Design of a utility-scale wind farm in Newfoundland and Labrador

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***Abstract*—The Muskrat falls hydroelectric project in Newfoundland and Labrador has faced many issues (economic, temporal and ecological). In this article, a study of a wind project of similar generation capacity (4.9 TWh) is conducted. The wind farm is able to generate the same annual energy output as muskrat falls for a fraction of the cost. St. john's international airport was chosen as the test location to introduce the methodology and to provide preliminary evaluation of a large-scale wind project in the province with the results being favorable (823 million USD profit). Using a comprehensive 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 (from different manufacturers) were selected for the study which areGE-2.5 XL, Vestas 164, Enercon E-126, GE 1.5s and Siemens SWT 3.6 120. A parametric study of 36 systems was then conducted to test each turbine type at each location at different hub heights. The study included both financial (LCOE, Profit) and area (Energy density, Profit/Area) considerations. The results of the study showed that different systems performed better at one category or another. After careful comparison of the 36-systems, Bonavista wind site with Enercon-126 wind turbine at 135m hub height was justifiably the best system. The study is then finalized by adding ACS880 inverter from ABB 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)**

I. PROBLEM STATEMENT

Newfoundland and Labrador have undergone an 824 MW hydroelectric project in Muskrat falls. However, the project has gone overbudget and over schedule. There are many concerns regarding this project such as environmental and ecological concerns including adverse effects on human health and possibility of landslides.

This project will examine the major criticisms of the Muskrat fall project and introduce the literature in support of a utility scale wind farm in Newfoundland and Labrador of equivalent production capacity. In order to extrapolate on the idea held by many that a utility scale wind project should have been developed instead of the muskrat falls hydro project.

Upon completion this project would have undergone the design of aforementioned wind farm and examined its various aspects such as economic, environmental, legal and social affects.

II. INTRODUCTION

A. *Criticism of the muskrat falls project*

The Muskrat falls project is one of two sites 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 [1]. The first phase of the project, Muskrat falls, includes the development of an 824 MW hydroelectric facility and over 1600 km of transmission lines across the province including a maritime link between Newfoundland and Nova Scotia according to Nalcor's website [2].

Nalcor promised the following benefits of the project [2]

- 98% sustainable long-term renewable power
- Reduction in Greenhouse gas 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 and to notoriously call it a "boondoggle" [3].

1) *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.

After reservoir flooding 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.

A main reason for higher MeHg levels in Inuit communities is the increased consumption of aquatic foods. Figure 1 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.

In [5] the authors have discussed some of the effects of MeHg on humans which include:

1. 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. In-utero infants who were subjected to high levels of MeHg were born with:

- Mental retardation
- Seizure disorders
- Cerebral palsy
- Blindness
- Deafness
- IQ deficits

2. A correlation between MeHg rich fish consumption and acute myocardial infarction was found.
3. 2x-3x increased rate of cardiovascular death.
4. Renal toxicity.
5. Weakened immunity.

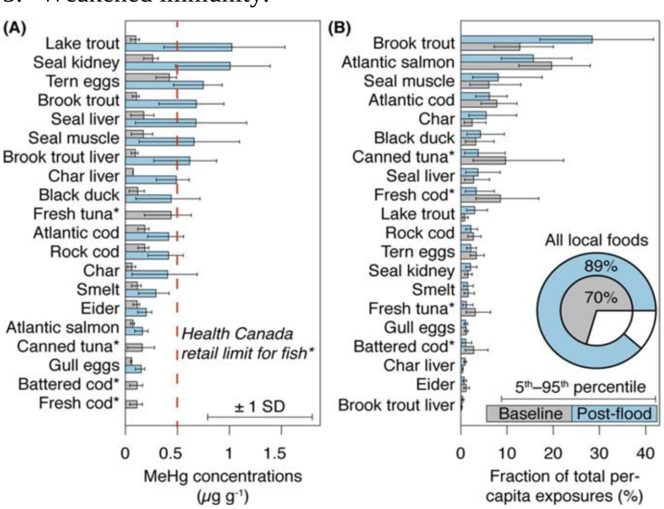


Fig. 1. MeHg in top 20 food sources affected by flooding consumed by nearby Inuit populations. [4]

2)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 fall 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 1.

TABLE I.
HYDRO-ELECTRIC DAM PROJECTS COMPARED TO ENERGY PROJECTS [6]

	Mean Cost Over run	Freq. of Cost over run	Schedule Over run	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

3)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 2 which is reproduced from [8].

TABLE II.
SUMMARY OF FINDINGS FROM [8]

	Wind Power	Reservoir Hydro Power
Number of studies	63	28
Variations in GHGemissions	4.6-55.4 (g CO_{2eq}/kWh)	4.2-152 (g CO_{2eq}/kWh)
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

4) 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 fall 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 Eastwards into the deep river whirlpool downstream of Muskrat Falls.

Fig. 2. 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 [9].

B. 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 [10]. Despite exhibiting this invaluable, climate friendly energy resource, the region dwells in the production and consumption of fossil fuels. The dependence on nonrenewable energy resources has exponentially drained the province’s economy due to the global fluctuation in the prices of fossil fuels [11],[13].

At present, hydroelectric power occupies a lion’s share in the province’s energy mix that will be further increased by the impending completion of 824 MW Lower Churchill Project (Muskrat Falls) [11]. However, the adverse ecological and imminent social impact of the hydropower plant decreases the benefits of such project [10].

Hence the best and most acceptable source of renewable energy for the province’s energy arena is the wind source. This is because of the geographical position of the province along the Atlantic coast which provides optimum wind distributions [15]. 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.

To support this assertion, the study from NL's Department of Natural Resources, NL, Canada (Figure 3) estimates that the province owns the capacity of generating 5GW of wind energy, however the current installed capacity of wind energy dispensation 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[10],[11].

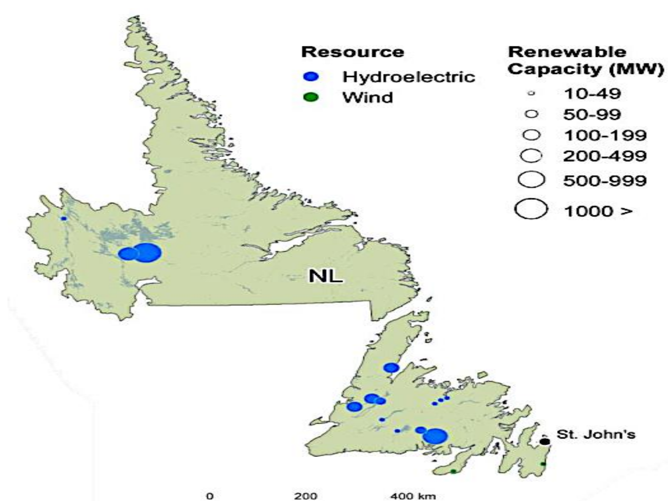


Fig. 3. The Current Renewable resources and capacity augmentation in Newfoundland and Labrador [18].

As can be seen in figure 3, The Newfoundland region of the province exhibits a distinguishing potential for wind energy development, unlike the Labrador region, where the ongoing Muskrat falls hydroelectric project is located.

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 [12].

