Volume 16
Spring
2021
ojs.library.dal.ca/djim

Spatial Analysis of Pumped Hydro Energy Storage Integration with Wind Farms

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Abstract

Renewable energy systems have been implemented globally to help lower carbon emissions; for example, pumped hydro energy storage (PHES) is a system that helps mitigate peak loads on electrical grids to reduce dependency on fossil fuel energy generation. As a form of energy storage, PHES involves using two water reservoirs at different elevations to generate electricity at times of peak demand. Integrating PHES near wind farms allows the required water-pumping electricity to be supplied by wind power, rather than fossil fuels. A spatial analysis was done using ArcGIS Pro to determine the most ideal sites for PHES within close proximity to wind farms in Nova Scotia. Five potential sites were identified, and map layouts were produced showing conceptual models of PHES at these locations throughout the province. Due to the topography of Nova Scotia, development of PHES is not feasible at many potential sites. Five suitable sites were ranked based on environmental and technoeconomic costs; the Barrachois Wind PHES hybrid project was ranked the highest, followed by the Digby, Ellershouse, Maryvale, and South Canoe wind energy sites. The study concluded that integrating PHES into wind farms in Nova Scotia would be a useful method for boosting electrical grid stability, and attaining emissions reductions targets throughout the province.

Keywords: pumped hydroelectricity, wind farm, GIS applications, spatial analysis, energy storage

Introduction

Introduction to Renewable Energy & Importance of Energy Storage

The 2018 Intergovernmental Panel on Climate Change (IPCC) Report sent a shockwave throughout the world, warning that immediate action would be required to limit global warming to 1.5 degrees Celsius (Tollefson, 2018). The majority of worldwide energy generation is still dependent on fossil fuels, and human energy use is releasing greenhouse gases at an unsustainable rate. The consequences of 1.0 degrees Celsius of global warming are already being observed around the world, inducing major coral bleaching events, extreme heat waves, permafrost thaw, air pollution, global sea level rise, biodiversity loss, and a host of other problems. Renewable energy systems are becoming more prevalent around the world to generate energy for human consumption without emitting greenhouse gases (Turner, 1999). There are various forms of renewable energy, with these technologies being improved frequently over time, including wind, solar photovoltaic, concentrated solar, geothermal, hydroelectric, wave, tidal, biomass, etc. (Rehman et al., 2015). Of these, wind, solar, and hydroelectric energy sources have taken the lead globally due to their well-researched technical applications and commercial acceptance. Right now, about 27% of Nova Scotia’s electricity is generated from renewable energy sources, with more renewable projects being installed every year (Nova Scotia Power, 2020a). Climate change poses a threat to Nova Scotian through sea level rise and extreme weather events; the provincial government has responded by committing to phase out coal-fired power plants by 2030 and continuing investment in renewable energy, energy storage, and energy efficiency initiatives throughout the province (Montague, 2021). Within the Halifax Regional Municipality, the new HaliFACT 2050 Climate Action Plan is being recognized as the most ambitious climate action commitment strategies in Canada, in which renewable energy and energy storage play a vital role in attaining emission reduction targets (HalifACT, 2020). As Nova Scotia transitions to more renewable energy, concerns have arisen with regard to the intermittent physical nature of renewable sources, particularly wind and solar power (Rehman et al., 2015). With the commitment to shut down coal-fired power plants, this begs the question as to how Nova Scotia’s electrical grid will adapt when the wind is not blowing and the sun is not shining. Energy storage has become increasingly important as a way to boost grid stability and provide support for further deployment of other renewable energy sources such as wind and solar.

Background of Pumped Hydro Energy Storage

Pumped hydro energy storage (PHES) is a relatively old method of storing energy, so that electricity can be generated during times of peak demand. PHES was first used in Switzerland in 1907, however, the technology did not become widely applied worldwide until the early 2000s. In Canada, there is only one operational PHES facility, located in the Sir Adam Beck Project in Ontario (Canada Energy Regulator, 2016). However, more projects have been proposed, particularly in the western part of the country. By the end of 2016, approximately 160 gigawatts of PHES capabilities were installed around the world, with the vast majority (85%) located in Europe (Lu et al., 2018). A study by Nzotcha et al. (2019) estimated that PHES accounted for 97% of the global energy storage capacity. Pumped hydro energy storage is installed using two water reservoirs at different elevations. An open loop PHES project has one or both of the reservoirs attached to a naturally flowing water feature (river, lake, the ocean, etc.). In contrast, a closed loop project uses two reservoirs that are separated from other water bodies (Lu et al., 2018). A turbine-pump between the two reservoirs acts to generate power when water from the higher elevation reservoir is released to flow downhill (Canada Energy Regulator, 2016). The downflow of water is implemented during times of peak electrical demand to reduce the strain on the electrical grid. During times of low demand, energy is consumed by the turbine-pump to push the water back uphill to the higher elevation reservoir.

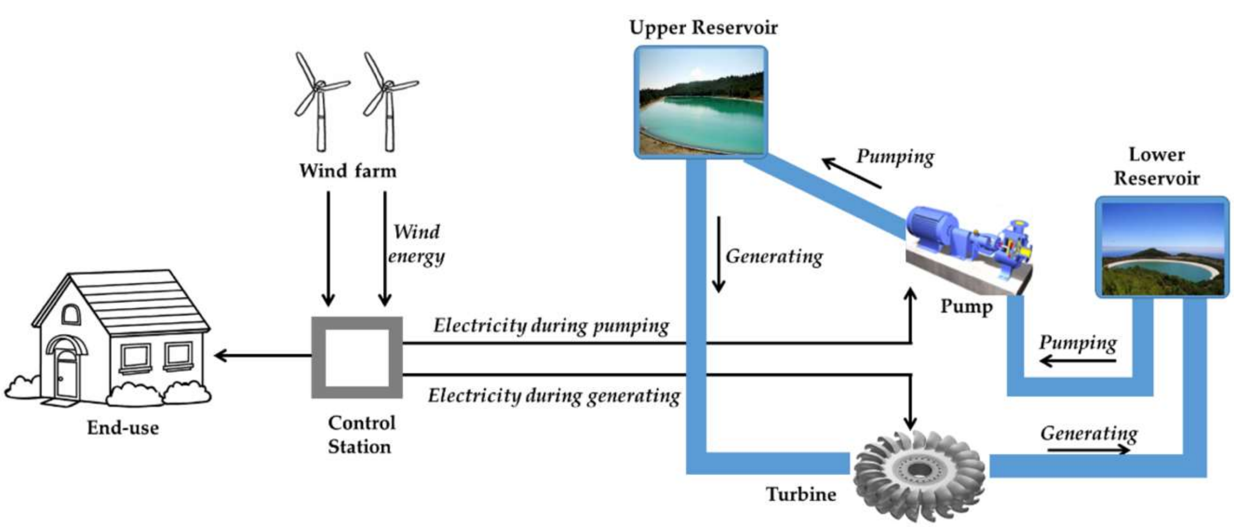


Figure 1. Wind – PHES "Hybrid" Power Station Conceptual Diagram (Sarasúa et al., 2018)

Purpose and Context of this Study

At this time, establishing PHES projects close to wind farms would allow the pumping system to operate primarily from renewable energy rather than burning fossil fuels, as shown in *Figure 1*. Another benefit is that the energy generation from the turbine can be integrated into the electrical grid where the infrastructure such as road networks, transmission towers, and powerlines already exist. By integrating PHES into sites that have already been disturbed by other renewable energy projects, the techno-economic, social, and environmental impacts can be significantly lower compared to undisturbed locations (Nzotcha et al., 2019). Therefore, the purpose of the study is to investigate where suitable sites are located in Nova Scotia for positioning pumped-hydro energy storage in close proximity to existing wind energy projects. A spatial analysis of potential pumped hydro energy storage sites in Nova Scotia was conducted using the Geographical Information Systems (GIS) computer program 'ArcGIS Pro', applying water systems, topography, land cover, and several other surficial data sets.

