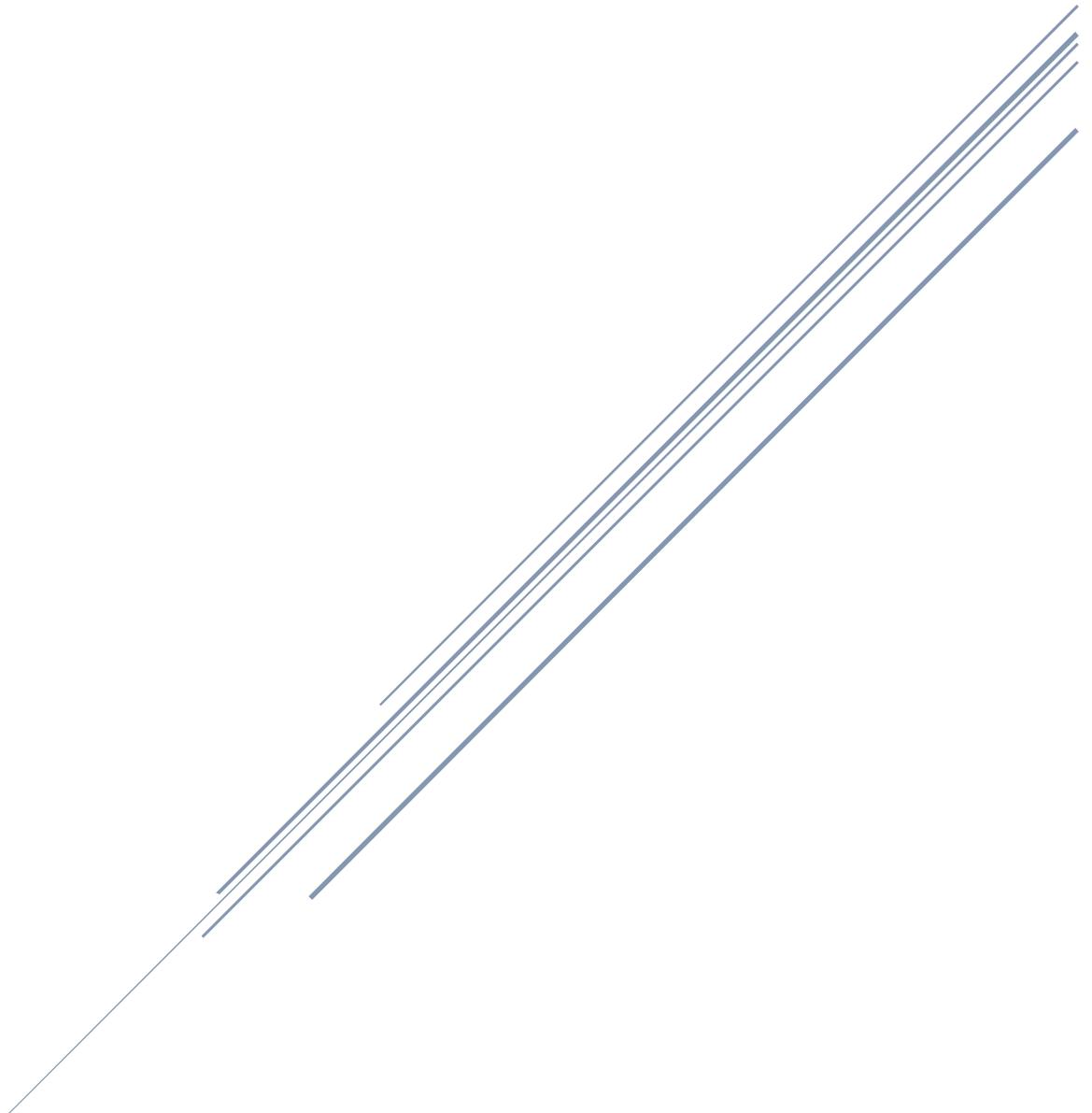


Wind: The Resource for Transforming St. Anthony, Newfoundland and Labrador

Prepared for SABRI



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Forward

As the whole world's push towards sustainable and Renewable Energy sources progresses steadily, wind energy cannot be overlooked neither understated. "Wind: The Resource for Transforming St. Anthony" is a comprehensive report that projects the untapped potential and promise that, the economy and future of St. Anthony can be reshaped when this natural resource is exploited and developed extensively.

This research document is more than just a collection of data and figures rather, it is a statement to the forward-thinking mindset of the Executive Director of SABRI, Mr. Christopher Mitchelmore, the Manager of Strategic Initiatives, Sam Woodford, the staff of SABRI and the Town Manager of St. Anthony, Mr. Curtis Richards in planning and projecting a transformed future and economy for the area of St. Anthony and the whole Northern Peninsula of Newfoundland.

It is also the symbol of the impact, contribution and readiness of academia through the supervision of Dr. Kevin Pope, the Engineering department, the Dean of Graduate School and the President of Memorial University of Newfoundland, Dr. Neil Bose, to support any interested, capable and determined entity in the field of Renewable Energy especially this project and any other applicable field of Engineering. The pages therein contain a meticulous and extensive collection of historical data on the wind resource of St. Anthony spanning a thirty (30) year period while contrasting it beside recent data. It also identifies the possible barriers to the establishment of a wind power project while prescribing mitigation strategies for the identified barriers. Furthermore, wind to power generation is investigated as a replacement to the standby 6 MW diesel generator of St. Anthony alongside Hydrogen and ammonia production from wind energy in St. Anthony.

Inherent in this report is an outlook of hope, transformation and possibility. It is a bright spot in a gloomy, polluted climate and overdependence on fossil fuel for power that, there exist an abundant, renewable and sustainable energy source – the wind – ready to be harnessed and transformed once more into a force for the good of humanity as it once did for the ancient civilization in the quest to conquer sea and air travel.

We applaud all researchers, engineers, scientist, policy makers who over the years have pushed for a halt in climate change through the use of renewable energy resources. Wind energy solutions has truly the potential of change for the world.

As St. Anthony and the whole world traverse the challenges associated with GHG and climate change, "Wind: The Resource for Transforming St. Anthony" can serve as a guiding light, shining ahead the path to greener energy sources. The winds of change are in our sails and together, lets harness their power to propel us towards an illuminated future for St. Anthony, Newfoundland and the world at large.

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Abstract

St. Anthony, the largest town in the Great Northern Peninsula, in addition to other towns, are serviced by a 248 km transmission line from the main island grid. A standby 6 MW diesel generating plant keeps the lights on when power is unavailable through the main transmission lines. This document investigates wind power potential for electrical power generation in selected locations in St. Anthony. This paper will further explore the application of the excess power generated for commercial processes, such as producing Hydrogen/Ammonia, which can be exported. These projects, when established, can help revive the economy of St. Anthony through revenue generation and employment opportunities for the inhabitants of St. Anthony and satellite communities.

St. Anthony was found to be part of the 10% windiest locations in Newfoundland. The average wind speeds recorded for the three (3) selected sites, Cape Norman, American Drive, and Cremaillere was over 4 m/s, which is the minimum required speed to turn a wind turbine to produce power. Through this report, it was found that St Anthony has great wind resource, and the resource can be used for power generation as set out. It was also noted that, like any other location with reference to wind power density, the higher the height, the better the results.

Development of this wind resource into energy is feasible as there is available land, and the population of St. Anthony is not close to the selected site. In as much as the wind resource is available for exploitation, barriers to this development were identified, and some mitigation steps were recommended. Key among the obstacles to wind energy development was the legislative barrier, which restricts the development of extra or external power generation beyond a specific capacity into the grid. There was also the case of a sole utility responsible for power generation and sale on the island. With tourism being a significant contributor to the economy of St. Anthony, ecological and natural barriers were also identified. Cape Norman has about 2 square kms as protected site for fossil hunting, and all three locations are good locations for iceberg watchers. Technical barriers were also observed, which would affect the overall performance and output of the turbines. Educational and public engagement activities were part of the suggested mitigation strategy and legislative changes that can open the market space for other sources of power generation or power generation firms to set up. There seems to be a change in the legislative front as more companies have ventured into the wind resource space of Newfoundland in recent times. A decision would have to be made on the tourism potential of the region, especially in proximity to the selected locations versus the use of the site for power generation.

The average wind speed of the three selected sites by SABRI was well over 4 m/s, which is sufficient to be used for power generation by most commercially available wind turbines [1]. The LCOE obtained using the wind resource from these locations ranges between 0.23 US\$ /kWh to 0.28 US\$ /kW, which is in the range of internationally accepted costs [2]. This LCOE obtained was incorporated into the cost build-up for the proposed cost of Hydrogen that could be produced from wind energy. The price range of 3.92 US\$ /kg to 9.87 US\$ /kg is well within global project prices. Upon further calculations, LCOA was obtained, which were equally within project pricing for such systems deployed worldwide, ranging from about 430 US\$ /ton to a high of 2200 US\$ /ton [3].

1. Introduction

St. Anthony Basin Resource Inc. (SABRI) has over the years, managed royalties earned from various economic activities on behalf of the 16 communities in the Great Northern Peninsula of Newfoundland and Labrador, Canada, as this was the main objective for its establishment. It is in line with such re-investment ventures that SABRI has sponsored a Mitacs Research Internship to investigate the wind resource potential and potential wind to Hydrogen or Ammonia production in St. Anthony. Due to the effect of the elements, especially icing during winter on the transmission line and routine maintenance of this transmission line, the town has a standby 6 MW diesel plant which serves the power needs when necessary. With a population hovering around 2500 and an economy which is dominated by fishery, institutions, and retail industry, electrical power is in regular demand. For consistency in the power supply while contributing to the global target of CO₂ and GHG level reduction, SABRI has partnered with St. Anthony Township to research the viability of a wind-to-power project and wind power to Hydrogen/Ammonia production. This research follows up on a document developed in 2009 [4], which looks at the effect of a 5.25 MW wind farm on the grid.

This document investigated wind resource availability and wind-to-power potential for selected locations in the Great Northern Peninsula of Newfoundland and Labrador, Canada. The research also includes analysing other opportunities for excess power, such as generating and exporting Hydrogen/Ammonia. The results of this project could provide significant economic and social benefits to the region. Newfoundland is an island province with many ports of export for different products. St. Anthony has a fishing terminal for receiving fishing vessels to offload their fish load. Currently, there is a planned harbour to be constructed at Cremaillere, but construction of same has no timeline as of now. Should this project be bankable and the port of Cremaillere finally be built for the export of Hydrogen or Ammonia, this would make it one of the few ports of export in the world for Hydrogen [5].

