-Pumped-Hydro-Cost-Modelling.pdf.

35. Lazard. (2018). Lazard's Levelised Cost of Storage Analysis, Version 4.0. https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf.

36. Schmidt, O., Hawkes, A., Gambhir, A., and Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. Nat. Energy *2*, 17110.

APPENDIX C

APPENDIX C - LIST OF CEATI PUBLICATIONS

Publication	Description	Date
T122700-0382	CPF: Criteria for the Identification and Selection of Environmentally Acceptable (EA) Lubricants	2013
T082700-0380	Hydro Generators - General Maintenance and Inspection Guide	2013
T082700-0357	Hydro Turbine/Generator Shaft Stress Analysis Methods and Limitations	2013
T112700-0376	Safe Protection of Hydraulic Units and Runaway Speed	2012
T112700-0375	Hydraulic Unit Excessive Headgate Leakage Measurement, Prevention Methods and Materials	2012
T112700-0370	Grounding and Bonding Best Practices	2012
T102700-0377	Hydraulic Unit Governor Upgrading Guide	2011
T102700-0371	CPF: Hydroelectric Industry's Role in Integrating Wind Energy	2011
T082700-0364	Hydraulic Phenomena that Occur in Operating Hydraulic Turbines	2011
T082700-0362	CPF: Headgate and Spill Gate Bushing Wear Assessment	2011
T082700-0360	CPF: Training for Hydro Plant Staff (Including Web Based Approaches)	2011
T092700-0358	Short Converging Intake Comparative Flow Rate Measurement Tests at Kootenay Canal	2011
T082700-0355B	Best Practice Guide for Planning and Executing Hydro Overhaul and Retrofit Projects: The Optimization of Hydro Plant Rehabilitation	2011
T082700-0354	Mechanical Overhaul Guide for Hydroelectric Turbine Generators	2011
T082700-0353	Vibration Analysis Force and Vibration Relationship	2011
T082700-0363	Quantifying the Non-Energy Benefits of Hydropower	2010
T082700-0359	Hydraulic Station Headgate Testing Protocols	2010
T082700-0355A	Best Practice Guide for Planning and Executing Hydro Overhaul and Retrofit Projects	2009
T072700-0349	Identification of Hydro Performance and Production Problems Including Effects of Start-Stop Operations	2009
T062700-0339	CPF: On-Line Cavitation Monitoring	2009
T052700-0321A	Optimum Timing for Generator Stator Rewinds Based on Generator Condition Assessment and Statistical Methods	2008
T072700-0340	Best Practices – Bushings and Seals	2008
T062700-0341	CPF: Head Gate and Spill Gate Maintenance and Testing	2008
T072700-0344	CPF: Inspection and Maintenance of Station Lifting Equipment	2008
T052700 0329	Hydroelectric Turbine-Generator Units Guide for Erection Tolerances and Shaft System Alignment	2008
T072700-0350	Dissolved Oxygen Monitoring – Technologies Applicable to Hydraulic Generating Station Reservoirs, Tailraces and Spillways	2008
T072700 0351	Hydro Plant Operations and Maintenance Safety Improvement	2008
T062700 0337	CPF: Hydro Plant Debris Management	2007
T032700 0323A	Component Surface Deterioration and Effect On Performance, Phase I	2007
T062700 0323B	Surface Roughness Testing on the McNary Turbine Model	2007
T052700 0334	CPF: Technology and Tools for Reduced Operations and Maintenance Costs	2007

APPENDIX D

Appendix D – Application of Feasibility Factors

This study project quantifies a Realistic Potential of PSH in Canada by filtering out the most promising percentage of the Theoretical Potential by applying Feasibility Factors against it. As shown in Figure D1, the Theoretical Potential consists of a data base compiled by ANU that identified over 100,000 sites in Canada. The Feasibility Factors consist of filtering parameters that qualify the economics of these sites related to:

- Access to transmission infrastructure with respect to costs and schedule
- Environmental, Social and Governance (ESG) attributes that suggest a faster, slower or improbable permitting timeline
- Constructability related cost adders
- Technology selection and associated costs, and
- Power market pricing by province

The Realistic Potential is a shortlist that passes conservatively established criteria within the above-mentioned timeframe of 2035 and 2050.

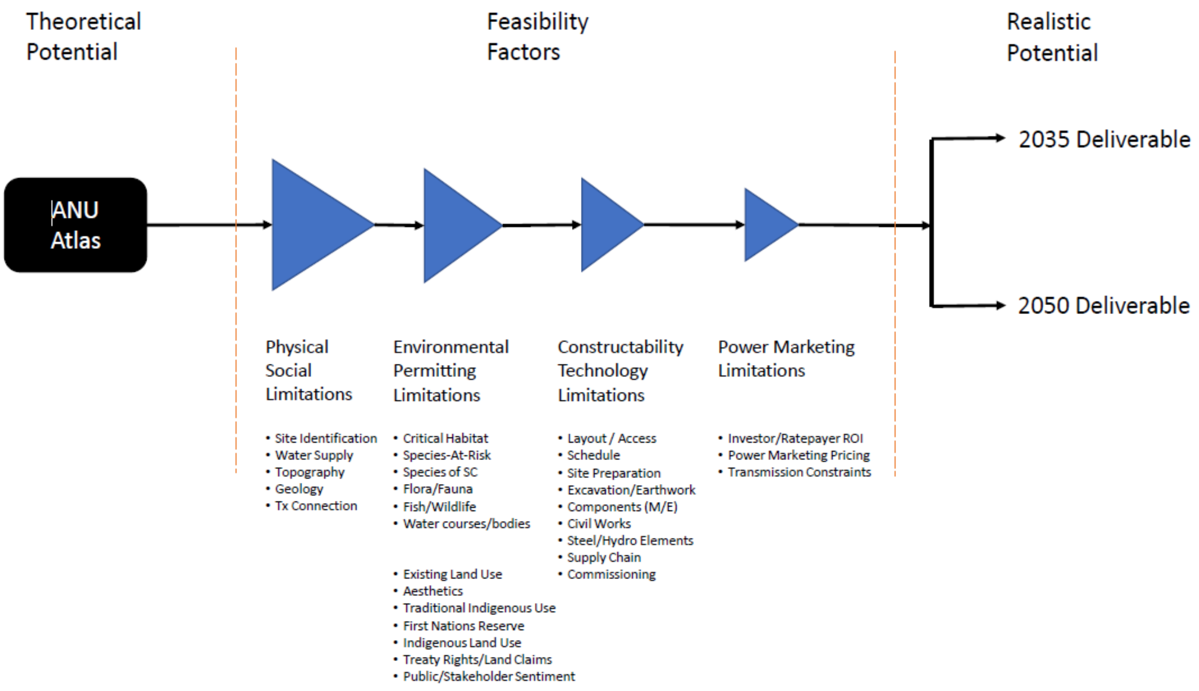

Figure D1: Schematic to Illustrate the Process from Theoretical to Realistic Potential

Specific details of how the Feasibility Factors are applied in the study are described below.

Transmission Constraints

To apply a feasibility factor related to costs of transmission line construction and interconnection, a simplistic approach was adopted to be able to deal with the large number of theoretically possible PSH sites. This approach assigned a required line voltage according to the installed PSH capacity and derived costs from this line voltage and the distance to the nearest line as shown in Table D1. One substation is assumed per proposed pump storage facility in this analysis.

