Muskrat Falls Project-A Critical Review

Energy Economics and Policy
Engineering 9853

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List of abbreviations

DG2	Decision Gate 2	CDM	Conservation and Demand Management
DG3	Decision Gate 3	HVDC	High Voltage Direct Current
MHI	Manitoba Hydro International	MeHg	Methyl Mercury (chemical symbol)
CPW	Cumulative Present Worth	EPA	U.S. Environment Protection Agency
NL	Newfoundland and Labrador	LCA	life cycle assessments
MUN	Memorial University of Newfoundland	CBA	Cost benefit analysis

LNG	Liquefied Natural Gas	GDP	Gross domestic product
O&M	Operation and Maintenance	GHG	Green House Gases
NYISO	The New York Independent System Operator	PJM	Pennsylvania-New Jersey-Maryland Interconnection
DOE	U.S. Department of Energy	ISO-NE	Independent System Operator of New England
WTI	West Texas Intermediate	PDF	Probability Density Function

Abstract—**The Muskrat falls hydroelectric project in Newfoundland and Labrador is an 824 MW hydroelectric facility and over 1600 km of transmission lines across the province including a maritime link between Newfoundland and Nova Scotia. It has important benefits for the province such as connecting it to the North American electricity market, increasing employment for local labor, CO_2 emissions reduction, and making the province's electricity 98% renewable. However, the project has faced many issues such as economic, temporal, political and environmental problems. In this article, a study is presented which highlights the different aspects of this project and the process involved in its assessment and implementation. Environmental and economic issues related to Methyl mercury, impact of COVID -19 pandemic, impact of oil prices and the contribution of the hiding hand principle to the project's development were addressed. From an engineering perspective and to expand on the wind alternative, original work designing a wind project of similar generation capacity to Muskrat Falls (4.9 TWh) is presented. Using a multifactorial wind farm sitting approach, four sites for possible wind energy deployment were selected which are: Portugal Cove, Bonavista, Grand Banks and Saint Bride's. Through a review of the most prominent wind farms inside and outside Canada, five types of wind turbines were selected for the study which are GE-2.5 XL, Vestas 164, Enercon E-126, GE 1.5s and Siemens SWT 3.6. A parametric study of 36 systems was then conducted to test each turbine model at each location at different hub heights. The study included both financial (LCOE, Profit) and area (Energy density, Profit/Area) considerations. After careful comparison, Bonavista wind site with Enercon-126 wind turbine at 135 m hub height was justifiably the best system. The system is then further developed by adding ACS880 inverter from ABB (for power conditioning and HVDC transmission) and reporting on the final system values (4.83 TWh energy production, 884 million USD profit and 3.06 million tons of CO_2 emissions curtailed per year). Finally, a gravity energy storage system is roughly calculated in order to make the wind farm as dispatchable as Muskrat Falls which increased the system cost to 4.33 billion CAD.**

Index Terms—Muskrat Falls, Hydroelectric Projects, Methyl Mercury, Nalcor Energy, Newfoundland and Labrador, Wind Energy, Gravity Energy Storage.

I. Problem Statement

This study discusses the beneficial and controversial aspects of the Muskrat Falls project from an environmental, political, economic, and engineering perspective in order to answer the question "Was Muskrat Falls a mistake?". While the study tried to do both sides justice, the substantial portion of the literature points to the answer to the posed question being yes and so striking a perfect balance between benefits and issues would be misleading. In the second part of the study, a wind farm was proposed and designed and large scale energy storage in the form of gravity storage was also included in order to examine the possibility of the wind alternative not being dismissed if Nalcor had waited till 2020 to enact major capacity addition.

II. Introduction

A. Overview

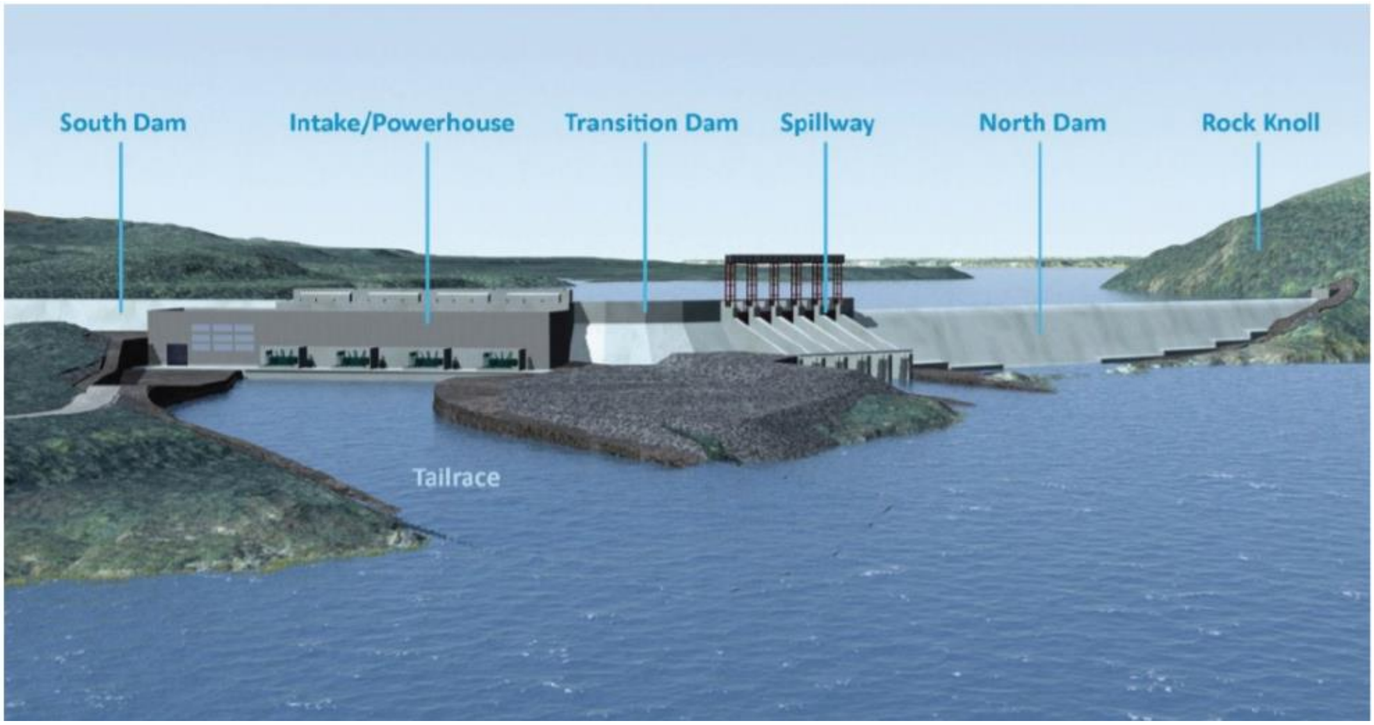


Fig. 1. Muskrat Falls Project

The Muskrat Falls (MF) project is one of two sites (the other being Gull Island) which combined as the lower Churchill project will provide 3000 MW of hydroelectricity to Newfoundland and Labrador. The project is developed by Newfoundland and Labrador's Nalcor Energy and Halifax’s Emera who have signed a deal for 6.2 billion dollars in 2010 with construction commencing in 2013 [1]. The first phase of the project Muskrat Falls, includes the development of an 824 MW hydroelectric facility (with an expected energy output of 4.9 TWh/yr) and over 1600 km of transmission lines across the province including a maritime 480km HVDC link between Newfoundland and Nova Scotia according to Nalcor’s website. The power produced by the project is to be delivered to Nalcor’s subsidiary and public utility company Newfoundland and Labrador Hydro to sell. Surplus power is to be exported to Nova Scotia [2]. The original agreement involved Emera investing $1.8 billion, $1.2 billion of which goes to fund the undersea transmission cable between the two provinces in exchange for 20% (1 TWh) of Muskrat Falls annual generation for 35 years

(40% will go to NL's load and 40% is to be exported). In return, NL would get access to said cable thus effectively ending its electricity isolation and connecting it to the North American grid. This scenario was dubbed "Interconnected Island" [48, 117].

Muskrat Falls project planning started in the mid 1960s (which was a few years before the upper Churchill project started generation in 1971) and continued till 2012 when the project was sanctioned by Newfoundland's government. The Upper Churchill hydroelectric facility is a 5428 MW project that Newfoundland only receives a small percentage of its power and benefits with the main share of power and benefits going to Hydro Quebec. The province must wait till 2041 when the project full ownership will revert back to Newfoundland. In figure 1 we observe a spillway structure is included between the North dam and the powerhouse block. The powerhouse is designed with four turbine-generator units using a concrete spiral case arrangement. A switchyard will be located at the MF site for interconnection of the power station with the transmission system. The system is made up of a 345 kV switchyard at the Muskrat Falls station, as well as a 345 – 138 kV substation located about five kilometers from the station [117].

Nalcor promised the following benefits of the project [2]

- 98% sustainable long-term renewable power
- Reduction in Greenhouse gas (GHG) emissions from electricity production in the province
- Economic diversification
- Ability to sell excess power to the north American market

However, as of 2019 the project has exceeded the planned budget by $6 billion dollars and is two years late with projected cost overruns skyrocketing from 7.4 billion Canadian dollars to 12.7 billion. This led the CEO of Nalcor Stan Marshall to admit the project was a mistake [3].

During the sanction phase (Dec 17th 2012), Muskrat Falls, which had a $6.2 billion estimated cost plus $1.2 billion financing cost, was selected from a group of potential projects as the least-cost option which was inaccurate due to the Decision Gate 3 (DG3) estimate being unrepresentative. The Budget was revised several times and is currently in excess of $10.1 billion plus $2.6 billion financing cost [12].

On September the 22nd 2020, first power (successfully synced to the grid) flew out of Muskrat Falls into the Labrador grid. However, Nalcor said the project will not become operational until further testing is conducted [39].

B. Background information

The reason Muskrat Falls project was undertaken was due to a load forecast done by Nalcor Energy in 2010 which stated that new electrical power generation projects are necessary in Newfoundland due to the demand for electricity growing steadily to a point where it will surpass the existing supply. Nalcor reached this conclusion by creating a load forecasting model which resulted in them believing the Newfoundland would experience an energy deficit by 2021 if no new generation capacity were added [10].

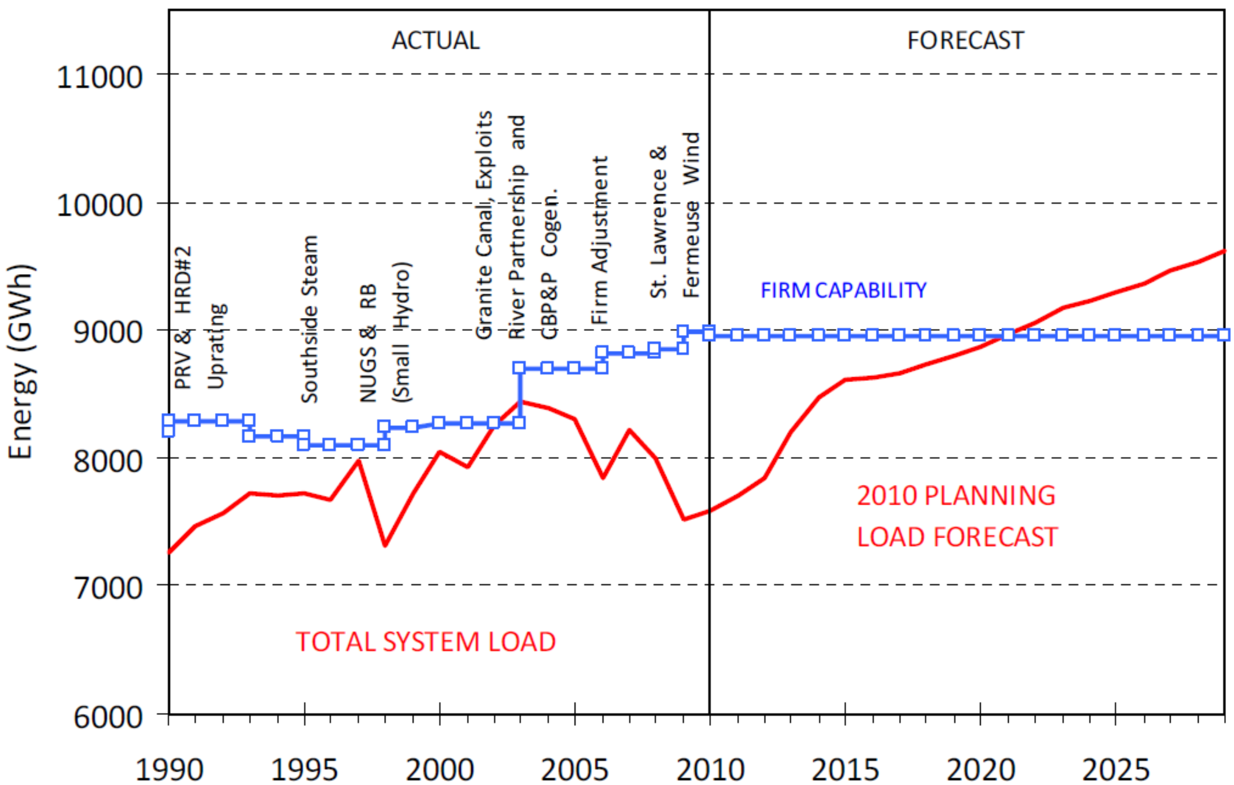


Fig. 2. Nalcor's Load Forecast

Nalcor then conducted a feasibility study to compare between four potential projects (which was later examined and verified by Manitoba Hydro International (MHI) [59]). Firstly, the Gull Island project involving the construction of 2.25 GW (11.9 TWh) hydroelectric facilities on Gull Island and the development of a transmission link from Labrador to Newfoundland. Secondly, the Muskrat Falls project involving the construction of an 824 MW hydroelectric plant and transmission link from Labrador to Newfoundland. Thirdly, the Isolated Island project involving the installation of small electricity generating fossil fuel-based power systems in Newfoundland, new wind developments, small on island hydro projects and the upgrade of Holyrood power station or the use of wind energy coupled with battery storage (to replace thermal generation). Lastly, the final option was to import energy from Quebec or New England [12]. Natural gas was also considered but dismissed to supply and price volatility according to Ziff energy [59].

In the sanction phase (phase 1), Gull Island and energy import projects were excluded. For Gull island there was an inability to obtain transmission access to Quebec markets which would result in excessive electricity supply that exceeds the province's demand and leads to the actual unit cost of Gull Island being greater than that of Muskrat Falls. Energy import option was excluded since importing electricity from other provinces introduces price volatility depending on the fuel used for generation and low energy security as the power would come from external suppliers [11].

In phase 2 of the screening process, cumulative present worth (CPW) was deployed to evaluate the remaining options to determine the present value of capital, fuel, operation and maintenance (O&M) future costs and power purchase agreements. CPW analysis is the global standard for comparing public development project alternatives. Muskrat Falls had a CPW that was $2.2 billion less than that of Isolated Island and so was the preferred project. Future oil prices, load growth, wind power and more variables were included in the CPW sensitivity analysis making its results robust [11]. Manitoba Hydro International reviewed Nalcor's proposal justification and practices and found that Nalcor's work was skilled, well founded and complying with industry practices [59].

C. How did Nalcor determine the project cost?

When Nalcor introduced the cost of the project they followed the following methodology as presented by Dr. Locke. First, they calculated that the energy produced from the 824 MW project would be 4,873 GWh. Then they calculated the nominal capital and operating costs, Innu payments and water rentals to provide the cost that would have to be reimbursed by the sale of electricity. They assumed that this cost is 100% equity financed with a required rate of return of 12%. They also assumed electricity rate inflation of 2% per year. They calculated that 7.582 cents per kWh is the price that would provide a rate of return of 12% for the energy produced which then increases at the annual inflation rate to provide the nominal price. Next, they applied the nominal price obtained earlier to the amount of energy used in NL which starts at approximately 2000 GWh per annum and eventually rises to 4,873 GWh. All of these calculations yielded in the end an 8.4% rate of return on equity for the share holder (the government of Newfoundland) which was seen as sufficiently high for the project to be approved. Since NL government at the time could borrow at less than 5% so 5% is the implicit cost of equity the government would contribute. If Nalcor's borrowing rate is less than 8.4% then borrowing a portion of the capital would increase the rate of return for the share holder [14].

D. The screening process

Nalcor used a screening process to determine the most viable options regarding the island's energy generation [12]. Nuclear, coal, solar, tidal and biomass were justifiably dismissed. Five electricity generation scenarios (besides Muskrat Falls) passed the initial screening and were analysed which include:

1. Extension of the service life of Holyrood thermal station and installation of scrubbers to reduce its pollution. This option enables the usage of cheaper fuel (no.6 oil).
2. Installation of simple cycle combustion turbines. These devices are ideal for peak generation but less effective when used for extended periods of time.
3. Installation of combined cycle combustion turbines. These devices are more expensive but more efficient for use for extended periods of time.
4. Three island hydro involved installing smaller generation in Island Pond, Round Pond and Portland Creek.
5. Wind generation, which was considered intermittent and non dispatchable.

A software called Strategist was utilized by Nalcor to study the aforementioned options allowing them to create 2 plans: the interconnected island option and isolated island option [12]. The screening process employed by Nalcor was verified by Manitoba Hydro International before Decision Gate 3. It was found out later on however (by the commission for inquiry and various other sources) that there were various problems with the methodology deployed by Nalcor [59].

The extension of Holyrood's service life meant the province can wait till 2041 when it can start benefiting from the lower Churchill project. This option had a CPW of $233 million and was cheaper than the Isolated Island option. It was however incorrectly dismissed by Nalcor [12].

The recall block, a 300 MW power supply from Churchill Falls, provides 220 MW towards Labrador winter energy needs and the excess is resold to Hydro Quebec. Nalcor screened out this power supply as an option because the 80 MW spare capacity was not enough to replace Holyrood, which is true. However, the recall block could have played a valuable role in the generation plan even if it did not fully replace Holyrood [12].

As far as energy imports are concerned, Nalcor considered New York and New England as energy suppliers but did not consider Quebec. Had negotiations occurred with Hydro Quebec in 2010 when it faced a shortage in winter capacity then it is possible that a plan regarding Gull Island development could have occurred [12].

Natural gas, which could have been used by combustion turbines to generate electricity, was also dismissed by Nalcor despite NL having large natural gas resources which never found a market. This was questioned publicly by Dr. Stephen Bruneau, PHD and director of Industrial Outreach at MUN, who argued that producing small amounts of natural gas for domestic consumption is an option worth considering. Nalcor assumed, however, that oil and gas suppliers would not have provided the province with fair prices and so dismissed the option. The reasons why they assumed this have not been disclosed [12].

Liquefied natural gas (LNG) was also screened out (during Decision Gate 2, DG2) based on uncertainty in its price in the global market. The CPW of LNG (calculated later in 2012) was found to be competitive with Isolated Island option. Nalcor is criticized in not investing the efforts needed to obtain an accurate CPW for the LNG option such as contacting LNG suppliers seeking quotes. These screening out decisions were later viewed as unreasonable and removed from Nalcor's credibility in their claim that they were objectively seeking the least cost option [12].

At DG3, a 10% limit was placed on the amount of wind generation that could possibly be utilized by the province to fulfill its energy needs. While the literature indicated that 10% penetration was the highest the grid can accommodate it also suggested that developments in the near future can increase this ceiling. Stan Marshal also testified that had additional hydro options been included (such as Bay d'Espoir unit 8) penetrations of more than 10% for wind energy in the Isolated Island option would have been viable as the hydro facilities can be used as pumped hydro storage which rectifies some of wind's intermittency problems [12].

Conservation and Demand Management (CDM), which involves persuading the consumers to use less energy, should have also been seriously considered instead of being dismissed by Nalcor as too speculative. Nalcor failed to consider CDM measures in its load forecast and as an alternative to increased generation [12].

E. Holyrood thermal generating station

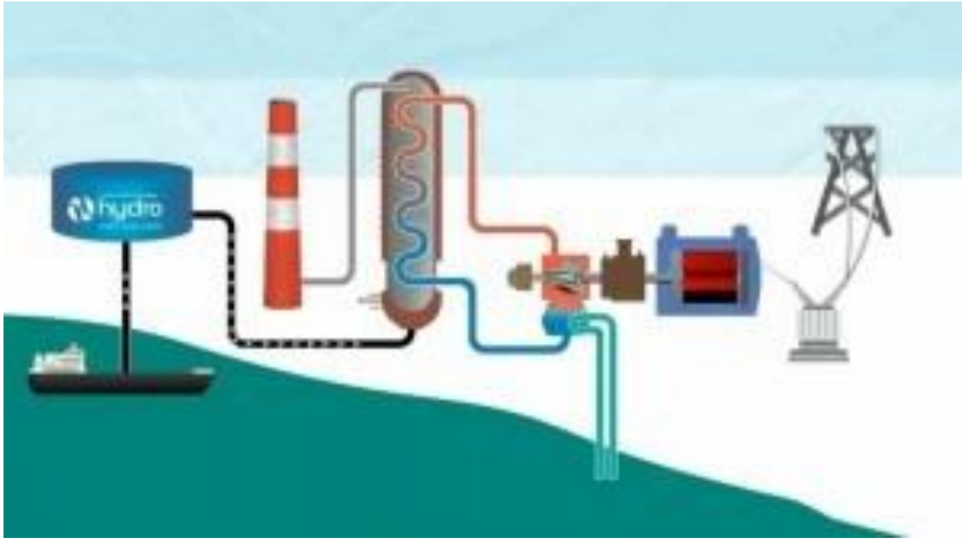


Fig. 3. Holyrood Station Schematic

This station is located in the town of Holyrood near Conception Bay South. It uses 0.7% sulphur fuel and has been operational since 1969. It consists of 3 turbines totalling 490 MW of cumulative capacity. Holyrood generates 15% to 25% of the province's electricity (3 TWh) but has the potential to generate up to 40% of the island's electricity needs. The plant can burn up to 18,000 barrels of oil per day. Several measures have been undergone by Newfoundland Hydro to reduce the plant's emissions which has been a significant source of GHG emissions and has incurred rising costs reaching $135/MWh in 2011. Nalcor argued that increased consumption will surpass Holyrood's capacity and lead to the installation of new oil-fired generation by 2021. [41,48].