Wind energy generation is highly intermittent in nature, as wind is totally dependent on climatic conditions. Granted, before wind installations are constructed, analysis is done to ensure that turbines are placed in the best locations for generating wind power, based on the average meteorological parameters of a given area. In Nova Scotia, over 300 wind turbines are widely spread throughout the province (Nova Scotia Power, 2020a). Therefore, the opportunity for wind-PHES hybrid power projects is immense.

When planning for the development of PHES, a variety of factors need to be considered with each individual project including profitability, appropriate turbine-pump technology, the social impacts to surrounding residents, and terrestrial and aquatic environmental concerns (Steffen, 2012). Each proposed project would require a provincial environmental assessment to ensure that research evidence is used to determine each sites' relative feasibility. The input of Indigenous peoples and the general public must be considered during the process as well, with frequent engagement between the proponent and these groups. Thirty-six PHES projects were proposed throughout the United States before 2010, 29 of which were for closed-loop projects involving either storage ponds or underground caverns for lower reservoirs (Yang & Jackson, 2011). Generally speaking, human made closed-loop PHES systems can help avoid impacts to existing water bodies, particularly if non-potable groundwater is used. The biggest downside with closed-loop PHES projects is that they are relatively expensive to develop, which can lead to longer return-on-investment. Opportunities for open-loop systems with lower environmental impacts involve using seawater. These systems typically require construction of an upper reservoir, with saltwater being pumped out of the ocean. Additional consideration for coastal projects is a strong, impermeable liner along the bottom and sides of the upper reservoir to ensure seawater does not leak into the surrounding environment (Fujihara et al., 1998). Groundwater PHES systems were not considered during analysis as these systems are not widely applied, and greater expertise in underground GIS modelling is required.

Another factor to consider for PHES projects is the appropriate pump and turbine technology. Currently there are two main options for creating electricity from PHES projects, and projects utilizing each type of electricity generation exist around the world. First, PHES projects could use a binary set of instruments, composed of two hydraulic machines (a turbine and a pump) that can operate simultaneously or independently (Deane et al., 2010). This type of PHES project is more traditional and has several benefits including a non-existent changeover time leading to much quicker electrical grid response, less stress on each machine, higher efficiency, and the ability of the turbine to start the pump during operation (West & Moeini, 2019). However, the drawback of this method is the much higher cost associated with larger powerhouse, additional mechanical equipment, and extra piping infrastructure.

The other approach to PHES projects has become more widely adopted in recent years, which involves a reversible "turbine-pump" unit, powered by a single electric machine (Deane et al., 2010). These units are able to reverse the direction of water flow by switching between generating and pumping modes, allowing water to flow downhill through the turbine, or push it back uphill to the upper reservoir. There are a large number of different models of these systems, ranging in capabilities such as fixed or variable speeds. A lower installation cost is the main benefit of this system. West and Moeini (2019) estimated that the infrastructure, machinery, and construction costs associated with implementing reversible turbine-pump technology ranges between 25 – 50 % lower than binary sets. Yet, reversible units also have drawbacks including a longer changeover time between generation and pumping, less grid stability, and a larger stress on the individual unit. The efficiency of turbine-pump units is estimated at 2 – 3 % lower than having separate machines for electricity generation, and water pumping (West & Moeini, 2019). The single unit turbine-pump model is more widely applied worldwide for small scale PHES projects (Deane et al., 2010); therefore, this model was used during Nova Scotia PHES site analysis and map creation.

The most recent attempt at integrating PHES projects with wind farms in Nova Scotia was carried out by Cape Breton Explorations Limited in 2007 (CBC News, 2010). The proposed project was in Richmond County, intended to pump water from Lake Uist over 3.5 km to a higher elevation reservoir in the East Bay Hills where proposed 44 wind turbines would be located (CBCL Limited, 2007). This project would have contributed around 300MW of power to the electrical grid, or 150MW if only the wind turbines were installed. Opposition from local organizations and First Nation communities developed when the project was registered for an environmental assessment, and eventually the proponent withdrew the project all together (CBC News, 2010). The project had a social license to proceed with the wind farm construction, and although some minor roads were built and land clearing was completed, wind turbine construction never started.

Method

ArcGIS Project Setup

Data layers were obtained from the Nova Scotia Government Geographic Data Directory, including Nova Scotia Topographic Database Digital Terrain Model (DTM), Utilities (transmission network), Water Features, Land Cover, Protected Areas, and Crown Land. The DTM file was interpolated from a point file into a raster surface using the “point to raster” spatial analyst tool. This new raster surface was used to create an elevation model, shown with contour lines every 10m throughout the province.

To locate the major wind farms in Nova Scotia, a shapefile from the Natural Resources Canada geodatabase, called “Renewable Energy Power Plants, 1MW+,” was used. This shapefile was queried using the “select by attribute” tool to isolate only wind projects located in Nova Scotia. The Provinces/Territories boundary shapefile was obtained via 2016 Census data from Statistics Canada. The “export features” tool was used to isolate the province of Nova Scotia, and the rest of the boundaries were removed. All of the shapefiles mentioned above were formatted using the “clip” tool, such that the analysis was done only within the boundary of Nova Scotia. The base map of “world imagery hybrid” was provided by the Environmental Systems Research Institute (ESRI), the developers of ArcGIS products. All layers were projected into the North America Datum of 1983, or “NAD83.”

Site Selection

Potential PHES sites in Nova Scotia were selected using a basic set of criteria. First, the site had to be within a relatively short distance of a wind energy project. Second, the site required substantial variation in elevation such that gravitational force between the two water reservoirs could maintain relatively high water velocity moving the turbine to create power. Third, the site could not be within protected areas such as provincial or national parks. Based on the satellite imagery of these areas, sites were selected that limited disturbance close to residences, and prioritized sites of least environmental impacts. Whether waterbodies around sites are used as local drinking water supplies was determined, and when they are, the waterbodies were not selected as reservoirs for energy storage. Where waterbodies are not used as drinking water, these lakes and ponds were evaluated as potential PHES reservoirs.

PHES Power Station Digitization

Two reservoirs were chosen for each site, ranging from newly constructed ponds, existing waterbodies, and the ocean. Reservoirs that had to be built were digitized in ArcGIS Pro using the "Edit – Create" tool, after creating corresponding layers as feature classes. Once the two reservoirs were chosen, a hydro flow pipe was digitized between the reservoirs, representing downstream flow (energy generation), and upstream flow (energy consumption). Near the lower elevation pond, a point was digitized that showed the location of the pumphouse, containing the turbine-pump machine and other required equipment. Afterwards, a transmission line was digitized that showed the route for electricity flow from the pumphouse to the electrical grid.