Table D1: Interconnection Costs

Installed PSH Capacity [MW]	Nominal Line Voltage [kV]	Line Construction Cost [CAD/km]	Substation Cost [CAD]
65	69	$1,100,000	$7,500,000
140	115	$1,200,000	$8,300,000
600	230	$1,400,000	$11,000,000
1000	345	$2,200,000	$16,000,000
2000	500	$2,800,000	$23,000,000
3700	735	$3,200,000	$47,000,000

Factors that would need to be considered for a specific site to refine the analysis include:

- Costs will be dependent on jurisdiction and terrain of the transmission line.
- The line capacities will be dependent on the conductor selected and the length of the line. Surge impedance loading impacts the amount of power that can be transmitted on a line and is related to the length of the line. The capacities in Table 8 can be assumed for a line length of approximately 100 km, with greater MW capacities for shorter lines and lower MW capacities for longer lines.
- Only single circuit lines have been considered in this analysis, for simplicity.
- Transmission projects can have long project timelines from initiation of feasibilities studies to commercial operation/in-service date. The following factors will contribute to the project timeline:
    - Number of jurisdictions/regulatory bodies
    - Terrain complexity
    - Remoteness
    - Number of impacted private landowners
    - Environmental issues along the route
    - Length of line
    - Indigenous relations
    - Number of navigable waterways

In Canada, energy infrastructure projects involving overhead transmission lines generally require entering an environmental assessment (EA) process before advancing to permitting and development stages. Based on the current Federal, Provincial and Territorial EA legislation and regulatory regimes of Canada, EA processes and associated timelines vary by jurisdiction and the Project location, duration, and type. Proponents will be required to conduct baseline data collection and Indigenous and public engagement as part of the EA process and to support the development of regulatory filings. Site specific factors and consultation concerns can also impact the length of time required to collect baseline data and conduct engagement programs. The average timeline for baseline data collection, engagement, and the development and submission of regulatory filings is approximated to be less than 5 years. With this estimate, the potential sites can be developed within the 2035 window of opportunity for Net Zero Targets.

Generally, transmission projects can be completed within approximately 10 years; however, in future it is anticipated that consultation and permitting requirements will become more complex and will likely extend project timelines.

For the sole purpose of providing a quantifiable factor in the analysis and given two project timelines of 2035 and 2050, it was assumed that projects with transmission lines less than 500 km could be completed by 2035 and project with lines greater than 500 km could be completed by 2050, as shown in Table D2.

Table D2 Projected Project Timeline based on Line Length

Transmission Line Length (km)	Projected Project Timeline
Less than 500	**By 2035**
Greater than 500	**By 2050**

Environmental, Social and Governance/ Considerations

The intent of the screening of potential development locations was to:

- Eliminate sites that were considered unlikely/impossible to develop because of ESG issues considered to be so significant or contentious that it would be difficult to justify any effort in their pursuit. These were considered 'No-Go' sites.
- Identify sites that would likely have more complex or prolonged permitting processes, due to potential ESG issues, with this prolonged permitting process delaying their development until closer to 2050.
- Identify sites that would likely have simpler/shorter permitting processes, due to potential ESG issues which may be more commonplace, less significant or less contentious, with these shorter permitting processes allowing their development sometime between the present and 2035.

The following feasibility factors were applied:

1. First Nation Reserve Lands

First Nation Reserves lie within legally surveyed boundaries, are federally owned, set aside for First Nation band use, and administered by the Chief(s) and Council(s) of the specified band(s). Any proposed use of reserve land would meet numerous legal and social hurdles which would be very difficult to overcome. Therefore, where potential sites which encroached on Reserve Lands, they were eliminated from further consideration.

2. Protected Lands

Lands may be protected by different levels of government for several reasons. Federal, provincial and municipal governments may accord different levels of significance and protection to lands. These lands may have ecological, geographical, cultural or social significance. While the levels of significance and protection may vary, it is reasonable to conclude that any proposed development on these lands will require comparatively lengthy and complex processes which will involve the partial or total removal of the legislated protection. For the purposes of the study, potential sites which encroached on known protected areas were considered to be less likely to be developed by 2035, but more likely to be developed by 2050.

For the purposes of the study, potential sites that were neither First Nation Reserves nor on protected lands were considered to be subject to a shorter, less difficult permitting process, with better chances of being developed between the present and 2035. While these high-level screening factors were applied, it should be noted that any proposed project would likely be subject to a provincial and/or federal environmental assessment process which would identify the site-specific impacts that would need to be addressed prior to the issue of any permits.

Constructability

A staged approach is always employed in hydroelectric design to permit risk identification, mitigation and appropriate layout and particularly geological understanding which will drive the construction methods and planning. To parse out site specific acceptability in our GIS to aid ranking from a constructability viewpoint, Stantec applied resultant cost multipliers or Go/No Go gates for the following:

- Presence or lack of permafrost – No Go decision implemented. Avoidance of permafrost areas is a key consideration in our GIS model. Permafrost excludes a great landmass in Canada's north. The head and thus energy storage potential in these areas is however limited.
- Road access, rail and proximity, hard rock – Cost increments applied. PSH projects involve transportation of very large amounts of materials and equipment, and rail access is likely preferred, however road networks are effective and particularly in areas where mining or logging infrastructure is already invested.
- For rock surrounding the conveyance system and the underground powerhouse and caverns, a cost increment was applied in stronger rock for excavation effort, and this was applied for sites within the Canadian Shield. For each site we identified local stratigraphy, seismicity and rock jointing understanding and treatment is a risk factor that is not easily discovered or understood even with testing and drill investigation.

Suitable Technology

To explicitly address the cost impact of technology selection in the feasibility screening a single predominant factor has been identified in the hydraulic head. At a threshold number of 500 m the reversible pump turbine which is the technology of choice for cost effective implementation of PSH becomes infeasible and a Francis-type reaction machine is no longer feasible in most cases and needs to make way to a Pelton-type impulse turbine. Inherently, impulse machines cannot reverse the flow direction from generating to pumping (a jet in free air cannot be reversed) and a multi-stage pump is typically required in pumping mode. In addition to this change in prime mover configuration, the costs associated with electrical equipment, hydraulic manifolds and balance of plant installation and construction increase substantially. In a high-level estimate a factor of 1.6 has been applied to the base costs of a reversible pump-turbine installation.

APPENDIX E

Appendix E – Stakeholder Questionnaire

1. ORIGINAL QUESTIONNAIRE FROM STANTEC

Date sent: June 29th, 2022

Stantec is conducting a Technical and Economic Potential Assessment of Pumped Storage Hydropower (PSH) in Canada for WaterPower Canada. We would appreciate your insights and will give credit in our report to your input or keep it anonymous according to your preference.

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?

a. Yes, we have studied potential project opportunities ☐

b. Yes, we are actively engaged in the development of projects ☐

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?

a. Initiation: ___ MW, ___MWh storage, CND$ ___ value for your firm

b. Definition: ___ MW, ___MWh storage, CND$ ___ value for your firm

c. Execution: ___ MW, ___MWh storage, CND$ ___ value for your firm

Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

3. In which Canadian Province(s) are your projects located?

____

4. What portion of the value for your firm would approximately be spent in Canada?

___ %

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study.