The Energy plan was a document issued by Newfoundland's provincial government on September 2007 where it directed NL Hydro to consider a couple of options to address the environmental concerns regarding Holyrood thermal power station. The 1st option was to replace Holyrood's electricity with power from the Lower Churchill River project through the High Voltage Direct Current (HVDC) transmission line/link to the island. The 2nd option involved the use of electrostatic precipitators and scrubber in Holyrood to control its emissions and to maximize the island's use of wind, small hydro and energy efficiency programs so as to lower the province's reliance on Holyrood produced electricity. These two alternatives required substantially differing strategies to enact which required the introduction of two different generation expansion plans to address the near-term generation strategy until an option is selected for future generation development [10].

F. Positive impacts of Muskrat Falls

As of 2019, 92% of the workforce was from local laborers, the project received the health and safety distinction award from building trades unions, the project successfully transmitted power from Labrador to Newfoundland, Upon completion, 98% of the province's electricity will come from renewables, 3-4 million tones of CO_2 emissions will be displaced annually which is equivalent to taking 1 million cars off the road for 1 year. As of 2019, 17.5 million hours were worked without a lost time injury. Connection to the North American electricity market (through Nova Scotia) is to be established. Connection between Labrador and Newfoundland electricity grid. The project also completely eliminates the province's reliance on Oil and so offers greater energy security [57].

G. Impact of COVID-19 Pandemic

Work on the Muskrat Falls project was suspended from March 2020 to June 2020 due to the COVID-19 pandemic. The resumption of the project came as Newfoundland began relaxing public health measures as the pandemic was relatively contained. The project resumed at a reduced workforce and productivity level which could add an additional 2-6 months delay to the already schedule overrun project. It was stated by Nalcor Energy's CEO Stan Marshal at Nalcor's annual general meeting in 2020 that the company expects the project will be complete by June 2021. The effects of COVID-19 also include an additional $200 million in direct costs due to added labour costs. Another $200 million can be incurred due to interest and financing charges. As Muskrat Falls is not currently profitable, the additional costs must be provided by the provincial government which is already in a financial crisis due to the fall of the oil and gas sector and the pandemic. The final cost can surpass $13 billion according to Mr. Marshall. The 2020 blizzard had minimal effects on the muskrat Falls electricity system. The software that is used to control the 1,100 km transmission line from Labrador to Newfoundland is currently being tested [40].

III. Environmental Perspective

A. Methyl mercury release

According to [4], the authors highlighted that methyl mercury (MeHg) is caused by microbial production. It is a bio accumulative neurotoxin caused by degradation of carbon present in flooded soils of hydroelectric plants. They stated that all proposed hydroelectric projects in Canada including Muskrat Falls are located within 100 km of indigenous communities. Through thorough simulation of MeHg levels at the Muskrat project the authors concluded that there will be 10 times increases in riverine MeHg levels and 1.3 to 10 times increase in locally caught species (such as fish) MeHg levels.

Methyl mercury forms as bacteria reacts to the mercury present in water, soil, and plants through the process of methylation. Its levels increase as it moves further up in the food chain. For example, people consume fish which consume plankton which consume algae. While in the initial stages, methyl mercury is low and widespread, it is concentrated, and dangerous in the final stages (in humans). For example, Trevor Bell, a MUN geographer, stated that in fish and seals methyl mercury levels can be as high as 10 million times the levels found in water. An example of this can be found in 1950's Japan's Minamata Bay where more than 1000 people died and many more were sickened by seafood consumption from methyl mercury contaminated waters due to the Chisso Corporations chemical factory. Today first nations communities in Ontario continue to suffer from mercury poisoning due to Reeds Paper's chemical factory set up in the 1960s. It should be noted that Muskrat Falls is not a chemical plant and so won't be dumping such high levels of mercury into the water. However, the mercury levels naturally present in the surrounding ecosystem is sufficient to cause a problem. The main concern is the increase in methyl mercury levels at Lake Melville estuary which is the Inuit's main source of fishing and hunting. The argument (for lower methyl mercury levels) has been framed by opposers as an appeal to science-based policy [37,38].

This issue also has local precedence as the Churchill Falls project (upstream of Muskrat Falls) caused fish methyl mercury levels to increase to 10 times baseline levels which was observable more than 300 km downstream of the hydroelectric project and lasted for more than 30 years [49].

After reservoir flooding at Muskrat Falls, the level of exposure to MeHg is predicted to double causing half of women and children to surpass the dosage of MeHg recommended by the U.S. EPA. The largest exposure pre flooding is found in the Rigolet, where 24% of individuals have shown levels higher than U.S EPA's recommended dosage. Post flooding these levels will increase to three times baseline values [4].

A main reason for higher MeHg levels in Inuit communities is the increased consumption of aquatic foods. Figure 4 shows the top 20 food sources pertaining to MeHg exposure for the Inuit population downstream of the project. The main species affected by post flooding MeHg increase are lake trout and brook trout. Lake trout and seal kidney will see over 1 μg/g MeHg concentrations and brook trout will be responsible for 30% of exposures [4].

In [5], the authors have discussed some of the effects of MeHg on humans which include: A correlation between MeHg rich fish consumption and acute myocardial infarction, a 2x-3x increased rate of cardiovascular death, Renal toxicity and weakened immunity. Prenatal exposure of the fetus hampers growth and migration of neurons and poses a risk of causing irreversible damage to the development of the central nervous system. Infants who were subjected to high levels of MeHg in-utero were born with: Mental retardation, Seizure disorders, Cerebral palsy, Blindness, Deafness and IQ deficits.

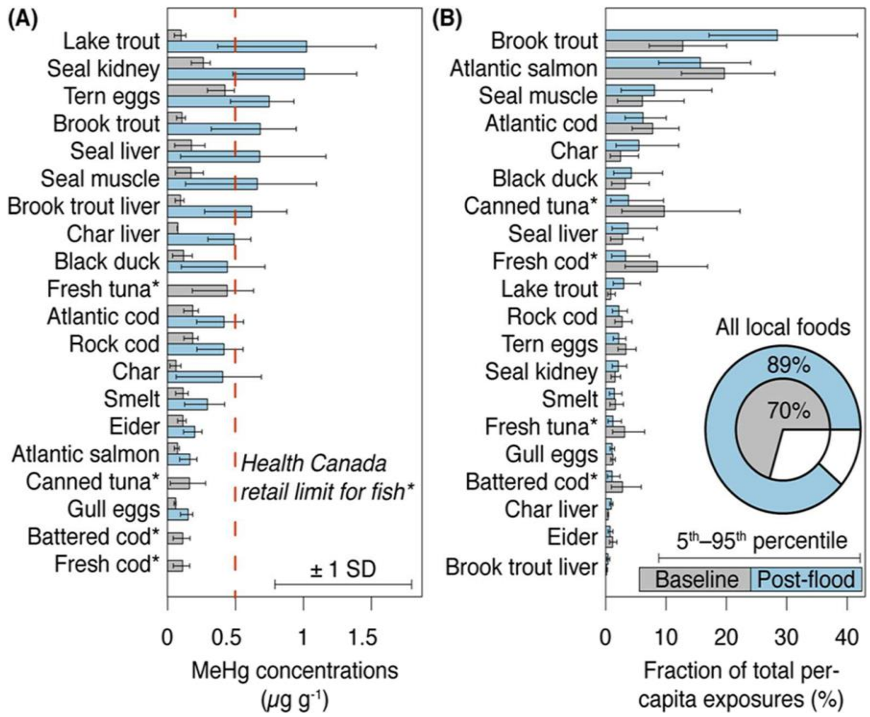


Fig. 4. MeHg in top 20 food sources affected by flooding consumed by nearby Inuit populations.

In 2016, protesters in Halifax have voiced concern about the methyl mercury from Muskrat Falls, which will feed Nova Scotian grids via the maritime link connection, will leak through the forest floor into watersheds in Happy Valley Goose Bay area. The protest involved one protester going on a hunger strike. A representative from the Inuit government of Nunatsiavut has stated that the forest and topsoil should be completely cleared from the reservoir prior to flooding in order to reduce the flow of methyl mercury down stream. This project has a political side to it as it negatively affects native populations who feel underrepresented and not sufficiently consulted by the government of Newfoundland [35]. As a reaction to increased protests (even in St. John's), in 2016 the government of NL ordered Nalcor to remove more forest cover at the reservoir to lower the release of methyl mercury according to Perry Trimper the environment minister of NL at the time [36]. However this effort did not actualize as the province did not act it out for over a year and finally declared in 2019 that the opportunity for this measure to be implemented was unintentionally missed [49].

B. Lifecycle assessment

In a comparative study between the life cycle assessments (LCA) of hydro, wind and nuclear [7] the authors found that hydro facilities with biomass decay had life cycle emissions of 15.2g CO_{2eq}/KWh which was higher than 12.05g CO_{2eq}/KWh for wind and 3.402g CO_{2eq}/KWh for nuclear.

The study took a comprehensive approach taking into account upstream phase, downstream phase and operation phase of the three technologies. The emissions studied were CO_2, CH_4, NO_x, SO_x and particulate matter. The environmental impacts studied were global warming, acidification, eutrophication, photochemical ozone creation and toxicity potentials.

In another study [8], researchers compiled various wind and hydro LCA studies the results showed that there was a large variation between the different studies however the upper range for wind power 55.4g CO_{2eq}/KWh was one third that of reservoir hydro power 152g CO_{2eq}/KWh (with emissions from flooded lands included). This can be seen from table I which is reproduced from [8].

TABLE I
SUMMARY OF FINDINGS FROM REFERENCE

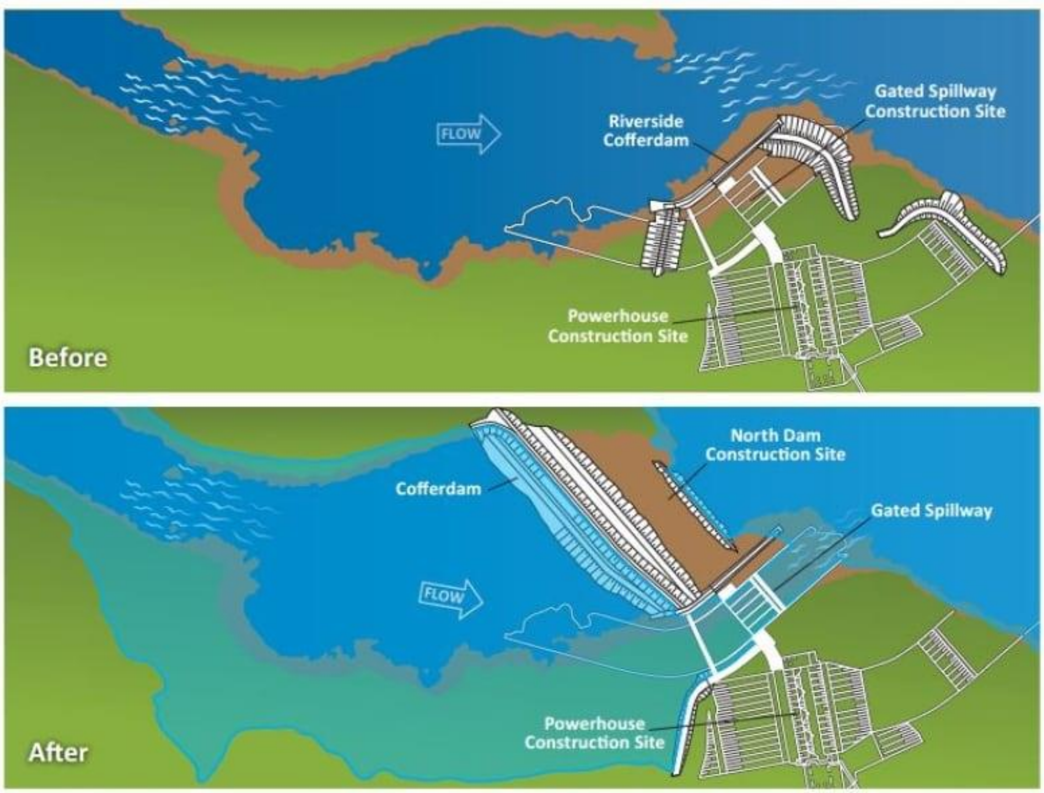
	Wind Power	Reservoir Hydro Power
Number of studies	63	28
Variations in GHG emissions (g CO_{2eq}/KWh)	4.6-55.4	4.2-152
Cause of GHG emissions	Infrastructure	Inundation of land
Proportion of infrastructure contribution	90-99%	56-99%
Main contributing activity	Steel production	Construction of dams and tunnels

C. Potential for landslides

In a recent paper [9], Bernander and L. Elfgren presented a geotechnical explanation to a stability problem relating to the north spur dam wall of the Muskrat Falls project. The land is composed of multilayer deposits of silty sands and sandy clays which have established the valleys and plains in the area. Some of the layers which were formed thousands of year ago in post-glacial times are susceptible to liquefaction when their equilibrium is disrupted. This has resulted in multiple slides along the Churchill River banks in the past. A possible progressive failure, the most hazardous one in respect of the safety of the North Spur is landslide development, may be triggered by the rising water pressure, when or after the dam is impounded. Such a slide could drive part of the North Spur ridge to slide along a failure surface sloping eastward into the deep river whirlpool downstream of Muskrat Falls.

Fig. 5. Aerial view of Muskrat Falls on September 27, 2004. The North Spur Ridge, susceptible to a possible dam breach, is located in the centre of the picture just above the falls and the Rock Knoll granite cliff.

D. Effects on adjacent structures



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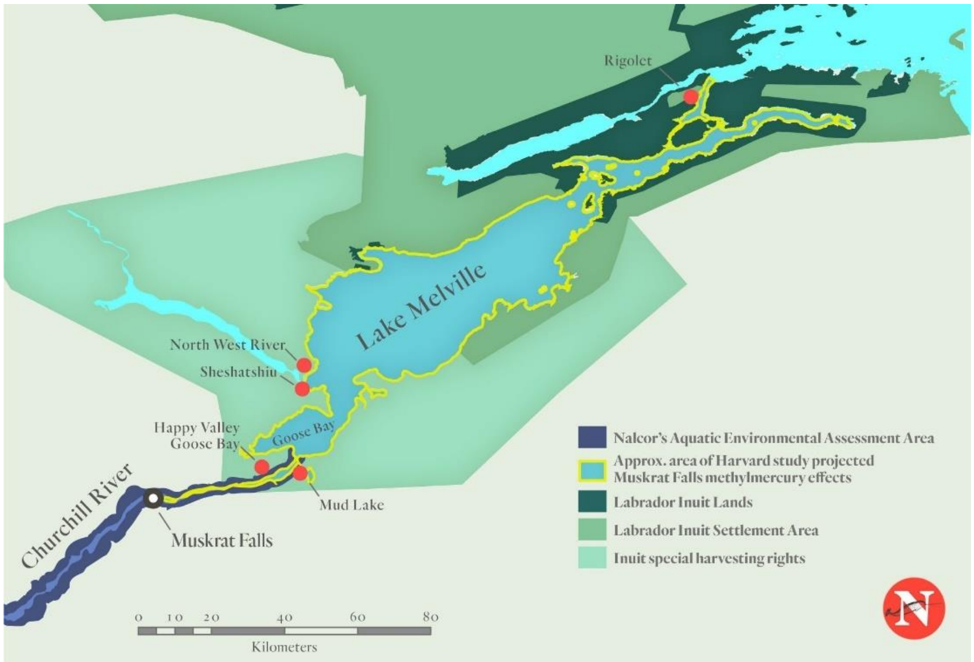


b

Fig. 6. a) Reservoir before and after flooding, b) Surrounding geology

In a 2020 study, the authors stated that the construction of the Muskrat Falls hydroelectric dam on the lower Churchill River (40 km from the river mouth) started in 2014 establishing a 100 km^2 reservoir. The area where flooding will take place is made up of highly erodible loose sandy sediments [33]. Minaskuat [34] forecasted that bank erosion from the reservoir to Happy Valley will rise significantly in the first 2 years as the shoreline rearranges to accommodate the new water level. This rise in bank erosion is predicted to cause a pulse suspended sediment downstream. The study calculated the sediment load increase of the Churchill River to lake Melville and Goose bay using a shoreline erosion potential of 5.25 m/year and assuming a 10 m bank height, shoreline of 35.5 km and bulk density of 2600 kg/m3. The result shows that the flow of suspended sediment to Goose Bay and Lake Melville would more than double (reaching 49.5 kg/year) in the 2 years after reservoir impoundment. This could lead to a reduction in phytoplankton productivity by lowering light penetration and narrowing down the euphotic zone. The increase in freshwater delivery will also decrease its residence time thereby increasing the export of primary producers. These effects can persist for nearly 20 to 50 years [34].

E. PESTLE analysis

A 2015 study [117] developed a sustainability index to assess hydroelectric projects in Newfoundland based on a four-pillar concept of sustainability where the four pillars are social, economic, environmental and governance impacts. This utilizes a PESTLE (Political, Economic, Socio-Cultural, Technological, Legal and Environmental) framework to identify the appropriate variables. This index was then applied to Muskrat Falls and the result showed that the project was moderately sustainable but with a few governance issues. In the PESTLE analysis 6 criteria were analysed as the following:

Political: Political issues have played and are still playing a major role in the MF project. More than fifty years of planning, research and development clearly highlight the importance of political factors and governance issues. In this case, political issues stretched from the local communities to the provincial government, and even beyond the boundaries of the province. The estimated cost of building the hydroelectric dam increased over time and has become a political issue as the increased burden shifts onto the taxpaying voters. The imbalanced and ill-fated agreement of NL government with the government of Quebec about the Upper Churchill project made their relationship sore. Additionally, Hydro Quebec and the government of Quebec have continued to dispute the water management and sharing policies that govern the two mega hydroelectric projects. Water management and sharing is the most common problem that most countries face while constructing a hydroelectric dam. There are water sharing dispute between India and Bangladesh, China and India, Ethiopia and Egypt and many more [118]. The MF project is expected to release NL from the geographic stronghold of Quebec since the MF transmission line effectively bypasses Quebec. One positive aspect of trans-border politics is the strategic tie and cooperation of the province with Nova Scotia. The Lower Churchill project is on the verge of reshaping the politics in Newfoundland and Nova Scotia even though it has yet to produce a single watt of power. Ruling parties always stay under immense pressure both from opposition and voters to be very cautious about investment and strategic ties. Another big political issue that has been ongoing for decades is the land dispute and the concerns for the cultural heritage of aboriginal and indigenous communities living in Labrador.

Economic: The MF project is expected to bring a revolutionary change to the oil and gas dependent (30% of Gross domestic product; GDP) Newfoundland economy. The power industries in Canada contribute only 2.2 percent of GDP (in 2010) and account for only 0.6 percent of total Canadian employment [119]. But all of these are direct contributions. Power is the most essential factor input for all industrial products and, in this way, power supply has a huge indirect contribution to both national GDP and employment in Canada. A 2015 estimate of Nalcor showed that the construction phases of the Muskrat Falls project will enhance the provincial income by $2.1 billion, where $700 million will be gained by project labor and businesspeople in Labrador. The project was also expected to generate 5600 person-years of direct employment in the province. Mega projects that require huge capital investment always come with some spill-over impacts. Infrastructural development is necessary as it supports the proper functioning of the project and transmission line construction processes, as well as operations and maintenance. The development of the project requires smooth communication facilities to the project site, and modern air, land and seaports, highways and other transportation infrastructures are also needed. This will also benefit the communities living in Labrador. It is expected that this infrastructure development will leave long-term socio-economic impacts in the locality including hotels and other accommodations, as well as the influx of new investments and businesses. Further, national and international companies may also expand their service to the localities. The development of the Trans Labrador Highway (TLH) already resulted in new commercial trading patterns, business expansions and tourism opportunities. These changes will raise the land property values and provide local people with employment, with the end result being that the government will receive more revenue. Presently, major business activities in Labrador are tourism related. More than 25 percent of the businesses are connected to the tourism industry. The presence of the dam and generation facilities is expected to attract more tourists each year. The communities around the project area are mostly wage employees and the project will expand employment opportunities for wage employees [117].

Social: The Muskrat Falls project brought dynamic social impacts upon the communities in Labrador. The majority of the populations in the project area and in Labrador are aboriginal peoples. They have many cultural heritages and resources, with different types of values: prehistoric, historic, cultural, spiritual, natural, scientific and aesthetic. Their cultural resources are mainly archaeological, natural, burial, cultural, spiritual and other heritage sites. Investment in the Muskrat Falls project can have both positive and negative impacts on these cultural resources. It could either destroy them or financially benefit them by bringing in more tourists. The impact of the project on population is uncertain. Population decline is a major issue in Labrador and the province as a whole. Labrador experienced 13.2 percent decline in the population from 1991 to 2006 compared to 11.1 percent decline in the entire province. The impact of the project on community health is another big concern. Primary health impacts will come from environmental pollution due to project construction activities. Community health may also be affected indirectly through demographic change and, specifically, through any in-migration and worker-community interactions within the Upper Lake Melville area. Construction of both the dam and reservoir demands heavy physical work, which may result in health hazards for workers. There is also the possibility of mercury emission, which may pollute the water and raise mercury beyond tolerable levels in fish, thereby creating an indirect health hazard for humans. Development of social infrastructure and services as described above may create employment and business opportunities for local people. This may also improve social security and education services, as well as housing and accommodation. Incremental power demand for local businesses and services, like consumers in Happy Valley-Goose Bay and elsewhere in Upper Lake Melville area, are expected to be met from the project without interrupting the supply [117].

Technological: The MF project is a high capital-intensive modern techno based investment project and most of the equipment for power generation and transmission are imported from different countries like France. Understandably, the unskilled and semi-skilled workers have minimum or no knowledge and expertise regarding the construction, installation, operation and maintenance of the technology. There was a shortage of skilled and knowledgeable persons meaning the project was not run efficiently since these workers were used in construction. Considering the similarity of the work, workers from the iron ore and mining sectors were employed on the project. This did not bring much efficiency. Technical institutions need to train students with modern applied technical education, so they not only work on such projects; but develop technologies to make similar undertakings more efficient. Communities in rural areas usually do not like drastic changes and the NL province consists mostly of rural areas. In some cases, the rural people of NL are scared of the changes that are brought about by dynamic socio-economic and environmental impacts of such technological installations. Also, people in these communities were not well-informed about the pros and cons of this project [117].