Results

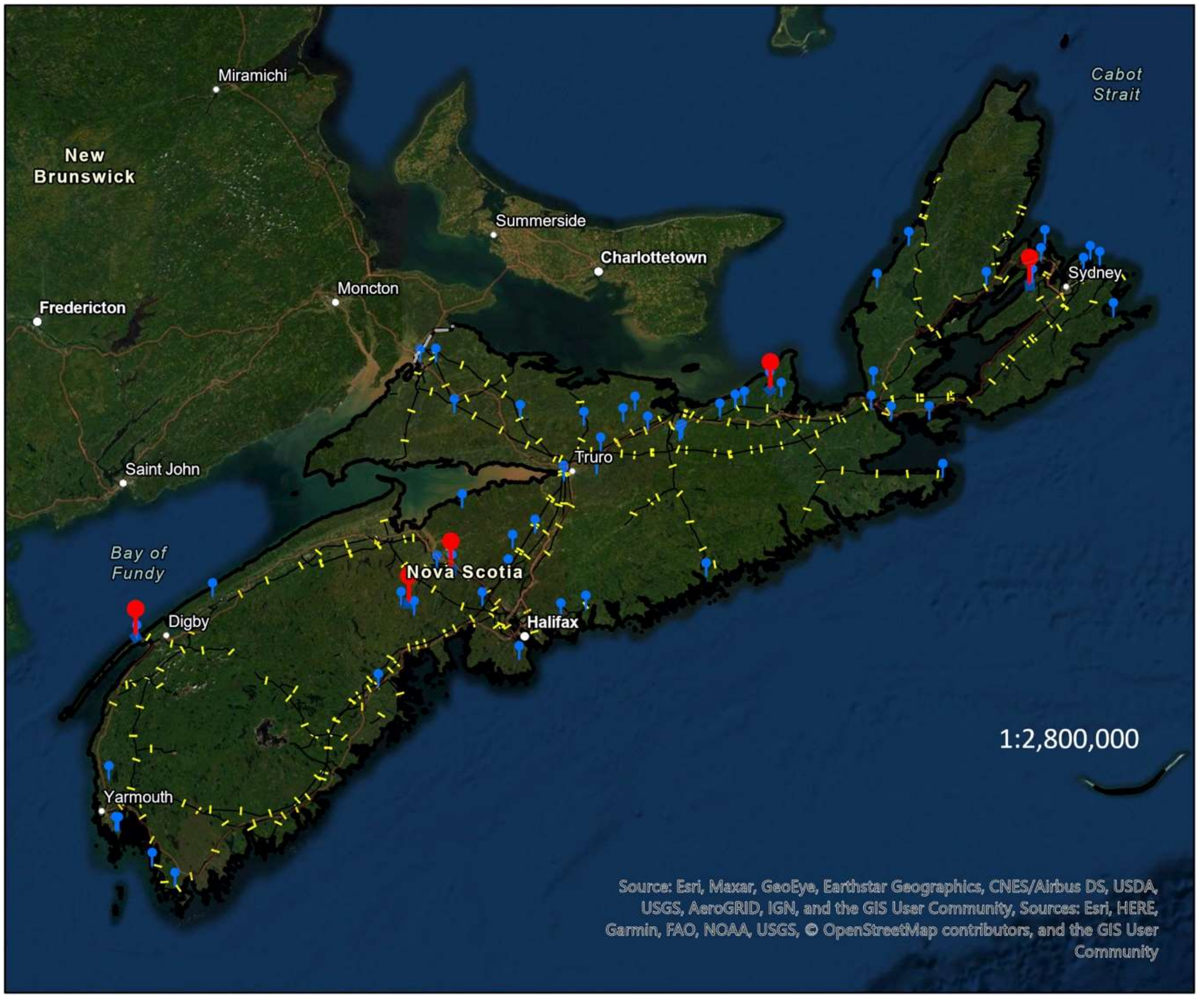
Map Layouts

Of the 78 wind energy projects in Nova Scotia, five projects were selected for analysis as potential PHES – wind hybrid power stations (shown in Table 1).

Table 1: Wind Energy Projects Analysed for PHES Hybrid Stations in Nova Scotia

Name	Capacity (MW)	# of Turbines	Latitude	Longitude
Digby Neck	31	20	44° 35' 50.7"	-65° 56' 49.7"
South Canoe	102	34	44° 46' 20.7"	-64° 20' 25.6"
Ellershouse	16	7	44° 55' 16.3"	-64° 1' 7.3"
Maryvale	6	4	45° 43' 50.0"	-62° 3' 57.0"
Barrachois	4	2	46° 8' 56.7"	-60° 24' 26.6"

Over the next six pages, a series of maps show the entire study area, and close up layouts of each location, with specific information for each potential PHES site.



Potential PHES Sites

Wind Energy Projects

Major Transmission Lines

Provincial Boundary

The purpose of this study was to locate potential sites for pumped hydro energy storage (PHES) projects, to act as hybrid power systems with existing wind energy projects in Nova Scotia. Sites were chosen based on a variety of factors including the distance to existing wind turbines, topography, drinking water supplies, and other environmental impacts. This map shows the entire study area, with five potential PHES sites highlighted. Corresponding maps show close-up images of the sites, moving from West to East across the province (Digby to Barrachois).