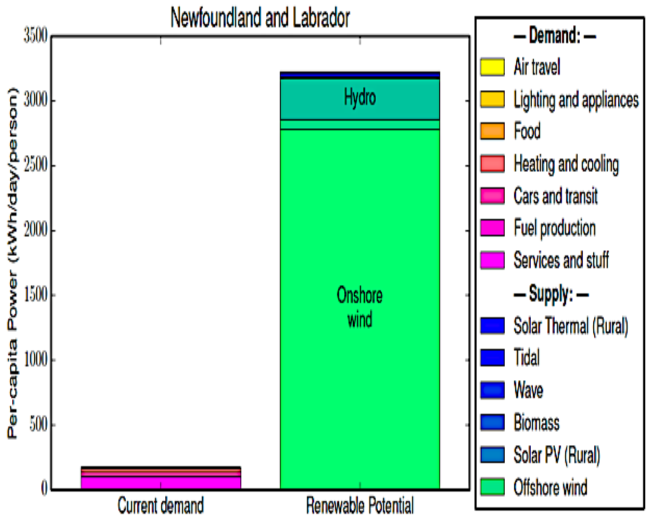


Fig. 4. Provincial summary of energy demand and renewable energy supply in Newfoundland and Labrador [11]

With reference to figure 4, 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 [12],[13].

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 [15]. With its enormous potential of wind source, HVDC links to the Atlantic coast in the U.S., possibly via Quebec, would form a well-streamlined strategy in the energy sector of the country as a whole.

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 [16],[18]. 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 [16]. Figure 5 affirms the view that Atlantic provinces exhibit a wide array of distribution of wind resources. [17][18]. Further, the estimates for NL wind potential ranges from 450MW to 102 times the provincial demand.

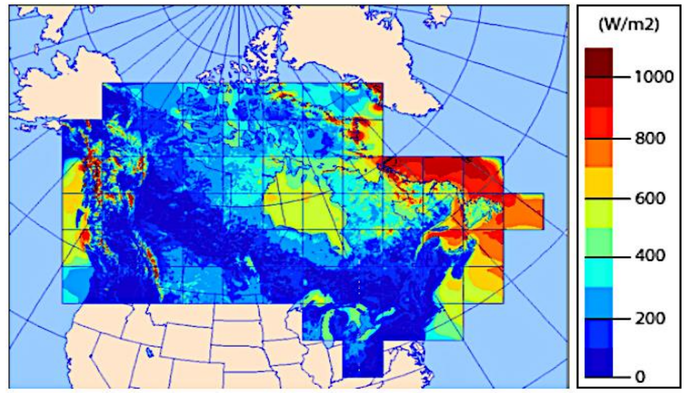


Fig. 5. Wind energy distribution across Canadian provinces [32] [33].

A magnified illustration of the province is depicted in figure 6 and based on the legend scale signifies the availability of wind as a source of energy per area (km^2). Thus, regions in the Northeast coast, the Burin Peninsula, the Northern Peninsula and parts of central Newfoundland can form an axis of wind energy production.

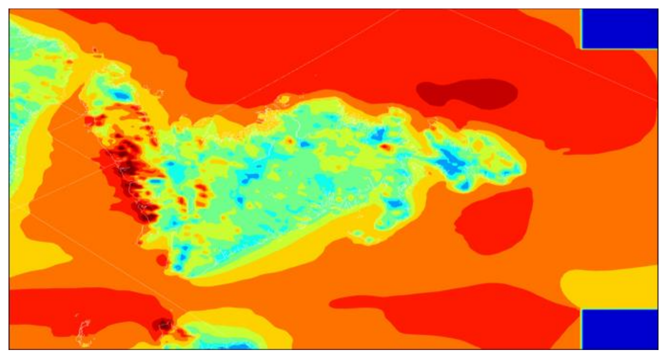


Fig. 6. Magnified version of Fig 5, representing Newfoundland and Labrador [16].

C. Barriers and Challenges

Barriers to wind energy development in NL involve multi-dimensional facets. Various studies have focused on exploring and analyzing these barriers and consequential challenges that arise to overcome those barriers [3]. Among all factors Trudgill's 'AKTESP' framework relies on six tangential aspects- *agreement, knowledge, technological, economic, social, and political aspects of wind energy development,* in delineating wind energy potential in the province of NL. This framework is widely acclaimed and accepted across the spectrum in energy industry [15].

The Study observes that the transition to renewable energy in the province of NL requires wide consultation across stakeholders as challenges emerge both at individual and institutional levels [13]. broad consensus augmented with policy level decisions would help bring the sea of change in transforming wind energy from a promising potential resource to a predominant active renewable energy resource in the region. The below section briefly discusses the focused area of barriers and challenges and are as follows; [15],[16] *1) Barriers at the public policy level*

The major political barriers that confront the Wind energy development are Barriers at the legislative level, acceptance of status quo and lack of public participation.

2) Economic barriers

Unlike other provinces in Canada, the economic status of the province of NL is unique and demand-supply mismatch in the energy econometrics hampers wind energy development. The study [15] analysed different aspects of these barriers such as:

1. Competitive pricing in wind energy development
2. The meagre energy demand in the province and dearth of external energy export markets.
3. Supportive prices for fossil-based fuels.

3)Information and Knowledge barriers

Inadequate knowledge and understanding of wind energy development and conservative attitude to share the information between the subjective and key stakeholders who are similarly placed- *'Silo effect'* and other factors may include- Energy illiteracy, Lack of dexterity etc.

4)Technical Barriers

Through data analysis, the study observed that the technical barriers only a 29% inhibiting factor in the development of wind energy amongst all barriers discussed so far. However, the fundamental technicalities remain a prime concern in augmenting large scale/Utility scale/Commercial scale wind farm particularly in Newfoundland and Labrador province [15]. Such as,

- Intermittent nature of the wind.
- Unique challenge of 'Icing of Turbines'.
- Conflict with existing other renewable infrastructure.

Having discussed with well-developed and genuine barriers facing by the province in its quest of developing wind energy. There are certain challenges intertwined which is concerned with the latitudinal alignment of the NL province. NL province is located in the place of vicinity where two strongest and furious ocean currents confluence-Heavy and cold Labrador current and Light and warm Gulf stream. Thus, the challenge of accompanying strong gusty winds and frequent occurrences of Blizzard and snowstorm pose a considerable existential threat to the wind energy infrastructure [15]. However, the Department of Natural resources, Canada have allayed these concerns through various scientific studies and concluded that gustiness of the wind can be overcome while adapting region specific wind farm layout and innovative turbine design specifications.

D. Wind energy resource map in Newfoundland and Labrador

The site for wind energy development is the indispensable primary step in tapping the potential effect of wind sources [17],[18]. Due to the coastal effect in NL, the coast of the province generally exhibits higher wind. Further, Eastern Newfoundland, Northern Peninsula and Burin Peninsula blessed have promising wind potential for utility scale wind energy development however, other regions such as Avalon Peninsula and the western coast are suitable of small-scale wind energy farms. Thus, in effect, wind varies positively from the central region of Newfoundland towards the coastal part [10],[11],[18].

The geographical site assessment of wind energy development is a long mathematical tedious process. A continues study of 6-12 years of surface data mobilization and a network of data measurement is fundamental in any wind energy analysis. Later this data can be corroborated with the available, acclaimed and adjusted climatological and terrain conditions could unveil a wind scale map of an interested region. As observed in its study by Canadian wind energy association (CWEA) [16].

The elevated terrain of the region confirms the higher capacity of available wind sources. Thus, referring to figure 7. 5.5 to 7 m/s of easterly wind variations can be seen at 10 m height and 6.5 to 9 m/s wind variations at 50 m level. These measurements can effectively be done using Measure-Correlate- Predict (MCP) method. This method is a predictive specific model which refines the combined collected data of surface geo study and global permutations and the parameters of the method includes vegetation cover, Geo-spatial data, wind calculation etc. [16],[18].

It is to be noted that measurement of wind data w.r.t low tower height with near-by obstacles such as hills, vegetation, houses, exhibit high turbulence at downwardly direction and hence low power density. Therefore, the calculation of wind speed w.r.t incendiary elevation can be done with the power law [18],

Hence, based on the figure 7, it can be inferred that the province's Bonavista Bay region possesses promising wind energy potential of 350–1050 W/m^2 at 10 m elevation.