Environmental: There are mixed opinions and research findings about the scale of environmental effects resulting from a hydroelectric dam and a reservoir. Hydroelectric energy is a renewable energy. It is also one of the cleanest sources of energy. Nonetheless, the construction stage of these projects causes greenhouse gas (GHG) emission and air pollution. The construction of the plant requires the clear-cutting of forest, as well as the demolition of hills and elevated regions. As a result, GHGs like CO_2 and CH_4 are emitted from the decay of organic matter on the forest floor. The remaining organic matter is either transported through wind or surface runoff to the Churchill River, resulting in both air and water pollution. Compared to a fossil fuel power plant, a hydroelectric project emits less GHGs. Counteraction activities, such as site preparation and the construction of site buildings (clearing, grubbing and blasting), excavation for and installation of generation components, concrete production, vehicular traffic onsite, quarrying and borrowing, as well as transportation and road maintenance pollute the surrounding air. Pollutants released in this way are PM, NO_X and SO_2. They can have adverse environmental effects on the atmospheric environment. Another potential source of environmental impact is the construction of the transmission lines. This project can cause problems both for the aquatic and the terrestrial environments. The transmission line passes under the ocean, which may hamper the normal activities of fish populations. The bulk of the overland transmission system located in NL can cause a decline in vulnerable species like caribou. Aquatic species can also be affected by the release of mercury into the Churchill River. The aboriginal group Innu reported that the Churchill Falls hydroelectric project affected how fish tasted and that they were told not to eat too many fish from the Smallwood Reservoir (Innu Nation Hydro Community Consultation Team 2000). Relevant literature has found that hydroelectric dams have less effect on the magnitude of floods as well as their recurrence intervals. In USA, the estimated reduction in median annual flood for large rivers averages 29%, for medium rivers 15% and for small rivers 7% because of hydroelectric dams. Another concern of such project is siltation and drying up of river due to a dam. Dam construction causes upstream sedimentation and erosion in the downstream. Modern hydroelectric generation technology largely minimizes such environmental impacts [117, 120].

Legal: The NL government and other project stakeholders had to face various legal issues both internal and external (with other provinces). The efficient operation of the MF project depends on the efficient operation of the Upper Churchill reservoir storage and generation station. Well-coordinated operation is required between these two adjacent projects mainly during the spring season. Coordinated effort will save energy as well as avoid waste. The upstream storage and generation project is legally bound to serve Hydro Quebec under the agreement signed in 1969 that will expire in 2041. The NL government went on with the construction work relying on the provincial Water Management Agreement established in 2010. Still there exist legal disputes with Hydro Quebec about the use and control of the Upper Churchill reservoir and generation assets for the MF project. Emera Inc. and Nalcor Energy have signed the final legal agreements about governing the MF power project but pricing of electricity may cause problems and legal disputes in the future [117].

Another concern is that the province of NL may not have a proper renewable energy policy. The government published an energy sector development plan in 2007 (Energy Plan, 2007). Proper policy guidelines for renewable energy development and coordination among all relevant policies to ensure the sustainability of the sector are needed. Lack of integration of the renewable energy sector in existing policies can leave some important issues undetected and unaddressed. This may result in serious harm to humans and the environment. The environmental assessment that was done by a review panel appointed by NL government and Environment Canada was not directed to take a sustainable approach. According to Doelle (2012) “The panel was hampered in its efforts by lack of clarity in its mandate and by lack of information to implement a full sustainability assessment. The end result was a poor sustainability assessment framework for government decision makers.” Good and effective governance is neither an automatic process nor a problem free process. It is shaped by traditions, cultures, and the social locations of all parties. It is essential to continue the path of devolution and ensure participatory governance, that will obtain the best outcome for the community, province and the country. In a 2017 study, the authors surveyed renewable energy experts about the lack of development of wind energy in Newfoundland and found that 71% of those surveyed agreed that the main barrier was political structures and policies [64]. Using the PESTLE analysis, a holistic picture of the project is obtained which involves all the necessary parameters for measuring the sustainability of the overall project [117]

IV. Economic Perspective

A. Cost and schedule overruns

The Muskrat Falls project has notoriously experienced cost and schedule overruns. According to [6] (which is the response to the inquiry made by the commission overseeing the Muskrat Falls project), Hydro-electric dam projects are high-risk projects with an average cost overrun of +96% and an average schedule overrun of +44%.

The cost and schedule overrun potential of hydro project is very large only exceeded by nuclear power which has a cost overrun of +122%. Alternatively, wind power has a cost overrun of +13% and schedule overrun of +22%. The frequency of cost overruns for wind is 64%, 13% lower than that of hydro, and the frequency of schedule overruns is 16% lower than the 80% chance of schedule overruns for hydroelectric dams as illustrated in table II [6].

70% of the Muskrat Falls cost overrun was due to construction contracts values exceeding the estimates as well as changes in design or order. These factors resulted from an underestimation of labor rates and amount of time required by contractors to undergo the work. The estimates also neglected to include poor geotechnical conditions, bad weather and complex terrain [13].

TABLE II
HYDRO-ELECTRIC DAM PROJECTS COMPARED TO ENERGY PROJECTS

	Mean Cost Overrun	Freq. of Cost overrun	Schedule Overrun	Freq. of Schedule Overrun	Size of Sample
Hydro	+96%	77%	+44%	80%	274
Wind	+13%	64%	+22%	64%	53
Solar	+1%	41%	0%	22%	39
Thermal	+31%	59%	+36%	76%	124
Transmission	+8%	40%	+8%	12%	50
Nuclear	+122%	97%	+65%	93%	191

B. Hiding Hand

How desirable a project is, is determined by its economic efficiency and net contribution to social welfare compared with its alternatives. If mega projects are not assessed correctly there is room for them to become "planning disasters". Problems associated with such projects include mismatch between demand and supply, adverse environmental impacts as well as cost and schedule overruns [15]. In [16], the authors assessed 2062 projects and concluded that 78% of those cases suffered from a *hiding hand* issue which, according to the authors, blinds unreasonably optimistic planners to both the unexpectedly lower net benefits and higher costs than estimated. The hiding hand principle was first defined by Hirschman as situations where the project planners underestimate the costs and overestimate the benefits in order to get the project built [17].

Cost benefit analysis (CBA) is an integral part of federal decision making for public projects. It estimates the present value of all benefits and all costs inherent in a project and decide whether the project is of merit or not. It assists on deciding on project size and choosing between alternatives [18]. The hiding hand comes into play by twisting the results of the CBA. For energy generation projects there are four main factors that influence the CBA which are: direct benefits, indirect impacts on the employment market, direct costs, and environmental impacts [58,61].

1) *Direct benefits*

Direct benefit is the quantity of electricity that can be consumed during the operation phase. Since excess electricity produced cannot be efficiently stored, accurate load forecasting is vital. There is evidence suggesting that the direct benefits were exaggerated due to an overstated load forecast. GDP growth rate and demographics might have been exaggerated by Nalcor [58].

In 2011, Conference board of Canada predicted that between 2011 and 2035 NL would see a GDP growth rate of 0.8% (Nalcor assumed 0.9%), population would decline to 473,478 (Nalcor assumed 507,000) and housing starts would drop from 3,700 in 2011 to 490 in 2035 (Nalcor assumed 2135 housing starts in 2029) [19].

The load forecasting model also disregarded energy efficiency and energy conservation programs which can reduce the province's long-term energy needs. In 2019, Carleton University's efficiency scoreboard estimated that Newfoundland's energy efficiency was 0.47% annual incremental savings as a percentage of domestic sales while Ontario's was 1.4% and certain U.S states (with aggressive electricity savings programs) like Vermont had savings of 3% per year [20]. The scoreboard defined electricity savings as having the ability to avoid expensive electricity generation options, increase reliability and reduce risks. For the customer electricity savings means reduced energy bills, improvement in health and comfort of home environment and increased house durability. For society, the benefits are a reduction in GHG emissions and other negative environmental impacts and a stimulation of the local economy in implementing energy conservation technology [20]. This information is not new and was available at the time of the project screening such as a 2008 study confirming the existence of substantial energy conservation potential in the industrial and residential sectors of Newfoundland and Labrador [21].

In the 2020 scoreboard, Newfoundland came in the 9th place (second to last followed by Saskatchewan) which is an upward movement of one rank from the last years scoreboard where NL was dead last. The 2020 scoreboard highlighted that NL faces substantial energy challenges due to cost overruns of Muskrat Falls. A relevant analysis showed that electrification of heat and transportation to be the most valuable mitigation opportunity as it reduces provincial oil expenditure. The province is preparing to update its building code to increase energy efficiency and commenced rolling out energy vehicle charging network and fuel switching of public buildings from fossil fuels to electricity (supported by the federal low carbon economy fund). The scoreboard suggests NL has an energy poverty problem where more than 38% of the population spend more than 6% of their after tax income on energy which can be reduced if the houses were more energy efficient [121].

It is possible that if the load forecast was different, Muskrat Falls would not have been pursued and instead the differed Churchill Falls option would have been optimal. This option involved the upgrade of existing thermal generation until 2041 at which point the supply contract with Hydro Quebec would expire and Newfoundland can access Churchill Falls' electricity production. To pursue this option would have meant no sizable development of new power generation projects but would also imply higher GHG emissions over that period. This potentiality was verified by Nova Scotia Utility and the Review Board in 2013 which stated that there would be no shortage of energy in NL when the Churchill Falls agreement expires in 2041 [22].

2) ***Indirect impacts on the employment market***

Multiplier effects are the second-round impacts that public projects will have on the market by requiring employment and making project expenditure [23]. Large scale energy projects could lead to competition over resources in the labor market and by diverting skilled employment to the project can lead to skill shortage in the private sector where less skilled workers will have to be trained [24]. This negative impact will be on highly productive trade sectors. A positive impact that could developed in such a case is on the lower productive sectors where vacancies can be filled by unemployed people thus reducing unemployment. The net effect can be either positive or negative depending on the conditions of the individual economy. To estimate the aforementioned impacts a model needs to include the unemployment statistics of the economy, costs of additional training and the impact on the productivity of the private sector. This was not included in the Muskrat Falls CBA. If it had been included, then Gull Island might have been more favorable as it was the option considered by every Newfoundland premier for 40 years until Hydro Quebec obstructed their plans [25]. The fall in negotiations over Gull Island occurred due to an inability to determine how the project's benefits will be divided between NL and Quebec. According to Hydro Quebec, Quebec had more hydroelectric electricity than it is able to sell with a surplus that ensures it is able to meet its electricity needs until 2026 with no additional projects [26]. After 2026, negotiations regarding Gull Island could have played differently. The inaccuracy in this category (employment benefits and export potential) lead to Muskrat Falls being preferred to Gull Island. Newfoundland might have been able to meet its short-term electricity shortage with small scale power generation and to defer any major hydroelectric projects until 2026 when Quebec's surplus ends opening up the opportunity for export [58].

3) ***Direct costs***

Direct costs include facility and transmission lines construction costs, yearly O&M costs, contingency cost and dam decommissioning cost at the end of the project lifetime. The contingency cost covers risks and uncertainties which are unknown but likely to occur. It is perhaps the most contentious cost estimate. For accurate direct cost estimation, project planners must assess the whole scope of the work including all elements and activities and create the proper contingency [27].

It is likely that Nalcor underestimated funding for some of the risk types such as strategic and tactical risk. A detailed report by Grant Thornton [28] highlighted that cost overruns resulting from an under appreciation of labor rates and hours necessary to fulfill the work required and neglection of issues associated with unfavorable geotechnical conditions, adverse weather and complex topography was an oversight. Strategic risk funding was calculated by Nalcor ($500 million) but was not included in the CPW formula. The definition of strategic risks are those risks that are outside the control of the project team. For example, schedule risks, resource competition and bad weather or remote location performance risks [29].

Tactical contingency, which includes project definition, scope omission, construction methodology, performance factors, and price was also undervalued by Nalcor. The tactical risk that resulted in Muskrat Falls overrun was the increase in the cost of the contract value as Nalcor misjudged the labor rate and the contractors' expected performance in completing tasks (number of hours needed). Nalcor chose a P-factor of 50, which means that there is a 50% chance of cost overruns, to estimate tactical contingency resulting in $368 million contingency budget [11]. However, a 2014 study showed that hydroelectric dam project cost overrun is 96% higher than estimated costs [30]. If Nalcor had selected P90 instead of P50 their capital cost estimate would have risen by $767 million [29].

4) *Environmental impacts*

Hydro electric projects can involve substantial environmental impacts by interacting with land usage, homes and natural habitats in the area of the dam. The dam can cause damage to local vegetation and wildlife by obstructing fish migration and changing the water's flow and temperature thus affecting the number of fishes caught and income of fisheries in the area. Hydro reservoirs can also cause people to have to relocate and archaeological and cultural sites to be submerged. Hydro projects therefore should have resettlement costs for the people affected and income restoration costs to be provided to the affected people as temporary income, cost of training and identification of employment opportunities.

Nalcor did include environmental costs in their analysis but the extent of the impact seems to have been understated. Originally, Nalcor allocated $27.98 million for fish rehabilitation and resettlement cost for those affected (mostly of the aboriginal community). In 2016 the locals protested, stopping site work and raising concerns around the projects environmental and ecological protection measures [31]. In 2017, Nalcor admitted having underestimated the environmental cost and increased its environmental budget by $9 million per year [32].

C. Energy pricing

In 2012, Dr. Jim Feehan argued that efficient electricity pricing and conservation measures would make Muskrat Falls unnecessary where any increase in demand growth can be met by smaller renewable projects on the island at a much lower risk [42]. He said that the provincial government should reform its pricing regime which he saw as implicitly encouraging inappropriate prices and therefore higher consumption. An important economic principle is that efficient resource allocation mandates the price of a commodity (electricity) be equal to the cost of producing an additional unit of it. This cost would be higher than the average cost of production utilized by Newfoundland's public utilities board. This principle suggests that variable prices are needed to decrease consumption. These prices would reflect seasonal and daily peak demands thus resulting in efficiency. For example, in 2011, consumers were paying $105/MWh of electricity while Holyrood was at a minimum incurring $135/MWh in generation costs. If the price of electricity was to increase, the professor argues, then people would consume less. During summer, consumption is much lower and can be met by NL hydro resources (those in existence in 2011). If time of day prices were used, then people would shift their loads from peak hours to cheaper hours thus eliminating the need for additional generation. He concluded by supporting the Isolated Island option as he expected that Nalcor's consumption growth projections could be 100% higher than actual consumption growth if prices were better regulated [48].

Most notably Dr. Feehan argued that a 20% increase in price would lead to a 5% decrease in consumption which would cut Holyrood’s production by one third which cuts back on pollution and delays the need for additional generation. However, Dr. Locke agreed that yes an increase in price would lead to consumption decrease since the demand curve for electricity is negatively sloping (demand elasticity is less than infinite) but Professor Locke asked how much do prices need to change and whether the adjustment costs are less than the costs of installing new capacity. He argued that you can keep raising prices until the problem disappears but that would negatively affect the most vulnerable of taxpayers and therefore might have social welfare implications. Dr. Locke extrapolated Dr. Feehan’s argument and showed that it implies that by 2041 to cut forecasted demand by another 20%, prices would have to be 80% higher in order to maintain Holyrood as 10% of the province’s electricity generation mix. Dr. Locke further argued that an annual rate stabilization adjustment plan was adopted in 1985 to protect consumers against fluctuating oil prices during the year. Such as rates increasing by 7% in July 2011 because oil prices increased from $84/bbl to $103/bbl. Dr. Locke concluded by noting that prior to 1985 the price of electricity coming from Holyrood was sometimes twice or thrice higher in winter months than what it was during the rest of the year. This was affecting families at their most vulnerable and led to mass demonstrations [48,14].

D. International market for Canadian electricity

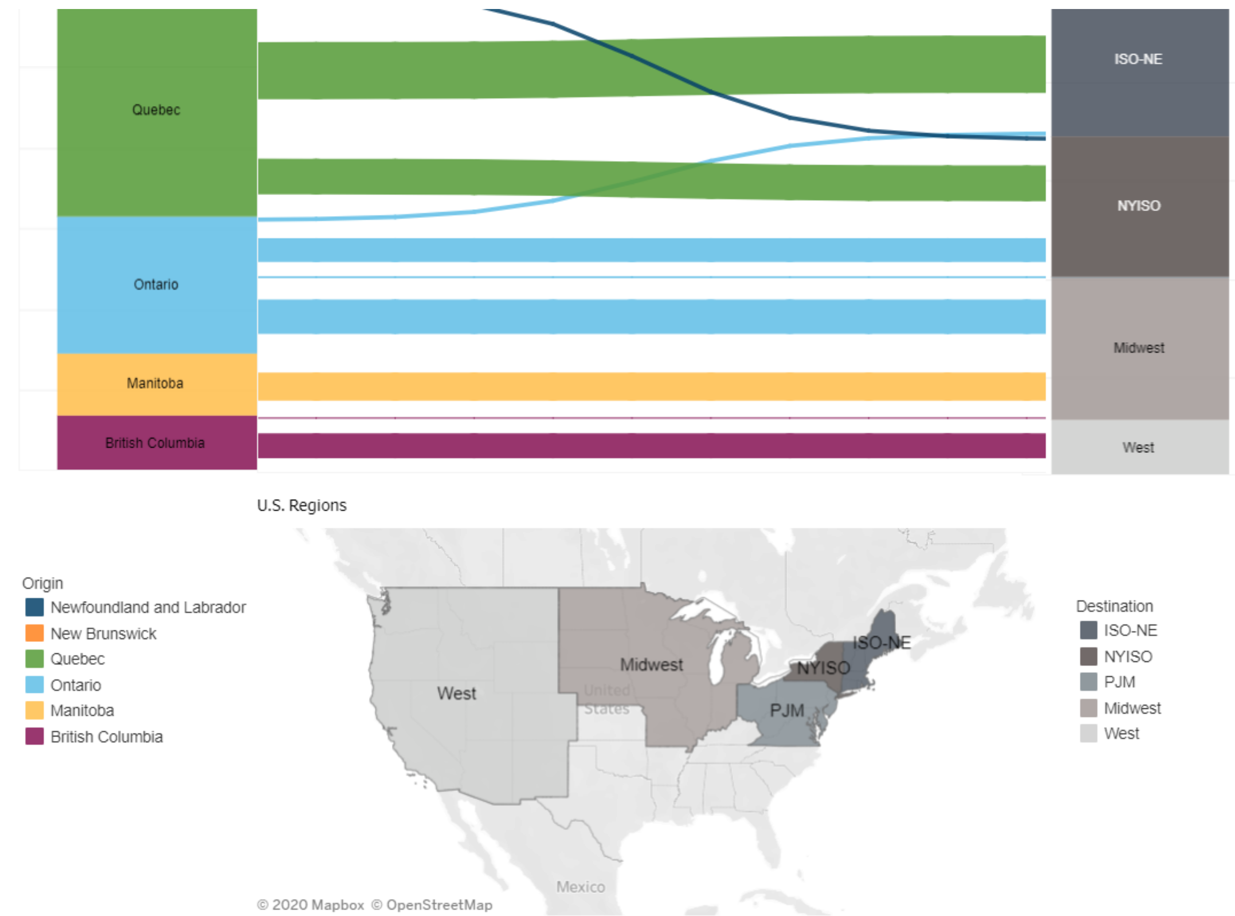


Fig. 7. Canada's International Electricity Market

In 2019, Canada exported 60.4 TWh of electricity (around 10% of its generation), mostly to the U.S., at a price rate of 40.71 $/MWh making the value of the exports $2.5 billion. Typically, provinces with significant hydro electric generation (such as Quebec and Ontario) exported the highest volumes with their highest export years coinciding with the highest precipitation years. Electricity imports reached a 20 year low in 2015 at 8.7 TWh while in 2019 it was 13.4 TWh. The reason some provinces choose to import is that it is seen as less costly than building extra capacity that would go unused during nonpeak times. Some Canadian provinces actually have a better capacity for electricity exchange with American states (along the north-south interconnection) than with other Canadian provinces. Electricity pricing is usually higher in U.S markets than in Canadian ones [50].

Figure 7 shows the flow of gross electricity exports from the most notable provinces of Canada to the three U.S regions which are the East, the Midwest and the West. The East region is made up of three smaller regions which are the Pennsylvania-New Jersey-Maryland Interconnection (PJM), The New York Independent System Operator (NYISO) and the Independent System Operator of New England (ISO-NE) with ISO-NE and NYISO being the largest import markets and Quebec being their main supplier as its relatively cheaper [50].

This huge market potential could explain why Nalcor was in favor of the Interconnected Island option as it would provide the province with access to the North American grid provinces like Quebec have benefited from resulting in a hydro electric boom in many provinces. In fact, northern U.S states actually consume Canadian hydropower to help meet their emission targets. This might however change as the U.S. environmental lobby is becoming increasingly antagonistic to the import of Canadian hydro power supporting instead the development of U.S. renewables such as wind energy [51-53].

There are however movements by several international rights bodies to reduce Canadian energy imports to the U.S. due to what is perceived as a violation of indigenous Canadian's rights. Such as the "Conservation of Law" foundation challenging the U.S DOE over their deference to Canada's ability to resolve ecological side effects of their power generation internally as Canada is a democratic country. Another movement was from the UN's Special rapporteur on human rights and hazardous substances who commented on the absence of meaningful consultation between aboriginal communities and Canadian legislative bodies regarding the impacts of methylmercury [54]. The article [49] suggests that Newfoundland should follow Quebec's example in re-examining their environmental impact assessment of hydro projects.

E. Possibility of electricity rate increase

As a consequence of the Muskrat Falls project, Nalcor energy needs to raise 725.9 million CAD annually in order to stabilize the electricity price in Newfoundland (NL) at 13.5 cents/kWh (even with the project taking a 0 return on investment equity), otherwise, the price is forecasted to increase to 22.9 cents/kWh which is almost double the current rate of 12.3 cents/kWh [43,44,48].