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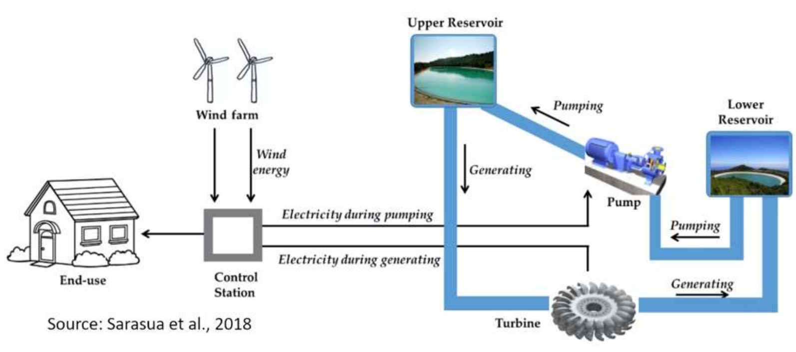
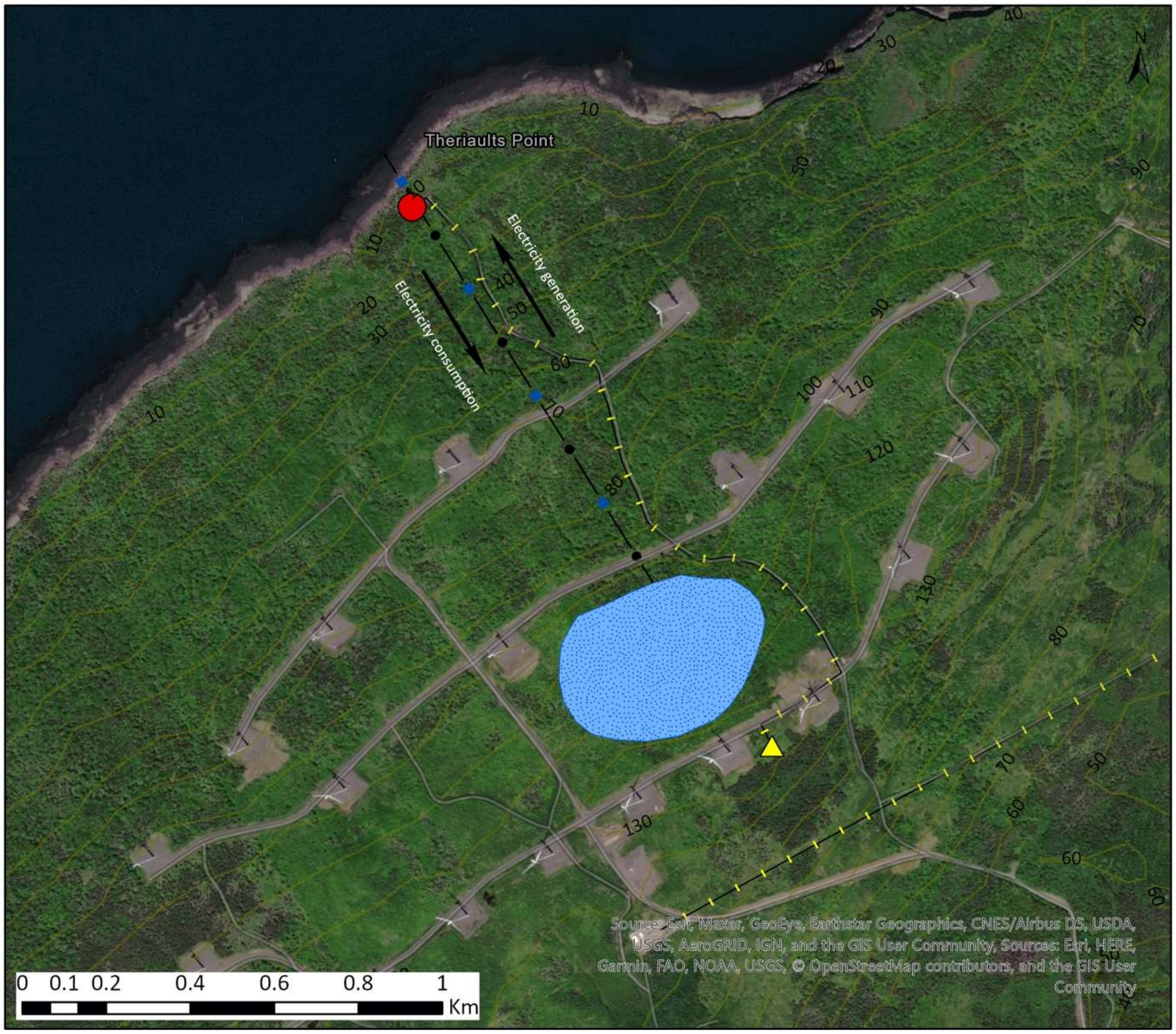


Source: Sarasua et al., 2018

Figure 2. Study Area of Spatial Analysis for Pumped Hydro Energy Storage Sites



- Transmission Tower
- Powerhouse
- Water Reservoir
- Electrical Transmission Lines
- Water Transport Pipe
- Contour Lines (metres)

The Digby Neck wind farm is a 31MW wind energy project consisting of 20 General Electric wind turbines, supplying power to over 10,000 homes. The upper reservoir for PHES would be at approximately 100m above sea level, and the lower water intake is the Atlantic Ocean in the Bay of Fundy. Land clearing would need to occur to situate the reservoir in this area, and an associated environmental assessment would accompany this proposed location. The proposed reservoir has a surface area of 147,000 square metres, and a depth of around 5m. A pipe carrying seawater stretches approximately 1.2km from the upper reservoir to the ocean. This proposed pipe would be above ground, such to limit the environmental impact. The powerhouse contains a reversible turbine-pump, connected to the grid for electricity consumption and generation. Transmission lines stretch from the powerhouse to the main transmission tower close to the road that connects to the rest of the grid. These electrical lines are situated along the edge of an existing trail through the site, so land clearing would be minimized. The arrows represent the direction of water flow through the pipe.

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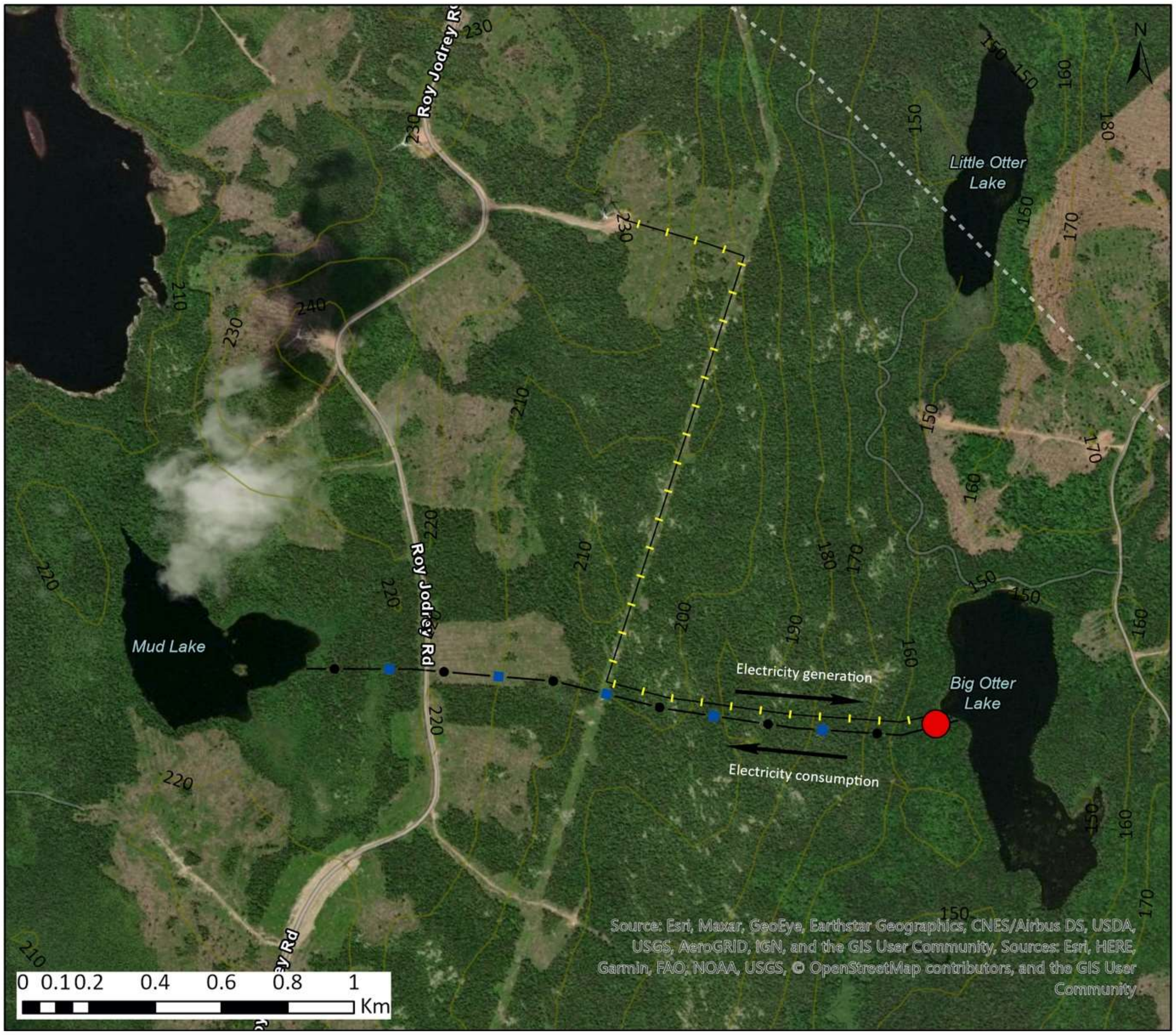
Figure 3. Digby Wind Farm – PHES Hybrid Conceptual Layout