Newfoundland and Labrador has one of the lowest greenhouse gas intensities for the electricity grid since most of its power generation comes from hydro. The 24 g of CO₂ per kWh for Newfoundland and Labrador is approximately 75% less than the national average of 110 g of CO₂ per kWh [6] for 2019. Of all Canadian provinces that have high wind power generation potential, Newfoundland and Labrador has the least installed wind energy projects [7]. Data from the global wind atlas suggest that the mean power density for the 10% windiest area in the province of Newfoundland is about 1272 W/m² [7]. The suggested locations of Cape Norman, American Drive, and Cremaillere have long been suspected of having good wind resource and can be assumed to be part of the 10%. Also, the average wind speed for these locations were 9.43 m/s, 8.3 m/s, and 8.88 m/s, respectively. SABRI's selection of these locations seems to have considered availability and accessibility since the 3 sites are not close to residential areas and also have access roads that will be vital in transporting construction materials.

The uncertainty surrounding wind power places a considerable challenge on power generated from the wind. To handle this uncertainty with wind energy connected to the grid, wind-to-Hydrogen or Ammonia projects are considered. Also, in Newfoundland, power is mainly from hydro, and with any extra external generation causing spillage of the dam, the consideration of wind to Hydrogen/Ammonia project is a step in the right direction. The three sites to be investigated were Cape Norman, American Drive, and Cremaillere. Cape Norman has fossils and unique protected plant species. American Drive and Cremaillere are in close proximity (approximately 10 km) to St Anthony's. American Drive was historically used by the American Army for a wharf in the 20th century. Cremaillere and American Drive are only separated by a slight geographic depression, making either location visible from the other. Wind power can be used for Hydrogen (H₂) production through electrolysis [8]. Wind energy is initially converted into electrical energy using a turbine. This generated energy/electricity is then deployed in the splitting up of water molecules into Hydrogen and Oxygen by passing a current through the water molecule. This process of splitting water into Hydrogen and Oxygen is termed electrolysis. The town of St. Anthony has many freshwater sources, which can be the direct supply of water needed for electrolysis through pipelines. The option of water desalination is considered as it produces brine, which can be sold or applied elsewhere to offset the cost of the desalination plant. With the planned harbour at Cremaillere, the to-be-produced Hydrogen/ Ammonia

can be exported to prospective markets/buyers. Typically, two main commercially available methods are currently used: alkaline and proton exchange membrane (PEM) electrolysis. Both alkaline and PEM electrolyzers require highly distilled and purified water in order to produce high-purity Hydrogen products. An electric motor-driven mechanical vapor compression (MVC) water purification plant can deliver the distilled and purified water needed by these electrolyzers to produce the Hydrogen. PEM is selected for this research due to its advantages related to Hydrogen density, partial load, and low-pressure operations [9]. Hydrogen is a vital participant in the global carbon reduction effort. The dependence on fossil fuel for energy generation can be reduced when renewable sources of energy are developed, especially wind energy. Wind power to Hydrogen generation is a way of maximizing the unpredictable nature of wind power production to other forms of energy or storing the produced energy in energy carriers, of which Hydrogen is currently the most developed. This serves as a way of using renewable energy sources to help tackle the effect of greenhouse gases and reliance on conventional fuels [10]. Hydrogen plays a vital role in the production of petroleum and petrochemical products from the oil and gas sector, which is currently a major contributor to the economy of Newfoundland. There exists a direct relationship between the amount of power input in the electrolyser and the amount of Hydrogen produced, which therefore makes it somewhat easy to propose a power-to-Hydrogen project. Hydrogen is an explosive gas and very dangerous to handle and transport. Ammonia is one of the best carriers of Hydrogen since it is more stable and has been in use around the globe for a very long time in many industries. The Haber – Bosch method of producing Ammonia is the most widely used and would be assumed in this project. Handling of produce, be it Hydrogen or Ammonia, is very vital as there is little to no Hydrogen or Ammonia plant at any port of Newfoundland. There currently are just about eight (8) ports around the globe capable of handling Hydrogen import and export at the same time around the globe, with newer projects being proposed and sponsored by governments raising the number to about 20 [5]. This report after considering all the available data and generating requisite data through formulas, approximations, assumptions, and calculations was able to conclude that, St. Anthony has the necessary wind resource to generate energy to replace the 6 MW standby diesel generator while producing excess power. This excess power can be redirected into a Hydrogen production plant or an Ammonia production plant which also produced sufficient amounts of Hydrogen and Ammonia at competitive prices [11].

2. Objectives

This report has addressed the following five key objectives.

1. Collect historical and recent wind data for selected locations for assessment.
2. Investigate wind energy generation potential of selected locations.
3. Investigate Hydrogen/Ammonia production potential from wind energy.
4. Identify the barriers to wind power generation
5. Propose mitigation strategy for barriers identified

The first objective consists of location selection and data collection. The second objective includes analysing wind speed data and corresponding turbine technologies. The third objective includes technical, economic, and environmental assessments. The fourth and fifth objectives will try to conceptualize the barriers to wind power development in Newfoundland and St. Anthony while proposing possible mitigation strategies for overcoming the identified barriers.

3. Site Visit

St. Anthony is located in the Great Northern Peninsula of the Newfoundland province with coordinates 51°22'13.4976" (51°22.225' N) for latitude and -55°35'45.114" (55°35.7519' W). It is about a 1-hour flight

from St. John's international airport. It was from this location that the selected sites of Cape Norman, American Drive, and Cremaillere were visited.



Figure 1. St. Anthony [12]

Cape Norman

Cape Norman is located about 45 minutes' drive from the St. Anthony airport and the township of St. Anthony. It is geographically located on the coordinates 51.62821° ($51^{\circ}37'42''$) N and 55.905861° ($55^{\circ}54'21''$) W. At this location, it was observed that the wind from the sea enters the bay at good speeds and the land to the eyes spreads out in a flat land nature. This site may not need much clearing should it be selected. There were, however concerns with the protection of the area. This a fossil hunting ground and has some unique species of plants that are protected species.



Figure 2. Cape Norman, St. Anthony, NL [13]

American Drive

American Drive lies about 59 km from St. Anthony airport about 6.2 km from the SABRI office in the township of St. Anthony with coordinates 51.33651° and -55.632362° . The general terrain to the naked eye looks hilly and undulating. This was a location selected by SABRI based on its nearness to town and having been historically used by the American Army for a wharf in the 20th century.

Cremaillere

Cremaillere is geologically within eye view from American Drive as these 2 locations are very close and only separated by a small depression having coordinates 51.350665° and -55.936375° . This location is also about 9.2 km away from the centre of the town. A visit to this location gave credence to the selection as it was windy compared to other locations in the town. This location has a similar topology as that of American Drive described above.



Figure 3. American Drive (left of image) and Cremaillere (Right of image), St. Anthony, NL [13]

4. Wind Resource

4.1 Historical Wind Data

Table 1, presents the wind data for the 3 selected locations on SABRI website for potential and proposed wind power plants. This data was obtained from the HOMER software, which will be used for this study to investigate the wind energy generation potential of these selected locations. The HOMER software uses data obtained from NASA's predictions of worldwide energy resources. This is an average of data gathered over a thirty (30) year period at 50 m height spanning the period January 1984 to December 2013.

Table 1. Average wind speed obtained from HOMER

Month	American Drive	Cremaillere	Cape Norman	St. Anthony Airport
January	7.98	7.98	9.25	6.47
February	7.80	7.80	8.94	6.36
March	7.46	7.46	8.54	6.10
April	6.81	6.81	7.59	5.70
May	6.04	6.04	6.96	5.11
June	5.74	5.74	6.72	4.88
July	5.47	5.47	6.61	4.71
August	5.73	5.73	6.44	4.93
September	6.62	6.62	7.03	5.63
October	6.80	6.80	7.80	5.66
November	7.50	7.50	8.36	6.16
December	8.10	8.10	9.08	6.57
AVERAGE	6.84 m/s	6.84 m/s	7.78 m/s	5.69 m/s

The 3 selected locations, namely Cape Norman, American Drive, and Cremaillere have the following coordinates 51.62821° ($51^{\circ}37'42''$) N and 55.905861° ($55^{\circ}54'21''$) W, 51.33651° and -55.632362° and 51.350665° and -55.936375° respectively which was utilized in accessing and obtaining historical wind data from HOMER. These coordinates were also key in obtaining current average wind speed from the global wind atlas page for the selected locations; 9.43 m/s, 8.83 m/s, and 8.88 m/s respectively for 2023.

These averages were markedly higher than data obtained by HOMER and can be argued to mean that the wind resource has improved since 2013. If this argument is valid, it therefore makes a case for the exploration of wind power systems at these locations. Cape Norman has for ages been acclaimed as very windy by the inhabitants of St. Anthony and its environs. Prior to this report, there existed a research paper on St. Anthony which selected Cape Norman as the best location for a wind turbine project [4].

4.2 Wind Resource Analysis

To predict wind speed at any given height, especially with respect of the hub height of the wind turbines yet to be selected for this project, a relationship exists for the calculation. Wind shear boundary layer power law is expressed below.

$$\frac{V}{V_r} = \left(\frac{H}{H_r}\right)^\alpha \tag{1}$$

where α , which represents the roughness factor, can then be expressed as follows

$$\alpha = \log_{\frac{H}{H_r}} \frac{V}{V_r} \tag{2}$$

The variable V is the observed/recorded wind speed at height H above the ground, while V_r and H_r are the reference wind speed and reference height (H) above ground. The roughness factor is a function of the topography of the selected site. The variable α is predicted by [9];

$$\alpha = a + b \ln V_r \tag{3}$$

where

$$a = \frac{0.37}{1 - 0.088 \ln\left(\frac{H_r}{10}\right)} \quad b = \frac{-0.088}{1 - 0.088 \ln\left(\frac{H_r}{10}\right)}$$