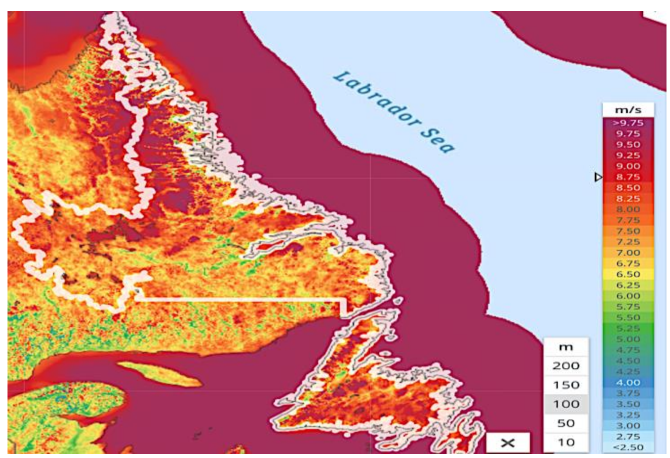


Fig. 7. Mean wind speed map (m/s) in Newfoundland and Province with varied colour index pattern [33]

Along with this the Burin and Northern Peninsula experience a power density of 160–350W/m2 at 10 m hub height and Wind speed in the Avalon Peninsula varies from 5.5 to 6.5 m/s at 10 m heights which is suitable for small scale and confined wind energy development[13],17],[18].

III.METHODOLOGY

A. *Muskrat falls energy production*

Assuming a 90% capacity factor. Energy produced by muskrat falls should equal 824*0.9*8760 = 6496416 MWH/year = 6.5 TWH/year.

There is a wide range of capacity factors for large scale hydro that exist in the literature according to EIA [19] the range of capacity factors for hydro in the U.S from 2009 to 2018 was 35.7 to 45.8%. but according to IRENA [20] large scale hydro can reach up to 90% capacity factor. And finally, according to energy.gov [21] The median capacity factor for hydropower plants in the U.S. from 2005 to 2016 was 38.1%

However According to Nalcor energy, the company that is creating the muskrat falls project [22], 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 67.8% will be taken as the capacity factor of muskrat falls. And the wind system must generate an annual 4.9 TWh of electricity to match the production of muskrat falls.

B. *Test location*

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:

1. Further assess the wind potential of the region
2. 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
3. Act as a venue from which the mathematical calculations and software simulation (methodology) can be introduced and compared
4. 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 [23] 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 [24] implemented in Mathcad and the other is using HOMER simulation software.

1) *Mathcad calculation*

Mathcad worksheet and MATLAB code have been provided in the appendix.

- *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 $\frac{m}{s}$ and k=1.9559 at 100m hub height.

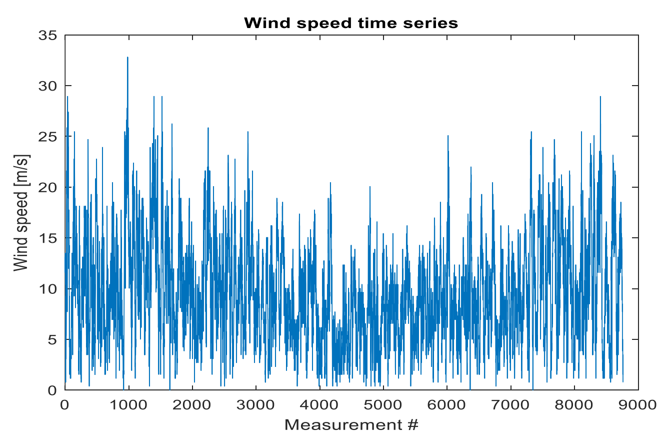


Fig. 8. Wind speed time series for every hour in 2019

Figure 8 shows the plot of the wind speed time series for every hour in 2019, figure 9 shows the Weibull probability density function fitted to the wind speed data and the cumulative Weibull probability density function and Table III shows the values of c and k for the test location all three figures are from MATLAB.

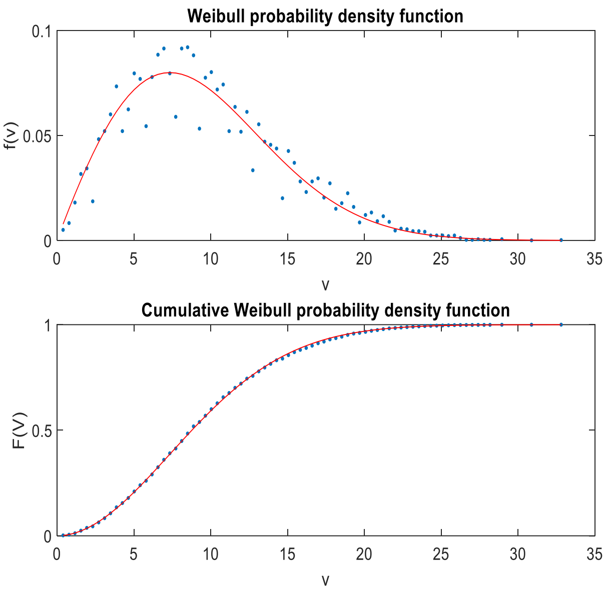


Fig. 9. Weibull probability density function fitted to the wind speed data and the cumulative Weibull probability density function (from MATLAB).

TABLE III.
MATLAB results

Output parameter	Value
C	10.5761
K	1.9559
cumDenFunction	76 x 1 double
cumFreq	1 x 76 double
Delta	1 x 76 double
densityfunc	76 x 1 double
freq	1
i	76

Next information about the test turbine is obtained. The chosen test turbine is Vestas164 8 MW turbine. Table IV illustrates key characteristics of the turbine. These values were selected as the most relevant values from the turbines data sheet. [25]. The power curve was also obtained from the same source and is shown in figure 10.

TABLE IV.
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

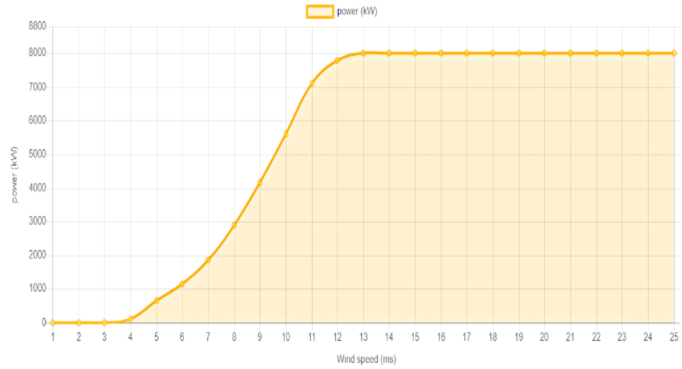


Fig. 10. Power curve of Vestas 164m

The maximum power density of the turbine P_{max} was then computed using equation 2 and is equal to 378.715 $\frac{W}{m^2}$

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

The above figure is much lower than the 800 $\frac{W}{m^2}$ value used in [26] 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 [27]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 represented in below table.

TABLE V
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/m^3

- *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.

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

$$P_{den} = 0.5 * \rho * v^3 \quad (4)$$

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 [24] where the example provided used c = 9 and k = 2. The result is shown in figure 11. 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 12. Which shows the distribution for c = 10, 15 and 20 mph at constant k [24].

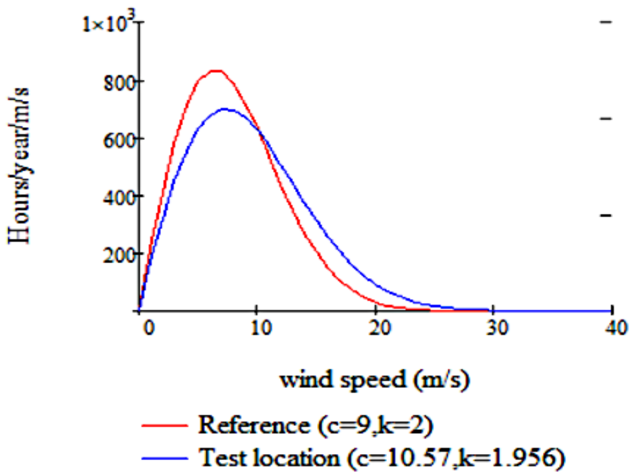


Fig. 11. Weibull distribution of test location versus example from reference [24].