- Transmission Tower
- Powerhouse
- Electrical Transmission Lines
- Water Transport Pipe
- Contour Lines (metres)

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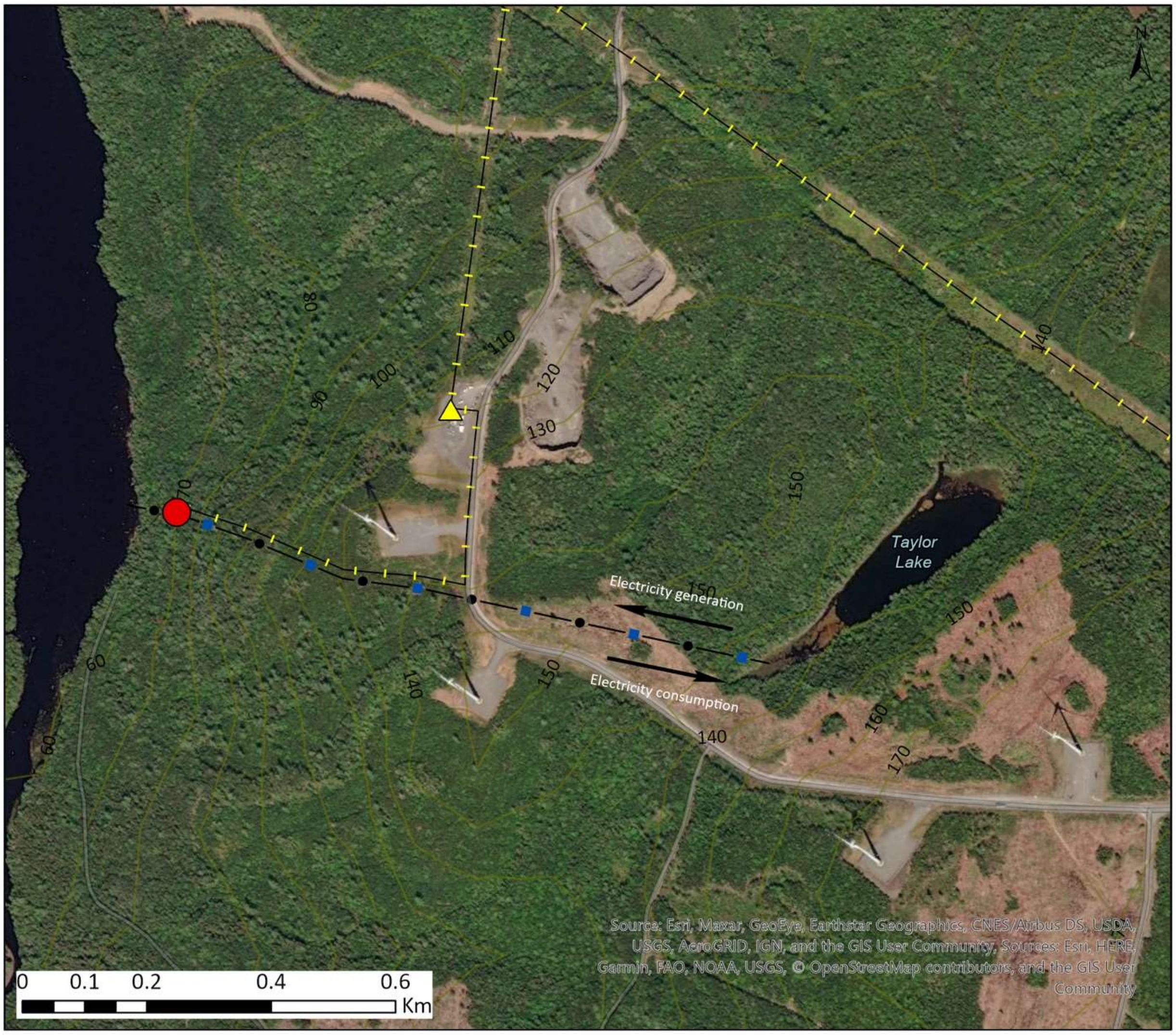
The South Canoe wind farm is a 102MW wind energy project consisting of 34 Acciona AW 3000/116 wind turbines, supplying power to over 32,000 homes. The upper reservoir for the PHES project would be around 220m elevation at Mud Lake, and the lower reservoir is at 150m, using Big Otter Lake. Little land clearing would need to occur to situate the reservoirs in this area, however an in depth environmental assessment would be required to determine the impacts of PHES between these two natural waterbodies. A pipe carrying freshwater stretches approximately 1.9km between the two small lakes. This proposed pipe would be above ground, such to limit the environmental impact. Where the pipe intersects Rod Jodrey Rd., a culvert would be required underneath the roadway. The powerhouse contains a reversible turbine-pump, connected to the grid for electricity consumption and generation. Transmission lines stretch from the powerhouse to the nearest South Canoe wind turbine, which connects to the rest of the grid. These electrical lines are mostly situated along the edge of an existing trail through the site, so land clearing would be minimized.

Figure 4. South Canoe Wind Farm – PHES Hybrid Conceptual Layout



Transmission Tower
Powerhouse
Electrical Transmission Lines
Water Transport Pipe
Contour Lines (metres)

The Ellershouse wind farm is a 16MW wind energy project consisting of seven Enercon E-92 wind turbines, supplying power to around 5,000 homes. The upper reservoir for the PHES project would be around 150m elevation at Taylor Lake, and the lower reservoir is at 60m, using the much larger Panuke Lake. Little land clearing would need to occur to situate the reservoir in this area, however an in depth environmental assessment would be required to determine the impacts of PHES between these two natural waterbodies. A pipe carrying freshwater stretches approximately 1.1km between the two small lakes. This proposed pipe would be above ground, such to limit the environmental impact. Where the pipe intersects the road, a culvert would be required underneath the roadway. The powerhouse contains a reversible turbine-pump, connected to the grid for electricity consumption and generation. Transmission lines stretch from the powerhouse to the on-site transmission tower, which connects to the rest of the grid. These electrical lines are situated along the edge of an existing road through the site, so land clearing would be minimized.