____

____

6. What obstacles to your PSH project(s) do you see in the following areas?

a. Electrical Power Transmission:

____

b. Environmental, Social and Regulatory Considerations:

____

c. Constructability:

____

d. Suitable Technology:

e. Energy Storage Potential:

f. Power Marketing:

g. Other:

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?

a. Electrical Power Transmission:

b. Environmental, Social and Regulatory Considerations:

c. Constructability:

d. Suitable Technology:

e. Energy Storage Potential:

f. Power Marketing:

g. Other:

2. RESPONSES RECEIVED

The following table summarizes organizations contacted and responses received:

Organization Contacted	Response Received	Response By
Aecon	No	
AESO	No	
Algonquin Power and Utilities	No	

Andritz	Yes	Vice President, Sales & Business Development
Barnard	Yes	Vice President, Business Development - Canada
BC Hydro	No	
Brookfield BRP Holdings (Canada) Inc.	Yes	Director
Columbia Power Corporation	Yes	Executive Director, Power Operations
FortisBC Inc.	Yes	Senior Engineer, Generation Assets
GE	No	
Hydro Battery (Revelstoke)	Yes	President
Hydro Ottawa / Portage Power	No	
Hydro-Quebec	Yes	Asset Management Lead
IESO	Yes	VP of Planning
Kiewit	No	
Manitoba Hydro	Yes	Vice President, Asset Planning & Delivery
Nalcor Energy	Yes	Manager, Safety, Health & Environment
Nelson Hydro	Yes	Operations Manager
New Brunswick Power	No	
Newfoundland and Labrador Hydro	Yes	Mechanical Engineer
Northland Power	No	Press Release with Ontario Power Generation
Northwest Territories Power Corporation	No	
Nova Scotia Power Inc.	No	
Ontario Power Generation	Yes	Senior Manager, Business Development
OWA	Yes	President
Rio Tinto Alcan	No	

SaskPower	Yes	Senior Engineer
Steep Rock (Boundary Waters Anishinaabeg LP)	Yes	Director Operations
TC Energy	Yes	Project Manager
Tent Mountain (Montem Resources)	Yes	Communications Coordinator
TransAlta Corporation	No	
Voith	Yes	Director of Proposals
Yukon Energy Corporation	Yes	Asset Manager

3. ANDRITZ RESPONSE

Interesting, if I look at the questions, questions 2, 3, 5, 6 and 7 (which are the main details of your questionnaire) are really questions for the developers of projects (end users). Not sure what an OEM would be responding on these elements. I can still provide some inputs where relevant below:

Question 1: We are involved in both a and b. We have helped customers with studies, budget pricing or responding to RFPs for some projects. As you know no recent project has been actually developed in Canada for PSP.

Question 3: The projects we have been in discussion with customers were in Ontario and Alberta. We let you get the relevant details for the project info from the developers as they had us sign NDAs.

Question 4: from an OEM perspective this can vary greatly depending on what premium the customer is willing to pay to have local content. We as an OEM can go do quite a bit of components in Canada as long as it is valued by the customer in their evaluation criteria. We at ANDRITZ can do gates, automation, large turbine/generator fabrication, windings, etc. in Canada. Some components such as stator cores and runners are not possible locally normally. Of course, the site works, and project management is local.

Some added general statements:

- There is a need for clarity on how developers will be paid or compensated for ancillary services (black start, regulation, operating reserve, fast response, etc.). PSPs can be distinguished from other storage technologies as they have a more complete range of services that can be covered and longer timeline prior to needing to overhaul or replace major components. It cannot be evaluated primarily based on initial costs to build the project as technologies such as batteries will definitely have lower costs to start. This needs government support as well to ensure the fact that hydro is renewable energy gets some preference in the potential storage landscape.
- With added solar & wind in many provinces, which is not very predictable, there is definitely a need for storage in those same provinces.
- Transmission capacity definitely needs to be looked at proactively to ensure the potential for PSP projects don't get hindered by missing transmission capacity.

4. BARNARD RESPONSE

Barnard is a heavy civil contractor that specializes in dams, reservoirs, hydroelectric plants, pipeline, underground and power transmission. In Engineering News-Record's annual nationwide survey of contractors, Barnard has consistently ranked in the United States' top heavy civil contractors since the late 1990s, including ranking #2 in Hydro plant construction and #3 in Dams and Reservoirs construction in 2021. In Canada, we have worked on two of the largest recent hydroelectric facilities with Barnard constructing the earthen and roller compacted concrete dam sections for Nalcor at Muskrat Falls and we're just finishing the Keeyask Generating Station in Northern Manitoba for Manitoba Hydro. As such, we regularly are approached to assist and bid on pumped storage projects.

Barnard has also been involved with seven major pumped storage projects that have yet to be constructed. Our involvement has included cost estimating, scheduling, value engineering, permitting assistance, constructability, preliminary design, stakeholder meetings, Board of Consultant meetings, and site selection input. These projects remain in various stages of development. We've invested millions of dollars and thousands of hours in these projects and pursuits, and none have moved forward to the construction stage. We've worked with clients to reduce risk, optimize designs and lower costs, but the projects have not moved forward. The complex nature of these facilities is consistent with the work we specialize in and execute every day and it excites us, but with the lack of certainty on these projects and competing opportunities, it is becoming increasingly difficult to justify further investment into the pursuit of these facilities.

5. BOUNDARY WATERS RESPONSE

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?
    a. Yes, we have studied potential project opportunities X
    b. Yes, we are actively engaged in the development of projects X

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?
    a. Initiation: ___ MW, ___MWh storage, CND$ ___ value for your firm
    b. Definition: ___ MW, ___MWh storage, CND$ ___ value for your firm
    c. Execution: 1500 MW, 15000MWh storage, CND$3B value for your firm

    Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

3. In which Canadian Province(s) are your projects located? Ontario

4. What portion of the value for your firm would approximately be spent in Canada?

    100% based on sourcing the engineered equipment through Canadian distributors.

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study. Please elaborate on separate page. Development and export of energy (all forms should be good for the Cdn economy. Storage is critical for advancing this.

    ____

    ____

6. What obstacles to your PSH project(s) do you see in the following areas?
    a. Electrical Power Transmission: Would be beneficial to have a simpler method for real time analysis /

simulation of the combined storage / transmission system.

b. Environmental, Social and Regulatory Considerations: _None. All's good here.

c. Constructability:
None.____

d. Suitable Technology:
None____

e. Energy Storage Potential:
None____

f. Power Marketing: Electric system operators could use a better system for analyzing the benefits of PSH to the

grid.____

g. Other: Development capital raise. Institutional investors and PE firms are looking for offtake agreements and land acquisition in advance of investing. These require significant development capital to conclude.

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?

   a. Electrical Power Transmission: Development of fa regulatory framework for east-west HVDC T-line (feds). Better coordination between ministries & electric system operators (provinces)

   b. Environmental, Social and Regulatory Considerations:
   _None____

   c. Constructability:
   None____

   d. Suitable Technology:
   None____

   e. Energy Storage Potential:
   None____

   f. Power Marketing: Standardization of a storage agreement.
   ____

g. Other: Provision of development capital grants/ loans (feds and provinces)____

6. BROOKFIELD RESPONSE

Stantec is conducting a Technical and Economic Potential Assessment of Pumped Storage Hydropower (PSH) in Canada for WaterPower Canada (WPC). We would appreciate your insights and will give credit in our report to your input or keep it anonymous according to your preference.