Newfoundlanders are switching back to oil-based heating since the island's residents are worried about the price of electricity due to Muskrat Falls as more than 70% of the island's residents who use electricity for heating can be severely impacted by a spike in electricity prices [45,48]. According to the government of Newfoundland, The consumption of heating oil in the province in 2015 was 98 GJ/household which is an approximately 10 GJ increase from the 2013 figure while household electricity consumption decreased from 65.5 GJ/household in 2013 to 64.3 GJ/household in 2015 highlighting the popularity of heating oil for water and space heating [46]. Heating oil is a petroleum product and thus is environmentally damaging and will eventually be depleted (fossil fuel's bell curve). 20% of all environmentally damaging oil spills in Newfoundland are from domestic heating oil which contaminates the soil and is hazardous to humans [47].

Based on the aforementioned reasons, Newfoundlanders might choose to deploy residential solar and wind system if the price of electricity from Muskrat Falls makes the payback period for residential project lucrative. The former premier highlighted that the Muskrat falls projects accounts for 30% of Newfoundland's net debt [55]. Whereas professor Tom Baird from MUN expressed that a bailout from Ottawa is unlikely and that he believes Newfoundland's taxpayers will have to pay for the bill themselves. Finance Minster Bill Morneau also expressed the same expectation. He suggested that austerity measures, public sector salary cutbacks and reduction in services will be needed [56].

Figure 8 highlights the sources of funding/cutback Newfoundland needs/plans to secure in order to stabilize electricity rates. $200 million will have to come from the federal government. Other sources include export of surplus energy, organizational change, reduction in Muskrat falls O&M, fuel switching, and performance credits awarded for GHG reductions from Holyrood station [43].

Managing Muskrat Falls			
		For the Year 2021	Amount Remaining
Funding Requirement (millions)[1]		**725.9**	
	NL Hydro Net Operations Savings - $178.2		
1	Holyrood net fuel savings and inflation impacts	-178.2	547.7
	NL Investment - $249.1 million:		
2	NL Hydro surplus energy	-49.1	498.6
3	Nalcor dividend	-200.0	298.6
	Reducing Expenses - $39.4 million:		
4	Organizational change	-20.0	278.6
5	Muskrat Falls operations and maintenance	-12.0	266.6
6	Isolated diesel systems	-7.4	259.2
	Raising Revenue - $59.2 million:		
7	Fuel Switching / Electrification	-15.0	244.2
8	Add value to energy surplus	-35.5	208.7
9	Holyrood Performance Credits (carbon credits)	-8.7	200.0
	Financial Management - $200 million:		
10	Collaborate with Government of Canada	-200.0	0.0
Cost Impact on You: $0			
Total Provincial Sources: $525.9 M		**Federal Involvement: Addressing $200 M Gap**	

Fig. 8. Provincial Government Price Stabilization Plan

F. Impact of declining oil prices

Fig. 9. U.S. Historical Oil (WTI) Prices

Since 2014, oil prices plummeted from \$150/bbl to \$30/bbl and to even lower rates during the COVID-19 pandemic. On Nov 12th, 2020, the price of a barrel of WTI crude was \$37.14. This greatly affects the efficacy of Muskrat Falls as the least cost option (even without cost overruns) as the alternative (increased thermal generation) has become cheaper. In an article publish by Dr. Tom Baird in the independent in 2014, the professor argued that given the decrease in oil prices and using Nalcor and Manitoba Hydro's methodology for CPW calculation, Muskrat Falls and isolated island (upgrade of Holyrood) were at that point essentially tied. This was before any major cost overruns. The projections used at DG3 were provided by PIRA energy group which assumed the price of WTI would continue at a $95/bbl average or at the lowest reach $60/bbl [60]. One need only imagine the effects of current (even lower) oil prices and the higher cost overruns of Muskrat Falls.

V. Engineering Perspective

Since wind energy was dismissed by Nalcor as unreliable and not cost effective, an up to date study regarding the construction of a wind farm in today's time is due to see whether wind can compete with hydro in the province as the province's main renewable source. This is assuming Nalcor would have opted to wait till 2020 to install a major addition to capacity.

* This is original work in the pre-publishing stage.

A. Wind energy potential in Newfoundland and Labrador

Canada's easterly province of Newfoundland and Labrador (NL) possess a higher wind energy potential than any Atlantic territory in the North American continent [62]. Despite exhibiting this invaluable, climate friendly energy resource, the region dwells in the production and consumption of fossil fuels. At present, hydroelectric power occupies a large share in the province's energy mix that will be further increased by the impending completion of 824 MW Lower Churchill Project (Muskrat Falls) [63]. However, the adverse ecological and imminent social impact of the hydropower plant decreases the benefits of such project [62].

Hence the best and most acceptable source of renewable energy for the province's energy mix is the wind source. This is because of the geographical position of the province along the Atlantic coast provides optimum wind distributions. Various studies have concluded that annually, the province of NL possesses the potential of generating 100 times the energy demand of the province and almost a quarter of Canada's energy demand when it utilizes its potential wind energy, provided the wind farms are designed and developed at utility scale [67].

To support this assertion, the study from NL's Department of Natural Resources, NL, Canada estimates that the province owns the capacity of generating 5 GW of wind energy, however the current installed capacity of wind energy in NL as of January 2019 stands at a mere 55 MW from 3 wind farms: *Ramea (2004), St Lawrence (2008), Fermeuse (2009) and Wind-Diesel-Ramea-Diesel (2010),* which prompted Canadian Wind Energy Association [CWEA], to rank the province bottom amongst all provinces in terms of renewable resource utilization [62],[63].

Mathematically, wind power is directly proportional to the cube of wind speed. this suggests that the potential wind development site in NL can theoretically generate more than twice the power of potential wind sites in Ontario and Quebec. Further onshore wind potential of NL can not only sustain the province's own needs but also generate a remarkable revenue of approximately $250,000 in per capita in terms of current energy prices [64].

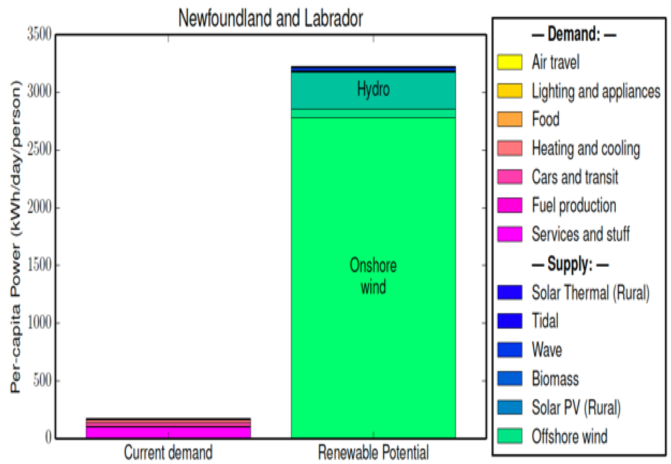


Fig. 10. Energy demand and renewable energy supply in NL

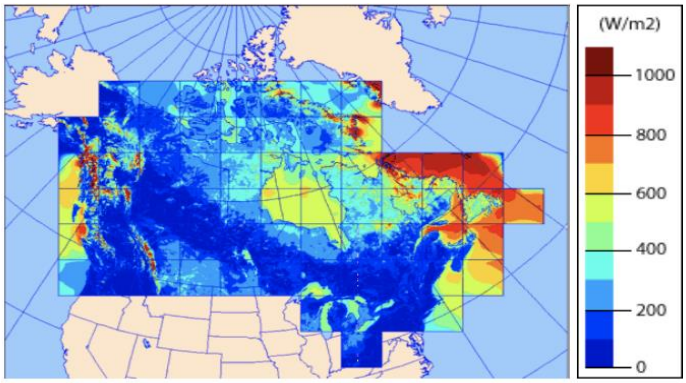


Fig. 11. Wind energy distribution across Canadian provinces.

With reference to figure 10, it is evident that Newfoundland and Labrador's renewable energy potential is the largest in the country. The province consumed a fraction percentage of Canada's total energy demand while it is blessed with extremely high wind speeds and ample geographical area for wind turbine placements [64],[65].

Indeed, the province of Newfoundland and Labrador is able to project itself as an energy export province, tapping the potential of wind energy would be the best-suited approach in the long-term economic perspective. With its enormous potential of wind source, HVDC links to the Atlantic coast in the U.S., possibly via Quebec or Nova Scotia, would form a well-streamlined strategy in the energy sector of the country as a whole [67].

Statistically, the average annual wind speeds (Ns) at wind turbine potential sites in Ontario and Quebec are only 7.33 m/s and 7.74 m/s respectively, while annual wind speeds at high potential areas in Newfoundland and Labrador stands at 9.38 m/s [68],[70]. Thus, the average high-potential wind site in Newfoundland and Labrador can theoretically generate more wind power than twice the power of average sites in Ontario and Quebec combined. Environment Canada has assessed the wind energy potential of Newfoundland and Labrador [68] and confirmed its potential. Figure 11 affirms the view that Atlantic provinces exhibit a wide array of distribution of high wind resources. The estimates for NL wind potential ranges from 450 MW to 102 times the provincial demand [69],[70].

B. Test location

According to Nalcor energy, the company that is creating the muskrat falls project [74], Muskrat falls is expected to produce 4.9 TWh of average annual energy. Making its capacity factor 67.8%. For the purpose of this report, the wind system must generate an annual 4.9 TWh of electricity to match the production of Muskrat Falls.

In the previous section of this project. The potential of wind energy in Newfoundland has been reported which showed Newfoundland as a promising location for large scale wind farm siting. In this section of the project a test location is chosen in order to:

- Further assess the wind potential of the region
- Provide a general estimate of the economics of a wind project of this scale in newfoundland as no projects of such capacities exist in the region
- Act as a venue from which the mathematical calculations and software simulation (methodology) can be introduced and compared
- Aid in site location selection and wind turbine selection

The site of the test location is St. john's international airport. The reason this location was chosen is because it is further away from the city compared to St. john's west meteorological station which can be said to be within a built environment so will produce wind speeds that are not representative of an ideal location of a wind farm. St John's international airport meteorological station is located at Latitude: 47°37'07.000" N, Longitude: 52°45'09.000" W and Elevation:140.50 m above sea level.

The wind speed data for the test location was obtained from [75] which is a website affiliated with the Canadian government that has all the meteorological data they have collected. By downloading the weather data for every month of 2019 the following information is provided: Longitude (x), Latitude (y), Station Name, Climate ID, Date/Time, Year, Month, Day, Time, Temp (°C), Dew Point Temp (°C), Rel Hum (%), Wind Dir (10s deg), Wind Spd (km/h), Visibility (km), Stn Press (kPa), Hmdx, Wind Chill, Weather and more

For the purpose of calculation only hourly wind speeds are needed. First wind speeds are converted from km/h to m/s in excel. Then the wind speeds for every month are integrated into one excel file that has 8760 data points each representing the wind speed at every hour in 2019.

In this section, two ways for calculating annual wind energy generation of a turbine at the test location are presented and compared. One is using equations provided by [76] implemented in Mathcad and the other is using HOMER simulation software.

1) ***Mathcad calculation***

i. Inputs

For Mathcad calculations the wind speeds have to be converted from anemometer height (10m) to turbine height (100m) using the shear factor as illustrated in equation 1

$$V_{hub} = V_{anem} * \left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \tag{1}$$

Where

V_{hub} is the speed of wind at hub height

V_{anem} is the wind speed at anemometer height

Z_{hub} is the hub height of the wind turbine

Z_{anem} is the height of the anemometer

Next MATLAB is used to obtain the scale parameter c and shape parameter k for the wind speeds at the test location at 100m hub height. The result of the calculation is that for the test location the values of c and k are c= 10.5761 m/s and k=1.9559 at 100m hub height.

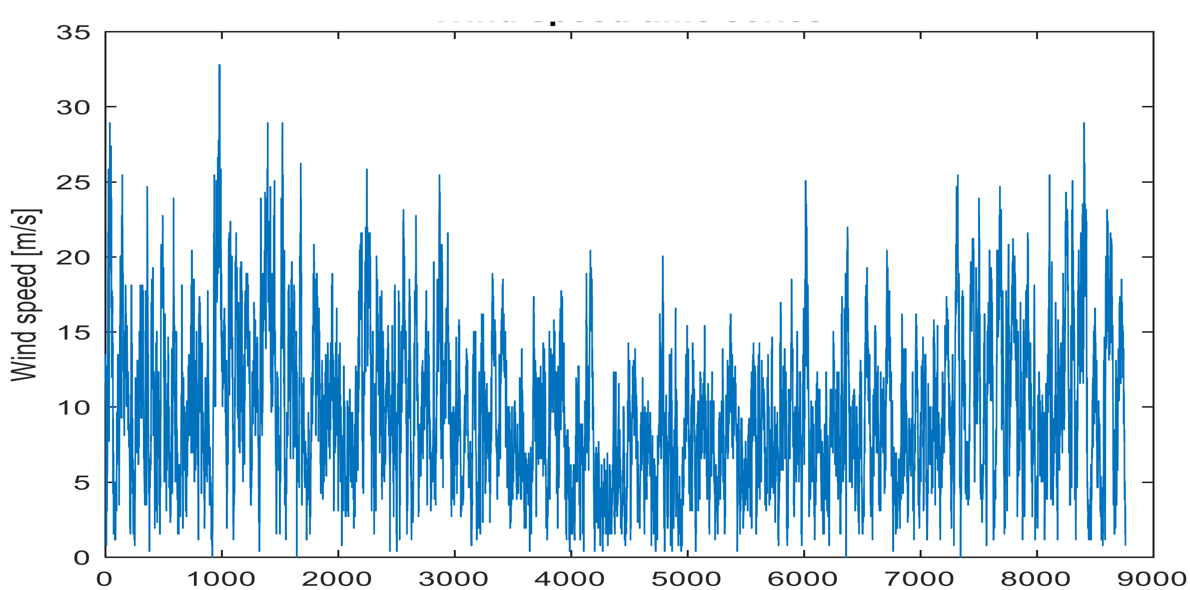


Fig. 12. Wind speed time series for every hour in 2019

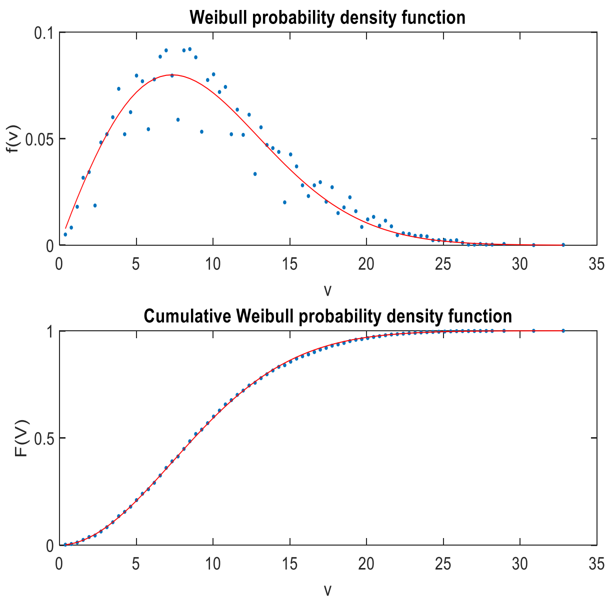
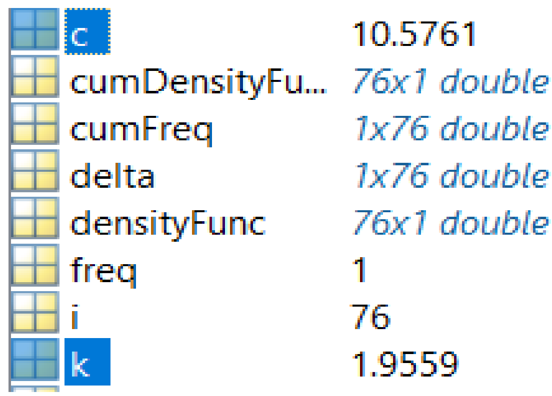


Fig. 13. Weibull PDF fitted to the wind speed data



.Fig. 14. Values of c and k for test location

Figure 12 shows the plot of the wind speed time series for every hour in 2019, figure 13 shows the Weibull probability density function (PDF) fitted to the wind speed data and the cumulative Weibull probability density function using Matlab and figure 14 shows the values of c and k for the test location all three figures are from MATLAB.

Next information about the test turbine is obtained. The chosen test turbine is Vestas164 8 MW turbine. Table III illustrates key characteristics of the turbine. These values were selected as the most relevant values from the turbines data sheet [77]. The power curve was also obtained from the same source and is shown in figure 15.

TABLE III
VESTAS164 TURBINE CHARACTERISTICS

Turbine characteristics	Value
Rated power	8 MW
Cut-in wind speed	4.0 m/s
Cut-out wind speed	25.0 m/s
Rotor diameter	164 m
Number of blades	3
Type of generator	Permanent Magnet
Tip speed	104 m/s
Voltage	66,000 V
Grid frequency	50.0 Hz

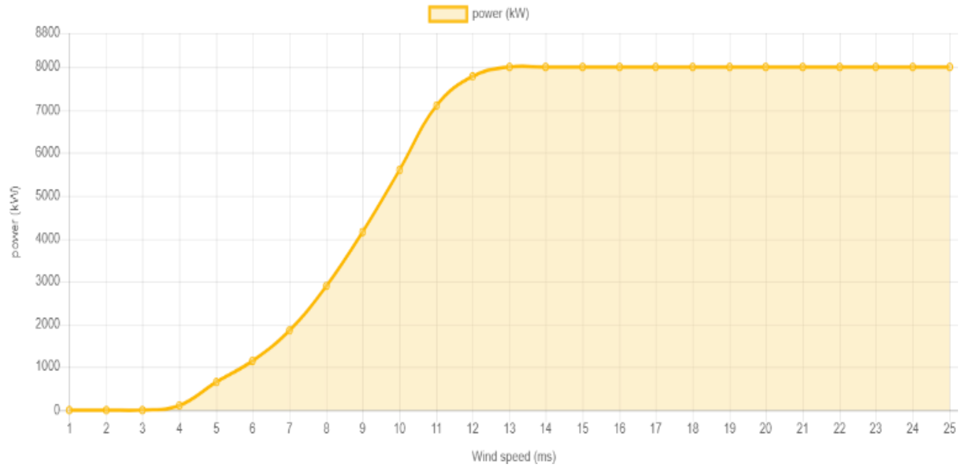


Fig. 15. Power curve of Vestas 164m

The maximum power density of the turbine P_{max} was then computed using equation 2 and is equal to $378.72\ \frac{W}{m^2}$

$$P_{max} = \frac{P_{rated}}{Rotor\ Area} \tag{2}$$

The above figure is much lower than the $800\ \frac{W}{m^2}$ value used in [78] and represents a more realistic figure. Initially using $800\ \frac{W}{m^2}$ for this application resulted in a 75% error.

C_p was not directly obtainable and was assumed to equal 0.45. The standard air density at sea level is $\rho_{standard} = 1.225\ \frac{kg}{m^3}$ however the elevation of the test location stands well above sea level at 140.5m and the tower height adds an additional 100m. therefore, air density was corrected for height using [79] where the new air density was found to equal $\rho_{actual} = 1.186\ \frac{kg}{m^3}$. These previously mentioned variables are the inputs to the Mathcad work sheet that differentiate one application (location and turbine) from another. For the sake of emphasis, the inputs are re-presented in below table.

TABLE IV
INPUT PARAMETERS

Input parameter	Value
c	10.576 m/s
k	1.9559
V_{cutin}	4 m/s
V_{cutout}	25 m/s
P_{max}	378.715 W/m^2
C_{pmax}	0.45
ρ	1.186 kg/m^3

ii. Calculation

Next the code implemented in Mathcad and an explanation of the calculation are presented. first the Weibull distribution is implemented using equation 3 and power density is calculated using equation 4.

$$h(v,k,c) = \frac{k}{c} * \left(\frac{v}{c}\right)^{k-1} * e^{-(\frac{v}{c})^k} \tag{3}$$

$$P_{den} = 0.5 * \rho * v^3 \tag{4}$$

Where P_{den} is the power density of the wind and v, the wind speed, is defined as a variable from 0 $\frac{m}{s}$ to 40 $\frac{m}{s}$ with 1 $\frac{m}{s}$ incrementation.

Next the Weibull distribution is plotted and compared with the distribution of [79] where the example provided used c = 9 and k = 2. The result is shown in figure 16. As can be seen from the figure the Weibull distribution of the test location has a relatively flatter curve. This is in line with the literature which state that as the c increases the probability of occurrence of higher wind speeds increases this is illustrated in figure 13 which shows the distribution for c = 10, 15 and 20 mph at constant k [79].

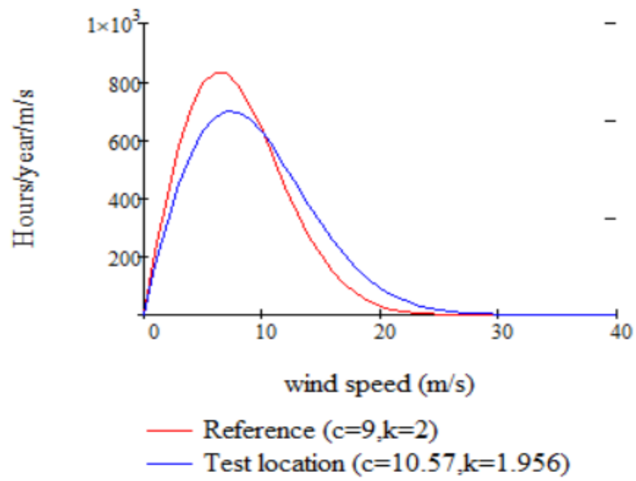


Fig. 16. Weibull distribution of test location versus reference

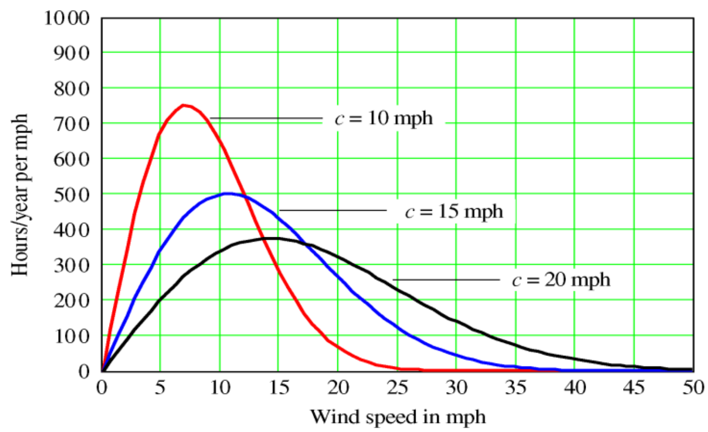


Fig. 17. Weibull distribution for various c values and k = 2.