Since the NASA wind data in HOMER are obtained at 50 m height (H_r), the above equation for the adjusted hub height wind speed calculation becomes;

$$\alpha = (4.31 \times 10^{-1}) + 1.025 \times 10^{-1} \ln V_r \tag{4}$$

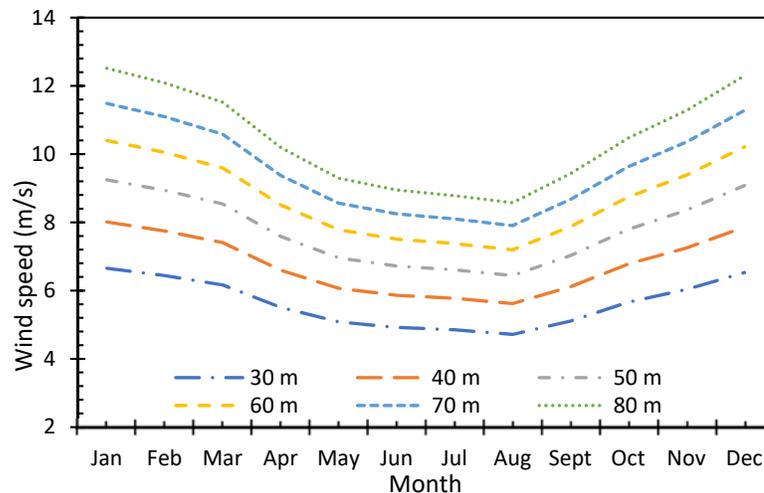


Figure 4. Predicted wind velocity for various hub heights at Cape Norman

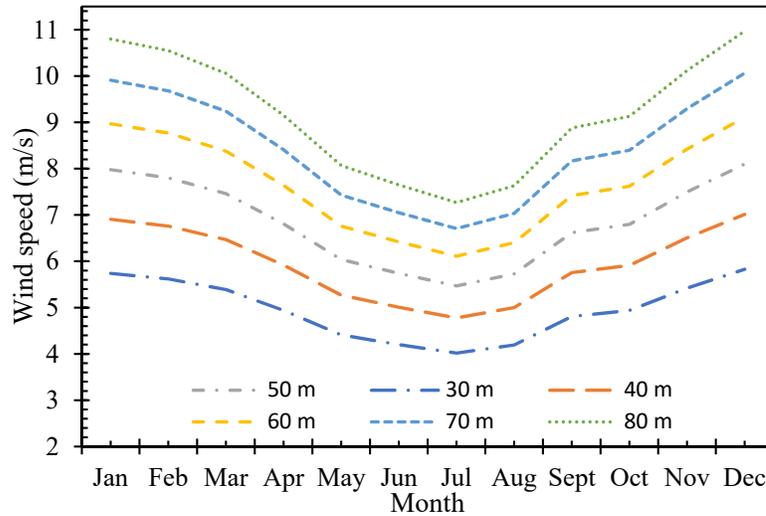
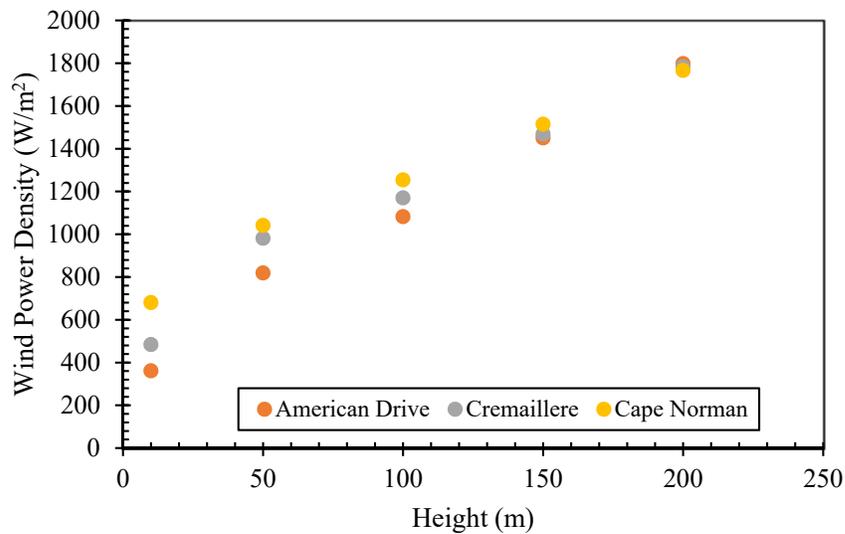


Figure 5. Predicted wind velocity for various hub heights at American Drive and Cremaillere

Table 2. Wind power (W/m^2) measurement at different height

Height (m)	American Drive	Cremaillere	Cape Norman
10	361	484	680
50	819	981	1041
100	1082	1170	1254
150	1450	1468	1514
200	1798	1783	1766



At every height measured, Cape Norman recorded the best wind power density, with American Drive and Cremaillere having nearly similar values. At 10 m, American Drive had the least power density of $361W/m^2$, followed closely by Cremaillere with $484 W/m^2$ and dominated by Cape Norman. When measured at 50 m for which wind data for HOMER was recorded, Cape Norman had the highest power density of $1041 W/m^2$, Cremaillere with $981 W/m^2$, and American Drive recorded $819 W/m^2$. When readings were taken at 100 m for which most current wind turbine hub heights are being designed to and beyond, the wind power density went up by almost 25%. When the readings were taken at 200 m, the wind

power density went up by over 700 W/m², 600 W/m², and 500 W/m² for American Drive, Cremaillere, and Cape Norman, respectively. This, therefore, confirms the power law.

5. Wind Energy – Hydrogen Production/Ammonia Production Route

5.1 System Design and Modelling

The wind resource of a given location can be highlighted and studied to understand the potential for energy generation. In the above section of this material, St. Anthony was acknowledged through historical data and site visit to have strong wind resource which can be further examined. The wind power density was obtained from global wind atlas for the selected locations since the selected sites did not have a wind monitoring system or station nearby. The closest wind monitoring system was at the new St. Anthony airport, which is in a totally different direction and location from the old airport. As such, new data had to be obtained from various weather data provision sources.

This section will look to project the potential energy generation from the wind resource identified at St. Anthony as a whole. After this energy potential was simulated, calculations were made to determine the Hydrogen production potential and subsequent Ammonia production. The needed technicalities and design of all systems for the production of green Hydrogen or Ammonia are discussed below [1].

1. Energy generation from the wind source using selected turbines, battery energy storage system, AC/DC converter.
2. Hydrogen and nitrogen production systems and requirements
3. Ammonia generation/synthesis facility and storage
4. Shipment including transportation system

5.2 Flow Diagram for Project

In the diagram below, wind turbines convert the wind resource into electricity which is supplied to the town of St. Anthony and any installation that will require electricity. This is based on the fact that the setup is oversized for the power demand of St. Anthony so that it includes the total power use of the Hydrogen/Ammonia generation plants which are to be exported.

The system is made up of wind power conversion units that produce electricity from wind which supplies the water desalination plant responsible for receiving and treating the sea water needed by the electrolyser. The water desalination unit produces high-purity clean water that is sent to the electrolyser for the production of Hydrogen, H₂, which can be stored and exported or used in the production of Ammonia. In the production of Hydrogen in the electrolyser, pure O₂ is a by-product that can be sent to the Hospital in St. Anthony and any Oxygen-dependent facility in St. Anthony. The air separation unit is necessary if Ammonia production is the objective of the project. In this unit, Nitrogen, N₂, is derived from the atmosphere. Subsequent to the production of NH₃, the produced Hydrogen from the electrolysis and nitrogen from the air separation unit are combined through a gas synthesizer system that combines these two products to form NH₃. The Haber – Bosch system is assumed in this project for the production of Ammonia in an Ammonia synthesis loop. In the production of Hydrogen/ Ammonia, molten salt (from the water desalination plant) and Oxygen (from the electrolyser) are produced as by-products of certain processes. These by-products can be sold for extra revenue generation.

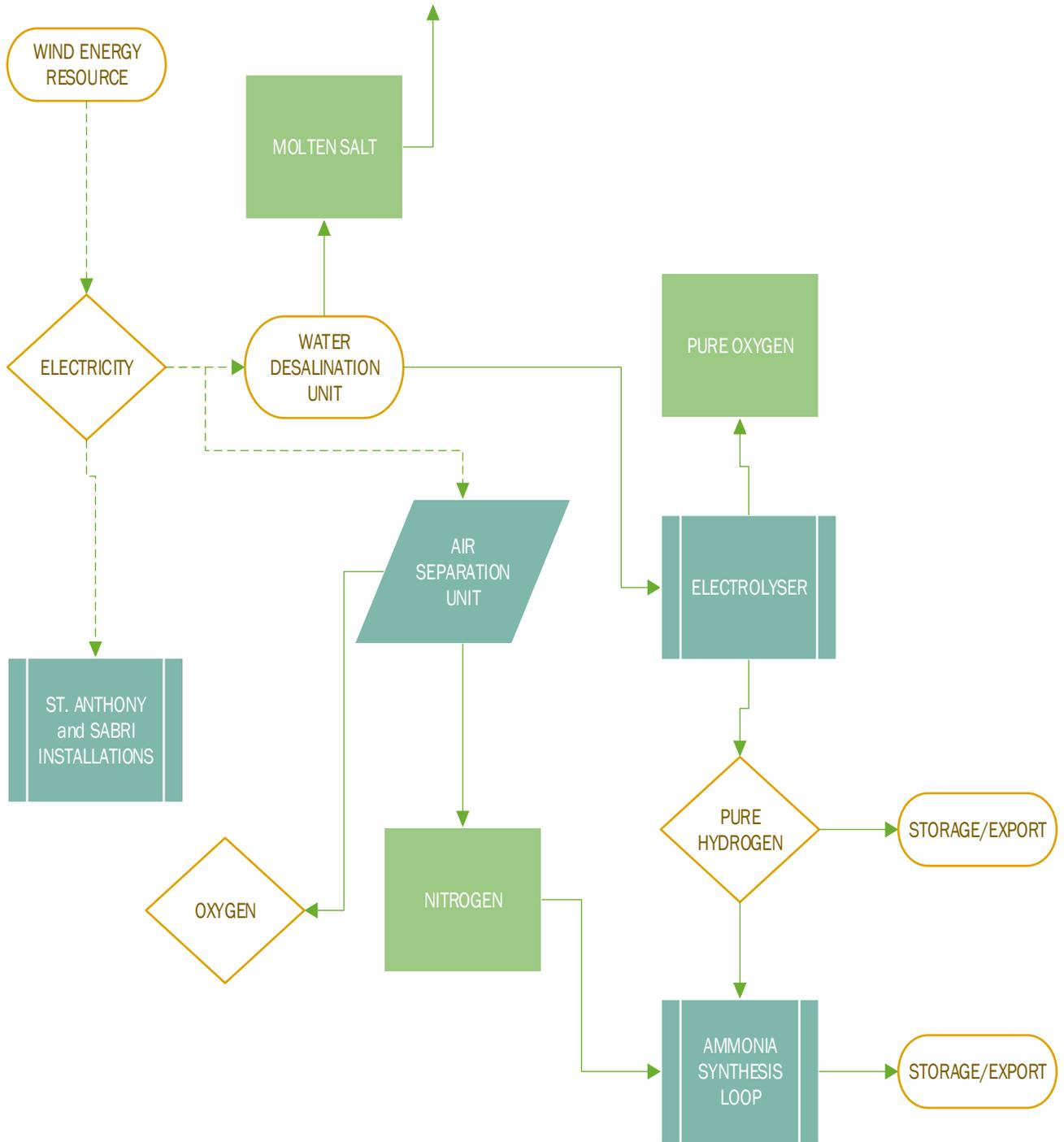


Figure 4. Flow diagram of potential wind to power and Hydrogen/Ammonia project

Table 3. Commercially Available Wind Turbine and Specifications

Model	Abbreviation	Power rating (kW)	Hub height (m)	Cut-in velocity (m/s)	Rated velocity (m/s)	Cut-out velocity (m/s)	Wing sweep (m ²)	Lifespan (years)
Large								
DE wind D7	DED7	1500	70	3	12	25	3846	20
Goldwind 1500	GW77/1500	1500	75	3	11	22	4649	25
ServionSE MM100	SSMM100	2000	100	3	11	22	7854	20
Alstom E110	AIE110	3000	100	3	11.5	25	9496	20
Gamesa G128	GG128	4500	140	4	13	18	12873	20
Normal								
Norwin 47/500	N47 – 500	500	65	4	13	25	1735	20
DE wind 48	DE48	600	40	2.5	11.5	25	1808	20
Norwin 47/750	N47 – 750	750	65	4	15	25	1735	20
Gamesa G58	GG58	850	65	3.5	12	21	2642	20
Small								
MICON	MI200	200	30	4	14	25	2827	20
Nord tank	Nt 3	300	31	4	13	25	2463	20
NEPC – MICON	NM 400	400	30.5	4	15	25	3019	20