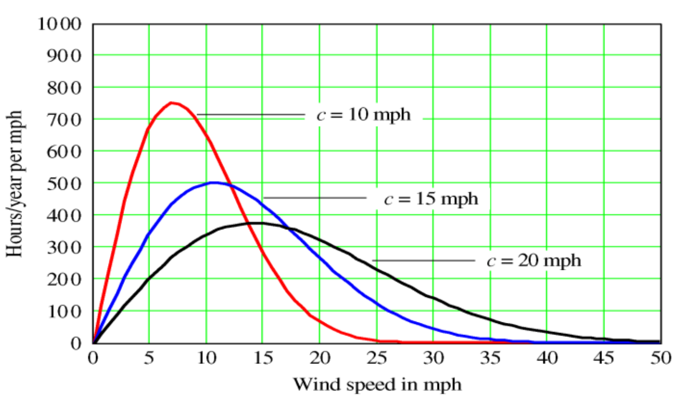


Fig. 12. Weibull distribution for various c values and k = 2. [24]

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 function (c). 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

$$v_m = 10\ \frac{m}{s} \quad (a)$$

$$\frac{d}{dvm}\left(h(v_m, k, c)\right) = 0 \quad (b)$$

$$V_{mode} := Find\ (v_m) = 7.334\ \frac{m}{s} \quad (c)$$

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 $P_{den}(V_{rmc})$ = 955.249 $\frac{W}{m^2}$.

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

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

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 13 shows the energy density of the wind from test location compared to the one from [28]

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

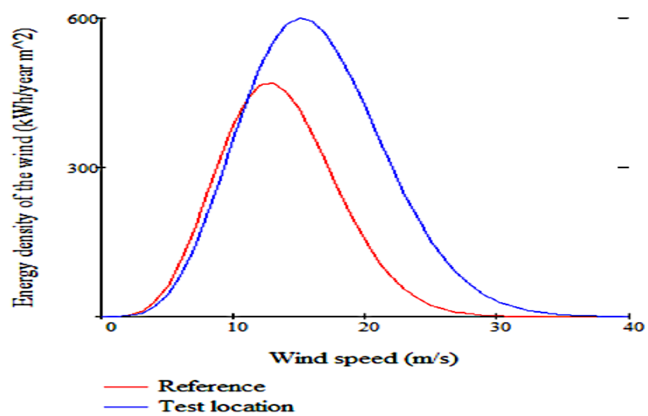


Fig. 13. Energy density from test location vs reference 24

The previous calculations have been regarding the wind resource itself. The following steps will now consider the wind turbine. function (d) 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 cannot 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.

$$Pdencon(v) \left\| \begin{matrix} 0 \ if \ v < vvutin \\ pmax \ if \ Pden > pmax \\ 0 \ if \ v > vcutout \\ Pden\ (v) otherwise \end{matrix} \right. \qquad (d)$$

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

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

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. $cf = \frac{E_{con}}{E_{rated}} = \frac{1.715*10^6}{P_{max}*8760} = 51.7\%$

- *Mathcad output summary*

The output values obtained are summarised below,

TABLE VI
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*

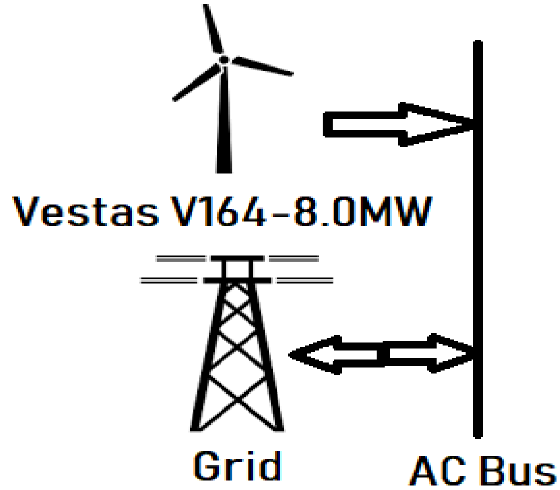


Fig. 14. System block diagram

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 [29]. 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 (6). According to [30] average cost of a large-scale wind turbine is 1.3-2.2 million USD/MW. Finally, according to (8) 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 [31]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 $/kWh for purchasing and 0.05$/kWh for selling.

- *Homer results*

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

TABLE VII
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 15 shows the average electricity production by the system for every month of the year.

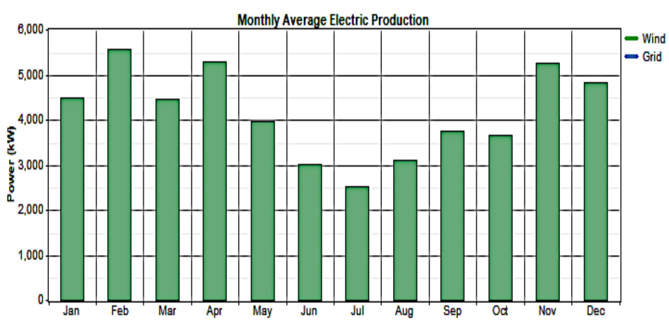


Fig. 15. Average monthly electric production.

3) *Homer and Mathcad comparison*

The energy density of turbine in Homer is $\text{HomerVesta164} = \frac{36322300000}{\pi * (\frac{D}{2})^2} = 1.719*10^6\ \frac{\text{W*hr}}{\text{m}^2\text{*yr}}$ the percentage of wind energy that turbine utilized is $\frac{\text{HomerVesta164}}{\text{E}_{\text{wind}}} = 20.55\%$. finally, the ratio of the output energy density of the system from Mathcad calculations to homer simulation is $\frac{\text{Econ}}{\text{HomerVesta 164}} = 99.763\%$ 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 VIII.

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 VIII, 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.

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 [33]. 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 [12]. 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 [34].

At present there exists three wind farm sites in the province of Newfoundland and Labrador namely, Ramea-Hybrid (1MW), St Lawrence (27MW) and 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 [12],[16].

1) 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 [16].

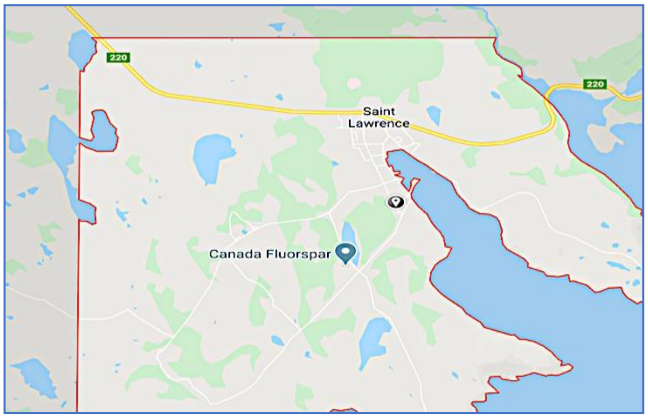


Fig. 16. Geographical location of St Lawrence Wind farm, NL [32]

2) Fermeuse wind farm

The Fermeuse wind farm is an Onshore wind farm was commissioned in the year 2009 located in the Avalon peninsula of Newfoundland and Labrador (46° 59' 3.5"and -53° 0' 22.6"), with a geodetic system WGS84 and is operated by EDF renewables and owned by Sky power. It employs 09 Vestas V90/3000 wind turbines, generating a total nominal power of 27MW [16].