Next the mode speed V_{mode} is calculated using a given-find function in Mathcad. Here the software looks for the point along the Weibull curve where the tangent is equal to zero. This point is the peak of the curve which corresponds to the mode velocity. In this case, the V_{mode} was found to equal 7.334 $\frac{m}{s}$ as can be seen in figure 18. The value of V_{mode} is plugged into equation 4 to obtain the value of P_{den} (V_{mode}) as 233.945 $\frac{W}{m^2}$

Given

$$vm := 10\,\frac{m}{s}$$

$$\frac{d}{dvm}(h(vm,k,c)) = 0$$

$$Vmode := Find(vm) = 7.334\,\frac{m}{s}$$

Fig. 18. Given-find function for mode velocity in Mathcad worksheet

Mean and rmc velocities are calculated using equations 5 and 6 the results are $V_{mean} = 9.377\ \frac{m}{s}$ and $V_{rmc} = 11.723\ \frac{m}{s}$. These results are plugged into equation 4 to obtain the values of $P_{den}(V_{mean}) = 488.967\ \frac{W}{m^2}$ and Pden(Vrmc) = 955.249 $\frac{W}{m^2}$.

$$V_{mean} = \int_0^{\infty} h(v,k,c) * v * dv \tag{5}$$

$$V_{rmc} = \sqrt[3]{\int_0^{\infty} h(v,k,c) * v^3 * dv} \tag{6}$$

The Energy density of the wind in the year (2019) at the test location is then calculated using equation 7. Which yields an $E_{wind} = 8.367 * 10^6\ \frac{W\,hr}{m^2\,yr}$. Figure 19 shows the energy density of the wind from test location compared to the one from [80].

$$E_{wind} = \int_0^{40} 0.5 * \rho * \mathrm{h(v,k,c)} * 8760 * v^3 * dv \tag{7}$$

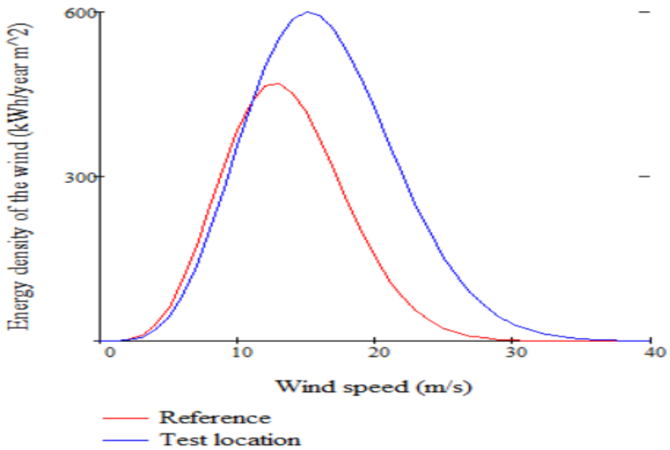


Fig. 19. Energy density from test location vs reference

Pdencon(v) := | 0 if v vcutin
| pmax if Pden(v) pmax
| 0 if v vcutout
| Pden(v) otherwise

Fig. 20. Mathcad continuous piece wise function

The previous calculations have been regarding the wind resource itself. The following steps will now consider the wind turbine. Figure 20 shows a portion of the Mathcad code which implements the turbines characteristics. This is done using a continuous piece wise function. If v is lower than the cut in velocity, power density is 0. Similarly, if v is higher than cut out power density is equal to 0. For values of v where P_{den} (v) is higher than P_{max}, P_{dencon} (v) is equal to P_{max}. This simply means that the turbine can not generate power higher than its rated capacity value. Lastly, if the value of the v lies within the v_{cutin} to v_{rated} range, P_{dencon}(v) = P_{den} (v). In this case equation 4 will apply and C_{pmax} will be included.

Now the Energy density after including the turbine can be calculated using equation 8. The result is Econ = $1.715 * 10^6 \frac{W\,hr}{m^2\,yr}$.

$$E_{con} = \int_0^{40} P_{dencon}(v) * h(v,k,c) * 8760 * dv \tag{8}$$

The capture ratio which is the ratio of the energy captured by the turbine to the energy present in the wind for the entire year can be calculated as $cr = \frac{E_{con}}{E_{wind}} = 20.501\%$

Finally, the capacity factor of the wind turbine can be calculated as the actual energy produced by the turbine divided by the energy it would have produced if it was producing rated power throughout the entire year. $cf = \frac{E_{con}}{E_{rated}} = \frac{1.715*10^6}{P_{max}*8760} = 51.7\%$

iii. Mathcad output summary

The output values obtained are summarised below,

TABLE V
OUTPUT SUMMARY

Output variable	Variable description	Value	Related to
V_{mode}	Mode speed	$7.334\ \frac{m}{s}$	
V_{mean}	Mean speed	$9.377\ \frac{m}{s}$	
V_{rmc}	Rmc speed	$11.723\ \frac{m}{s}$	
$P_{den}(V_{mode})$	Power density at mode speed	$233.945\ \frac{W}{m^2}$	Wind resource
$P_{den}(V_{mean})$	Power density at mean speed	$488.967\ \frac{W}{m^2}$	
$P_{den}(V_{rmc})$	Power density at rmc speed	$955.249\ \frac{W}{m^2}.$	
E_{wind}	Energy density of the wind for the entire year	$8.367 * 10^6\ \frac{W\ hr}{m^2\ yr}.$	
E_{con}	Energy of the turbine output	$1.715 * 10^6\ \frac{W\ hr}{m^2\ yr}.$	
cr	Capture ratio	20.501%	Turbine
cf	Capacity factor	51.7%	

2) *Homer simulation*

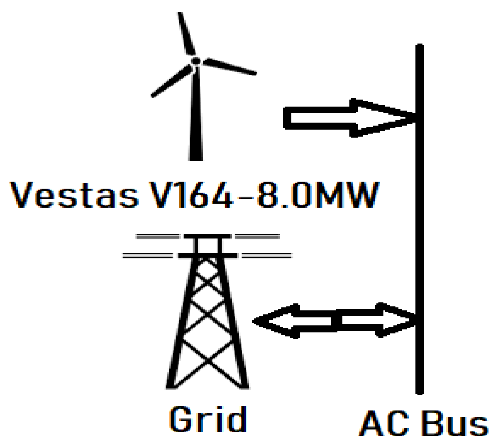


Fig. 21. System block diagram

Wind resource was configured where the hourly wind speed time series for the test location in 2019 was inputted. Then the altitude was set to 140.5m and anemometer height set to 10m. under variation with height the default option is logarithmic 0.01m surface roughness length which corresponds to rough pasture landscape. Leaving the default setting on results in 4% higher error than changing it to power law where α = 1/7. The value of α is assumed in both cases as 1/7.

Vestas164 was not a present choice in HOMER beta version and had to be inputted manually from the turbine's data sheet. The capital cost of the turbine was not directly obtainable therefore prices from multiple sources were compared. The first value was obtained from IRENA [81]. Where the average price of a wind turbine in 2018 is 1.5 million USD/MW which dropped from 1.7 million USD/MW in 2012 [72]. According to [82] average cost of a large-scale wind turbine is 1.3-2.2 million USD/MW. Finally, according to [73] Vestas reported an order intake for turbines with a capacity of 1.55GW in its results for the third quarter of 2013, valued by Vestas at EUR 1.5 billion. This gives us a price of EUR 967,742 per megawatt or 1.06 million USD/MW. Given the above figures this report will assume 1.5 million USD/MW capital cost. Making the 8 MW turbine cost 12 million USD.

According to [83] O&M costs average between $42,000 and $48,000/MW during the first 10 years of a wind turbine's operations. Therefore, for this project 50000 USD/MW will be used making the total O&M cost for the 8 MW turbine 400,000 USD.

For this project 25-year turbine lifetime and 25-year project lifetime will be assumed. Meaning that there will be no replacement cost or income from salvaging. 100m hub height was selected.

Grid was added and its purchase capacity was increased to an a nearly infinite amount. Not doing so results in a lot of the energy generated being labeled excess and the economics of the project suffering. The grid rates were left at their default values 0.1 $/kWh for purchasing (which is equivalent to 0.13 CAD/kWh which is NL’s rate) and 0.05$/kWh for selling.

i. Homer results

After calculation was done the following results were obtained for a 1 turbine system the results are summarized in Table VI.

TABLE VI
HOMER RESULTS SUMMARY FOR 1 TURBINE

Result	Value
Capital cost	12,000,000 USD
O&M cost	5,113,346 USD
Total costs	17,113,348 USD
Income	23,216,064 USD
Profit	6,102,720 USD
Electrical generation	36,322,300 kWhr/yr
Amount of generation sold to the grid	100%
Capacity factor	51.8%
Hours of operation	8160 hr/yr
CO_2 emissions saved	22,955,704 kg/yr

As can be seen installing wind turbine at the test location is largely profitable with almost 35% return on investment. Figure 22 shows the average electricity production by the system for every month of the year.

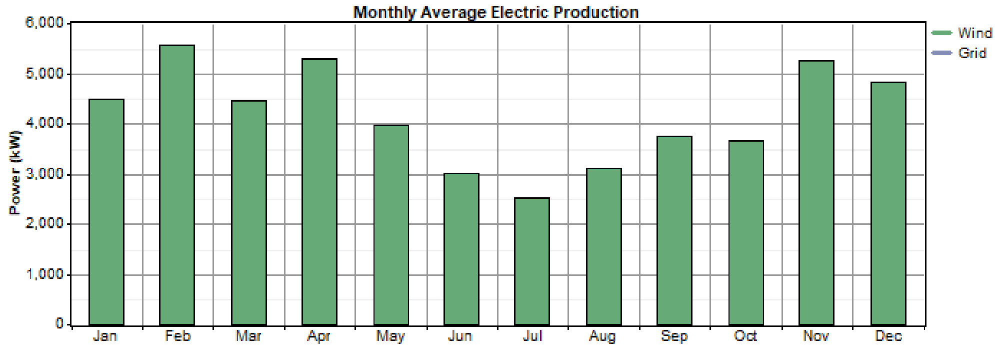


Fig. 22. Average monthly electric production.

3) ***Homer and Mathcad comparison***

The energy density of turbine in Homer is $HomerVesta164 = \frac{36322300000}{\pi*(\frac{D}{2})^2} = 1.719 * 10^6\ \frac{W*hr}{m^2*yr}$. The percentage of wind energy that turbine utilized is $\frac{HomerVesta164}{E_{wind}} = 20.55\%$. finally the ratio of the output energy density of the system from Mathcad calculations to homer simulation is $\frac{Econ}{HomerVesta\ 164} = 99.763\%$ meaning that the error is only 0.237%. For the proceeding parts of this project a combination of homer and Mathcad will be used for calculations.

4) ***Wind farm at Test location***

This section concludes with a full wind farm at the test location that is able to produce the same energy as the Muskrat falls project (4.9 TWh/year). The number of Vestas 164m turbines required is 135 turbines at 100m hub height. The Capital and O&M cost, Profit, electrical generation, capacity factor, CO_2 emissions and more are illustrated in Table VII.

TABLE VII
HOMER RESULTS SUMMARY FOR 135 TURBINES

Result	Value
Capital cost	1,620,000,000 USD
O&M cost	690,301,568 USD
Total costs	2,310,301,440 USD
Income	3,134,174,976 USD
Profit	823,873,600 USD
Electrical generation	4,903,561,216 kWhr/yr
Amount of generation sold to the grid	100%
Capacity factor	51.8%
Hours of operation	8160 hr/yr
CO_2 emissions saved	3,099,025,664 kg/yr

As can be seen from Table VII, the project is largely profitable earning over 823 million USD through the project's lifetime and saving over 3 million tons of CO_2 emissions per year (comparable with Muskrat Falls).

C. Wind site selection

Taking a cue from the previous section which described the wind potential in this project's scope of study, this section unveils the best possible and satisfactory wind farm sites across the province of Newfoundland and Labrador to accommodate utility scale wind energy development. The site selection includes, the Predictive-specific model, which uses geo-spatial analysis in bringing out the multi-dimensional selection patterns to extract the optimum wind capacity in the chosen areas [85]. These approaches adopt both inclusionary and exclusionary principles and are very much in tandem with international wind energy standards.

The best possible approach in wind site selection is choosing the region's proximity to existing and/or planned onshore wind farm infrastructure instead of a random location [64]. Thus, consistently abide by the test of pragmatic acceptance. Further, the wind experienced at any given location is highly dependent on local topography, instantaneous wind speed and direction etc. which vary on hourly basis. Apart from technical considerations in determining the suitable wind site there exists many unquantifiable aspects in regard to the social and economic dimensions in wind energy development, which are discussed in the following sections [86].

At present there exists three wind farm sites in the province of Newfoundland and Labrador namely, Ramea-Hybrid (2004), St Lawrence (27MW), Fermeuse (27MW) with a cumulative capacity of mere 55MW. As this study focusing on utility scale wind power, the existing wind infrastructure of St Lawrence (27MW) and Fermeuse (27MW) wind farms are used to build a predictive and comparable analysis in wind farm site selection [64],[68].

1) *Existing Wind farms*

i. St Lawrence wind farm

The St Lawrence wind farm, an Onshore wind farm, commissioned in the year 2011, is located in the burin peninsula of Newfoundland and Labrador (46°55'12" and -55°23'24"), with a geodetic system WGS84 and is operated by Enel Green power. It employs 9 Vestas V90/3000 wind turbines, generating a total nominal power of 27MW [68].

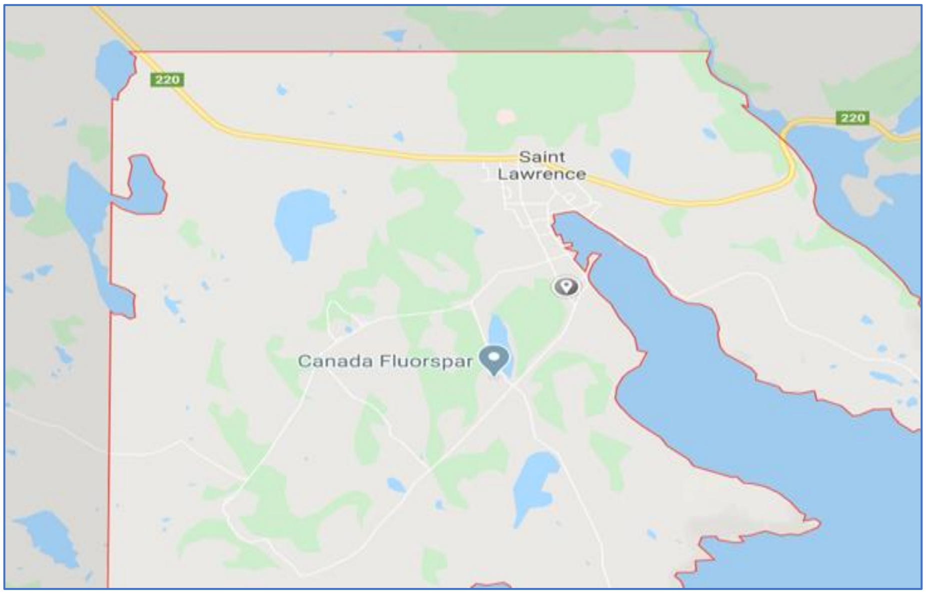


Fig. 23. Geographical location of St Lawrence Wind farm, NL

ii. Fermeuse wind farm

The Fermeuse wind farm is an Onshore wind farm is commissioned in the year 2009 located in the Avalon peninsula of Newfoundland and Labrador (between 46° 59' 3.5"and -53° 0' 22.6"), with a geodetic system WGS84 and is operated by EDF renewables and owned by Skypower. It employs 9 Vestas V90/3000 wind turbines, generating a total nominal power of 27 MW [68].

Fig. 24. Schematic View of Fermeuse wind farm, NL

2) *Methodology in Wind site selection*

i. Influence of Noise

Large wind turbines must be sited at least 550 metres from all domestic or non-participating noise receptors, and, depending on project specifics (such as the number and location of turbines), may have to be sited at distances much greater than 550 m [64]. Unless a noise study report is prepared, transformer substations (50 kilovolt or more) that are part of wind energy projects must be sited at least 1,000 m from any restricted areas or should be surrounded by an appropriate acoustic barrier, at least 500 m away [86].

ii. Renewable Energy Projects

Locating a project near other renewable energy facilities may increase overall (cumulative) noise levels.

iii. Ecological considerations

The following lists sensitive ecological features that should be taken into consideration when locating/siting wind projects and an environmental impacts assessment report (EIA), is to be prepared about the effects from the project on these features and identify and implement mitigation measures to address any anticipated impacts [86].

- Aquifers
- Significant wildlife habitats
- Significant woodlands
- Provincially significant areas of natural and scientific interest
- National parks or conservation reserves

Consideration of natural features and water bodies is essential. For most wind energy projects unless additional reports are prepared certain project components must be sited anywhere between 30 metres to 300 m from these ecological features depending on the scale of utility establishment involved.

- 30-120 m from water bodies
- 50-120 m from significant natural heritage features (woodlands, wildlife habitat, wetlands, etc.)
- 300 m from lakes.

iv. Infrastructure considerations

The distance between the centre of the base of the wind turbine and any public road rights of way (RoW) or railway rights of way must be, generally, at a minimum, the length of any blades of the wind turbine, plus 10 metres. If on prime agricultural land, proponents of wind energy projects should ensure accessible roads are designed and constructed to have minimal impact on agriculture [86].

Further wind projects proposed to be located adjacent to or in the vicinity of an airport/aerodrome should be stopped due to shadowing and doppler effects. prior notification from NAV Canada and Transportation Canada is obtained regarding the proposed project location to determine how it may impact local airports/aerodromes [85], [86].

Other Considerations

- Weather radar towers
- Telecommunications towers
- Aviation radar towers
- Natural gas, electrical, and water sewage infrastructure
- Aggregate resources, landfill sites, and petroleum wells/facilities

3) ***Wind Sites Selection***

Based on the above discussed factors and methodology involved in wind site selection, four major wind sites are selected which exhibits the underlying characteristics to develop wind energy infrastructure. Each site is described with its potential annual wind distribution and based on methodological factors discussed above [68].

i. ***Portugal Cove south region***

Considering the above selection criteria, the site characteristics is as mentioned below,

Table VIII
PORTUGAL CAVE SOUTH

SITE PARAMETERS	
Latitude and Longitude	46.70573°, -53.20353°
Wind speed	9.19 m/s @ 100m height
Power/Area	914 W/m^2
Nearest Weather Station	Cape Race, Nfld

The hourly wind speed recorded at the Portugal Cove south, Newfoundland ranges from 11.8 mph to 19.6 mph between two extremities of windiest day and calmest day in the month of January and August respectively [84].

Fig. 25. Selected region in Portugal Cove South

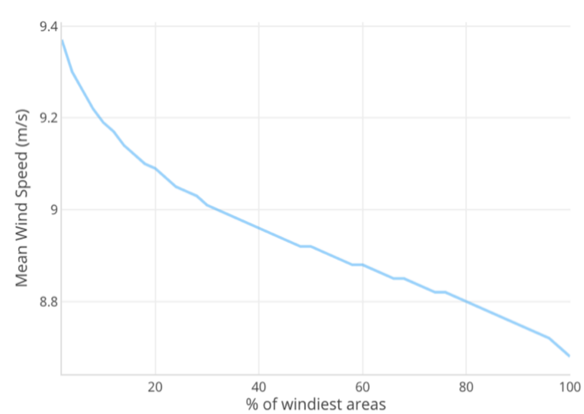


Fig. 26. Mean wind speed for varying heights.

ii. Bonavista region

The predominant average hourly wind direction in Bonavista varies throughout the year.

TABLE IX.
BONAVISTA

SITE PARAMETERS	
Latitude and Longitude	48.62451°, -53.04989°
Wind speed	9.75 m/s @ 100m height
Power/Area	1051 W/m2
Nearest Weather Station	Bonavista

The wind is most often from the south from March to September, with a peak wind distribution percentage of 48% in the month of July and from the west with a peak percentage of 51% in the month of January [84].

Fig. 27. Selected region in the Bonavista

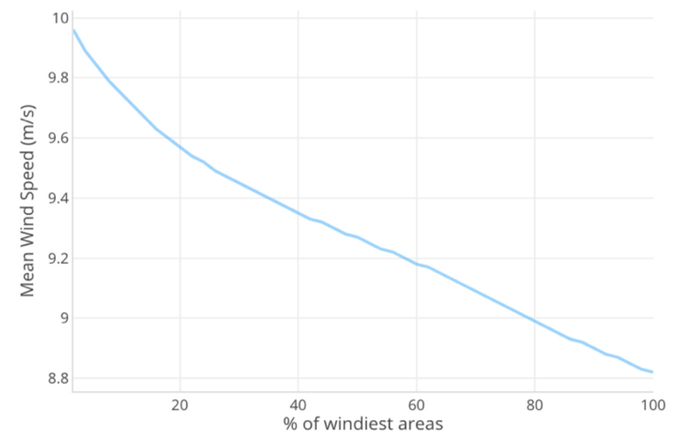


Fig. 28. Mean wind speed for varying heights. (Bonavista)

iii. Grand Banks region

This region has a wide-area hourly average wind vector (speed and direction) at 10 meters above the ground. The Surface wind speeds average 18–29 km/hour and very strong gusts of 105–120 km/h are a common feature along the southern coast of the region [84],[85].