There are usually three (3) categories of wind turbines based on the hub height: small, medium, and large. Wind turbines will be classified as small for this project when the hub height is between 30 – 40 m, medium class (40 – 70 m), and large (70 m and above). For the purpose of data generation, a 10 m upward step was adopted to generate wind velocity profiles for the hub heights of the wind turbines. The maximum hub height assumed was 80 m, which falls within the large/huge class of wind turbines, whereas 30m was selected for the small class.

5.3 Power Demand Estimates and Assumptions

For this section of the project, three (3) scenarios are proposed;

Wind power generation as replacement of 6 MW standby diesel generator

Wind power as replacement of 6 MW diesel generator + Hydrogen production, storage and export

Wind power as replacement of 6 MW diesel generator + Ammonia production, storage and export

5.4 Scenario Table

Table 4. Scenarios for project

Unit	Major Component	Project	Projected Power (MW)			
1	St. Anthony Township and Other Installations	Power Supply	6.9(S1)	SCENARIO 1	SCENARIO 2	SCENARIO 3
2	Water Desalination Unit	Pure Water	0.00721(S2)/0.406(S3)			
3	Electrolyser	Hydrogen Production	1.83(S2)/10.3(S3)			
4	Hydrogen Storage Tank	Hydrogen Storage	0.038(S2)/0.214(S3)			
5	Air Separation Unit	Nitrogen Production	0.090(S3)			
6	Ammonia Synthesis Loop	Ammonia Production	0.310(S3)			
7	Ammonia Storage Tank	Ammonia Storage	N/A			

Scenario 1 (S1)

Under this Scenario, the project will focus on producing power for the township of St. Anthony from wind as a replacement for the standby generator. The town of St. Anthony has a standby 6 MW diesel generator, as per documents submitted by SABRI. This can be assumed to be the maximum instantaneous demand. A reserve margin of 15% is assumed, thereby making the power demand 6.9 MW approximately 7 MW. Another approach to Scenario 1 would be to assume the excess power produced is channelled into Hydrogen production or Ammonia production to find the cost that would be associated with the Hydrogen/Ammonia generated. This is to compare how available power affects the LCOH or LCOA in this project.

Scenario 2 (S2)

This Scenario is represented by the generation of power to replace the 6 MW standby diesel generator while meeting the power demand necessary to operate and produce Hydrogen in commercial quantity for export. Calculations will be done to find the Levelized Cost of Hydrogen, LCOH. Under this setup, the total power demand will be modelled as a load based. Assumptions made under this scenario were that, all things being equal, if the power demand of the various components of the setup are met, the projected amount of H₂ by the equipment manufacturers can be met. Since the main focus of this scenario was meeting the power demand of St. Anthony and a Hydrogen production plant, all excess power produced was re-injected into the Hydrogen production plant. Also, the power requirement for the production of Hydrogen was calculated for the production of 1 ton of Hydrogen when the systems were turned on [14]. Furthermore, another angle to this Scenario was the coupling of the power demand of St. Anthony with an Ammonia production plant. The LCOA was determined under this condition as well after all the excess power was directed back to the Ammonia production plant.

Scenario 3 (S3)

Scenario 3 has the power demand of St. Anthony coupled with the Ammonia production plant. Since Hydrogen is an important component for the production of Ammonia, LCOH was calculated subsequent to the calculation of produced Ammonia, hence LCOA. The power demand of the various major equipment for the production of a ton of Ammonia was generated with data from reference [14].

6. Wind Energy Generation Potential for Selected Locations

Peak power for most wind power projects is obtained between 11 – 15 m/s. Viability of most wind projects occurs at locations where the average recorded velocity exceeds 15 km/h (4.17 m/s) [15]. The selected locations by SABRI, as obtained on HOMER and global wind atlas provide average wind speed data of more than 5 m/s for recorded wind velocities. Cape Norman leads the way with an average wind velocity of 7.78 m/s, with both American Drive and Cremaillere having averages of 6.68 m/s at a 50 m anemometer height. These figures point to promising prospects for wind power and must be investigated in depth and in real-time to provide concrete data for decision-making.

7. Energy Generation from Wind

7.1 Homer Simulation

In this simulation, weather and renewable energy resource data are obtained from NASA as embedded in this software. The energy equation below must be balanced at every step of the simulation to make this project viable for the various scenarios respectively.

$$P_{\text{wind}} = P_{\text{Township and installations}} \quad (5)$$

$$P_{\text{wind}} = P_{\text{Township and installations}} + P_{\text{H produced}} \quad (6)$$

$$P_{\text{wind}} = P_{\text{Township and installations}} + P_{\text{NH}_3, \text{produced}} \quad (7)$$

where P_{wind} is the power generated from the wind, $P_{\text{St. Anthony}}$, $P_{\text{NH}_3 \text{ produced}}$, represents the power demand of St. Anthony and other installations that SABRI has that may not be part of the whole power demand of St. Anthony, Hydrogen/Ammonia production process, respectively [16]. Scenarios 1, 2, and 3 are represented by Equations 5, 6, and 7 respectively.

The three selected locations for the wind power plants are in close proximity to the sea. This gives an advantage to the project and makes the design of the whole system favourable. The power generation unit (wind turbine, battery storage system, converter), desalination unit, Hydrogen unit (production, storage/export), the air separation unit, the Ammonia unit (synthesis, storage, and export) can all be installed in close proximity to the sea making it the source of water for the proposed project.

System set up;

- a. Wind turbine: A wind turbine will be chosen from 2 category listed for this simulation. This will help prove a point on the wind turbine cost affecting the LCOE and also prove that bigger wind turbines produce more power. The average installed cost of a wind turbine is \$1500/kW [2]. The operation and maintenance cost was estimated to be \$44/kW [1]. For the purpose of comparison, 3 MW and 1.5 MW were selected for the simulation.
- b. Converter: A 1500kW rated Caterpillar BDP250 converter was selected for this simulation in all wind turbine cases with at \$300/kW cost.
- c. Battery Storage Unit: A 100kWh battery was selected with a cost of \$324/kWh, nominal voltage of 600V and efficiency of 90%.
- d. Electrolyser: The electrolyser of choice in this simulation is the NEL M5000. This is a 25 MW rated electrolyser with capital cost of 600 USD/kW, replacement cost of \$450/kW, and an operation and maintenance of \$18.1/kW.
- e. Hydrogen storage tank: Based on the mass flow rate determined, a projected total annual production of approximately 78767 ton of Hydrogen will be produced. Therefore, an 80,000-ton storage tank capacity will be required.
- f. Ammonia production unit: A commercially available Haber – Bosch system would be assumed with a daily capacity of about 24 tons.

- g. Ammonia storage tank: A 500,000 ton was anticipated based on the mass flow rate table provided, as there exists a ratio of 1:5 between Hydrogen and Ammonia in the production process.

Scenario 1 load

A 6 MW standby generator is to be replaced with wind energy. Therefore, it was assumed that the energy requirement of St. Anthony would be 6 MW. A 15% over – production assumption was made, increasing the total demand to 6.9 MW.

Scenario 2 load

The load regime for this Scenario was projected to be the total of St. Anthony, the power demand by the processes leading to the production of Hydrogen and storage of same. From the selected data on the equipment necessary for this process, a total load assumption for Hydrogen production in this Scenario was set at 2.15 MWh, which included the assumed 15% reserve margin needed for the production and storage of 1 ton of Hydrogen gas.

Scenario 3 load

The total load demand projected for this Scenario was evaluated to be the load of St. Anthony plus approximately 12.6 MWh needed for the production and storage of 1 ton of Ammonia, which translates into about 12.6 MW inclusive of the 15% overengineering.

Overall Assumed load

Scenario 1 = 6.9 MWh approximately 7 MW

Scenario 2 = 7 MWh + 2.15 MWh = 9.15 MWh

Scenario 3 = 7MWh + 12.6 MWh = 19.6 MWh

8. Hydrogen / Ammonia Production

8.1 Hydrogen / Ammonia Production Potential

Hydrogen and/or Ammonia production from renewable sources has, over the years, seen a gradual upscaling. This is in line with the general idea of reduction of GHG generation, which conventional Ammonia production from coal, natural gas is associated with. Ammonia emits water vapor when burnt alongside Nitrogen gas, which are not so harmful to the environment. Gasoline's volumetric energy content is 60% higher than that of Ammonia but is harmful to the environment; as such, a shift to Ammonia is appropriate [16]. Ammonia does not produce CO₂ when combusted since it does not contain carbon and can be stored easily as liquid at atmospheric pressure [17]. Synthesis of Ammonia is an old process and can be termed as matured due to its longevity in existence. It has previously been synthesized by using coal or natural gas as the feedstock [16].

8.2 Water Desalination Unit

For the purpose of this project, a mechanical vapor compression (MVC) technology that utilizes electric driven motor is considered. This technology yields purer water as compared to other water desalination processes. It is also very compatible with the selected PEM electrolyser and possesses heat integration [1]. The electrolyser and water desalination plant in this project would be installed at the same location. A 3000 t/d pure water production maximum capacity is considered for this project.

8.3 Electrolyser

Wind power can be used for Hydrogen (H₂) production through electrolysis [8]. There exists a direct relationship between the amount of power input in the electrolyser and the amount of Hydrogen produced [13]. Production losses due to electrical conversion will not be considered at the moment as the major focus is on the power aspect.