Fig. 17. Schematic View of Fermeuse wind farm, NL [32]

3) Methodology in Wind site selection

- *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 [12]. 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 [34].

- *Renewable Energy Projects*

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

- *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 [34].

a. Aquifers
b. Significant wildlife habitats
c. Significant woodlands
d. Provincially significant areas of natural and scientific interest
e. 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.

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

- *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 [34].

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 [33], [34].

- *Other Considerations*

a. Weather radar towers
b. Telecommunications towers
c. Aviation radar towers
d. Natural gas, electrical, and water sewage infrastructure
e. Aggregate resources, landfill sites, and petroleum wells/facilities

4) 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 [16].

- *Portugal Cove south region*

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

TABLE IX
PORTUGAL CAVE SOUTH

SITE PARAMETERS	
Latitude and Longitude	46.70573°, -53.20353° (from the centre of the chosen area)
Wind speed	9.19 m/s @ 100m height
Power/Area	914W/m2
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 [32].

Fig. 18. View of the selected region in Portugal Cove South [32]

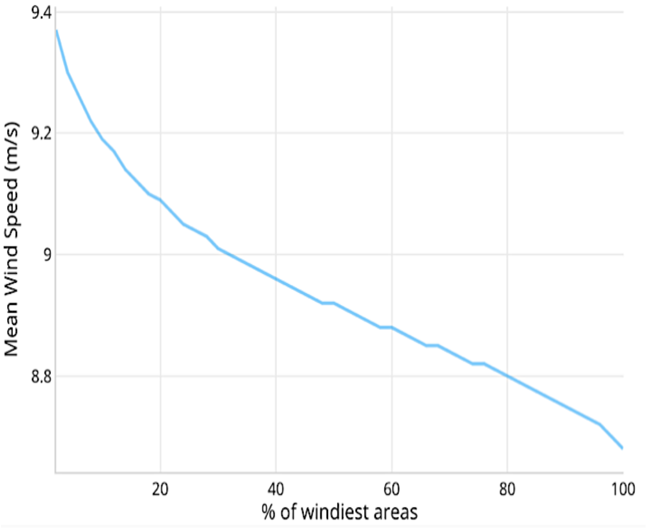


Fig. 19. Mean wind speed for varying heights. (Portugal cove south) [32].

- *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° (from the centre of the chosen area)
Wind speed	9.75 m/s @ 100m height
Power/Area	1051W/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 [32].

Fig. 20. View of the selected region in the Bonavista peninsular region [32]

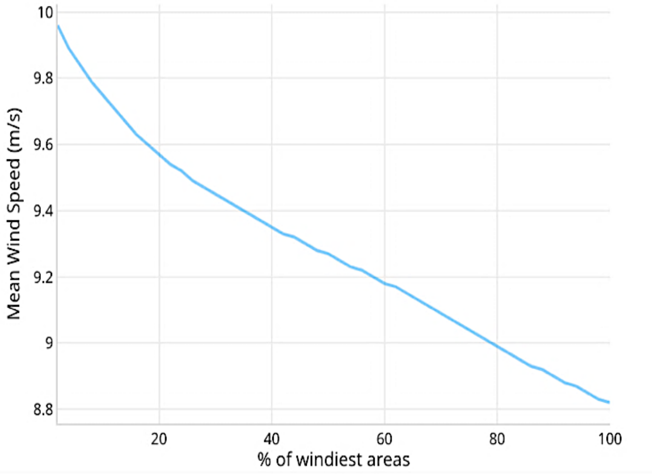


Fig. 21. Mean wind speed for varying heights. (Bonavista) [32].

- *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 [32],[33].

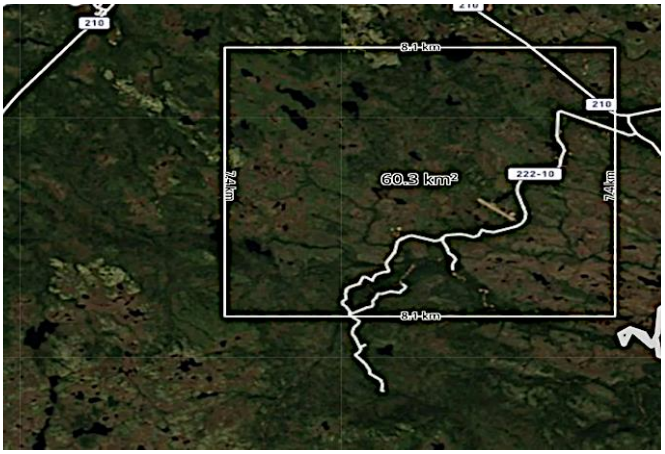


Fig 22. View of the selected region in Grand Banks [32]

TABLE X
GRAND BANKS

SITE PARAMETERS	
Latitude and Longitude	47.14373°, -55.34981° (from the centre of the chosen area)
Wind speed	8.51 m/s @ 100m height
Power/Area	707 W/m2
Nearest Weather Station	St. Lawrence

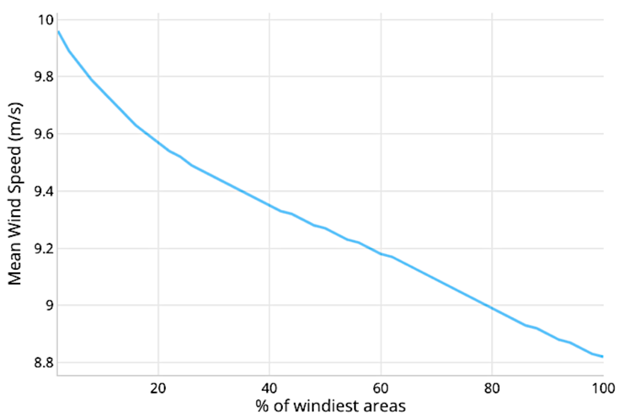


Fig. 23. Mean wind speed for varying heights. (Grand Banks) [32].

- *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 [33].

According to the data recorded at the Argentia weather station, [16] 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° (from the centre of the chosen area)
Wind speed	9.67m/s @ 100m height
Power/Area	1067W/m2
Nearest Weather Station	Argentia

Fig. 24. A view of the selected region in Saint Bride's region [32]

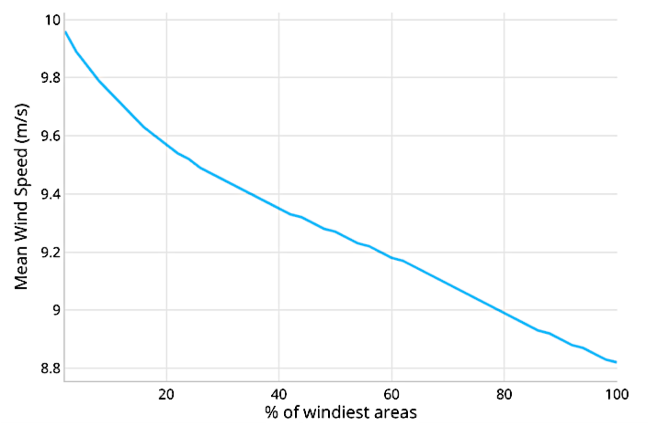


Fig. 25. Mean wind speed for varying heights (Saint bride's) [32].