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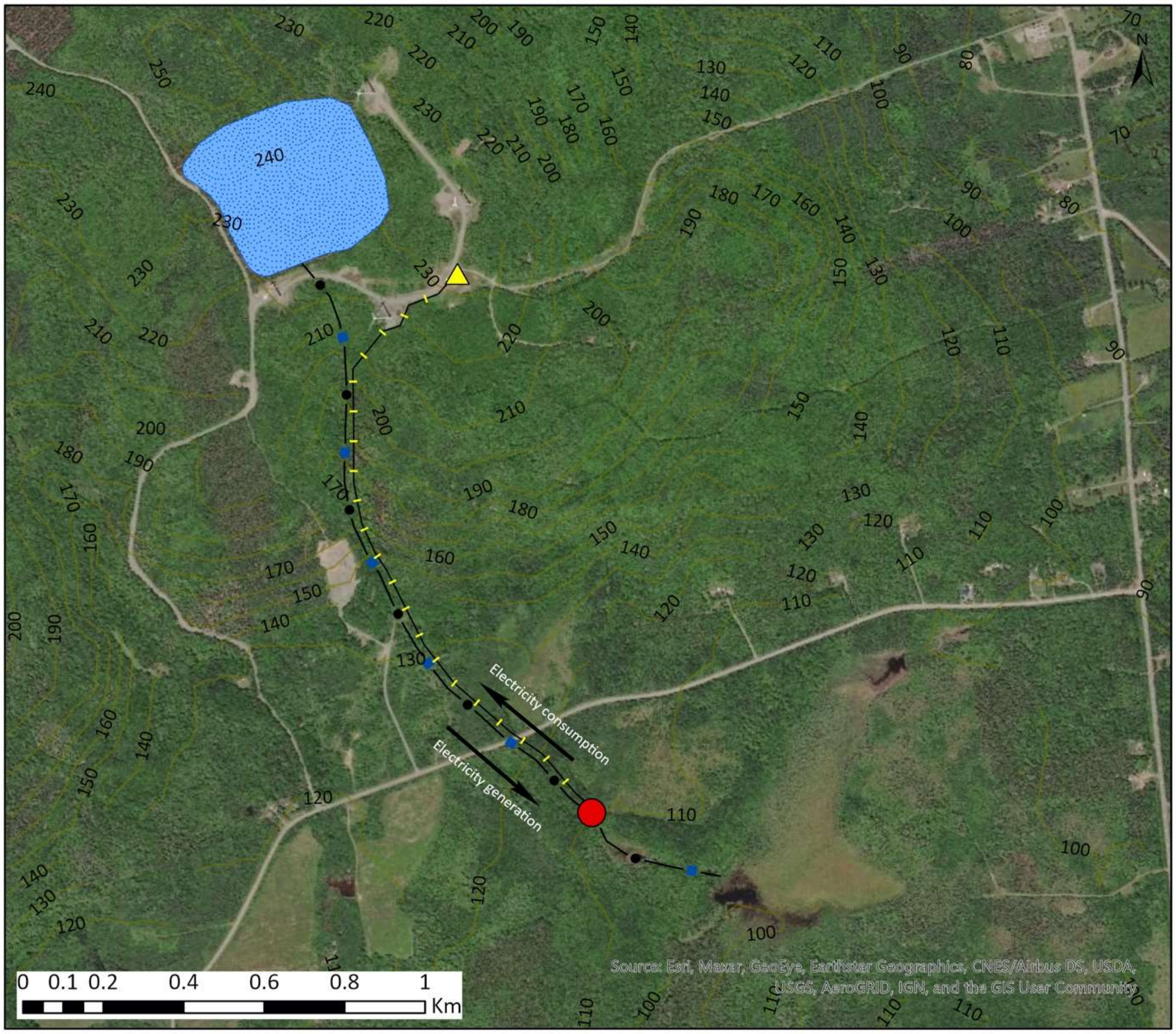
Figure 5. Ellershouse Wind Farm – PHES Hybrid Conceptual Layout



- Transmission Tower
- Powerhouse
- Water Reservoir
- Electrical Transmission Lines
- Water Transport Pipe
- Contour Lines (metres)

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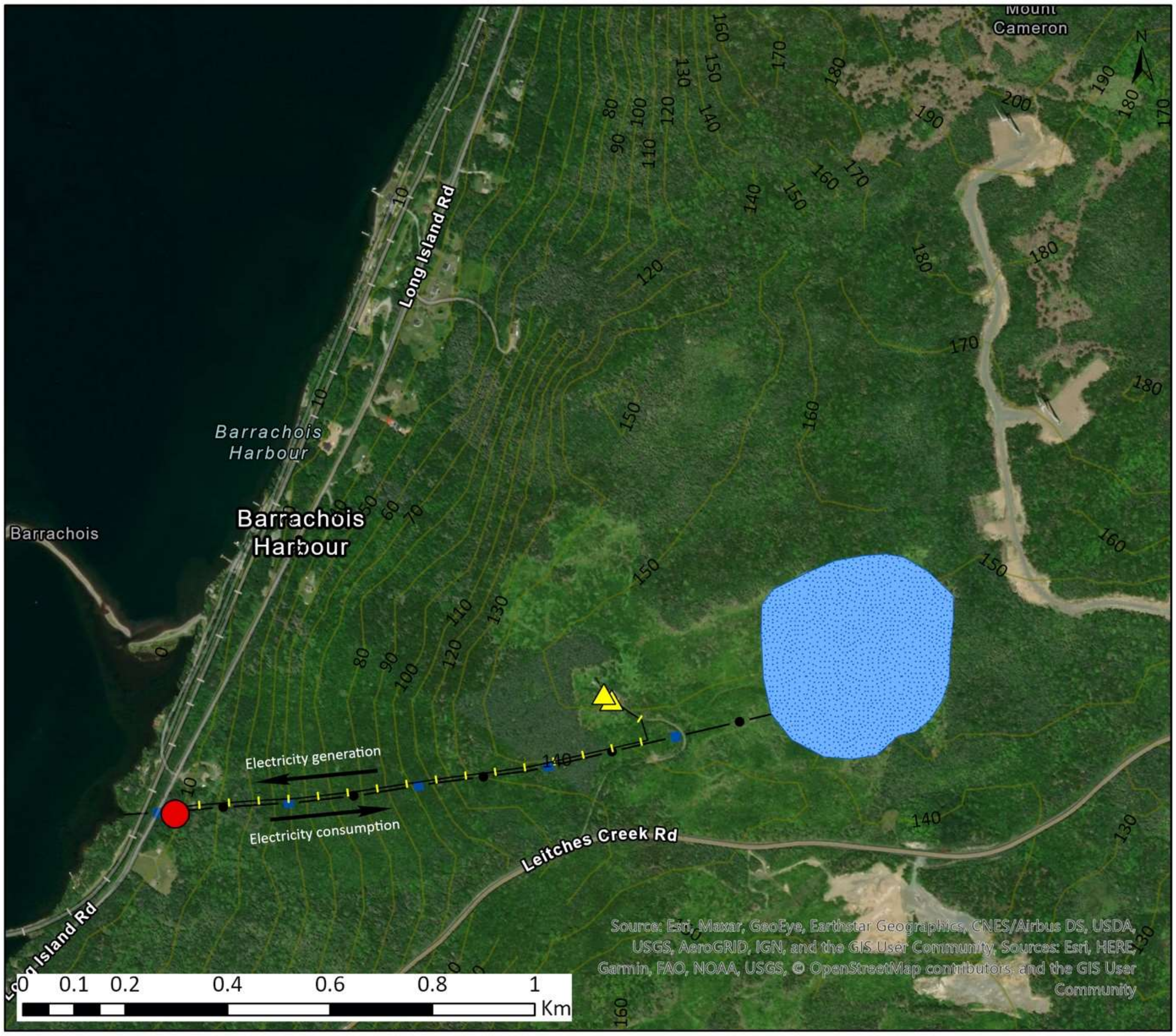
The Maryvale wind farm is a 6MW wind energy project consisting of four Vensys 77 wind turbines, commissioned in 2010. The upper reservoir for PHES would be at approximately 230m elevation, and the lower reservoir is an existing unnamed lake. The site for the upper reservoir is pre-disturbed, thus little land clearing would occur. However, an associated environmental assessment would be required for both proposed reservoirs. The lower reservoir is a seasonal waterbody, so some alterations would be required to maintain a year-round water supply. The human-made upper reservoir has a surface area of 152,000 square metres, and a depth of around 5m. A pipe carrying freshwater stretches approximately 2.0km between reservoirs. This proposed pipe would be above ground, such to limit environmental impact, except for the road crossing, in which a culvert would be installed. The powerhouse contains a reversible turbine-pump, with electrical lines connecting the appliance to the grid for electricity consumption and generation. Transmission lines stretch from the powerhouse to the main transmission tower close to the road that connects to the rest of the grid.