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?

a. Yes, we have studied potential project opportunities ☐

b. Yes, we are actively engaged in the development of projects ☐

c. NO ☒

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?

a. Initiation: __0_ MW, ___MWh storage, CND$ ___ value for your firm

b. Definition: __0_ MW, ___MWh storage, CND$ ___ value for your firm

c. Execution: __0_ MW, ___MWh storage, CND$ ___ value for your firm

Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

3. In which Canadian Province(s) are your projects located?

____

4. What portion of the value for your firm would approximately be spent in Canada?

___ %

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study.

____

____

6. What obstacles to your PSH project(s) do you see in the following areas?

a. Electrical Power Transmission:

_ __________

b. Environmental, Social and Regulatory Considerations:

_major regulatory hurdles that make project development risky, uncertain and at best, very long

c. Constructability:

_very capital intensive______________________

d. Suitable Technology:

e. Energy Storage Potential:

f. Power Marketing:

insufficient valuation of long-term storage ____

g. Other:

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?

a. Electrical Power Transmission:

b. Environmental, Social and Regulatory Considerations:

_faster approvals, less regulatory hurdles__

c. Constructability:

_tax breaks, funding favorable as for other renewables_____________

d. Suitable Technology:

e. Energy Storage Potential:

f. Power Marketing:

Proper valuation of pumped-storage, including RECs and the advantages it brings to grid stability and the integration of further intermittent renewables_____

g. Other:

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7. CEATI RESPONSE

from Jean Pellerin –Technical Advisor:

For what it's worth, here are my comments on pump storage plant Greenfields:

A pump storage plant as an overall negative energy balance, the pumping mode consumes more energy than what the generating mode can achieve, this is normal. A few utilities have done pump storage potential site searches and the market is a critical component to determine the feasibility of a given potential site. Ancillary demand is usually a component that a feasibility study would consider.

The topography of a site is also an essential component, a fairly high head is required and there should be room for an upper reservoir that would determine the number of hours a plant can generate power. Andritz, has explored small hydro technologies for pump storage plants but I'm not sure if this ended up with good economical solutions.

All this to say that to my knowledge there isn't a pump storage in Canada unless I'm missing one(?) in Ontario.

8. COLUMBIA POWER CO. RESPONSE

We have no intention of adding pumped storage to our portfolio nor do we currently have pumped storage.

9. FORTIS BC RESPONSE

FBC does not have any pump storage projects.

10. HYDRO BATTERY RESPONSE

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?
   a. Yes, we have studied potential project opportunities ☐
   b. Yes, we are actively engaged in the development of projects ☐ ✓

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?
   a. Initiation: ___ MW, ___MWh storage, CND$ ___ value for your firm
   b. Definition: ___ MW, ___MWh storage, CND$ ___ value for your firm
   c. Execution: ___ MW, ___MWh storage, CND$ ___ value for your firm

See Attached documents

Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

3. In which Canadian Province(s) are your projects located?

- **BC**

4. What portion of the value for your firm would approximately be spent in Canada?

~75+%

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study. Please elaborate on separate page.

At 4 GW full scale, the Hydro Battery PSH project resource would become the flexible anchor energy storage resource for the long-proposed Western Canada Integrated Grid, an essential development for meeting Canada's Climate Change targets due to ***The Electrification of Everything***

6. What obstacles to your PSH project(s) do you see in the following areas?
   a. Electrical Power Transmission:

      BC Hydro System 500 KV transmission lines are nearby with many options for interconnection

   b. Environmental, Social and Regulatory Considerations:
      Environmentally, it is a low impact project using existing BC Hydro reservoir
      Socially: Given that the project will be owned by impacted Indigenous groups, it is unknown at this time, how and what benefits will accrue. To Be Determined.

      Regulatory: Depending on how this Transmission System Asset is integrated or controlled within the Western Canada Grid, there will be issues between the BC's Crown-owned BC Hydro and Alberta's de-regulated electrical grid system - AESO. For SK and MB, it is To Be Determined.

c. Constructability:

The overall proposed design is typical of PSH projects elsewhere that are largely underground

d. Suitable Technology:

New methods of tunneling, turbine and HVDC technology will be deployed

e. Energy Storage Potential:

The upper lake storage capability could be increased substantially to optimize ES duration

f. Power Marketing:

Projects of this size have a large stack of valuable grid services (GS) that will be essential for upgrading variable intermittent renewable resources. Much will depend on how these GS are monetized and shared.

g. Other:

Due to the scope and scale of this project, it is expected this project will break the logjam of political and institutional barriers that have heretofore prevented the integration of the Western Canadian grid.

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?

a. Electrical Power Transmission:

Stated Fed Govt commitments to backstop transmission for WestCan grid integration is necessary

b. Environmental, Social and Regulatory Considerations:

Indigenous support is crucial to facilitate Enviro and regulatory approvals

c. Constructability:

PSH projects require active positive cooperation between all govt agencies to succeed

d. Suitable Technology:

TBD

e. Energy Storage Potential:

Fed Govt support for WestCan Grid Integration Studies would be helpful

f. Power Marketing:

New Blockchain technologies for VRE IPP & prosumer trading of generation and firmed capacity are now emerging in the marketplace - or BC Hydro/Powerex/AESO/SK Power/MB Hydro could share the Grid services

g. Other:

Experts all agree that Institutional and Section 32 (a) provincial energy fiefdom control is the major impediment to integrating a national East-West grid. The HB PSH can help overcome this constraint.

11. IESO RESPONSE

1 Is your firm planning to participate in the Pumped Storage Hydro (PSH) **Mark.9'in** Canada?

1.1 Yes, we have studied potential project opportunities

2 Yes, we are actively engaged in the development of projects ☐

3 Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?

3.1 **Initiation:w1.CIDe.**MW, _MWh storage, CND$ _ value for your firm

3.2 Definition: **..G...** MW, **.o_MWh** storage, CND$ **_it** value for your firm

3.3 Execution: **..Q_** MW, **..Q.-MWh** storage, CND$ .... **2.** value for your firm

Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

4. In which Canadian Province(s) are your projects located?

5. What portion of the value for your firm would approximately be spent in Canada?

- ***LFFO.%***

6. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study. Please elaborate on separate page.

7 What obstacles to your PSH project(s) do you see in the following areas?

7.1 Electrical Power Transmission:

7. Environmental, Social and Regulatory Considerations:

c. Constructability:

d. Suitable Technology:

e. Energy Storage Potential:

f. Power Marketing:

g. Other: COST (CAPEX) AND TIME TO DEVELOP

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?
   a. Electrical Power Transmission:
   b. Environmental, Social and Regulatory Considerations:
   c. Constructability:
   d. Suitable Technology:
   e. Energy Storage Potential:
   f. Power Marketing:
   g. ~~Other~~: Government funding + active participation of the CIB

To be able to incorporate in our study, we would appreciate receiving your **response by July 8th** to the following email:

Megan.Grosso@Stantec.com

12. MANITOBA HYDRO RESPONSE

Manitoba Hydro has no plans to pursue pumped storage.