D. *Wind turbine selection*

1) Wind farms 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 [35]. 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 [36]. 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 [35]. 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	206Km²	2.072 TWh
Riviere-du-Moulin, Quebec	RE Power MM82 and MM92	175	350	68 Km²	1.76 TWh
Blackspring Ridge, Alberta	Vestas V100	166	300	154 Km²	1.23 TWh
Lac Alford, Quebec	Senvion MM82 and MM92	150	300	132 Km²	1.08 TWh
Niagara Region, Ontario	Enercon E101	77	230	140 Km²	847GWh
Gros-Monroe, Quebec	GE Energy 1.5sle	141	211.5	112 Km²	650 GWh
Amaranth, Ontario	GE 1.5 MW	133	199.5	127.4 Km²	545 GWh
Wolfe Island, Ontario	Siemens SWT 2.3- 101	86	197	175.2 Km²	503GWh
Prince Township, Ontario	GE Energy 1.5sle	126	189	105 Km²	495GWh
Meikle, British Colombia	GE 1.5 MW	61	184.6	64 Km²	221 GWh

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 [37]	GE 2.5 XL -2.5 MW	338	845	78 km²	1.67 TWh
Burbo Bank, Liverpool, UK [38][39]	Vestas 164	32	258	40 km²	315 GWh
Norther N.V, Belgium [40]	Vestas 164	44	370	38 km²	1.39 TWh
Horns Rev 3, Denmark [41]	Vestas 164	49	406.7	19 km²	1.7 TWh
Estinnes, Belgium [42][43]	Enercon E-126	11	81.8	NA	1.6 GWh
Markbygden, Sweden [44	Enercon E-126	1,101	4000	500 km²	12 TWh
Noordoostpolde, Netherlands [45]	Enercon E-126 & Siemen 3.0 DD-108	38 & 48	429	8 km²	1.4 TWh
Le Mont des 4 Faux, France[46]	EnerconE-126	47	356	NA	NA

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

2) *Wind turbines selection*

The power curves for the selected turbines were obtained from [47]-[51] 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 30 is obtained which compares the power curves for the 5 turbines used in this study.

IV. RESULTS AND DISCUSSION

A. *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 164m which was assumed to be equal to the hub height of Enercon E-126 (135). The Area occupied by each turbine was obtained from [24] 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

B. 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.

C. 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 [35]. 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 2.072TWh/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.[52]

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.MWwind 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 1.97TWh/year, spanning the area of 213Km^2, results in 92.87GWh/Km2 Energy density [53].

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

If these parametric values are compared with 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 35.35Km^2. Therefore, with this analysis we can infer that the proposed utility scale wind farm outperforms both Seigneurie de beauprewind 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.

D. Selected system

In this section more information will be presented regarding the selected system (Enercon E-126 at Bonavista) which are shown in figure 26.

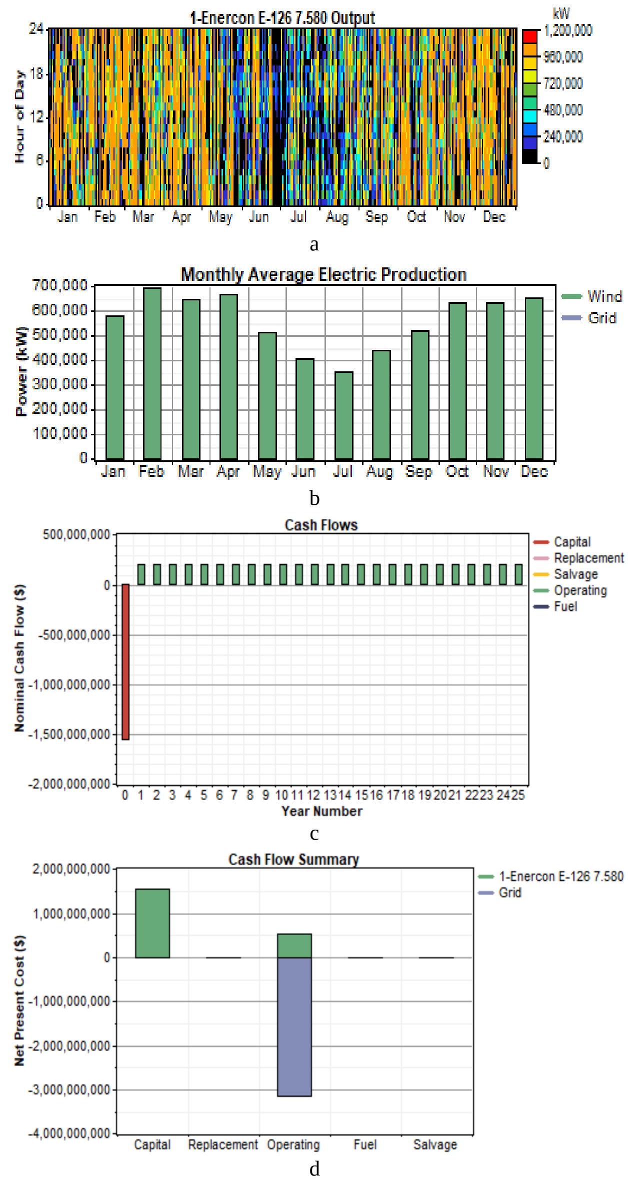


Fig. 26. Curves regarding selected system. a) Wind turbine output. b) Monthly average electricity production. c) Cash flows d) Cash flow summary

E. 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 (54) 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 (55) 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.

F. Finalized system

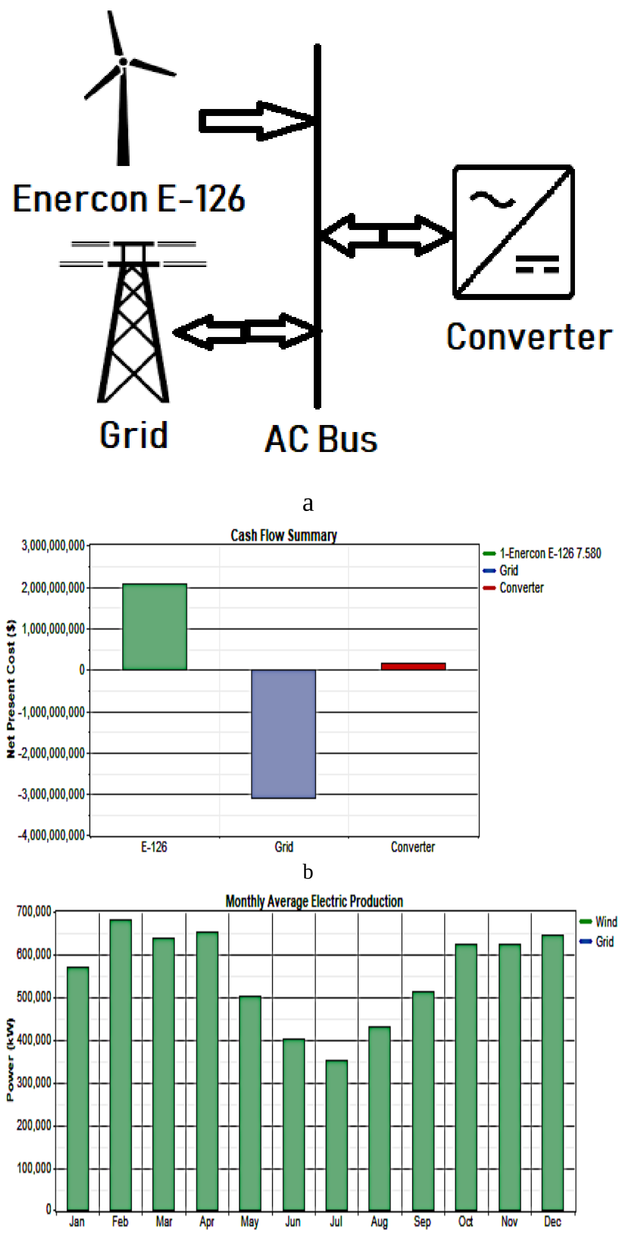


Fig. 27. Final system curves. a) System Block diagram. b) Cash flow. c) Monthly energy production.

Table XVII shows important concluding values for the final system which includes the inverter.