Figure 6. Maryvale Wind Farm – PHES Hybrid Conceptual Layout



- Transmission Tower
- Powerhouse
- Water Reservoir
- Electrical Transmission Lines
- Water Transport Pipe
- Contour Lines (metres)

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The Barrachois wind farm is a 4MW wind energy project consisting of two Enercon E92 wind turbines, supplying power to around 1,500 homes. The upper reservoir for PHES would be at approximately 140m above sea level, and the lower water intake is Bras d'Or Lake, an inland sea in the center of Cape Breton Island. Land clearing would need to occur to situate the upper reservoir in this area, and an associated environmental assessment would accompany this proposed location. The proposed reservoir has a surface area of 121,000 square metres, and a depth of around 5m. A pipe carrying mixed fresh and saltwater stretches approximately 1.3km from the upper reservoir to the lake. This proposed pipe would be above ground, such to limit the environmental impact. Where the pipe crosses Long Island Rd., a culvert will be installed. The powerhouse contains a reversible turbine-pump, connected to the grid for electricity consumption and generation. Transmission lines stretch from the powerhouse to the main transmission towers, which intercepts power generated from the two wind turbines, shown in the top right of the layout.

Figure 7. Barrachois Wind Farm – PHES Hybrid Conceptual Layout

Site Sustainability Ranking

Sustainable development of pumped hydro energy systems is incredibly important to ensure that current site installations help meet energy requirements for the current population without compromising the land and water needs of future generations. Nzotcha et al. (2019) developed a multi-criteria matrix method of determining the sustainability of PHES development sites relative to other potential sites. Therefore, the five potential PHES sites selected for Nova Scotia are ranked in terms of feasibility and sustainability using the following variables:

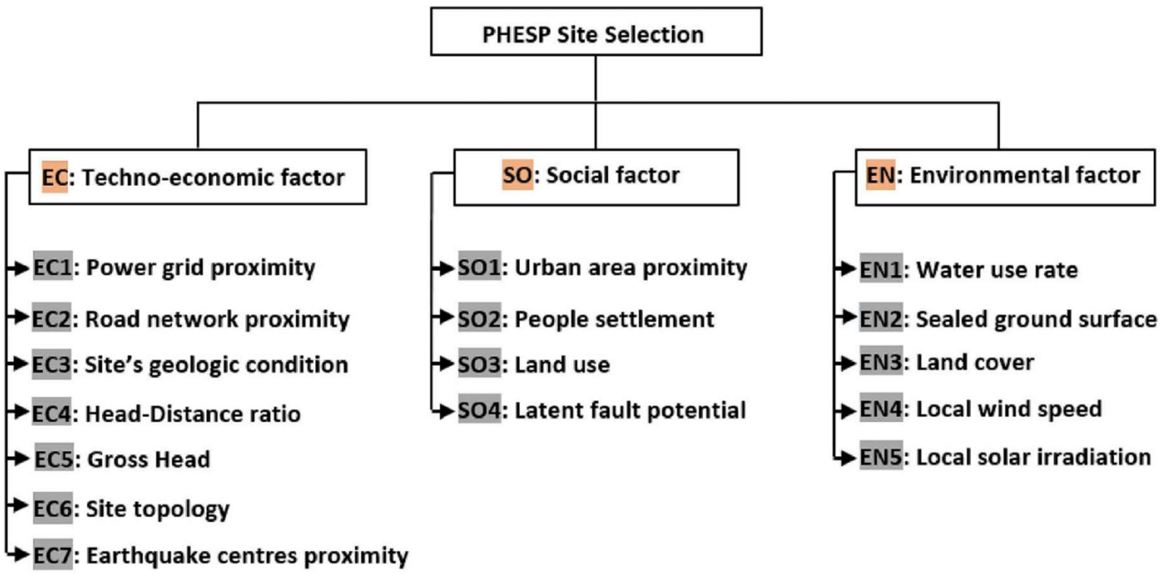

Figure 8. Ranking Criteria for PHES Site Selection (Nzotcha et al., 2019)

Due to limitations of the study, all of these metrics could not be measured to the full extent possible. Some of the social factors could not be measured as the criteria require travelling to each site in the province to conduct in-person interviews with local residents, including Indigenous groups. Using the ArcGIS layers mentioned in the methods section, surface features and other types of data were used to estimate the criteria corresponding to EC1, EC2, EC4, EC6, SO1, EN1, and EN3 in Figure 2. Thus, the priority of site development, pending comprehensive provincial environmental assessments for each site is as follows:

1. *Barrachois Wind Farm PHES Hybrid*

Strengths: There is a relatively short distance between reservoirs (1.3km), short distance for transmission line construction (1.2km), a large elevation difference (140m), easy existing road access, and long-term consistent water supply from Bras d'Or Lake in Cape Breton.

Weaknesses: The upper reservoir requires construction, even though the area is a recently logged patch of forest.

2. *Digby Wind Farm PHES Hybrid*

Strengths: A relatively short distance between reservoirs (1.2km), reasonable elevation difference (100m), easy existing road access, and a long-term consistent water supply from the Atlantic Ocean.

Weaknesses: The upper reservoir requires construction, even though the site is semi-disturbed between 5 wind turbines, relatively long distance from any urban environments and farther distance for transmission lines (2km), although they follow a previously disturbed trail through the site.

3. *Ellershouse Wind Farm PHES Hybrid*

Strengths: Both reservoirs do not require construction, and the site has the closest distance between waterbodies (1km), shortest transmission line route (800m), and easy road access.

Weaknesses: The upper reservoir uses the natural water body of Taylor Lake and small areas of wetland, which would likely require alterations. Also, there is only a 90m elevation difference between reservoirs. Possibly a less consistent water supply could be obtained from the lower reservoir, Panuke Lake.

4. *Maryvale Wind Farm PHES Hybrid*

Strengths: There is a large difference in elevation (130m) between the reservoirs, and road access is reasonable.