This project will assume the use of the model M5000 from NEL electrolysers having a system efficiency of 70.9% [1], [8]. A PEM electrolyser makes use of direct current electrical energy ranging from 43 kWh to 58 kWh [18]–[20] and 10.6 kg of water to produce 1 kg of Hydrogen, as suggested by Hinkley et al. This can be made into a relationship to predict the quantity of green Hydrogen production [18]:

$$M_{H_2} = \frac{P_{WES}\eta_{rec}}{P_{ez}} \quad (8)$$

where P_{WES} is the electrical power output of the wind energy system, η_{rec} is the rectifier efficiency assumed to be 0.709, P_{ez} is the amount of power the electrolyser needs, in this case, 51 kWh/kg for the selected electrolyser.

8.4 Mass Flow Rate

In the synthesis of Ammonia, reaction rate and flow rate can be used to predict the Ammonia production potential. this provides a relationship for the major chemical component of Ammonia generation. This also helps in the calculation of the specific power consumption of the various components as a relationship can proposed based on the ratio of flow rate of specific fluid to the amount of Ammonia produced.

Table 5. Mass flow rate for products in an Ammonia generation plant

Substance	Coefficient (kg/kg _{H2})	Mass flow rate (t/d)
Hydrogen	1	10
Desalinated water	10	100
Nitrogen	4.632	46.32
Ammonia	5.632	56.32

8.5 Hydrogen Storage

Hydrogen storage has challenges such that for 1 kg of Hydrogen to be stored at room temperature and atmospheric pressure, it would need a storage volume of 11.13 Nm³. To achieve a feasible storage capacity, the most common and mature Hydrogen storage technology is the high-pressure gas cylinder with a working pressure value of 200 bars. This storage option works best for this research since the Hydrogen produced from the electrolyser is assumed to exit at 30 bars and then pressurized to about 160 bars. The electrical power required for the compression is obtained by adopting the following equation.

$$P_c = (97.5336 \times 10^{-6}) \left(\frac{\gamma}{\gamma - 1} \right) Q T_{suc} N \left(\frac{Z_{suc} + Z_{dis}}{2} \right) \left(\frac{1}{\eta_{s,C}} \right) \left[\left(\frac{p_{dis}}{p_{suc}} \right)^{\frac{1}{N}} \right]^{\frac{\gamma-1}{\gamma}} - 1 \quad (9)$$

For the anticipated large flow rates of produced Hydrogen, this research assumes centrifugal compressors due to their flexibility. The isentropic efficiency $\eta_{s,C}$ is considered to be 0.8, $Z_{(dis/suc)}$ represents compressibility factor(s) for discharge and suction, $p_{(dis/suc)}$ is the discharge or suction pressure of Hydrogen which is measured in bars, N is the number of compression stages, T_{suc} is the suction temperature, Q is the volumetric flow rate of produced Hydrogen at standard conditions, γ is the specific heat ratio of Hydrogen and P_c is the required power for the compression in the Hydrogen storage tank [1].

The power consumption of any selected Hydrogen storage tank can be deduced by dividing the total required power by the mass flow rates of the produced Ammonia. The equation below, which determines the specific power consumed, is reminiscent of other specific power consumption calculations as determined in this document, therefore establishing a ground for comparison of power consumption by the different components of the system [1].

$$P'_{HST} = \frac{P_{HST}}{\dot{m}_{NH_3}} = 214.3 \text{ kWh} / t_{NH_3} \quad (10)$$

8.6 Air Separation Unit

The air separation unit is primarily needed for the supply of Nitrogen to aid in the Ammonia synthesis loop. During the supply of Nitrogen by this unit, Oxygen O_2 , which is a precious and in-demand substance, is generated as a by-product. When sold, it can help reduce the cost incurred for this project. This document will consider cryogenic distillation for air separation since it produces high-grade Nitrogen in parts per billion range, with estimates reaching nearly 400000 Nm^3/h . Power consumed during this separation process all goes to the compressors used for the refrigeration process and can be calculated by the formula;

$$P_{ASU} = \dot{m}_{NH_3} P'_{ASU} \quad (11)$$

The variable P'_{ASU} represents the specific power consumption by the selected cryogenic air separation unit, \dot{m}_{NH_3} [t/h] is the mass flow rate of the produced Ammonia, thereby making P_{ASU} the power consumption of the selected configuration for the air separation unit [1].

8.7 Ammonia Synthesis Loop

Almost all Ammonia plants operate on the Haber – Bosch process for their Ammonia synthesis loop, which has been in operation for a century and over. All of the equipment to be used in this loop will be electrically powered in order to stay within the confines of the renewable-to-gas nature of this project. Hydrogen H_2 and Nitrogen N_2 are mixed outside the loop and used as feed for the synthesis loop. The pressure of this feed is raised to 200 bars when it passes through the first compressor and is mixed with synthesis gas returning from the reactor. After temperature increment to about $500^\circ C$, the mixture is pushed into the reactor. The synthesis gas is subsequently fed into a fixed-bed catalytic reactor, which is the main part of the synthesis loop. A condensation process is employed to remove the generated Ammonia while the remaining gas enters the loop again. This process is thermodynamically restricted to generate between 15% to a maximum of 35% of Ammonia. As such, the whole process is repeated for several cycles till the highest achievable purity level is obtained.

All the power used in this synthesis loop is consumed by the compressor, and the formula used for calculating the power consumed by the Hydrogen process can be applied. For calculating the total power consumption of the system, a conversion rate of 0.25 is assumed in each pass, and five intermediate stages for compression units are considered. Ammonia production plant sizes range from just a couple of tons per day to 3300 tons per day plants. However, the generalized industrial acceptable size is 1000 tons per day of Ammonia [9].

8.8 Ammonia Storage Tank

A stainless-steel tank is often used for Ammonia storage. This is due to the toxic, highly flammable and corrosive nature Ammonia has on Carbon steel tanks [1], [5], [16]. A 9000-ton Ammonia storage tank will consume about 17 kW of energy as all this goes to the compressor used. We can neglect this power consumption since it is much lower than all other power consumption systems in the process. For this paper, 30 days of storage was assumed, and a double-walled stainless steel tank was chosen[1]. As industry standards would have it, if an Ammonia plant is to produce 9000 tpd_{NH_3} , nine plants of 1000 tpd_{NH_3} would be considered [9].

9. Feasibility Studies of St. Anthony

9.1 Stakeholders in St. Anthony

The town of St. Anthony has a population of about 2500 people on the regular but increases significantly due to tourism as visitors tour the community and region in summer time . There is a major hospital located in St. Anthony, which receives a lot of medical tourists from other parts of the island.

The major occupation of people in St. Anthony was found to be fishing, as that has existed since. There also exists a normal blue-collar job market, which is very small as most firms and franchises are not present, as well as other small local firms/companies. The major stakeholders in St. Anthony from the site visit are the inhabitants, SABRI, the Hospital, small firms, schools, and other social amenities. There is NL hydro

and NL power, which are responsible for meeting the power demand of the town and all installations that need power. There is the 6 MW standby diesel power plant for emergency situations when the grid cannot serve the town due to problems.

The inhabitants are represented by the Town Manager, Mr. Curtis Richards, who also serves as the head for all social and community level amenities. The role of the town manager is interconnected to all aspects of community operations and other related economic and social development policies and decisions. SABRI, which stands for St. Anthony Basin Resource Incorporated, is an organization that manages the use of revenue accrued from the resources that the town of St. Anthony generates. It is, therefore, present in many, if not all, organizations, meetings, boards, and decision-making bodies in St. Anthony.

9.2 Barriers to Wind Power Development

Under this section of this document, various barriers that have been identified for the whole of Newfoundland will be downsized to fit St. Anthony. These barriers will be broadly categorized under which sub – section will be further explained.

Political barrier to wind power development in St. Anthony.

i. Newfoundland Utility's Role

In as much as the utility companies of NL have tried to diversify their energy portfolio, their role is to make sure there is light for everyone every time. This makes the utilities conservative, needing to be pushed for more power production systems since the source of power generation for the island far outstrips the power demand of the whole island.

ii. Low Public Engagement on Energy Policy:

Most of the people the site visit team randomly spoke to were happy about the research or the possibility of having a wind power plant in St. Anthony but said this was the first time any "official" has reached out to them in respect of wind energy generation.

iii. Legislative Barriers (1 Seller of Electricity)

Bill 61 in the 47th General Assembly of 2012 first session gives an exclusive right to the existing utilities to supply, transmit, distribute, and sell electricity to all residents and firms. Therefore, any firm that intends to produce power has to sell to the utilities in Newfoundland for onward sale to consumers [21]. This, in some way, does not promote competition and more investments into other sources of energy generation by the private sector.

Knowledge Barrier

iv. Energy illiteracy

There is wide spread misinformation about new technologies like wind power, which can lead to delays in adopting these technologies. Reference [7], suggests that the general public in Newfoundland, St. Anthony included, possess inadequate knowledge and understanding about energy sources. There is also a huge amount of misinformation about wind energy, as many residents think it is cheap since the wind resource exists on the island.

v. Siloed Knowledge

'Siloed knowledge' has been present in many fields of energy policy and resource management as a barrier to effective environmental action. Silo effect as concluded by [22], was a major factor in the unwillingness of key – stakeholders with similar mandates to share vital information. Hence, there is a lack of credible information in policy formation, and this can be seen in [23], where poor communication amongst key – stakeholders was a barrier to further development of wind energy and planning in China. This is also present in this research as there seems to be a disconnect between private sector ongoing research and that of academia on wind energy creating "research siloes".

Technical barriers

vi. Spilt energy

The size of the power generation dam in Newfoundland is huge and serves as a good reservoir for all the water needed for power generation. With the connection of new power generation sources to the existing grid, some amount of water cannot be drafted to generate electricity; as such, it has to be spilt. The maximum capacity of addition to the grid before the spilling of the dam was found to be about 80 MW [7].

vii. Icing of turbine

St. Anthony is in the northern peninsula, and all the selected locations are near waterfront as such, these locations are at the mercy of the element, specifically the cold Atlantic air front, which can have chills beyond -30C. This can lead to icing on the turbines, which can reduce wind energy generated by the turbines between 10 – 15%.

Economic barriers

viii. Cost competitiveness of wind energy

Conventional generation technologies have a competitive cost advantage over renewable technologies. Spot market price for power generated from natural gas are about half the price for utility – scale wind energy in Newfoundland (\$0.07 - \$0.14) [7]. The current price range of wind turbines, as per literature studied for this report were higher [1], [8], [18], [24].

ix. Insufficient demand in St. Anthony

With a current population of just above 2,500 inhabitants and a few establishments, the demand for power in St. Anthony, which is a microcosm of the Newfoundland province, does not make wind energy development a profitable venture. The cost of wind-generated power pales in comparison to the current rate for NL hydro.

x. Limited export avenues

As of 2022 when the Canadian prime minister signed the MOU with their German counterpart for the development of a Hydrogen economy, nothing of materialistic value had been identified relating to the use of the wind power potential for the generation of energy and possible export of the generated energy.