TABLE XVII
FINAL SYSTEM METRICS

LCOE $\left(\frac{\$}{kWh}\right)$	Energy generated (TWh)	Profit (mil USD)	CO_2 emission saved $\left(\frac{kg}{year}\right)$	Energy density $\left(\frac{GWh}{km2}\right)$	Profit per Area $\left(\frac{million\ \$}{km2}\right)$	LCOE * Area $\left(\frac{\$.km2}{kWh}\right)$
0.0333	4.839	884	$3.06*10^9$	136.91	25.01	1.18

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.

G. 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 [24]. [24] 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 [56]. 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 135m 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 (30), figure (31), table XVIII and table XVIX.

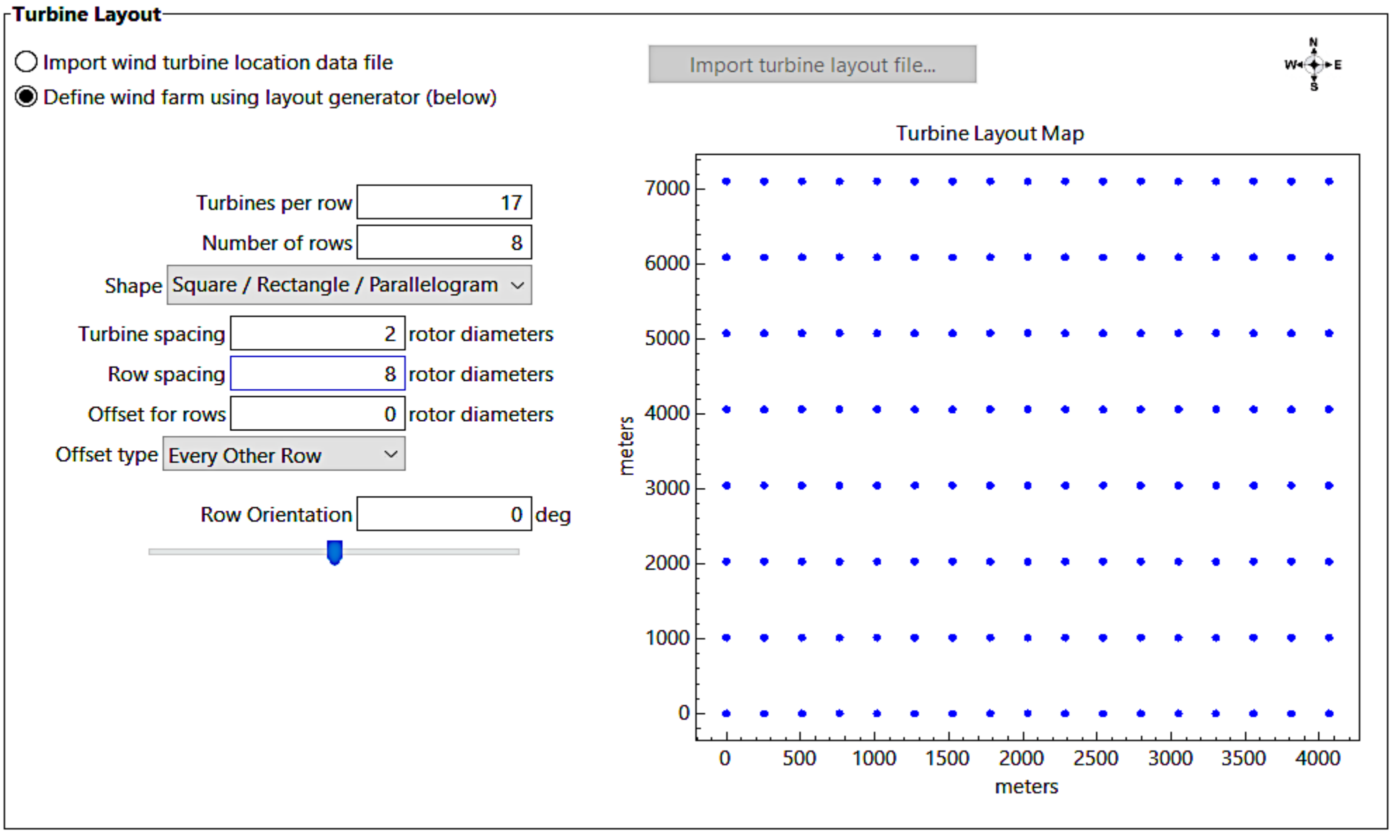


Fig. 28. Turbine layout of lower range (2D and 8D)

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

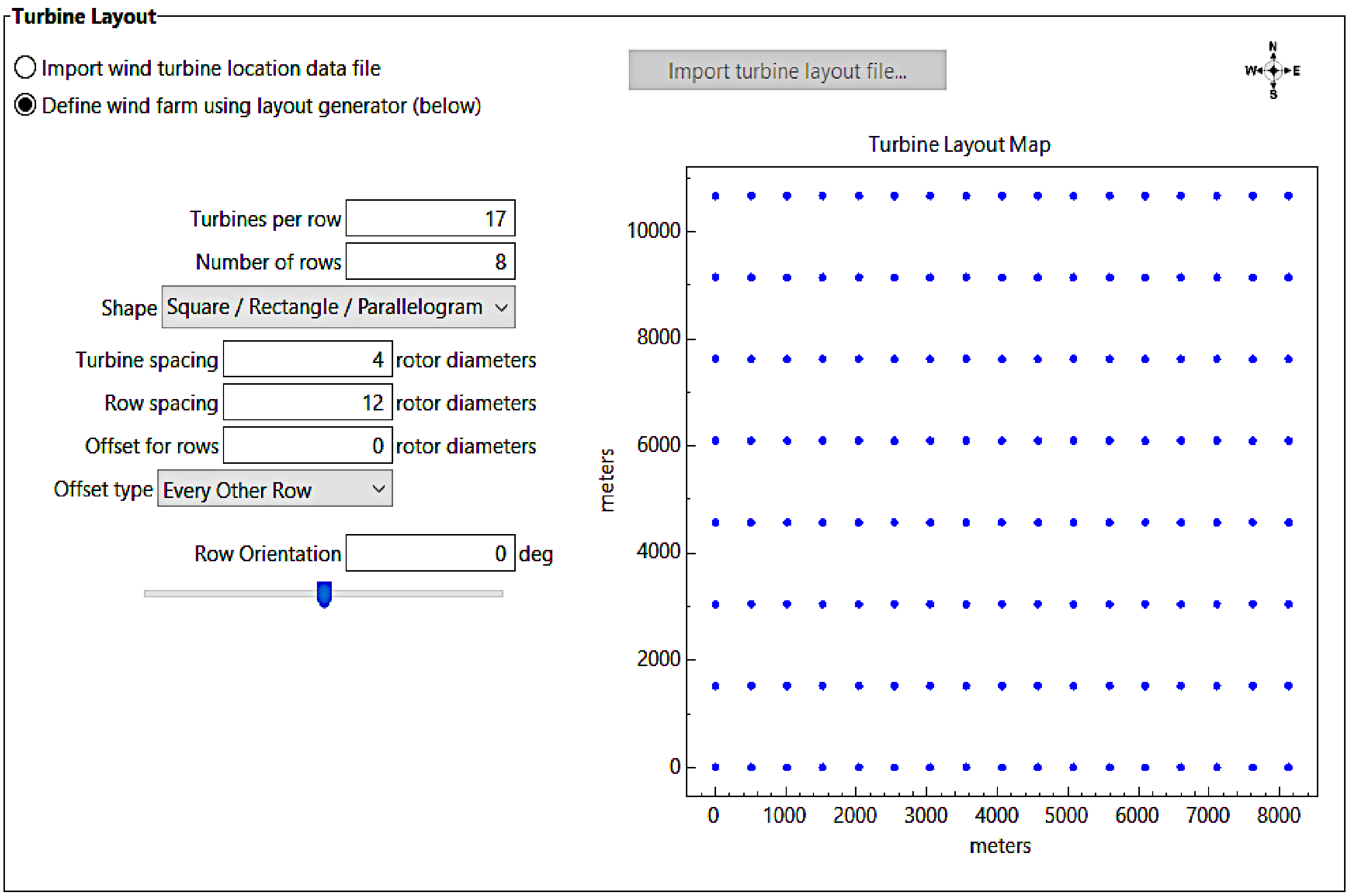


Fig. 29. Turbine layout of upper range (4D and 12D)