Weaknesses: The upper reservoir requires construction in a previously disturbed site, and the lower reservoir requires significant alterations to consistently retain water. The distance between reservoirs is the largest (2km) and the transmission line route is fairly long (1.8km), with the travel route through largely undisturbed forest.

5. *South Canoe Wind Farm PHES Hybrid*

Strengths: Both reservoirs do not require construction.

Weaknesses: The reservoirs use the natural water bodies of Mud Lake and Big Otter Lake, each with areas of wetland, which may require minor alterations. Also, there is only a 70m elevation difference between reservoirs, and poor road access. The distance between reservoirs is large (1.9km) and the transmission line route is the longest (3km), although the lines largely follow a previously disturbed road. Possibly a less consistent water supply would be available from the lower reservoir, Panuke Lake.

Discussion

Limiting Factors during Site Selection

In exploring potential locations for PHES in Nova Scotia, certain parts of the analysis criteria acted as limiting factors. Most noticeably, the topography of Nova Scotia eliminated many of the wind energy projects from PHES integration due to very small changes in elevation. Particularly, the wind projects located on the South and East coast regions of the province were practically all eliminated due to the majority of them being proximate to sea level. For example, although the 27MW Pubnico Point Wind Farm in Southern Nova Scotia was a suitable size, and had appropriate space for a seawater pumped hydro storage reservoir, the site was only a few metres above sea level. The feasibility of PHES at these sites is not impossible, but it is not economically sensible to construct water storage reservoirs at much higher elevations than naturally present. Another way that topography influenced site selection was if elevation differences are too great. Because wind farms are often built on higher elevation plateaus where wind speed is higher than in the lower elevations, they can be ideal for integrating PHES. However, analysis determined that often long distances exist between where the electrical grid and wind turbines were located, and a drop off in elevation to a lower level where a lower reservoir could be installed. If the pipe carrying water had to stretch over a distance greater than 2 kilometres, the site was not selected. There are two reasons for this decision: an additional cost to construct the water pipes and the lower water velocity at the powerhouse, leading to less of a benefit from energy generation.

Project Development Opportunities

The most obvious company to undertake a PHES project would be Nova Scotia Power Inc., which owns and operates 33 hydroelectric projects, and owns or partially owns approximately 30 wind energy projects throughout the province (Nova Scotia Power, 2020a). As more renewable energy systems are added to the electrical grid every year, grid stability becomes an utmost priority for companies like Nova Scotia Power, ensuring that residents, commercial entities, and industrial clients have power at all times of the day or night (Nova Scotia Power, 2020a). The company has been experimenting with pilot projects involving community solar, home battery storage, and electric vehicle charging infrastructure (Nova Scotia Power, 2020b). Energy storage through battery technology has improved substantially in recent years, but outfitting every Nova Scotia Power client with this capability has posed a huge task for the company. Independent energy project developers could also partner with Nova Scotia Power to undertake a PHES project; however, this option may be less likely. Nova Scotia Power (2020b) has provided funding in the last few years to increase the number of electric vehicle charging stations throughout the province. Therefore, pumped hydro energy storage could support the electrical grid during peak demand, particularly as more electric vehicles are added to the transportation network across Nova Scotia.

For any future proponent of a PHES project in Nova Scotia, it is recommended that a critical analysis of the 2007 Lake Uist PHES proposal failure is undertaken. The fate of the Lake Uist project ultimately depended on appropriate site selection and thorough consultation with surrounding communities and First Nations, both of which the proponent failed to accomplish. The Lake Uist project documents are still available on the Nova Scotia environmental assessment project registry (https://novascotia.ca/nse/ea/CBWindHydro.asp) and the lessons learned through this failed PHES project should be considered when planning for any new PHES developments.

Study Limitations & Directions for Further Research

Funding and time were significant limiting factors in this research study as producing an accurate feasibility analysis for energy related projects requires substantial fieldwork, community consultation, industry knowledge, and environmental assessment processes. Geographical Information Systems (GIS) provide access to incredible tools for spatial analysis; however, a fieldwork component is required to ensure accuracy for the environmental and social science data being analyzed (Jackson et al., 2013). The proposed PHES projects outlined in the study fall under Category 1 Environmental Assessments (EA), under the Nova Scotia Government Environmental Assessment Branch (NSEAB, 2018). Further, the fees associated for the EA registration and report documents cost approximately $35,000 per project (NSEAB, 2018). The study was completed by a single author, and travel to every potential PHES site to conduct fieldwork with a consulting team for site analysis would not have been possible in a four-month period, or without any funding.

Under less time or funding constraints, an interesting aspect of the study that could be pursued would be a calculation of the maximum power capacity at each site. Water depth measurements of the natural lakes that would be used as PHES reservoirs are not publicly available, and information such as flow rate could not be estimated accurately for any of the sites. The formula used to calculate the power for each system is (Renewables First, 2015):

$$P = f \times g \times H_{net} \times \eta$$

where P = Power output (Watts), f = flow rate (litres/second), g = gravitational constant (9.8m/s^2), H_{net} = net head (difference in elevation between upper reservoir and turbine minus any head losses, assumed to be around 10%, thus $H_{net} = H_{gross} \times 0.90$, measured in metres), η =

product of component efficiencies (turbine, drive system, generator, etc.). With accurate field measurements taken at the potential sites, and better knowledge of efficiencies within energy generating equipment, these calculations could be made. When renewable energy developers explore new options for renewable systems, having an estimate of power and energy from a proposed project is essential.

Opportunities for further research could include a similar study, but expanding the project area to cover all of Canada. Wind energy projects exist in every province and territory except Nunavut, and many waterbodies could be used as PHES reservoirs (Natural Resources Canada, 2020). Other studies could explore the integration of other renewable energy systems with PHES, such as concentrated solar, solar photovoltaic, or biomass. Another research area that could be expanded is the environmental impact of PHES on natural freshwater lakes, particularly due to daily fluctuating water levels. An interesting approach could study whether or not human-made PHES reservoirs can be naturalized into the landscape by introducing natural aquatic species of vegetation, amphibians, reptiles, or fish. In these situations, it may be possible that constructing reservoirs can actually benefit certain ecosystems. Additionally, the field of groundwater PHES study is still relatively untouched, so further research and development in this area could prove extremely useful for mitigating environmental impacts. Particularly, if contaminated groundwater sources could be used to create energy, these reservoirs could transform from an environmental burden to an environmental benefit.

Conclusion

Pumped hydro energy storage could play a large role in load balancing the electrical grid in Nova Scotia in the future. In response to the 2018 IPCC Report, the Province of Nova Scotia, and particularly the Halifax Regional Municipality, set the most ambitions greenhouse gas reductions targets of anywhere else in Canada, aiming for a 40% reduction in carbon emissions by 2030 and net-zero by 2050 (HalifACT, 2020). This study shows that pumped hydro energy storage is an extremely effective method for providing large-scale energy storage, and boosting the province of Nova Scotia towards its emissions reduction goals. Additionally, the applications of GIS are highlighted for demonstrating capabilities of project planning in this sector, aiding in the decision-support process for regulators, development managers and community members. This study should serve as a discussion topic and starting point for renewable energy companies, like Nova Scotia Power, to consider when exploring opportunities for pumped hydro energy storage within Nova Scotia.

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