13. NALCOR ENERGY RESPONSE

I had dug into this and identified that there are no pumped storage facilities planned or anticipated in Newfoundland or Labrador, and none currently in place.

14. NELSON HYDRO RESPONSE

Nelson Hydro is a small municipal utility and will not be considering any pumped storage due to cost and economies of scale for a small power producer.

15. NEWFOUNDLAND AND LABRADOR HYDRO RESPONSE

Historically we also have not looked at pumped storage as an option to increase our capacity. However, next year we are talking about investigating pumped storage further as a resource option, likely for both existing assets and potential future hydro projects. It's interesting that no other utility in Canada is currently looking at this as an option. I'm assuming because of cost?

Although not considered up to this point, that will change next year as seen below.

16. ONTARIO POWER GENERATION RESPONSE

Currently there are 3 pumped storage projects under Gate 2 review with the IESO; therefore, most of the technical and cost information on the Project is commercially sensitive.

We may be able to share more information mid-2023 after the Minister announces the results of the Gate 2.

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?

a. Yes, we have studied potential project opportunities ☒

b. Yes, we are actively engaged in the development of projects ☒

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?

a. Initiation: 400 MW, 2,000 MWh storage, CND$ TBA value for your firm

b. Definition: ___ MW, ___MWh storage, CND$ ___ value for your firm

c. Execution: ___ MW, ___MWh storage, CND$ ___ value for your firm

Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

Marmora Pumped Storage Project

OPG has a 50:50 ownership of the Project shared with Northland Power Inc

Located adjacent the town of Marmora, Ontario, 2km south-east of the Marmora town center. Roughly halfway between Toronto & Ottawa.

Closed loop system using an abandoned iron-ore mine void as the lower reservoir and reshaping the above ground mine spoil pile into the upper reservoir.

Expected to be 400MW output, and 2,000 MH.hr capacity. Around 65MW minimum output.

Project would connect to the existing Hydro One 230KV corridor located around 10km north of Marmora.

The head varies; penstock is around 260 meters vertical drop

3. In which Canadian Province(s) are your projects located?

Ontario

4. What portion of the value for your firm would approximately be spent in Canada?

>70%

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study.

The Marmora Project has multiple positive impacts to the Canadian and Ontario economy:

- Due to the ongoing IESO Gate 2 review of this project; the direct economic impact and cost to store / generate electricity cannot be shared at this point in time

- Unlike other storage technologies; the majority of the construction cost is reinvested in Canadian companies and the Canadian workforce.

- The Project transforms a crown liability for mine rehabilitation (as the Marmora mine was abandoned in 1978 prior to mine closure rehabilitation requirements) and transforms this into an environmentally positive long life (>90 years) clean energy storage asset for Ontario.

- The Project enables further decarbonization of the Canadian economy by storing excess clean energy during periods of excess generation; and generating electricity during higher value periods reducing the demand for peak gas generation

- Flow-on impacts for tourism and the local economy has been estimated at up to $35M per year

What obstacles to your PSH project(s) do you see in the following areas?

a. Electrical Power Transmission:

The location of the Marmora project is not directly constrained by transmission.

Overall, the ongoing electrification of the economy will create new bottlenecks and will change the electricity demand curves that need to be considered when investing in generation projects.

---

b. Environmental, Social and Regulatory Considerations:

There are no specific obstacles in this regard for the Marmora project beyond those that are expected and reasonable. As Marmora is a closed loop system and repurposes an abandoned mine-site; there are minimal / no negative impact on fisheries, waterways, wildlife, agriculture, tourism, flora or fauna.

Community is supportive to rejuvenate the local economy and repurpose an abandoned mine.

First Nations engagement continues and is generally supportive.

c. Constructability:

There are no specific obstacles regarding constructability beyond those expected of a typical generation project. The location of the project has a wide catchment for labour; and is adjacent a major highway. Short term threats relate to supply chain constraints and inflationary pressures.

d. Suitable Technology:

There are no specific obstacles concerning suitable technology; any technology that can improve efficiency and operational reliability improves the business case.

e. Energy Storage Potential:

There are no specific issues regarding energy storage potential.

f. Power Marketing:

The contracting of long-life high capital cost assets can be difficult when compared to shorter life or GHG emitting assets. The system operators may use processes to compare assets that are not well suited for assessing the value of pumped storage. This can be problematic to justify the capital investment.

The fair assessment of pumped storage can be difficult as the overall services provided can be undervalued; pumped storage can provide more than just capacity with opportunities to provide operating reserve; AGC, and voltage regulation.

Considering only benefits to the Hydro ratepayers, rather than the overall benefits to the taxpayer or the overall Ontario economy, stymies innovative approaches such as Marmora which is transforming an abandoned mine and thereby reducing the Crown's (taxpayer's) potential liability to remediate the property. It would be beneficial if the overall value to the Province was more broadly considered when assessing pumped storage projects.

g. Other:

6. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?

a. Electrical Power Transmission:

Transmission would benefit by a more progressive forward-looking plan and investment associated with increased electrification ensuring generation assets have increased transparency on expected future transmission capacity.

Transmission approvals and construction seems to lag the demand for clean energy generation / storage.

b. Environmental, Social and Regulatory Considerations:

No additional actions

c. Constructability:

No specific actions

d. Suitable Technology:

No specific actions

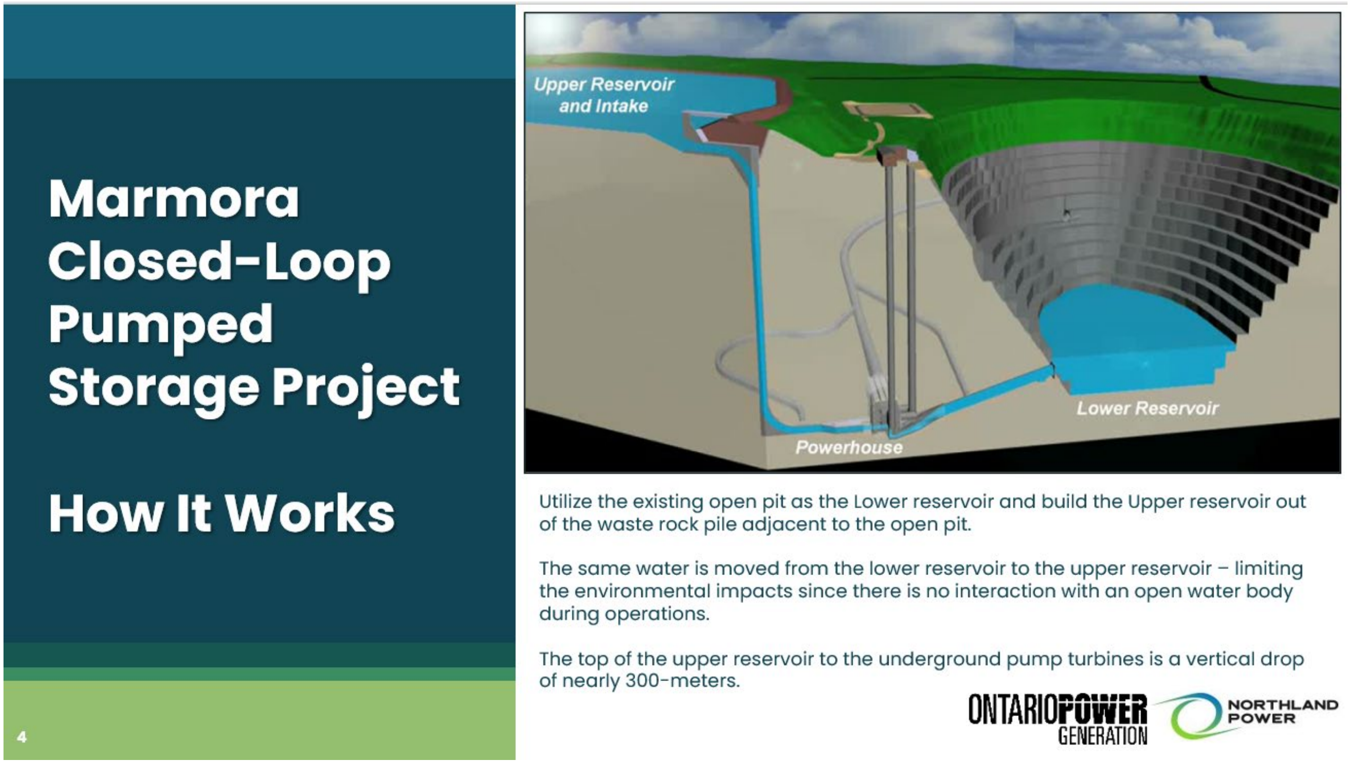
e. Energy Storage Potential:

No specific action

f. Power Marketing:

Review the approach for considering long life capital assets and how the value of pumped storage is compared versus other technologies.

g. Other:



Marmora Closed-Loop Pumped Storage Project

How It Works

Utilize the existing open pit as the Lower reservoir and build the Upper reservoir out of the waste rock pile adjacent to the open pit.

The same water is moved from the lower reservoir to the upper reservoir – limiting the environmental impacts since there is no interaction with an open water body during operations.

The top of the upper reservoir to the underground pump turbines is a vertical drop of nearly 300-meters.

ONTARIO POWER GENERATION NORTHLAND POWER

Marmora Project Overview

Innovative and first of its kind in Canada by converting an abandoned mine to create a large scale closed loop (recirculating same water) hydroelectric energy storage facility for improving use of Ontario's zero carbon renewable assets.

- Long-life (+90 years)
- Large scale (Avg 400MW @ 5hrs / 2,000 MWh) – enough to power 400,000 homes

Major Regional economic development opportunity creating jobs, tourism and education.

Marmora Mine ….. 213 M vertical
(approx. 4 x the drop of Niagara Fall

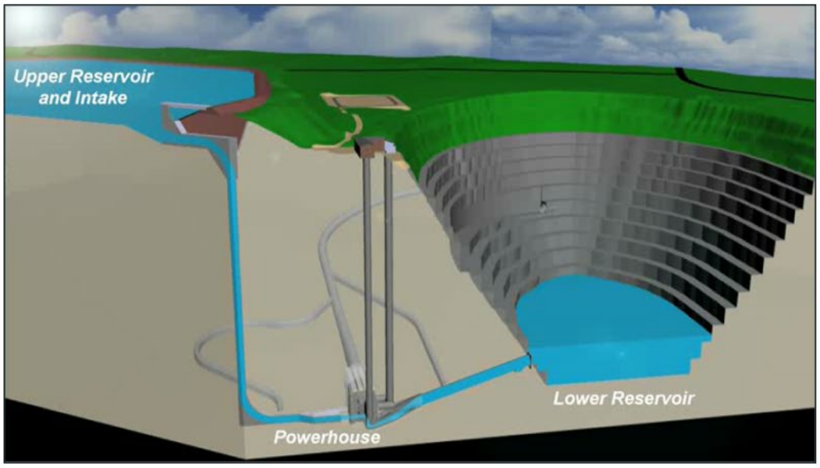
ONTARIO POWER GENERATION NORTHLAND POWER

What makes Marmora a preferred site?

- The Project is environmentally positive; transforming an abandoned mine-site into an economic asset benefiting the community and Ontario.
- Enables the storage of excess clean energy and further reduces the greenhouse gas emissions from the Ontario electricity sector
- The use of a closed-loop system at an abandoned mine-site avoids impacts to waterways and fisheries. Minimal impact to wildlife habitats.
- Close to existing infrastructure adjacent to Highway 7, Hydro One transmission (6.5km north); as well as multiple communities within driving distance to support construction and operations.
- Ideally located near electricity demand with the project located halfway between Toronto and Ottawa.
- Global top percentile LH Ratio (length / height) due to the short horizontal distance between the reservoirs leads to higher net efficiency

Marmora Closed-Loop Pumped Storage Project

How It Works



Utilize the existing open pit as the Lower reservoir and build the Upper reservoir out of the waste rock pile adjacent to the open pit.

The same water is moved from the lower reservoir to the upper reservoir – limiting the environmental impacts since there is no interaction with an open water body during operations.

The top of the upper reservoir to the underground pump turbines is a vertical drop of nearly 300-meters.

17. OWA RESPONSE

At present, there are four (4) pumped storage projects moving through the IESO's "Unsolicited Proposals" process file:///C:/Users/Owner/Downloads/sac-20210217-unsolicited-proposals%20(7).pdf

Marmora
Meaford
Steep rock
Schreiber

An inventory of Ontario's Pumped Storage potential sites can be found in Table A4 of this report:

https://secureservercdn.net/198.71.233.206/jzd.e4e.myftpupload.com/wp-content/uploads/2017/01/Evaluation-and-Assessment-of-Ontarios-Waterpower-Potential-Final-Report-.pdf

"As early as 2030, Ontario's Independent Electricity System Operator (IESO) has identified that the province will need an additional 6,000 MW in new capacity. Energy storage projects are increasingly being enabled through the IESO's Resource Adequacy Framework, with potential applications both for pumped storage and for the co-location (i.e., hybrid systems) of storage resources with existing waterpower assets. Advancing pumped storage as a solution among the suite of energy storage options available and supporting our members in pursuing pumped storage projects are key objectives for the OWA," said Paul Norris, President, Ontario Waterpower Association.

18. SASKPOWER RESPONSE

I do not believe that we are looking at adding Pumped Storage Capability in the near future.

19. UNDISCLOSED UTILITY 1 RESPONSE

Stantec is conducting a Technical and Economic Potential Assessment of Pumped Storage Hydropower (PSH) in Canada for WaterPower Canada (WPC). We would appreciate your insights and will give credit in our report to your input or keep it anonymous according to your preference.

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?

a. Yes, we have studied potential project opportunities ☒

b. Yes, we are actively engaged in the development of projects ☐

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?

a. Initiation: ___ MW, ___MWh storage, CND$ ___ value for your firm

b. Definition: ___ MW, ___MWh storage, CND$ ___ value for your firm

c. Execution: ___ MW, ___MWh storage, CND$ ___ value for your firm

Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

We found many PSH potential sites characterized by installed capacity from 500 to 2000 MW and duration varying between 8 to 15 hours (must be kept in confidence)

3. In which Canadian Province(s) are your projects located?

4. What portion of the value for your firm would approximately be spent in Canada?

100 %

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study.