Fig. 29. Selected region in Grand Banks

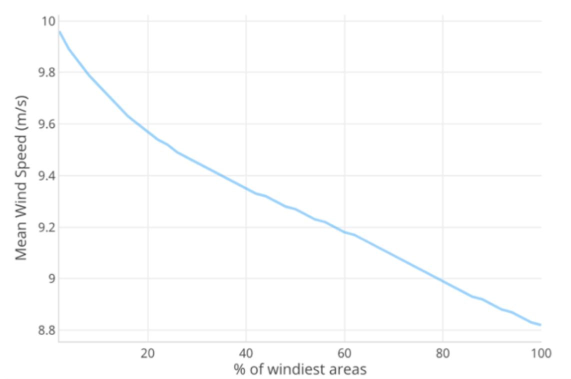


Fig. 30. Mean wind speed for varying heights. (Grand Banks)

TABLE X
GRAND BANKS

SITE PARAMETERS	
Latitude and Longitude	47.14373°, -55.34981°
Wind speed	8.51 m/s @ 100m height
Power/Area	707 W/m2
Nearest Weather Station	St. Lawrence

iv. Saint Bride's region

The region Located at the Southern part of the province exhibits a promising varied wind distribution throughout the year, this region near to Argentia weather station augurs well in collection of wind data for the development of wind energy, thereby encircling the southern part of the province with ample wind infrastructure [85].

According to the data recorded at the Argentia weather station, [68] the windier part of the year lasts 6 months with an average hourly wind speed of 10.89 miles per hour.

Table XI
SAINT BRIDE'S

SITE PARAMETERS	
Latitude and Longitude	46.90958°, -54.11196°
Wind speed	9.67m/s @ 100m height
Power/Area	1067 W/m2
Nearest Weather Station	Argentia

Fig. 31. A view of the selected region in Saint Bride's region

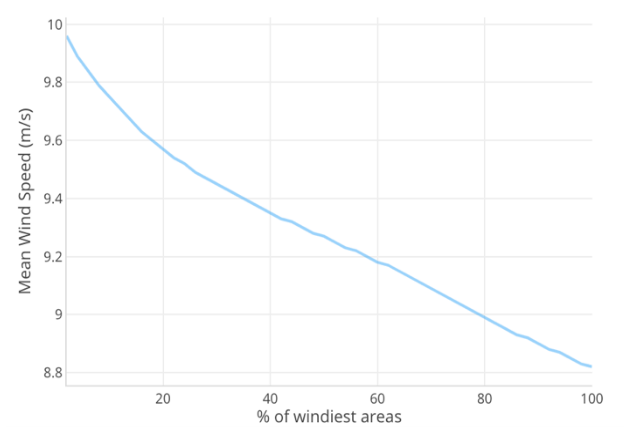


Fig. 32. Mean wind speed for varying heights (Saint bride's)

D. Wind turbine selection

1) *Wind turbines used in Canada*

Wind energy development has enjoyed growing success in many countries in recent times, it is a relatively new contributor to the existing power infrastructure in Canada [87]. The wind energy currently supplies approximately six per cent of Canada's electricity demand, generating enough power to meet the needs of over three million Canadian homes [88]. There are 299 wind farms operating from coast to coast, including projects in two of the three northern territories. In 2019, Canada's wind generation grew by 676 megawatts (MW) spread among 7 new wind energy projects, representing an investment of about $2 billion [87]. The installed capacity of wind generation reached 14,936 MW in 2019. Among many, the ten most prominent wind farms considering their capacity, annual energy output and other factors are described in Table XII.

TABLE XII.
LISTS OF UTILITY SCALE WIND FARM ACROSS CANADA

Wind farm Name	Turbine used	No of Turbines	Wind farm capacity (in MW)	Land size	Average annual energy
Seigneurie de beaupre, Quebec	Enercon E-70 & E-82	154	363.5	206 Km^2	2.072 TWh
Riviere-du-Moulin, Quebec	RE Power MM82 and MM92	175	350	68 Km^2	1.76 TWh
Blackspring Ridge, Alberta	Vestas V100	166	300	154 Km^2	1.23 TWh
Lac Alford, Quebec	Senvion MM82 and MM92	150	300	132 Km^2	1.08 TWh
Niagara Region, Ontario	Enercon E101	77	230	140 Km^2	847GWh
Gros-Monroe, Quebec	GE Energy 1.5sle	141	211.5	112 Km^2	650 GWh
Amaranth, Ontario	GE 1.5 MW	133	199.5	127.4 Km^2	545 GWh
Wolfe Island, Ontario	Siemens SWT 2.3-101	86	197	175.2 Km^2	503GWh
Prince Township, Ontario	GE Energy 1.5sle	126	189	105 Km^2	495GWh
Meikle, British Colombia	GE 1.5 MW	61	184.6	64 Km^2	221 GWh

2) ***Wind turbines used internationally***

In order to select the turbine optimum for this study first a quick review of large-scale wind farms is due. A summarized wind farm review of some wind farms internationally is presented in the Table XIII. the purpose of table XIII is to provide some examples of the application of the wind turbines that are included in this study which are GE-2.5 XL, Vestas 164, Enercon E-126, GE 1.5s and Siemens SWT 3.6 120. It should be noted that in Table XII manufacturers of turbines used in the large-scale wind farm across Canada were the same as the manufacturers from Table XIII, namely, Vestas, GE, Enercon, Siemens

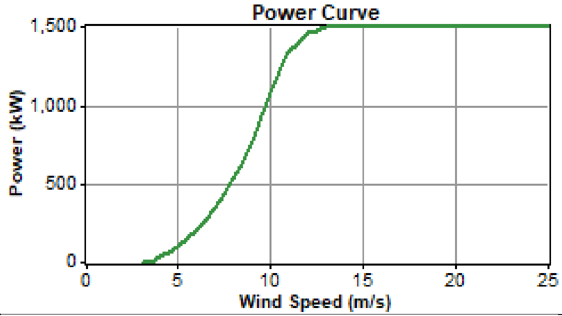
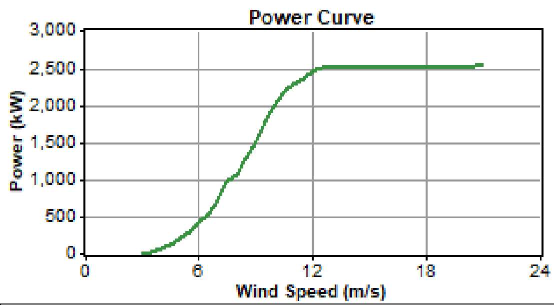
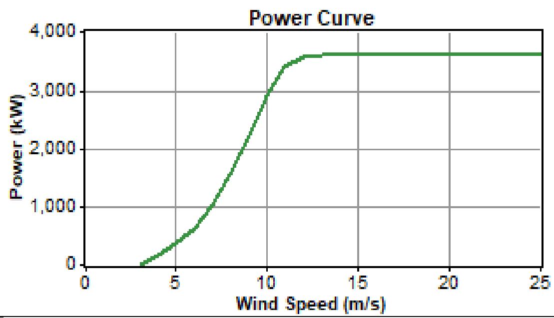
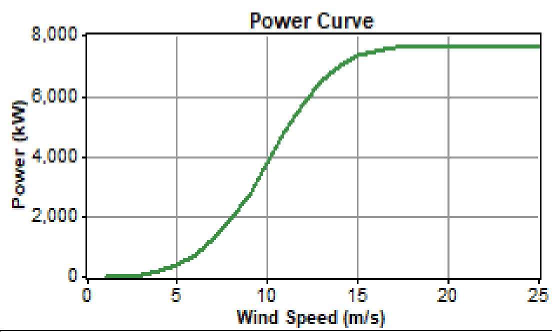
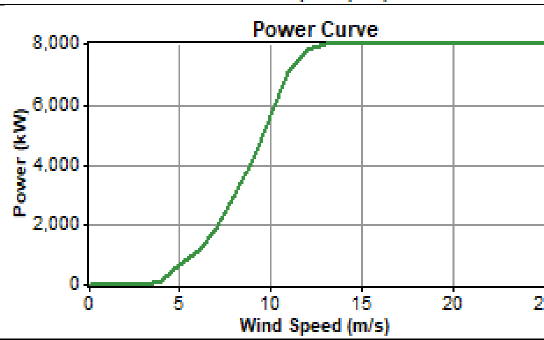
TABLE XIII
EXISTING WIND FARMS USING THE SELECTED TURBINES.

Wind farm Name & Location	Turbine used	NoT	WFC (MW)	Land size	AAE
Shepherds flat, Oregon, USA [89]	GE 2.5 XL -2.5 MW	338	845	78 km^2	1.67 TWh
Burbo Bank, Liverpool, UK [90][91]	Vestas 164	32	258	40 km^2	315 GWh
Norther N.V, Belgium [92]	Vestas 164	44	370	38 km^2	1.39 TWh
Horns Rev 3 Denmark, [93]	Vestas 164	49	406.7	19 km^2	1.7 TWh
Estinnes Belgium [94] [95]	Enercon E-126	11	81.8	NA	1.6 GWh
Markbygden, Sweden [96]	Enercon E-126	1,101	4000	500 km^2	12 TWh
Noordoostpolde Netherlands [97]	Enerco E-126 & Siemen 3.0 DD-108	38 &48	429	8 km^2	1.4 TWh
Le Mont des 4 Faux,France [98]	EnerconE-126	47	356	NA	NA

NoT: No of Turbines; AAE: Avg. Annual Energy; WFC: Wind Farm Capacity

The power curves for the selected turbines were obtained from [99]-[103] and inserted into Homer. The power curves from homer along with important parameters of the wind turbines are presented in Table XIV Note: all turbines are onshore turbines except Vestas 164 which is listed as both onshore and offshore. By combining all the power curves from table XIV, figure 33 is obtained which compares the power curves for the 5 turbines used in this study.

TABLE XIV
TURBINE CHARACTERISTICS

Turbine name	Rated power (kW)	Rotor diameter (m)	No of blades	Type of generator	V &freq.	Power density (W/m^2)	Hub heights (m)	Power curves [99]-[103]
GE 1.5s and	1500	70.5	3	Doubly fed asynchronous generator	690 V 50 Hz	384.2	64.7 80 85 100	
GE 2.5 XL	2500	100	3	NA	NA	318.3	75 85	
Siemens SWT 3.6 120	3600	120	3	Asynchronous generator	690 V 50 Hz	318.6	90	
Enercon E-126	7580	127	3	Synchronous generator	690 V 50 Hz	598.4	135	
Vestas 164	8000	164	3	Permanent Magnet generator	660 V 50 Hz	378.7	NA	

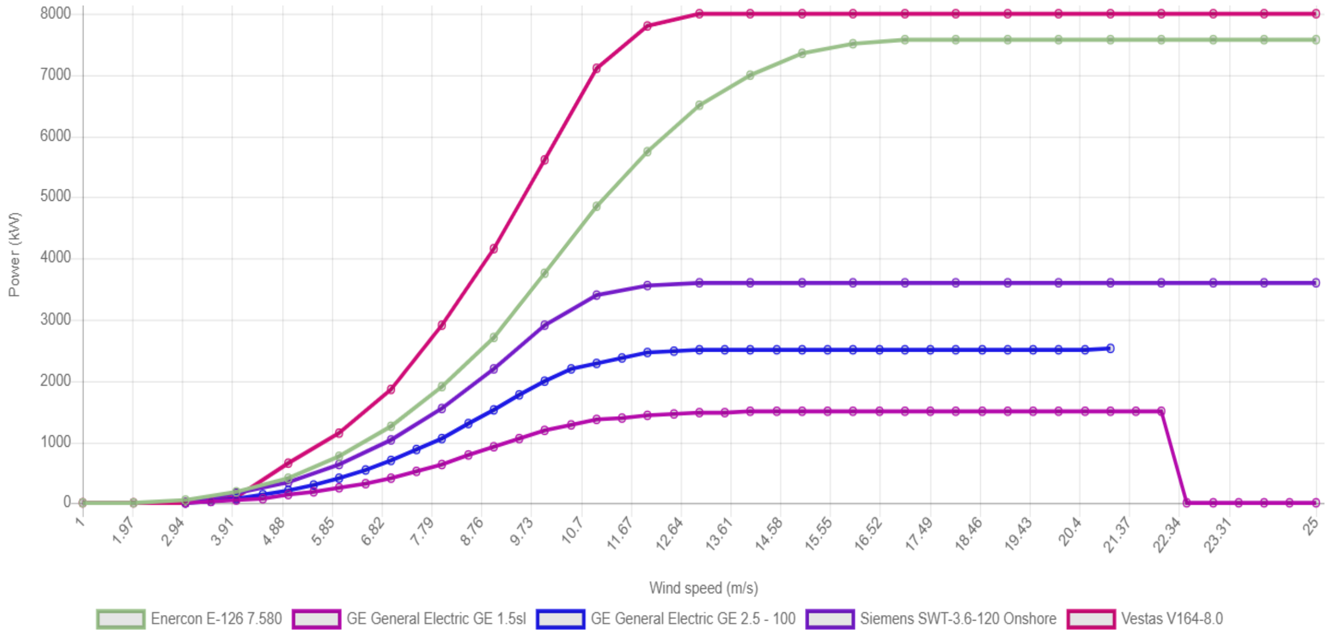


Fig. 33. Power curves from 5 selected turbines [99]-[103] combined and compared.

E. Parametric study

In this section, a parametric study will be conducted studying the different turbines at different hub heights at the 4 proposed locations but first a table illustrating the characteristics of the 4 locations is presented which illustrates some important values relating to the data from the four locations. The values include C and K values for the Weibull curve that most closely fits the data. V_{mode}, V_{mean} and V_{rmc} (from Mathcad) and the amount of energy density available in the wind. These parameters are

TABLE XV
SITE CHARACTERISTICS

Site name	SN & SE (m)	C	K	$V_{mode}\left(\frac{m}{s}\right)$	$V_{mean}\left(\frac{m}{s}\right)$	$V_{rmc}\left(\frac{m}{s}\right)$	$EDA\left(\frac{MW.Hr}{m^2.yr}\right)$
Saint bride's	Argentia, 19	7.6	1.7	7.1	6.89	8.8	3.5
Bonavista	Bonavista 25.6	9.3	1.9	6.3	8.32	10.4	7.5
Portugal Cove south	Cape race 26.5	7.9	1.8	6.5	7.07	9.0	3.9
Grand Banks	St. Lawrence 48.5	6.3	1.6	3.5	5.75	7.6	2.3

SN: Station Name; SE: Station Elevation; EDA: Energy Density Available.

From table XV, it can be seen that Bonavista location stands out from the rest with the highest available energy density in the wind. it is likely that the result of the following parametric study will show that this location is the most optimum. Table XVI displays the parametric study for the 5 turbines at the four locations. Hub heights were obtained from the data sheets of each turbine except for the case of Vestas 164 m which was assumed to be equal to the hub height of Enercon E-126 (135 m). The Area occupied by each turbine was obtained from [76] which shows that the minimum separation distance between wind farm columns as 2 rotor diameter and between rows as 8 rotor diameters. The LCOE in this table is not representative of full wind farm cost as it is simply made up of turbine capital and O&M costs.

TABLE XVI
PARAMETRIC STUDY

Location	Turbine Name	Hub Height (m) ([99]-[103])	No of Turbines	Energy Generated $\left(\frac{\text{TWh}}{\text{year}}\right)$	LCOE $\left(\frac{\$}{\text{kWh}}\right)$	Profit (mil.. USD)	Area taken (km^2)	LCOE *Area $\left(\frac{\$.\text{km2}}{\text{kWh}}\right)$	Energy Density $\left(\frac{GWh}{\text{km2}}\right)$	Profit/Area $\left(\frac{million\ \$}{\text{km2}}\right)$
Saint bride's (Argentia)	GE 1.5s	64.7	780	4.89	0.0376	778.4	62.03	2.34	78.99	12.55
		80	754	4.902	0.0363	859.03	59.96	2.18	81.77	14.33
		85	746	4.904	0.0359	883.9	59.32	2.13	82.68	14.9
		100	727	4.900	0.035	938.8	57.81	2.03	84.77	16.24
	GE 2.5 XL	75	441	4.902	0.0354	916.3	70.56	2.5	69.49	12.99
		85	434	4.902	0.0348	950.9	69.44	2.42	70.6	13.69
	Sie.SWT-3.6	90	288	4.907	0.033	1,051	66.36	2.21	73.95	15.84
	Enercon E-126	135	164	4.923	0.039	646.34	42.32	1.69	116.33	15.27
	Vestas 164	135	130	4.904	0.035	909.79	55.94	1.99	87.67	16.26
Bonavista (Bonavista)	GE 1.5s	64.7	632	4.898	0.0304	1,224	50.26	1.53	97.47	24.36
		80	624	4.901	0.031	1,250.1	49.62	1.49	98.78	25.19
		85	619	4.898	0.0298	1,263.2	49.23	1.47	99.5	25.66
		100	619	4.900	0.029	1,264	49.23	1.47	99.53	25.68
	GE 2.5 XL	75	405	4.904	0.0325	1,098.2	64.8	2.11	75.68	16.95
		85	405	4.901	0.0325	1,096.6	64.8	2.11	75.65	16.92
	Sie. SWT 3.6	90	247	4.902	0.028	1,345	56.91	1.63	86.14	23.63
	Enercon E-126	135	137	4.911	0.033	1,051	35.35	1.18	138.94	29.72
	Vestas 164	135	115	4.931	0.031	1,184	49.49	1.55	99.63	23.91
Portugal Cove south (Cape race)	GE 1.5s	64.7	774	4.903	0.0373	799	61.55	2.3	79.67	12.98
		80	751	4.901	0.0362	866.9	59.72	2.17	82.07	14.52
		85	744	4.904	0.0358	890.1	59.17	2.12	82.89	15.04
		100	730	4.903	0.035	931.63	58.05	2.04	84.47	16.05
	GE 2.5 XL	75	453	4.8975	0.0364	852.4	72.48	2.64	67.57	11.76
		85	447	4.898	0.0359	883.2	71.52	2.57	68.49	12.35
	Sie. SWT 3.6	90	289	4.905	0.033	1,043	66.59	2.23	73.66	15.66
	Enercon E-126	135	162	4.894	0.039	657.97	41.81	1.66	117.04	15.74
	Vestas 164	135	131	4.895	0.035	886.81	56.37	2.02	86.84	15.73
Grand Banks (St. Lawrence)	GE 1.5s	64.7	1023	4.901	0.0493	46.48	81.35	4.02	60.25	0.57
		80	981	4.902	0.0472	173.7	78.01	3.69	62.84	2.23
		85	969	4.902	0.0466	210.1	77.06	3.6	63.62	2.73
		100	940	4.9048	0.045	299	74.75	3.38	65.62	4

	GE 2.5 XL	75	569	4.904	0.0456	273.2	91.04	4.16	53.86	3
		85	557	4.902	0.0447	332.5	89.12	3.99	55.01	3.73
	Sie.SWT 3.6	90	368	4.904	0.042	469.8	84.79	3.61	57.84	5.54
	Enerco-126	135	212	4.904	0.051	-97.47	54.71	2.83	89.64	-1.78
	Vestas 164	135	167	4.905	0.045	277	71.87	3.28	68.24	3.85

i. Analysis

This section provides a comprehensive parametric analysis of the study. As can be seen in the Table XV, different parameters are calculated against each potential wind site location. The parameters Energy density, LCOE, profit margin, Area taken, and LCOE*Area are more prominent in this analysis.

This feasibility study is made by taking into account the hourly distribution of wind speed (m/s) for a year w.r.t each different location. The wind data extracted is used in HOMER to calculate each parametric value for five different turbines from different manufacturers (at different heights). These turbine models, manufactured by GE, Siemens, Enercon and Vestas, exhibit varying capacities, rotor diameters (size), power curves and hub heights.

These turbines are tested at each different location; Saint bride's, Bonavista, Portugal cove south and Grand Banks at varying hub heights (in m) of 64.7,80,85,90,100, and 135.

Each individual site is analysed with respect to each turbine, which are in turn associated with different parametric values. The total number of systems in this study is 36. This approach provides a holistic and informed view to conclude the best turbine for the best site at the end of the analysis.

As can be seen in the Table XV, at the Saint Bride's wind site location, the parametric value of profit margin and LCOE* Area of GE 1.5s turbine is low compared to Siemens SWT- 3.6 and GE 2.5XL respectively. However, in Area taken and in the Energy Density, Enercon E-126 outperforms all other turbines. The Vestas 164 turbine shines in Profit/Area parametric value. Thus, in Saint Bride's wind site location each of the five versions of the turbine performs positively in any one or two of the parametric values.

The Siemens SWT-3.6 for 90m hub height provides the highest profit margins (1.34 billion USD) and exhibits better LCOE value in Bonavista wind site while Enercon E-126 at 135m hub height exhibits high energy density with greater profit /area, fair LCOE and less area taken. Based on this, Enercon E-126 wind turbine may be adjudged as the best suited turbine for Bonavista wind site.

Similarly, GE 1.5s for 100m Hub height has more profit/area at Portugal cove south wind site and Siemens SWT-3.6 does possess high profit margin while Enercon E-126 shows high energy density. Thus, depending on the intended parametric value the choice can be made among Enercon E-126, Siemens SWT-3.6 and GE 1.5s for Portugal cove south wind site.

It is interesting that Enercon E-126 which has a good parametric record in the above discussed wind sites, has shown poor parametric performance at Grand Banks wind site. The negative profit margin and profit/Area have made accommodating Enercon E-126 in this site Uneconomical and Non feasible.

However, Siemens SWT-3.6 for 135m hub height has fairly performed in LCOE, profit margin and profit/area parametric values and Vestas 164 for 135m hub height does possess high energy density with comparatively low area taken. Hence for Grand Banks wind site the most preferable wind turbine is Siemens SWT-3.6.

To sum up the analysis of the suitability, affordability and efficiency of different turbines at each wind site. It is necessary to have a holistic and common ground in the analysis made so far. Among all sites, the favourable hourly wind distribution in the Bonavista wind site region has led to the generation of parametric values which are equitable in the practical design considerations. All five turbines according to their power capacity and design standards performed better in two or three parametric values.