Natural and Ecological barriers

xi. Tourist site

The town of St. Anthony is a very hot spot for tourism. This is due to the perennial drifting of icebergs and other natural movements of wildlife through migration paths. This brings a lot of tourist traffic, hence revenue generation. Parts of Cape Norman, which is a great spot for wind power generation, may not be considered for wind power development due to this barrier.

xii. Conservation and protected sites

There is a proposed conservation and ecological protected site of about two (2) square kms at Cape Norman due to the presence of fossils and pre-historic flora. This area does not overlap with prospective location for the wind project but has to be acknowledged accordingly.

9.3 Mitigation strategy

This section of the report will try to give possible solutions to the barriers identified and explained in the preceding section. A case will be made for the development of wind energy in St. Anthony, as most of the stated barriers can be worked upon to bring the project to life. Of all the stated barriers, the following can be given a localized approach, whereas the remaining are of provincial or federal scale.

Political barriers, as identified, were provincial in nature and would require that level of engagement and negotiation to help resolve or address them. For example, the legislative barrier of 1st seller of energy has to be modified to allow entities generate their own electricity and allow for grid integration of these projects to power any installations of these entities located across the island. Low public engagement can be

addressed by conducting provincial-wide public engagement programs to address and communicate the issues and the potential wind power projects can have on the economy of St. Anthony. The knowledge barriers identified can also be addressed through strategic and targeted education of the public using the most utilized form of information dissemination. In the case of siloed knowledge, industry, academia, and other stakeholders with the appropriate information can resolve whatever differences in approach in order for information to be shared among them.

A multi-phased approach can be used to address the economic barriers identified. The demand for energy in a location can be increased by making the location attractive for the setting up of larger consumers of generated energy in that location. This has a direct effect on the cost of energy generation, as with all other commodities relating to supply and demand. For the wind to Hydrogen/Ammonia project to be considered very effective, a concentrated approach of making St. Anthony a viable investment location for the setting up of more power-intensive facilities or industry. This will, in turn lead to higher demand for energy, which would have a cascading effect on the pricing of energy, therefore solving the issue of price competitiveness for wind-generated energy. As has been done by SABRI for this project, natural and ecological barriers when identified should be acknowledged, considered and incorporated during planning and decision-making phase in order to obtain the necessary clearance from appropriate authorities.

10. Economic Analysis

10.1 General parameters

The viability of green Hydrogen/Ammonia production is a function of the cost of power generated from the wind through the use of wind turbines. This cost is related to the amount of energy that is obtained from the wind turbine due to the wind regime in the locality. It is a function of the design and operating parameters of the wind turbine matching the wind regime and the capital cost of the project [1], [18]. Levelized cost of Energy (LCOE), Levelized Cost of Hydrogen (LCOH), and Levelized Cost of Ammonia (LCOA) will be the parameters of assessment for the whole wind to energy, wind to Hydrogen/ Ammonia system. The levelized cost of a product, in this case, energy, Hydrogen, and Ammonia refers to the amount of capital required to generate or produce a unit of the said product.

Table 6. Assessment parameters for economic analysis

Product	Economic measure	Rate
Power	LCOE	US\$/kW
Hydrogen	LCOH	US\$/ton
Ammonia	LCOA	US\$/ton

In order to calculate the capital cost of an energy project, C_{EP} , the specified energy conversion system cost (ECS) made up of all the components and engineering works must be included. In the case of a wind energy project C_{WEP} , the energy conversion system consists of the battery energy storage C_{BES} , tower and controllers C_{TCS} , rectifier and inverter C_{RI} ; civil engineering works C_{CEW} and miscellaneous cost covering all other equipment necessary C_{MISC} . The capital cost calculation for wind energy project formula then becomes;

$$C_{WEP} = C_{BES} + C_{TCS} + C_{RI} + C_{CEW} + C_{MISC} \quad (12)$$

The real interest rate (i) was calculated using the equation below;

$$i = \frac{i' - f}{1 + f} \quad (13)$$

where i' is the nominal interest rate, assumed to be 2.5%, and f is the expected inflation rate also assumed to be 1.5%. The annualized net present value of the project can be calculated when the discounted values are obtained using the inflation formula above to calculate the net present value (CNPV) and the capital recovery factor (CRF) through the equation below;

$$C_a = CRF(i, n)C_{NPV} = \frac{i(1+i)^L}{(1+i)^L - 1} C_{NPV} \quad (14)$$

The assumed lifetime of the project is 25 years and is denoted by L in the above equation.

10.2 Wind Turbine Economics

Newfoundland is an island province as such, the economics for this onshore(island) wind energy project differs from normal onshore locations. Most, if not all, equipment must be ferried to the island's easiest port of entry and transported to St. Anthony. This may be the case where the port located at St. Anthony does not have the capacity to receive such supplies. Also, some of the selected locations do not have asphalted roads, which would require other arrangements to be made to meet the transportation of required components of the project, thereby adding to the overall cost of the project.

That being said, there exist such onshore(island) wind projects, where in 2009, Cianbro Construction Company reported that 18 erection cranes load, 27 turbine loads, and 30 concrete loads were required, therefore increasing the overall cost of the project. This led to a cost of about \$14.5 million for the installation of three (3) GE 1.5 MW wind turbines [16], taking the cost per kilowatt of energy to \$3222. It was against this backdrop that the price of the wind turbine for this project was assumed at \$1500/kW, considering the advancement in technology and the overall reduction in the price of wind power project components. The levelized cost of all generated products are calculated and used to estimate the possible cost of all generated or produced products to break even financially. This is an economic metric for determining the viability of production/generation of a product over the life period of the plant [1], [18].

Therefore, the levelized cost of wind energy for a wind energy project can be calculated below;

$$C_{LCOE} = \frac{C_{BES} \cdot K_{BES} + C_{TCS} \cdot K_{TCS} + C_{RI} \cdot K_{RI} + C_{CEW} \cdot K_{CEW} + C_{MISC} \cdot K_{MISC} + C_{(OM)ESC}}{E_{WES}} \quad (15)$$

where K_{BES} , K_{TCS} , K_{RI} , K_{CEW} , and K_{MISC} represent recovery cost in terms of capital for the battery energy storage system, tower and controllers, rectifier and inverter, civil engineering works, and miscellaneous, respectively. It should also be noted that economic viability takes into account the initial investment, replacement, operation and maintenance, and so many more. E_{WES} represents the electrical energy output of any wind energy system, while $C_{(OM)ESC}$ represents the maintenance and operation cost when escalated. Capital recovery cost (K) can be calculated with the formula,

$$K = \frac{d(1+d)^L}{(1+d)^L - 1} \quad (16)$$

with d representing the discounted rate, and L as the useful life of the system in years. The values of d and L depend on the project component for wind power and are provided in the table below.

Table 7. Discounted rate for system components

Project component	Discounted value (%)	Useful life (years)
Battery energy storage	5	15
Wind turbine	10	25
Civil engineering works	5	25
Rectifier and inverter	5	15
Misc components	5	25

With a known specific cost of a wind turbine to be used, the capital cost of any wind power project CWPP can be estimated with the relationship;

$$C_{wEp} = S_{WT}P_R(\$) \quad (17)$$

with S_{WT} and P_R as the specific cost for the selected wind turbine and rated power, respectively employed in the project. For this project, a specific cost of US\$1500/kWh [2] was used. Other component cost used in the wind power project was determined below;

$$C_{TCS} = f_1 C_{WPP} \quad (18)$$

$$C_{BES} = f_2 C_{WPP} \quad (19)$$

$$C_{RI} = f_3 C_{WPP} \quad (20)$$

$$C_{CEW} = f_4 C_{WPP} \quad (21)$$

$$C_{MISC} = f_5 C_{WPP} \quad (22)$$

where f_1, f_2, f_3, f_4 , and f_5 represent the fractional percentage of cost of the wind power project (CWPP) and are 74%, 9%, 3%, 4%, and 10% respectively, as stated in [18]. The operational and maintenance cost, $C_{(OM)ESC}$ (\$/yr) as escalated and calculated is as follows;

$$C_{(OM)ESC} = \frac{m_o}{d - e_{om}} [1 - (1 + e_{om})^L (1 + d)^{-L}] \quad (23)$$

with m_o and e_{om} representing the cost of operation and maintenance for the inception year and the escalation ratio of operation and maintenance, respectively taken as 5% and 3.5% of the cost of the wind power project [18], L is the lifetime of the project taken as 25 years. The whole formulae needed for this already exist in HOMER, as such, figures, data, or results obtained from HOMER simulation represents the equivalent values if the formulae stated above were employed.

10.3 Economic Analysis of Hydrogen and Ammonia Production from Wind Energy

The Levelized Cost of Hydrogen and Levelized Cost of Ammonia method is used in the analysis of Hydrogen cost per ton and Ammonia cost per ton in US\$. In the Hydrogen production system, the following components: electrolyser, stack, storage tank, and water desalination unit were employed and, as such contributed to the total investment in addition to the cost of energy generation from the WPP. Therefore, the total cost can be calculated with the following component cost;

$$C_{T(EZ)} = C_{CT(EZ)} + C_{INS(EZ)} + C_{STK} + C_{WDU} + C_{ST} + C_{OM(EZ)} \quad (24)$$

where $C_{CT(EZ)}$, $C_{INS(EZ)}$, C_{STK} , C_{WDU} , C_{ST} and $C_{OM(EZ)}$ represent the capital cost of the electrolyser, installation cost, cost of the stack, cost of water desalination unit, cost of Hydrogen storage tank and operation and maintenance cost of the electrolyser.

The capital cost of the electrolyser can be obtained with the specific cost and the capacity of the deployed electrolyser by the relationship;

$$C_{CT(EZ)} = S_{EZ} G \quad (25)$$

with S_{EZ} representing the specific cost of the electrolyser employed and G is the capacity in kW of the electrolyser. This project employs the NEL electrolyser model M5000 with a capacity of 25 MW with a specific cost of \$600/kW [1], [25].

The other costs were also calculated below;

$$C_{IST(EZ)} = h_1 C_{CT(EZ)} \quad (26)$$

$$C_{STK} = h_2 C_{CT(EZ)} \quad (27)$$

where h_1 , h_2 are given as 12% and 40%, representing a fraction of the cost of the capital cost of the electrolyser [18].