____

____

6. What obstacles to your PSH project(s) do you see in the following areas?

a. Electrical Power Transmission:

____

b. Environmental, Social and Regulatory Considerations:

Difficulty of putting into perspective the analysis of the local environmental impacts of a PSH in relation to the need to promote the use of renewable energy. The industry is turning to solar and wind because the environmental impacts seem more acceptable but involves major constraints in the management of power and energy.

c. Constructability:

____

d. Suitable Technology:

____

e. Energy Storage Potential:

____

f. Power Marketing:

____

g. Other:

____

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?

a. Electrical Power Transmission:

____

b. Environmental, Social and Regulatory Considerations:

____

c. Constructability:

____

d. Suitable Technology:

____

e. Energy Storage Potential:

f. Power Marketing:

g. Other:

20. UNDISCLOSED UTILITY 2 RESPONSE

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?
   a. Yes, we have studied potential project opportunities
   b. Yes, we are actively engaged in the development of projects ☑

Confidential

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?
   a. Initiation: ___ MW, ___MWh storage, CND$ ___ value for your firm
   b. Definition: 75 MW, 2700 MWh storage, CND$ ___ value for your firm 300MM
   c. Execution: ___ MW, ___MWh storage, CND$ ___ value for your firm

   Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

3. In which Canadian Province(s) are your projects located?

   Alberta

4. What portion of the value for your firm would approximately be spent in Canada?

   70 %

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study. Please elaborate on separate page.

6. What obstacles to your PSH project(s) do you see in the following areas?
   a. Electrical Power Transmission:

   Current AESO tariff requires energy storage to be both a generator and a load and there is

   b. Environmental, Social and Regulatory Considerations:

c. Constructability:

d. Suitable Technology:

e. Energy Storage Potential:

f. Power Marketing:

g. Other:

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?
    a. Electrical Power Transmission:

Property Tax. Considering these assets are long term (50+ years) and will continue to contribute to the tax base for their life, getting some type of tax incentive for early in its

    b. Environmental, Social and Regulatory Considerations:
    c. Constructability:
    d. Suitable Technology:
    e. Energy Storage Potential:
    f. Power Marketing:
    g. Other:

Having some sort of emissions quantification protocol that encourages the deployment

21. VOITH RESPONSE

1. Is your firm planning to participate in the Pumped Storage Hydro (PSH) Market in Canada?
    a. Yes, we have studied potential project opportunities ✓
    b. Yes, we are actively engaged in the development of projects ☑

2. Do you have presently specific Canadian PSH projects in the initiation, definition or execution stage?
    a. Initiation:
    b. Definition:
    c. Execution:
    d.

4000 MW, 12,000 MWh storage, CND$ 1.6 B value for your firm
1000 MW, 2,000 MWh storage, CND$ 0.5B value for your firm
0 MW, 0 MWh storage, CND$ 0 value for your firm

Please list supplementary information about each project on separate page including name, location (latitude/longitude), size, projected on-line date, power and energy capacity, head, reservoir size, electrical interconnection point, type (closed/open-loop), equipment, configuration, type of ownership and all other information you consider relevant. Indicate if any of this information must be kept in confidence.

Due to the competitive structure all projects are cover by Non Disclosure Agreements between Voith Hydro and the Developers - Information can be found in public domain on projects names and locations.

3. In which Canadian Province(s) are your projects located?
    Alberta, British Columbia, Ontario, Yukon

4. What portion of the value for your firm would approximately be spent in Canada?
    40 %

5. Your commentary on potential impacts on the Canadian economy from the advancement of your PSH projects would help put context to this study. Please elaborate on separate page.
    Please see answer on attached page

6. What obstacles to your PSH project(s) do you see in the following areas?
    a. Electrical Power Transmission:
        Please see answer on attached page
    b. Environmental, Social and Regulatory Considerations:
        Please see answer on attached page
    c. Constructability:
    d. Suitable Technology:
    e. Energy Storage Potential:
    f. Power Marketing:
    g. Other:

7. What actions from government at the federal, provincial, municipal or First Nations level would aid your PSH project(s) in the following areas?
    a. Electrical Power Transmission: ____________________
    b. Environmental, Social and Regulatory Considerations: ____________________
    c. Constructability: ____________________
    d. Suitable Technology: ____________________
    e. Energy Storage Potential: ____________________
    f. Power Marketing: ____________________
    g. Other: ____________________

22. YUKON ENERGY RESPONSE

There is a pumped storage project in Yukon included as part of our 10 year resource plan. The project is Moon Lake. The resource plan is publicly available on our website. Lack of response is because of time and resources on our part.

APPENDIX F

APPENDIX F – STUDY TEAM

The team of this study alliance is composed of a group of peers, assembled to represent high caliber expertise in their respective areas, under the leadership of Stantec's **Dr. Michael Morgenroth** as principal investigator. This group of peers was supported by junior researchers to conduct industry polls and data analysis and interpret their findings.

A review of our publication lists reveals that we co-author what are considered the industry standards for pumped storage planning and modeling.

1. STANTEC RESOURCES

Michael Morgenroth DIPL. ING., PH.D., P.ENG.

Michael is a mechanical engineer with 31 years of experience from concept to implementation of water and wind power projects worldwide. He is currently responsible for the Canadian hydropower and dams' sector at Stantec. Michael's technical latitude has spanned component and system level design, site engineering, commissioning, laboratory and field performance testing, equipment selection inspection and assessment, troubleshooting, assessment of aging infrastructure, risk, and other specialty studies. He has managed projects, emerging technologies, contractor prequalification, technical bid evaluation, and contract negotiations for equipment supply, construction, and service contracts.

Donald Erpenbeck PE, PMP

Donald has extensive capabilities in the design and operation of hydroelectric generators/turbines, control systems, and hydro-mechanical equipment. He is a recognized authority in the Hydro industry for his unique perspective and understanding of requirements for executing a successful refurbishment program. Donald uses this diverse experience to manage and oversee projects at Stantec and to perform high level evaluations and management consulting tasks including developing risk allocation strategies and assistance in contract negotiations for turnkey and equipment supply rehab contracts. Donald was a project manager for Rocky Mountain Pump Storage Project Uprate in Georgia, USA.

Michael Manwaring PG

Michael Manwaring has over 25 years of technical, project management, and business development experience in the renewable energy industry, with a deep understanding of the dams and hydropower sector. Over the past 15 years he has become a recognized industry expert in the development of new hydropower and pumped storage projects, including planning, licensing, preliminary design, operations modeling, and power marketing. Michael has served in a variety of industry leadership roles, including as Board Member for the National Hydropower Association (NHA), Northwest Hydroelectric Association (NWHA), and Hydropower Foundation. He has supported the U.S. Department of Energy (DOE) as a technical advisor.

Trion Clarke PH.D.

Trion is a Senior environmental expert with over 30 years of Canadian and international experience in project management, environmental and social impact assessment (ESIA) and permitting. He has applied his expertise across many sectors including the renewable energy industry where he has worked on various environmental aspects of hydro power projects. He has designed and conducted hydro power environmental assessments at provincial and federal levels and has also completed environmental due diligences and reviews of hydro projects for international lending agencies, including the World Bank. He has also completed technical reviews for the Federal Impact Assessment Agency. Having worked on projects in several provinces over his career has led to his familiarity with different region-specific nuances which will be of significance for this project. Trion has completed negotiations with various federal, provincial and municipal regulatory agencies as well as with stakeholders and indigenous communities in relation to hydropower and other energy sector developments.