However, on close examination Enercon E-126 has outperformed other turbines in some critical and important parametric values at Bonavista wind site. The area taken by the Enercon E-126 is almost half of the assumed value while exhibiting high energy density. Further, the manufacturing unit of Enercon company is located in Canada and therefore the economic costs involved in procuring Enercon E-126 design wind turbines are minimum (initially transportation costs were neglected in order to evaluate each turbine merit based on its performance)

Thus, to conclude the parametric analysis, the Bonavista wind site with Enercon-126 for 135m hub height will be the best combination for having utility scale wind farm in the province of Newfoundland and Labrador, Canada.

F. Case studies

In order to obtain a wide area of understanding about the existing wind farms, an effort is made to analyze the technical attributes of some of the major wind farms located around the world. This section come across two major wind farms both located inside and outside Canada [87]. For analyses this study take Seigneurie de Beaupre wind farm located at Quebec, Canada. At present, the Seigneurie de beau wind farm is the largest wind farm in the country with an annual energy generation of 2.072 TWh/year, with an energy density of 94.56 GWh/km^2 having 154 turbines (installed in Phase manner) of Enercon E-72 and E-82 [104].

Similarly, this study takes Capricorn Ridge wind farm, Texas, USA as an example to elaborate the comparative analysis of wind farms beyond the border. The Capricorn ridge is a 665.MW wind farm, made up of 345 GE 1.5-sle wind turbines and 65 Siemens SWT-2.3 wind turbines with an annual energy generation of 1.97 TWh/year, spanning the area of 213 Km^2, results in 92.87 GWh/Km^2 Energy density [105].

As discussed earlier, the Bonavista wind site is best suited location of having wind farm in the province of Newfoundland and Labrador and also out of five turbines, and through an exhaustive analysis Enercon is shortlisted as the best suitable wind turbine.

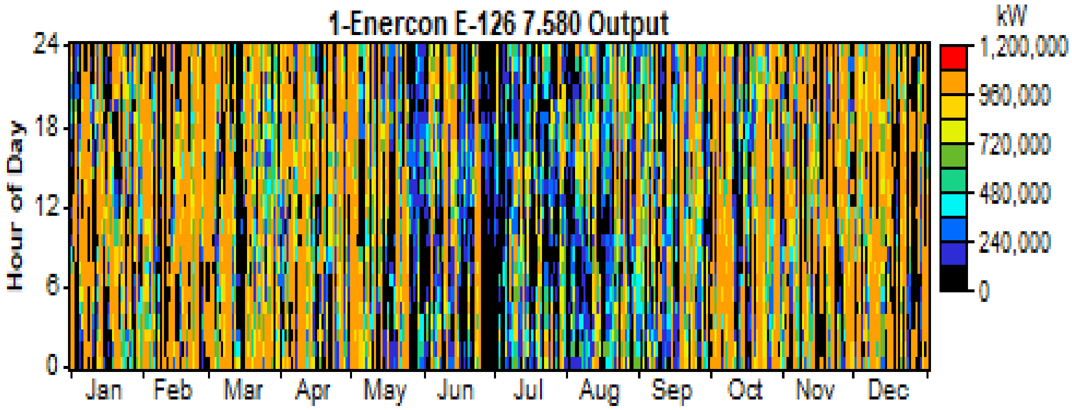
Comparing this study to Seigneurie de Beaupre wind farm, a notable feature that can be observed is the area taken by the Seigneurie de Beaupre wind farm is 206 Km^2 to generate 94.56 GWh/Km^2 of Energy density while Capricorn Ridge wind farm, Texas, USA in an area spanning 213 Km^2 would possess a mere 92.87 GWh/Km^2 energy density.

If these parametric values are compared with the proposed wind farm at Bonavista with 137 Enercon E-126 wind turbines in all for 135m hub height can generate 138.94 GWh/Km^2 of Energy density with an area of just 35.35 Km^2. Therefore, with this analysis we can infer that the proposed utility scale wind farm outperforms both Seigneurie de Beaupre wind farm and Capricorn ridge wind farm w.r.t annual energy generation (4.9TWh/year), area required, and energy density extracted.

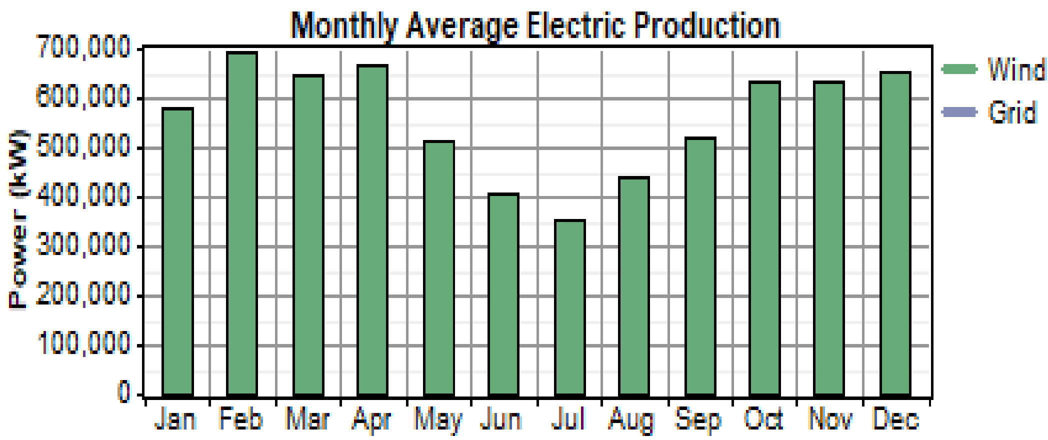
Hence, the above comprehensive analysis made w.r.t the proposed parametric study and comparison thereof with other major wind farms have testified the feasibility and efficacy of the proposed utility scale wind project in the province of Newfoundland and Labrador, Canada.

G. Selected system

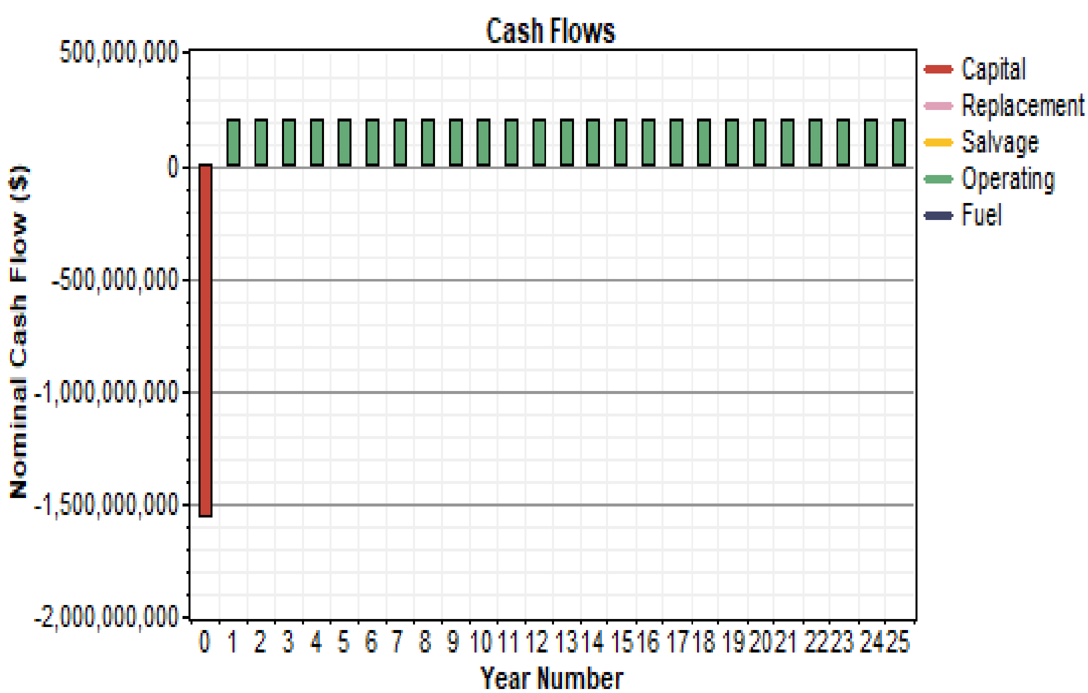
In this section more information will be presented regarding the selected system (Enercon E-126 at Bonavista) which are shown in figure 34.


1-Enercon E-126 7.580 Output
Hour of Day
24
18
12
6
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
kW
1,200,000
960,000
720,000
480,000
240,000
0

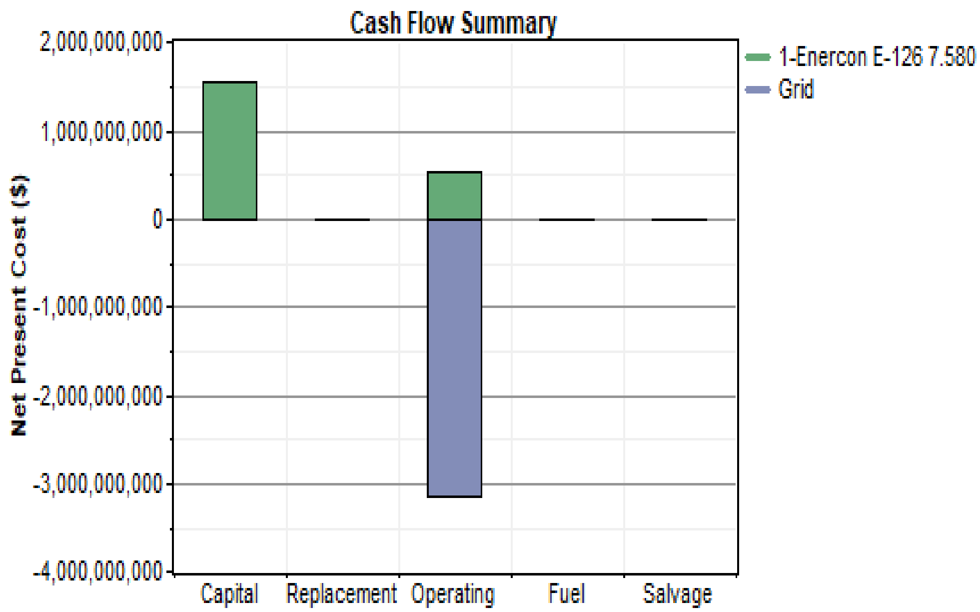
a


Monthly Average Electric Production
Power (kW)
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Wind
Grid

b


Cash Flows
Nominal Cash Flow ($)
500,000,000
0
-500,000,000
-1,000,000,000
-1,500,000,000
-2,000,000,000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Year Number
Capital
Replacement
Salvage
Operating
Fuel

c



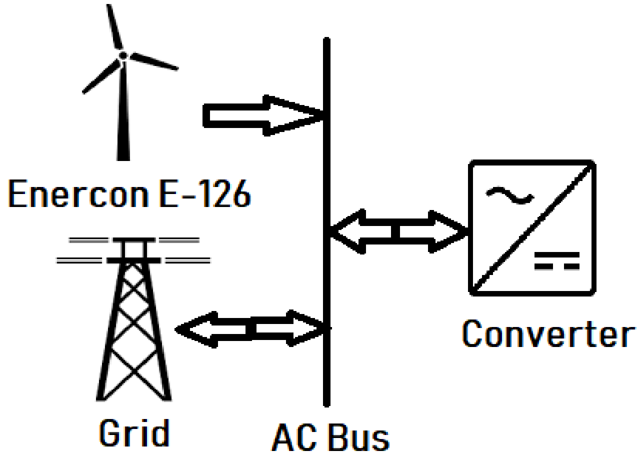
d

Fig. 34. Curves regarding selected system. a) Wind turbine output. b) Monthly average electricity production. c) Cash flows d) Cash flow summary

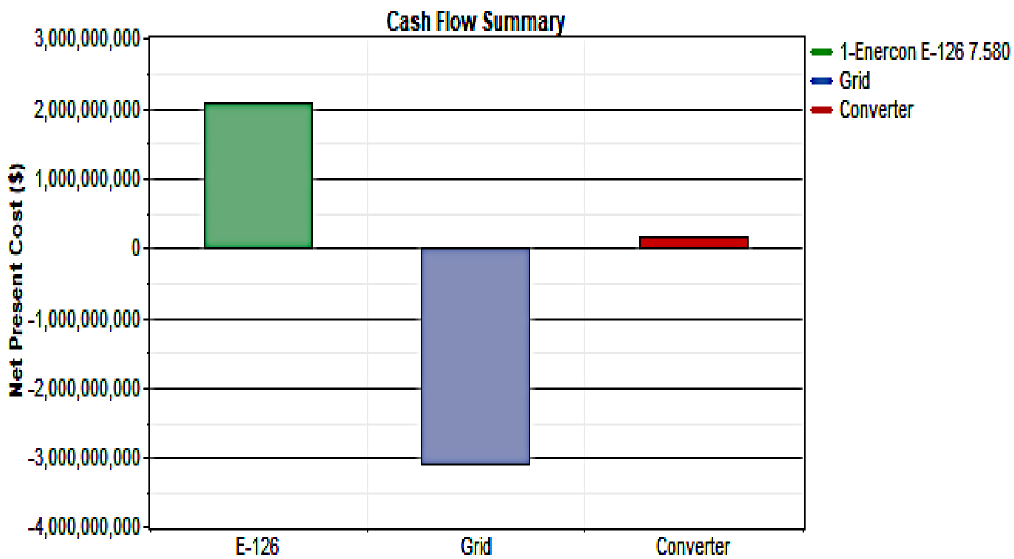
1) ***Inverter***

Initially, parametric study was conducted on wind turbines alone but to make the project more realistic an inverter will be included now. The selected inverter is ACS880 from ABB. The inverter's data sheet can be found in [106] the inverter has 97% efficiency and up to 8 MW capacity. Making it suitable for the 7.58 MW turbine. As there are 135 turbines used in the proposed system 135 inverters will also be used. The price of the inverter was not directly obtainable but IRENA [107] states that the average price is 0.14$/Watt. Making the cost of the inverter 1.12 million USD including cost of Power electronics, Control card Filters, Distribution board and others, Indirect costs, Margin and O&M costs. Inverter lifetime was not presented in the datasheet and will be assumed to equal 25 years.

H. Finalized system



a



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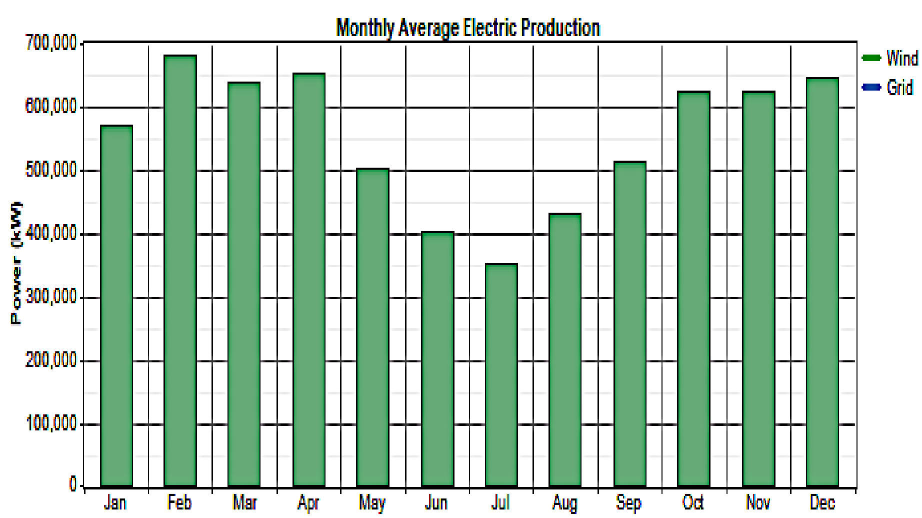

c

Fig. 35. Final system curves. a) System diagram. b) Cash flow. c) Monthly energy production.

Table XVII
FINAL SYSTEM METRICS

LCOE $\left(\frac{\$}{kWh}\right)$	Energy generated (TWh)	Profit (mil USD)	CO2 emissions saved $\left(\frac{kg}{year}\right)$	Energy density $\left(\frac{GWh}{\text{km2}}\right)$	Profit per Area $\left(\frac{million\ \$}{\text{km2}}\right)$	LCOE * Area $\left(\frac{\$.\text{km2}}{kWh}\right)$
0.0333	4.839	884	$3.06*10^9$	136.91	25.01	1.18

Table XVII shows important concluding values for the final system which includes the inverter. As can be seen energy generated and the economics of the project reduced by factoring the inverter into the study. However, the metrics still show favorable results with over 3.06 billion tons of CO_2 saved per year as a result of the project and over 880 million USD in profit and as the project costs 2.209 billion USD this means that the Return on investment for this project is over 40%. And the payback period is 9.13 years. Compared with muskrat falls project, the proposed project will cost around 80% less than what has been invested in muskrat falls so far (2.209 vs 12.7 billion USD) given that no competency issues (like the ones seen with muskrat falls) arise. These figures are however limited in as far as it compares an intermittent source (wind) with a dispatchable source (hydro) for true accuracy energy storage has to be included.

I. Farm layout and wake effect

One limitation of HOMER is that it does not simulate energy losses due to wake effect between turbines. The minimum separation distance used in this work was 2 rotor diameters between adjacent turbine columns and 8 rotor diameters between turbine rows. this was obtained from [76]. [76] suggests using 2-4 rotor diameters between columns and 8-12 rotor diameters between rows. The different separation distances, their contribution to the wake effect and loss of annual energy output will be examined in this section

System Advisor Model or SAM is a software developed by NREL [108]. The software is able to simulate multiple types of renewable energy projects at different scales and provide detailed economic analysis in case a power purchase agreement (PPA) is available. SAM will not be used in this work however for its detailed economic analysis but rather as an evaluation tool of the wake effect. One major limitation of this software is that it is only limited to U.S locations. In the case of solar projects, irradiance data can be easily edited to tailor the simulation to any location but in case of wind projects this is a much more difficult task. Therefore, a U.S. location will be selected, and the upper and lower ranges of turbine separation distances are evaluated.

In SAM under "wind resource" southern Texas is the chosen location. Under "wind turbine" Enercon E-126 at 135 m hub height is chosen (which is built into SAM library). SAM automatically sized the number of turbines as 136 turbines. This is one more turbine than the proposed system since SAM looks for an even number of turbines in order to have a balanced number of rows and columns. Under “wind farm” the selected farm power capacity is inputted as 1,023,300 kW to match HOMER simulation. Under “turbine layout” turbine spacing is inputted as 2D and 8D for the first simulation and 4D and 12D for the second simulation. All other economic variables of the power purchase agreement were left at their default values as a PPA is not available for this study and the economics of the project have already been covered by HOMER and so are of little interest. The number of rows and turbines of rows were left at their default values (17 turbines per row and 8 rows). The results of both simulations are shown in figure (36), figure (37), table XVIII and table XIX

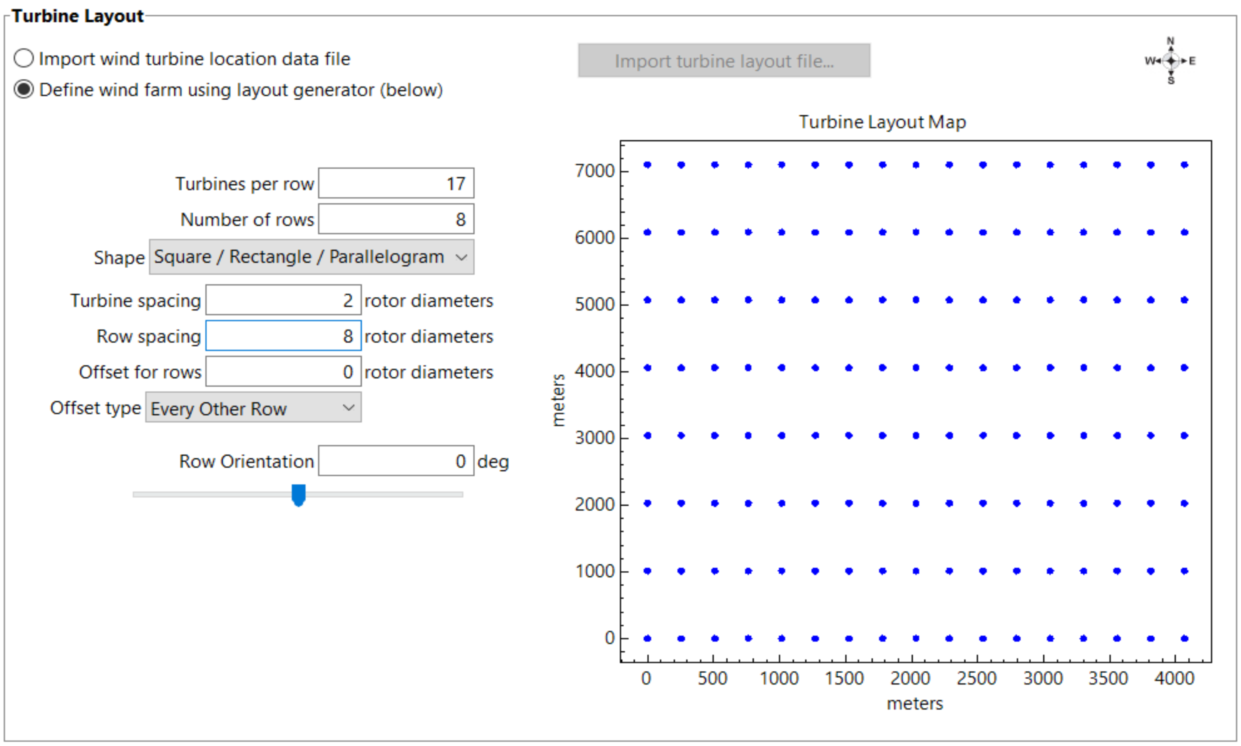

Fig. 36. Turbine layout of lower range (2D and 8D)

TABLE XVIII
SIMULATION RESULTS OF LOWER RANGE (2D AND 8D)

Metric	Value
Annual energy (year 1)	3,566,626,304 kWh
Capacity factor (year 1)	39.9%
PPA price (year 1)	4.91 ₵/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	5.32 ₵/kWh
Levelized PPA price (real)	4.22 ₵/kWh

Levelized COE price (nominal)	
Levelized COE price (real)	3.92 ₵/kWh
Net present Value	$131,898,816
Internal rate of return (IIR)	11.0%
Year IRR is achieved	20
IRR at the end of the project	11.93%
Net capital cost	$1,596,208,128
Equity	$857,585,792
Size of debt	$738,622,400