The formula below was used to generate the maintenance and operational cost of the electrolyser over the period of the project;

$$C_{OM(EZ)} = C_{initial} \left(\frac{1+a}{1+b} \right) \left[\frac{1 - \left(\frac{1+a}{1+b} \right)^L}{1 - \left(\frac{1+a}{1+b} \right)} \right] \quad (28)$$

with a and b representing inflation and interest rate in Canada with values of 3.3% [26] and 5% [27]. L represents the lifespan of the electrolyser, in this case, 25 years. The cost of the Hydrogen storage tank used for this project is assumed to be \$350/kg of Hydrogen with a specific operation annual cost of \$3.5/kg [1]. The capital cost of the water desalination unit is assumed to be US\$531/LPH, with an operation and maintenance cost of US\$ 49.8/LPH. Therefore, the Levelized Cost of Hydrogen can be calculated by;

$$LCOH = \frac{C_{T(EZ)}}{M_{H_2}} \quad (29)$$

We can subsequently generate the total cost associated with Hydrogen production(\$/ton) at a selected site as;

$$C_{H_2P} = LCOH + C_{LCOE} \quad (30)$$

In the subsequent production of Ammonia, an air separation unit (ASU) is employed to produce the needed nitrogen N_2 . The produced Nitrogen is then sent to an Ammonia synthesis loop, where it is combined with the produced Hydrogen to generate Ammonia. The produced Ammonia is either stored in a storage tank or sent via pipelines to be shipped or transported.

To calculate the final capital cost for an Ammonia plant, the formula below can be used but is only valid for small plants with capacity of up to 5tpd $_{NH_3}$;

$$C_{NH_3} = 3,322,500X^{0.6} \quad (31)$$

where X is the capacity of the plant in metric tons per day [16]. If the capacity goes beyond 5 tons, the relationship changes to the following;

$$LCOA = \frac{C_{a,A}}{(m_{NH_3})_{tot}} \quad (32)$$

In the presented equations, E_{tot} (kWh) represents the total electricity produced in 1 year, $C_{a,H}$, $C_{a,A}$ symbolizes the sum of the annual cost of components in Hydrogen production system and Ammonia production system, respectively.

10.4 Component Cost

For the purpose of this project, data was obtained from the International Renewable Energy Agency (IRENA). This project looks to go beyond an assumed 5 MW of wind power. Hence, a 25 MW data sheet was considered from NEL for the M5000 model electrolyser. This led to an estimated 1500 US\$/kW as CAPEX for a wind turbine. The electrolyser cost is fundamental to the final CAPEX and can be seen to increase the CAPEX somewhere more than \$ 1360 but not more than 2400 US\$/kW for anything 5 MW and below. OPEX is fixed at 1.5% and 1.52% of the specified CAPEX in relation to the material and labour associated operational costs, respectively. For the purpose of this document, the variable OPEX is not considered since it has been fused into the cost of electricity. Even though the auxiliary components of the electrolyser unit have an average of 10 years for operation and must be replaced as needed, the electrolyser is considered to last for 25 years. This auxiliary component cost is projected at 25% of the total capital cost of the electrolyser [1]. The cost of the Ammonia synthesis loop was assumed to be 4983 US\$/kg of NH_3 [1] based on the suggested location of the production plant. The CAPEX for the Ammonia storage tank and air separation unit was calculated with the formula below using the assumed flow rates table in this document;

$$CAPEX_{ASU} = (2.1 \times 10^6) m_{N_2}^{-0.6249} + 12163 \quad (33)$$

$$CAPEX_{AST} = (6.083 \times 10^3) m_{NH_3}^{-0.864} + 700.8 \quad (34)$$

10.5 Excess Electricity

This document assumes that all the electrical energy generated will be directed to existing facilities or will be channelled into the Hydrogen/Ammonia production unit. It is also to be assumed that there is the possibility of generating excess power. For the economic viability of the project, this excess can be transmitted to other facilities as necessary in the surrounding towns. An example is the green house facility at Carbonear. It is also possible to use the knowledge of potential excess power generated to increase the capacity/size of the Hydrogen or Ammonia.

10.6 Salvage Value

This represents the value of the equipment or facility after the end of life has been reached in monetary terms. Each component of the system has a salvage value, which is determined with the following equation.

$$SV_k = C_{r,k} \left[(N_{r,k} + 1) - \frac{L}{L_k} \right] \quad (35)$$

where $N_{r,k}$ is the number of replacements of the specific component, L_k is the lifetime of the component, k ; L is the projected lifetime, and $C_{r,k}$ is the replaced component cost.

11. Results and Analysis

The average wind speed of more than 6 m/s for the 3 selected locations was indicative of the magnitude of wind resource available. The highest wind speed recorded from HOMER/NASA was 9.25 m/s, with the lowest speed being 5.47 m/s. This is well above the wind speed 3-4 m/s needed to cause most industrial wind turbines to spin and generate electricity.

All three (3) locations recorded impressive wind speeds, with Cape Norman having the highest of the three (3). American Drive and Cremaillere recorded similar data as these 2 locations are within eye-view of each other. 9.25 m/s was the highest speed recorded for Cape Norman in January, while American Drive and Cremaillere both recorded 8.10 m/s in December. American Drive and Cremaillere both recorded 5.47 m/s as the lowest wind speed in the month of August, while 6.44 m/s was the lowest recording for Cape Norman in July. The wind power density for the three (3) locations also presents good numbers at the recorded heights. A low of 361 W/m² was recorded for American drive. With current wind turbines having hub heights in the 100 m region, it was instructive to observe that, all three (3) locations recorded over 1000 W/m². This further goes to point out the impressive wind resource potential of the locations. With winter months being the most energy-intensive period, it was instructive to observe that all 3 locations had the best wind speed recorded just about the same time.

Scenario 1

The annual load served was 61.29 GW/yr with daily power demand of 168 MWh/day and peak demand hitting 12.8 MW. To meet this demand, a 45 MW wind generation setup and a battery storage system of 146.4 MWh was simulated through HOMER. The highest total power produced from wind was 268.99 GWh/year from 18 turbines with an hourly load of 7 MW setup in HOMER for American Drive and Cremaillere, with Cape Norman generating 215.46 GWh/yr utilizing 15 turbines with 3 MW capacities. 1.5 MW turbines generated 258.02 GWh/year and 185.23 GWh/year from 31 and 25 turbines for Cape Norman, American drive respective locations. Excess electricity ranges from 205.86 GWh/year for 3 MW turbines to 121.39 MWh/year for 1.5 MW turbines. Monthly power generation is plotted below. The LCOE as calculated through HOMER ranged from as low as 0.23 US\$/kW at Cape Norman to a high of 0.27 US\$/kW at American drive and Cremaillere using a 3 MW turbine. The 1.5 MW turbine generated an LCOE of 0.24 US\$/kW at Cape Norman and 0.27 US\$/Kw using a 1.5 MW turbine at either American Drive or Cremaillere, respectively.

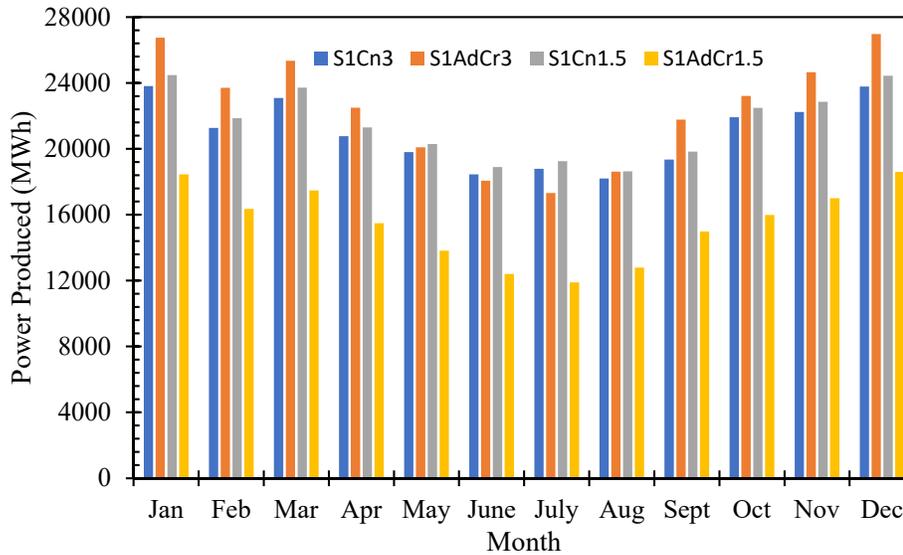


Figure 8, Monthly power production in Scenario 1

Tables 8 and 9 represent the potential Hydrogen and Ammonia production if all the excess power from scenario 1 was used to power the various generation plants as per their power demands.

Table 8. Hydrogen Production Potential from excess electricity.

Total power input (GW/yr)	Turbine size (MW)	Hydrogen Production Potential (ton/yr)	Location
188.27	3	87390	Cape Norman
194.82	1.5	90430	
205.86	3	95550	American Drive and Cremaillere
121.39	1.5	56350	

Table 9. Ammonia Production Potential from excess electricity

Total power input (GW/yr)	Turbine size (MW)	Ammonia Production Potential (ton/yr)	Location
188.27	3	14940	Cape Norman
194.82	1.5	15460	
205.86	3	16340	American Drive and Cremaillere
121.39	1.5	9630	

Table 10. Levelized Cost of Hydrogen for Scenario 1

Total power Input (GW/yr)	Turbine size (MW)	Hydrogen Production Potential (ton/yr)	Hydrogen Production System cost (\$M)	LCOH (\$/ton)	Location
188.27	3	87390	556.2	6360	Cape Norman
194.82	1.5	90430		6150	
205.86	3	95550		5820	American Drive and Cremaillere
121.39	1.5	56350		9870	

Table 11. Levelized Cost of Ammonia for Scenario 1

Total power Input (GW/yr)	Turbine size (MW)	Ammonia Production Potential (ton/yr)	Ammonia Production System cost (\$M)	LCOA (\$/ton)	Location
188.27	3	14490	21.9	1468	Cape Norman
194.82	1.5	15460		1419	
205.86	3	16340		1342	American Drive and Cremaillere
121.39	1.5	9630		2277	

The Levelized Cost of Hydrogen and Ammonia in this section was very high due to the cost of the power production infrastructure as compared to the total amount of Hydrogen and Ammonia produced. Levelized Cost of Hydrogen ranging from a high of US\$ 9870/ton to a low of US\$ 6360/ton were higher than those obtained for scenario 2 and 3. The subsequent cost of Ammonia production was also very high when compared to prizes obtained in scenarios 2 and 3. This can be attributed to the amount of power produced as compared to gas production.