Ivor Shaw P.ENG.

Ivor has over 42 years of experience in the energy and power sector worldwide. He has been involved in the development, design, construction, rehab and commissioning of hydro and wind projects and applications to improve the client's return on investment. Ivor has been involved in multiple complex projects developing innovative and reliable installations in hydro power projects for public and private entities, ranging from 6 – 300 MW. Today, his main responsibility is the hydropower and dam sector in Canada. He serves as Project Manager for power projects including project initiation, definition, preliminary and detailed engineering, contracting and permitting, implementation, erection of turbines, management and commissioning to commercial operation.

Robyn Koropatnick, P.ENG., PMP, SMIEE

Robyn has 23 years of experience in the high voltage power transmission industry, including Project Management, HVDC transmission systems, engineering of submarine and underground cables, and system studies.

Ralph Kurth, P.ENG., PMP

Ralph has over 35 years of experience in the study, design, and implementation of power system projects with emphasis in HVDC transmission, ac substations, and substation automation systems. His experience ranges from initial project feasibility assessments through to project commissioning. Ralph has served as technical advisor, project manager, and commissioning manager on several technically advanced substation and HVDC transmission projects. He has provided advice to project teams and clients in the area of technology selection, system configuration, contracting strategy, project risks, schedule and costs.

Pavel Ionita P.Eng., PE, PMP

Pavel has over 26 years of HV / EHV substation design and detailed design experience including AC switchyard layout designs of outdoor high voltage switchyards, structure and equipment grounding, switchyard apparatus / equipment / structure installations and high voltage bus design. He possesses significant knowledge associated with relevant AC design codes, standards, and guidelines.

Lara Stregger P.Eng.

Lara has over 12 years of power transmission industry experience, which includes HVDC specification development, bid evaluation, design review, and budgetary cost estimate development; NERC CIP compliance analysis; system operation planning and studies; power system modeling and interconnection studies; system planning studies including economic analysis; and project management.

Megan Grosso

Megan has gained industry experience working with Stantec as an Engineering Intern. She supports Civil/Structural, Hydraulics and Geotechnical Engineers/PMs and has experience with technical report writing, Risk Analysis and PFMA workshops, ArcGIS Pro data analysis, Emergency Action Plan development and structural engineering. Megan is a Civil Engineering student at Queen's University in Ontario, Canada.

Phaedra Taiarol P.Eng.

Phaedra has over twenty years of experience in the high voltage power transmission industry, including planning and development of HVDC systems, grounding systems analysis and design, development of cost estimates, NERC Critical Infrastructure Protection (CIP) compliance, and project management.

2. AUSTRALIAN NATIONAL UNIVERSITY

Andrew William Blakers PH.D.

Andrew is a E2 Professor, Engineering at University of New South Wales (UNSW) since 1079. His expertise and research focus on Solar photovoltaic energy: silicon solar cells, solar concentrator systems, PV tandems, Energy policy, economics and markets, Research and public discussion around 100% renewable energy futures and the large role that this plays in reducing greenhouse emissions, pumped hydro energy storage: off-river pumped hydro as a very large-scale low-cost and mature energy storage technology to support 100% renewable energy futures. He has published several articles and research report about pump hydro energy storage.

Cheng Cheng PH.D. CANDIDATE

Cheng is a Ph.D. candidate at Australian National University since 2022, he is thesis focuses on pathway to decarbonized energy. He has multiple research and article related to Renewable Energy Integration, Decarbonization, Solar Photovoltaics, Wind Energy and Energy Storage. Cheng's work can be accessed here.

Christopher Hayes P.ENG.

Christopher is Vice President of Account Management at CEATI International. Chris looks after all CEATI member utility accounts covering programs related to Generation, DERs/Integration, Transmission, Distribution, Asset Management and Security. He is a member of the Professional Engineering Order of Québec and has a bachelor's degree in mechanical engineering from McGill University, Canada. He has been working with experts and utility leaders in the electric power industry through CEATI since 2002 and has actively grown and supported the CEATI Hydropower Program since that time, which now includes a participation base of over 100 utilities and government agencies from around the world.

Akbar Naqvi MBA

Akbar is Vice President of Product Strategy at CEATI International. Akbar manages the development and advancement of CEATI programs related to Generation, DERs/Integration, Transmission, Distribution, Asset Management and Security. He has a bachelor's degree in Material Science and Engineering from Northwestern University, Canada and an MBA from Georgetown University. He has been with CEATI since 2021. He spent the prior 14 years in various research leadership and product management roles at CEB/Gartner.

Jean C. Pellerin B.Sc.

Mr. Jean C. Pellerin graduated from the University of Ottawa with a bachelor's degree in electrical engineering. He has over 36 years of experience in the operation, maintenance, and development of renewable energies, with a focus in hydro generation. During his career with Brookfield Renewable Energy, he was director of areas such as technical services, asset optimization, and engineering development, and contributed to the company's growth through acquisitions and greenfield developments. He currently provides technical and strategic advice for several engineering firms.

Alexandra Sammons B. Sc.

Alexandra is an associate program manager at CEATI, an organization that provides electric utilities with the knowledge and tools to help solve their most challenging needs. Alexandra's current portfolio includes Asset Management and Hydropower, but she has also worked on the Energy & Integration Strategy front, as well as Demand Side Management. Before CEATI, Alexandra studied Neuroscience at Concordia University in Montreal. After graduating with a Bachelor of Science, Alexandra's interest in renewable energies and the environment led her to work for CEATI.

3. POWER ADVISORY

Michael Killeavy M.ENG., MBA, P.ENG.

Michael is an experienced electricity sector consultant with over 30 years of experience in both the public and private sectors working on energy and infrastructure projects. He has advised clients on contractual and commercial matters, undertaken due diligence for equity investors and lenders, prepared financial and energy models for generation projects, and advised clients on integrating contracts into electricity markets in Ontario, Alberta, and across the United States. Michael also provides end-to-end procurement-related advice to clients from project initiation to close-out. Prior to joining Power Advisory, he was the Director, Contract Management at the Ontario Independent Electricity System Operator and was responsible for over 30,000 MW of generation contracts, including 1,500 MW of contracted hydropower.

Brady Yauch MA

Brady is an Energy Economist with nearly 10 years of experience in the electricity sector, both with regulated utilities and electricity markets. He has participated in dozens of regulatory hearings at the Ontario Energy Board, including drafting arguments and cross-examining witnesses. Brady also appeared before parliamentary committees. His research and commentary on the electricity sector and other regulated sectors has been published and quoted extensively in the media and the legislature. Prior to coming to Power Advisory, Brady worked as a Senior Analyst within the Market Assessment and Compliance Division at the Independent Electricity System Operator. As part of that role, he conducted analysis on the competitiveness of Ontario's electricity market and assessment of potential exercises and abuse of market power, including drafting reports published by the Market Surveillance Panel among other reports and studies. He was also an economist and Executive Director of the Consumer Policy Institute, a public advocacy group that regularly participated in regulatory proceeding