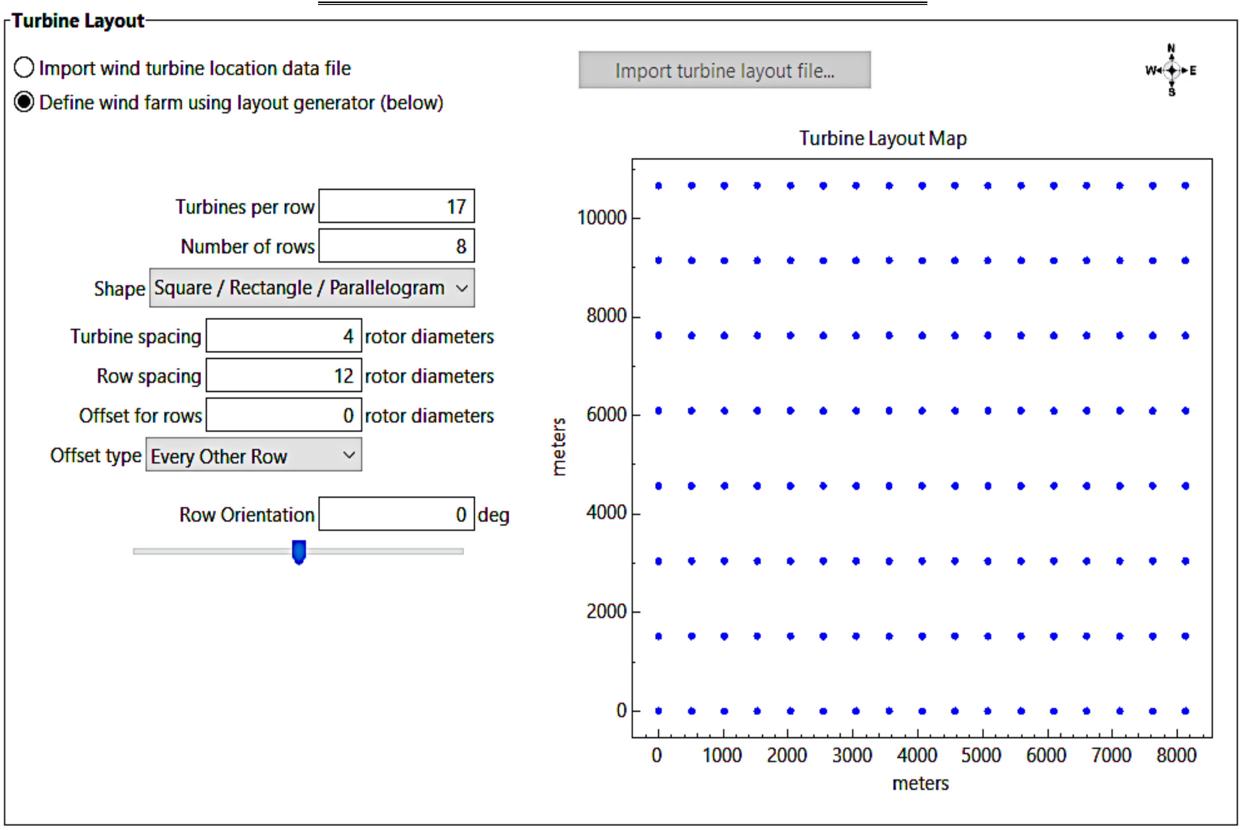

Fig. 37. Turbine layout of upper range (4D and 12D)

TABLE XIX
SIMULATION RESULTS OF UPPER RANGE (4D AND 12D)

Metric	Value
Annual energy (year 1)	3,742,550,784 kWh
Capacity factor (year 1)	41.9%
PPA price (year 1)	4.61 ₵/kWh

PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	4.99 ₵/kWh
Levelized PPA price (real)	3.96 ₵/kWh
Levelized COE price (nominal)	4.63 ₵/kWh
Levelized COE price (real)	3.67 ₵/kWh
Net present Value	$131,838,464
Internal rate of return (IIR)	11.0%
Year IRR is achieved	20
IRR at the end of the project	11.89%
Net capital cost	$1,596,208,128
Equity	$857,585,792
Size of debt	$738,622,400

A few observations are of note from the above figures and tables. The difference in energy output for these otherwise identical systems is 0.176 TWh which is roughly 4.9%. this number might seem insignificant but in a project of this scale it translates to a large amount of money as missed opportunity. If this number is applied to the system proposed in this project (4.839 TWh) it becomes 0.237 TWh which given the 12 cents/kWh grid price of Newfoundland leads to 28.45 million USD lost profit. The decision on whether to use the lower range of the separation distance or the upper range for this project needs to be determined on economic basis. If the cost of the extra land required to achieve the upper range (4D and 12D) is higher than 28.45 million USD then the lower range is better. realistically speaking however, this is not likely to be the case.

A final observation here is that the energy produced by the U.S. location produced at least 1 TWh less annual energy output than the Newfoundland location. Proving once more the efficacy of the site selection deployed in this work and the remarkably high wind energy potential of Newfoundland.

J. Wind system conclusion

In this study a wind farm in Newfoundland and Labrador was proposed. The annual energy produced by the wind farm was set to equal the annual energy produced by the muskrat falls hydroelectric project (but without muskrat falls many ecological issues) at 4.9 TWh.

A preliminary test of a large wind farm was conducted in St. john's international airport using Vesta 164 turbines and the result shows the province as having sufficient wind resources for a profitable large-scale wind energy deployment. (823 million USD profit). Two methods for wind energy calculation were deployed and compared which were the use of HOMER simulation and the use of Mathcad equation solver. The results show that the error (difference between the two methods) is minimal at 0.237% therefore a combination of both software is used.

Site selection was carried out by employing a holistic approach which factored in effect of noise, proximity to renewable projects, ecological/geological considerations and proximity to roads/ existing infrastructure. The result of site selection was four potential sites which were Portugal cove, Bonavista, Grand banks and Saint Bride's. Wind turbine selection procedure involved the study of wind farms inter and intra nationally to arrive at the five turbines used in this work (GE-2.5 XL, Vestas 164, Enercon E-126, GE 1.5s and Siemens SWT 3.6 120) which were tested at each location using the different hub heights available from the manufacturer. This resulted in a parametric study involving 36 systems.

After conducting a comprehensive parametric study involving both economic and area considerations, the best system was selected. The wind farm uses 135 Enercon E-126 wind turbines in Bonavista location at 135m hub height. After including the inverter, the final system costs 2.209 billion USD while selling electricity that is worth 3.094 billion USD to the grid. Making the system profitable with approximately 884 million USD in profit which represents 40.06% return on investment (ROI) over the project's lifetime and 1.36% annualized ROI. The Payback Period of the project is 9.130 years and the Discounted Payback Period is 13.62 years assuming a 6% discount rate which is the default value in HOMER. The usage of SAM software showed that the farm stands to gain at additional 5% or 0.237 TWh annual energy production if the separation distance between turbines was increased to 4D and 12D. this corresponds to an additional 28.45 million USD in profit.

Further research that expands on this work can be conducted in order to evaluate the potential of hybrid horizontal/vertical wind turbine farm and hybrid solar/wind farm. These systems can be compared against the current system in terms of economics, area and grid integration considerations. Large scale energy storage can be proposed in Newfoundland and Labrador to accommodate the intermittency of wind energy.

K. Gravity energy storage

1) *Overview*

The dominant form of large-scale energy storage for the past several decades has been Pumped Hydro Storage systems (PHS). In this potential energy based technology, water is pumped from a lower reservoir to an upper reservoir when electricity rates are low (supply exceeds demand), and let to flow back through the turbine when electricity is needed (at a roundtrip efficiency of 80% or slightly higher). This, however, requires naturally elevated grounds (such as hills) for the construction of the upper reservoir. A new concept called "Gravity Energy Storage" (GES) eliminates this requirement. Gravity Energy Storage (also known as gravity battery) was first invented by Professor Eduard Heindl in 2010. The concept of this system involves the hydraulic lifting of massive rock structures using water pumps. The system is built in a deep underground shaft and exhibits similar efficiency to PHS. The most promising aspect of this technology is how well its performance improves at larger scales. For example, its storage capacity is proportional to the fourth power of the radius of the lifted rock, which means that the energy stored increases 16 folds each time the radius of the rock is doubled, while facility construction costs increase 8 folds only. For a 250m diameter rock, the energy storage is estimated at around 8 GWH which is competitive with large PHS stations [109]. If a piston is selected for the Gravity Energy Storage having a radius r and a length l = 2r, then the piston can be lifted to the height h = r. which is due to the fact that the seal must lie somewhat above the center of gravity, thus at a distance r above the bottom of the cylinder so that the cylinder is hydrostatically stable while floating [116].

According to recent news (11/05/2020) a Scottish company, Gravitricity, is developing the UK's first gravity-based system to be coupled with wind and solar generation [110]. Gravitricity is planning a 250-kW grid connected facility which involves a 16m rig and 150-1500m shaft. The mass of the rock formation ranges from 500 to 5000 tons and the company anticipates the system will be able to power 30,000 homes for 2 hours. Gravitricity claims the project will be able to stabilize electricity at grid frequency of 50 Hz and can respond to full power demand in less than 1 second as well as offer 25 years service life with no performance degradation [111]. The project pilot will start construction in October 2020 and costs 1 million euros. The company mentioned that abandoned coal mines are ideal locations that minimize drilling costs and environmental concerns; however, the project can be sited anywhere even in urban settings [112]. In March 2020, Gravitricity won a £300,000 grant from Innovate UK's Energy Catalyst programme to assess the suitability of former mine shafts in South Africa with project partners RESA Energy [113].

Austrian researchers claimed that gravity-based storage can cost 50-100 USD per MWh of storage and 1-2 million USD per MW of installed capacity. Since the generation is fully controlled the system can be used to generate a lot of energy fast (high power) or to generate a small amount of energy steadily depending on the power rating of the turbine used [114].

The drawbacks of this technology are that it requires a large rock formation with minimal amount of cracks that the water can slip through and construction of such projects involves large amounts of concrete which has a large carbon foot print [109]. There is also concern whether this type of system can compete with lithium ion batteries which are exhibiting falling prices and ultra fast response times [112]. However, other sources claim the technology is competitive even with lithium ion batteries due to high service life, rapid charge and discharge cycles and high efficiency [115].

Gravity storage has high potential to overcome the ecological and environmental impacts of PHS as well as offer greater energy density and higher flexibility in terms of location siting. However, despite its simplicity the technology has yet to be tested. The construction of the appropriate sites could prove to be technically challenging, as the gravity-based system facility has tough geological requirements for the shaft and the lifted rock formation. On the other hand, it is exciting to see this technology become mainstream and compete with established storage technologies such as Lithium ion batteries or Pumped hydro storage as the future of energy storage should be a mixed variety of different technologies with each offering certain advantages and disadvantages instead of simply relying on one technology.

2) ***System sizing***

Since Muskrat falls produces 4.9 TWh in a year. If we assume equal daily loads (which is justified since hydro usually works as baseload generation) then this corresponds to approximately

560,000 kWh generation per hour. Therefore, the proposed wind energy system needs to provide this hourly load every hour. This is however not doable without energy storage given wind's intermittency. Therefore, a gravity energy storage system will be roughly estimated to turn the wind farm to functionally the same as Muskrat falls for comparative accuracy. The equation that governs the energy storage capacity of the GES is

$$E = \left(2 * \rho_r - \frac{3}{2} * \rho_w\right) * \pi * g * r^4 * c \tag{9}$$

Where:

E is the energy storage capacity of the system (Wh)

ρ_r is the density of the rock (assumed as 2600 kg/m^3)

ρ_w is the density of water (1000 kg/m^3)

g is the gravitational constant (m/sec^2)

r is the radius of the rock (m)

c is the correction factor ($2.874*10^{-4}$)

Using the above equation yields 1 GWh for 150m diameter rock, 3 GWh for a 200m diameter rock and 8 GWh for a 250m diameter rock which are the same results obtained by Heindl Energy [116].

To determine the required storage capacity for the proposed wind farm, MS excel was used to deduct 560,000 kWh from the hourly load generated by the farm to find if for any given hour the generation is in surplus or deficit. If in surplus the excess energy is to be stored and if in deficit then the missing energy is to be extracted from storage. Integrating the surplus/deficit data yields the overall pattern required by the storage system and is shown in figure 38. From the blue curve we can see that overall, the 1st quarter of the year runs at a surplus reaching 246 GWh around March. This is due to winter having stronger winds. From March to June an overall deficit can be observed which drains the earlier accumulated surplus reaching 0 kWh at the middle of the year. In the 3rd quarter the deficit continues reaching its peak of -241 MWh at the end of summer. As fall begins the surplus stored energy starts to increase until energy reaches 0 again. In order to make this storage work, 241 MWh have to present in the system at the beginning of the year which shifts the blue curve up to become the orange curve at which the energy storage is self sustaining and has a rated capacity of 487.4 GWh. From equation 9, 349.2 m (approximate to 350 m) rock radius is required to store 487.4 GWh. The rock piston should have a diameter of at least 100 meters in order to be competitive with other bulk storage solutions [116].

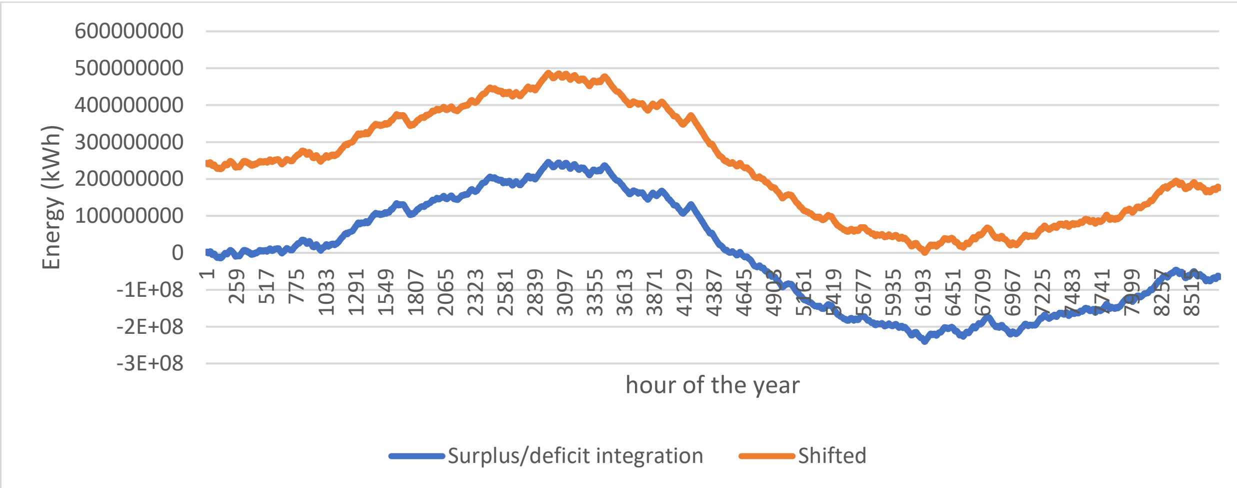

Fig. 38. Energy deficit/surplus integration

3) *Cost*

The Levelized Costs of Storage (LCOS) vary between 0.09 USD/kWh for 10 GW and larger systems and 0.18 USD/kWh for a 1 GW system [116]. This makes the total cost of the 487.4 GWh system $1.097 billion (assuming 25-year lifetime). Adding this figure to the cost of the wind farm results in 3.31 billion USD or 4.33 billion CAD (in today's exchange rates) which is less than the 7.4 billion initial budget for Muskrat Falls leaving room for a 63% (2.8 billion) for unincluded cost elements and cost overruns. Therefore, it is this work's position that had Nalcor waited till 2020 to add additional capacity, wind energy might have been seriously considered. The question of project lifespan adds complexity to this calculation for example if Muskrat Falls will last 50 years (twice the lifespan of the wind farm) with no equipment replacement then it might be the more viable alternative. This calculation was from a broad perspective and might not have included all sources of cost. It was performed primarily as a proof of concept to attract further analysis.

VI. Conclusion

In this study a critical review of Muskrat falls was conducted followed by a wind farm design. The review evaluated literature on the advantages, drawbacks, and implications of the mega hydroelectric project. The project was justified due to a 2010 load forecast by Nalcor which suggested that the province would suffer from electricity deficit by 2021 if no new generation were added. Nalcor then did a study (which was later reviewed and verified by MHI) using CPW analysis to evaluate the potential alternatives (such as small on island hydro, wind, Holyrood upgrade, Gull Island, Energy import, Combustion turbines and LNG) before deciding on the 824 MW hydroelectric plus maritime link "Connected Island" project as the best option. Some of the benefits of the project include 92% local labor employment, 98% renewable electricity, 3-4 million tonnes CO_2 emissions reduction, access to the North American electricity grid via the link to Nova Scotia and eliminating the province's reliance on oil for electricity production. On the other hand, the drawbacks of the project include methyl mercury release affecting the health of indigenous communities, possibility of landslides due to rising water pressure after reservoir flooding, release of sediment pulse to downstream lakes as shoreline erodes, over $6 billion cost overrun, over 2 year schedule overrun and possibility of increased electricity pricing.

A wind farm in Newfoundland and Labrador was proposed with an annual energy output similar to Muskrat Falls. A preliminary test of a large wind farm was conducted in St. John's international airport using Vesta-164 turbines and the result shows the province as having sufficient wind resources for a profitable large-scale wind energy deployment (823 million USD profit). Two methods for wind energy calculation were deployed and compared which were the use of HOMER simulation and the use of Mathcad equation solver. The results show that the error (difference between the two methods) is minimal at 0.237% therefore a combination of both software is used. Site selection was carried out which resulted in four potential sites (Portugal cove, Bonavista, Grand banks, and Saint Bride's). Wind turbine selection procedure involved the study of wind farms inter and intra nationally to arrive at the five turbines used in this work (GE-2.5 XL, Vestas 164, Enercon E-126, GE 1.5s and Siemens SWT 3.6 120) which were tested at each location using the different hub heights available from the manufacturer. This resulted in a parametric study involving 36 systems.

The parametric study included both economic and area considerations. The best system was selected as the wind farm which uses 135 Enercon E-126 wind turbines in Bonavista location at 135 m hub height. After including the inverter, the final system costs 2.209 billion USD while selling electricity worth 3.094 billion USD to the grid. Making the system profitable with approximately 884 million USD in profit which represents 40.06% return on investment (ROI) over the project's lifetime and 1.36% annualized ROI. The Payback Period of the project is 9.130 years, and the Discounted Payback Period is 13.62 years assuming a 6% discount rate which is the default value in HOMER. The usage of SAM software showed that the farm stands to gain at additional 5% or 0.237 TWh annual energy production if the separation distance between turbines was increased to 4D and 12D. This corresponds to an additional 28.45 million USD in profit. Next a large-scale gravity energy storage system is added to the system thus converting it from an intermittent supplier of power to a more even baseload generator with an hourly generation capacity of 560,000 kWh (same as Muskrat Falls). Assuming an LCOS of 0.09 USD/kWh this, however, increases the project cost to 4.33 billion CAD which is 63% cheaper than Muskrat Fall's initial budget leaving room for unincluded expenses and cost overruns. However, if the project lifespan of Muskrat falls is 50 years (twice the lifespan of the windfarm) with no equipment replacement then it might be the more attractive alternative

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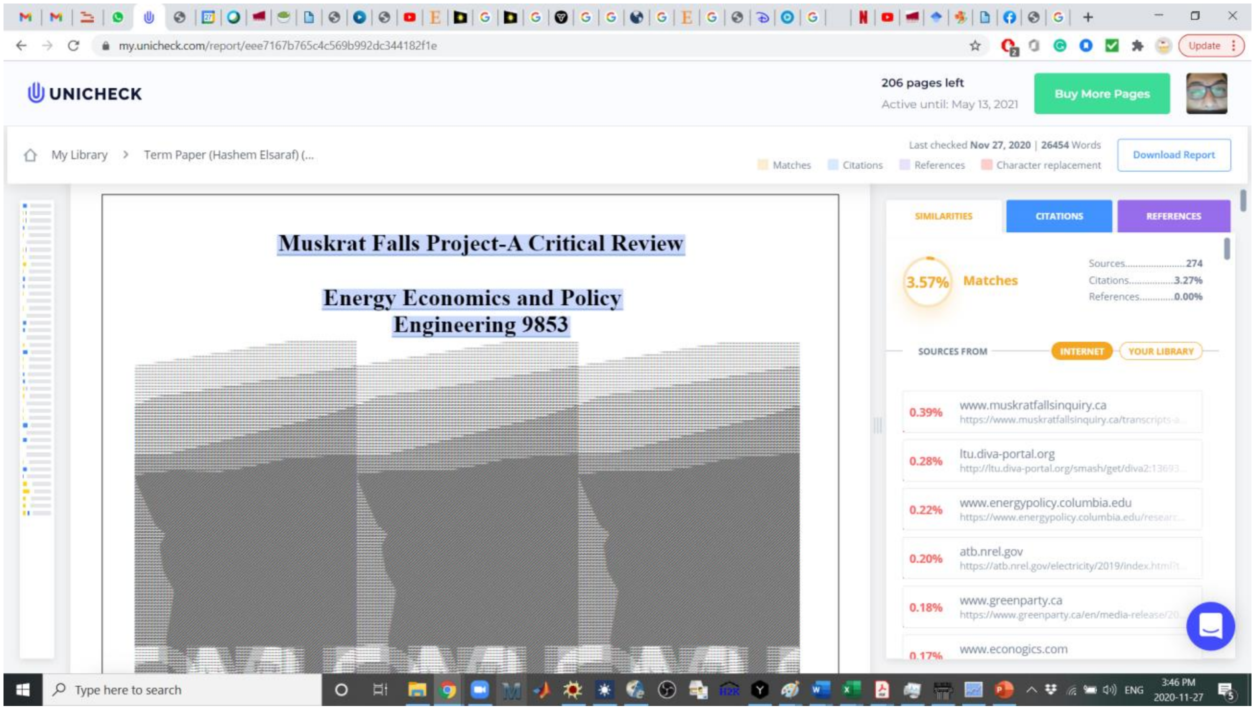
Appendix



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