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

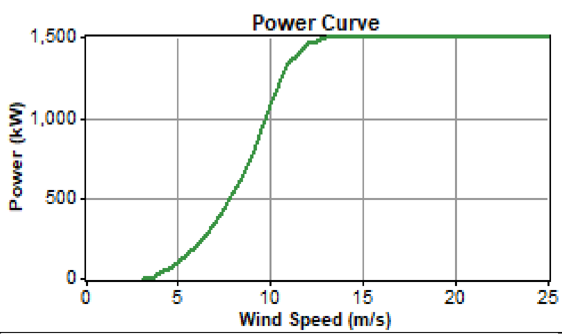
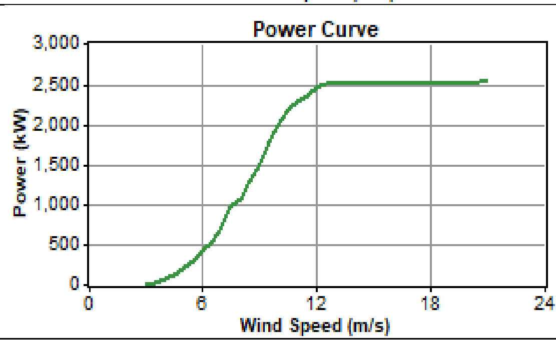
Metric	Value
Annual energy (year 1)	3,742,550,784 kWh
Capacity factor (year 1)	41.9%
PPA price (year 1)	4.61 ₵/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	4.99 ₵/kWh
Levelized PPA price (real)	3.96 ₵/kWh
Levelized COE price (nominal)	4.63 ₵/kWh
Levelized COE price (real)	3.67 ₵/kWh

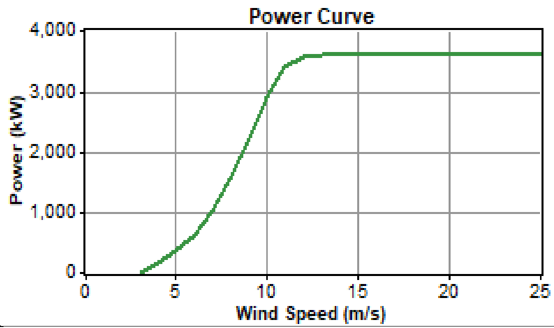
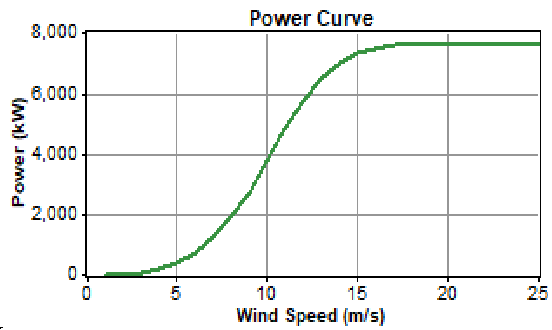
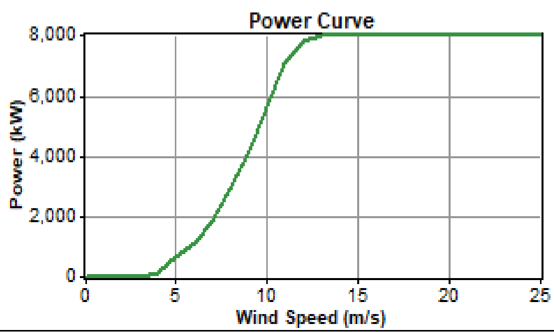
Net present Value	$131,838,464
Internal rate of return (IIR)	11.0%
Year IRR is achieved	20
IRR at the end of the project	11.89%
Net capital cost	$1,596,208,128
Equity	$857,585,792
Size of debt	$738,622,400

A few observations are of note from the above four figures. 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.

TABLE XIV
TURBINE CHARACTERISTICS

Turbine name	Rated power (kW)	Rotor diamet er (m)	No of blades	Type of generator	V &fre q.	Power density (W/m^2)	Hub heights (m)	Power curves [47]-[51]
GE 1.5s and	1500	70.5	3	Doubly fed asynchro nous 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	

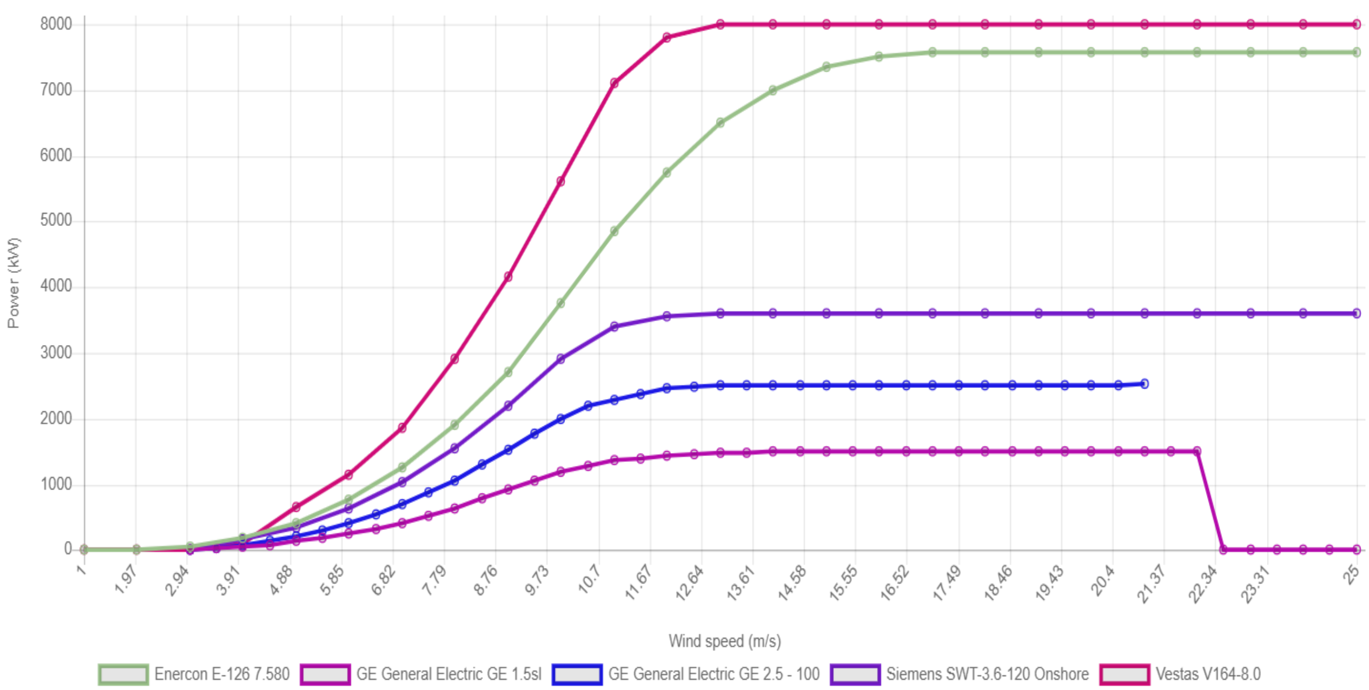


Fig. 30. Power curves from 5 selected turbines ([47]-[51]) combined and compared

TABLE XVI
PARAMETRIC STUDY

Location	Turbine Name	Hub Height (m) ([47]-[51])	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.SW T-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.SW T 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

V. 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.

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