Scenario 2

The total load for the year was about 80.15GW with a daily power demand of approximately 220 MWh and peaking at 16.8 MW. American Drive and Cremaillere surprisingly produced the least power of 283.93 GWh/yr and 237.10 GWh/yr, with the selected 3 MW and 1.5 MW turbines, respectively, while Cape Norman produced the most power of 368.8 GWh/yr and 332.9 GWh/yr respectively. American Drive and Cremaillere used 19 turbines (3 MW) and 32 (1.5 MW), with Cape Norman utilizing 22 (3 MW) and 40 (1.5 MW). Excess power generation ranged between 286.32 GWh/yr to 153.57 GWh/yr for 3 MW and 1.5 MW, respectively. Cape Norman generated an LCOE of 0.24 US\$/kW and 0.23 US\$/kW while using 3 MW and 1.5 MW turbines, respectively, with American drive and Cremaillere generating 0.271 US\$/kW and 0.272 US\$/kW for each turbine respectively. A 48MW wind turbine setup alongside a battery energy storage system of about 305 MWh was needed to meet the load demand.

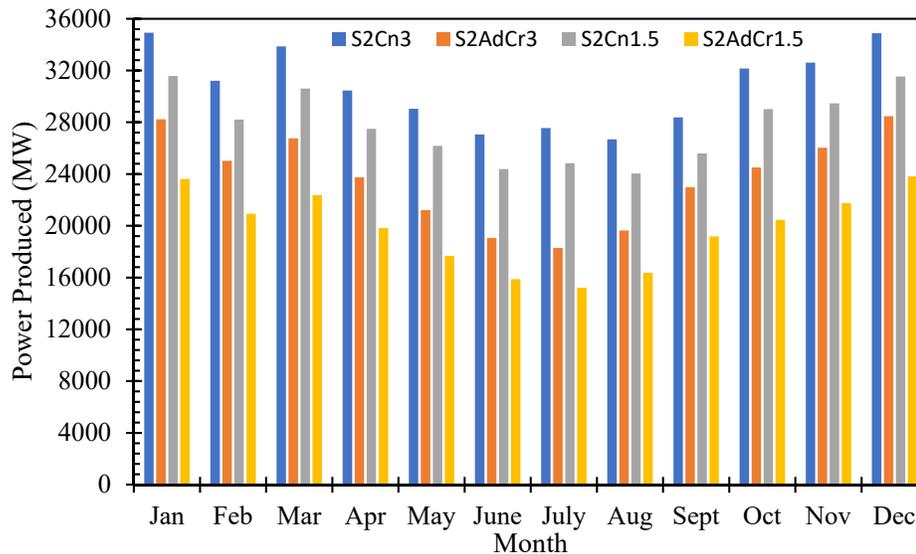


Figure 9, Monthly power production for scenario 2

Table 12. Hydrogen Production Potential in Scenario 2

Total power Input (GW/yr)	Turbine size (MW)	Hydrogen Production Potential (ton/yr)	Location
305.32	3	141,719	Cape Norman
269.27	1.5	124,986	
219.76	3	102,005	American Drive and Cremaillere
172.57	1.5	80,101	

Table 13. Ammonia Production Potential in Scenario 2

Total power input (GW/yr)	Turbine size (MW)	Ammonia Production Potential (ton/yr)	Location
305.32	3	24,232	Cape Norman
269.27	1.5	21,371	
219.76	3	17,441	American Drive and Cremaillere
172.57	1.5	13,696	

Table 14. Levelized Cost of Hydrogen for Scenario 2

Total power input (GW/yr)	Turbine size (MW)	Hydrogen Production Potential (ton/yr)	Hydrogen Production System cost (\$M)	(LCOH) (\$/ton)	Location
305.32	3	141,719	556.2	3902	Cape Norman
269.27	1.5	124,986		4450	
219.76	3	102,005		5450	American Drive and Cremaillere
172.57	1.5	80,101		6940	

Table 15. Levelized Cost of Ammonia for Scenario 2

Total power input (GW/yr)	Turbine size (MW)	Ammonia Production Potential (ton/yr)	Ammonia Production System cost (\$M)	(LCOA) (\$/ton)	Location
305.32	3	24,232	21.9	905.2	Cape Norman
269.27	1.5	21,371		1026	
219.76	3	17,441		1257	American Drive and Cremaillere
172.57	1.5	13,696		1602	

The Levelized Cost of Hydrogen in this scenario is very comparable with data from many of the references used in this report, which hovers around 3.8 US\$/kg to 7 US\$/kg [28], [29]. When these figures from the reference materials are converted to ton-based cost, results from this report are very comparable. In the case of Ammonia pricing, there is not much difference. The differences are as a result of the equipment size and other inputs, which did not aid larger production quantities.

Scenario 3

A setup of a 114 MW wind power plant and a battery storage system of about 454 MWh capacity was needed to meet the load demand of about 171.6 GW per year. The daily power demand was about 470 MW, with a peak of 35.9 MW. Cape Norman produced the most power of about 637.02 GW/yr while using the 3 MW, as compared to about 552.92 GW/yr for American Drive and Cremaillere while using the same turbine. Surprisingly, American Drive and Cremaillere produced the most power of about 703.88 GW/yr, using the 1.5 MW turbine when compared to about 682.51 GW for Cape Norman.

Cape Norman generated the cheapest power at LCOE of 0.23 US\$/kW when using the 3 MW turbine as compared to 0.27 US\$/kW for American Drive and Cremaillere. When using the 1.5 MW, Cape Norman's LCOE was cheaper at about 0.23/kW as compared to 0.281 US\$/kW for American drive and Cremaillere. The maximum number of turbines projected to be deployed in this scenario would be 95 of 1.5 MW capacity at either American Drive or Cremaillere. The same location has the least number of 3 MW turbines deployed to meet the load.

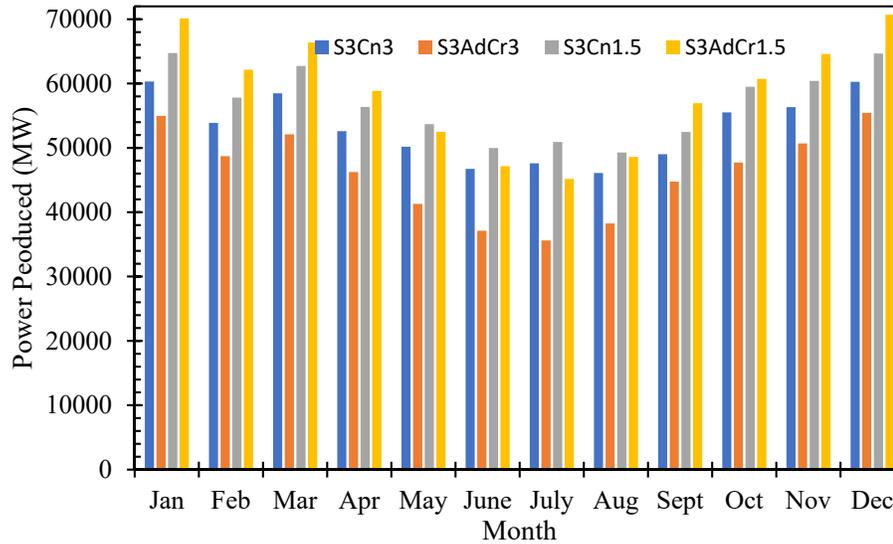


Figure 10. Monthly power production for scenario 3

Table 16. Levelized Cost of Ammonia for Scenario 3

Total power input (GW/yr)	Turbine size (MW)	Ammonia Production Potential (ton/yr)	Ammonia Production System cost (\$M)	LCOA (\$/ton)	Location
569.84	3	45,225	21.94	485	Cape Norman
615.41	1.5	48,842		449	
484.51	3	38,453		570	American Drive and Cremaillere
636.10	1.5	50,484		434	

The levelized cost of Ammonia LCOA in this Scenario is very impressive, considering the amount produced. These prices are consistent with current market prices as referenced in this report [17], [29], [30]

12. Result Validation and Comparison

The Levelized Cost of Energy (LCOE) obtained from HOMER simulation ranging between 0.23 US\$/kW to 0.28 US\$/kW compares favourably with references [1], [18]. Cape Norman produced, in most cases, the cheapest price for all generated products. The LCOH ranged between 3902 US\$ /ton for Scenario 2 at Cape Norman and a high of 9870 US\$ /ton for scenario 1 at American Drive and Cremaillere. The LCOA, LCOH as obtained for all scenario and selected locations in this research through simulation and calculation, compares favourably to existing material [29]–[31] This goes to show that, for a comprehensive material with all the practical and real values, practical estimates can be made for the LCOE, LCOH, and extended to LCOA for St. Anthony, which will correspond to existing field data.

13. Sensitivity Analysis

Sensitivity analysis will look at factors in the existing document that play a major role in result determination. As such, various vital component costs and other factors will be manipulated to ascertain the level of variance it will generate in the data obtained so far. Being a wind turbine power generation project, the price of the major components in this project, namely wind turbine cost, will be investigated in all three (3) scenarios to measure the effect this price changes will have on the end economic products, that is LCOE, LCOH and LCOA.

A ten percent (10%) reduction in the capital cost of the wind turbine was investigated changing the capital cost from 1500 US\$/kW to 1350 US\$/kW. Factors considered for the assumption of a 10% reduction in installation cost were [2]

- I. Decreasing price of wind turbine pre – covid and increasing demand of wind projects post – covid.
- II. Project commissioning and equipment order time lag.
- III. Scale and location of project.

There was very minimal difference in LCOE for all locations and all scenarios when the 10% reduction was instituted which had negligible changes in the overall LCOH and LCOA.

For Scenario 1, LCOE for Cape Norman decreased from the range 0.24-0.23 US\$/kW to 0.228-0.221 US\$/kW across the chosen turbines while American drive and Cremaillere remained fairly unchanged at 0.27 US\$/kW. For Scenario 2 at the same locations stated, LCOE remained majorly unchanged at 0.225 and 0.226 US\$/kW from 0.23 US\$/kW and 0.24 US\$/kW for Cape Norman and 0.263 US\$/kW from 0.271 US\$/kW for American drive and Cremaillere respectively. Scenario 3 did not see any major changes as LCOE reduced from 0.23 US\$/kW to 0.227 US\$/kW for Cape Norman and a range of 0.262-0.271 US\$/kW from the range of 0.281-0.27 US\$/kW.

It can therefore be inferred that, there may have to be a major price reduction to see any significant effect on the LCOE for this project at the selected locations. A further sensitivity analysis must be conducted to investigate the overall changes in the LCOH and LCOA when component costs are adjusted in any direction to see the economic viability of the affected processes.

14. Port Readiness

The handling of Ammonia by industry has been long in existence as such, there exists ways for transporting Ammonia out of produced regions to buyers. Existing established infrastructure is available for the trade of H₂, which will be carried by Ammonia. As of 2021, almost 500 carriers of liquified petroleum gas were estimated to be able to be carriers of produced Ammonia since both products have similar characteristics. A total of nearly 40 ports exists worldwide for exporting Ammonia while close to 90 import ports exist. These also include 6 ports that can both export and import Ammonia [5].

In order to consider setting up or upgrading an existing facility to export H₂ in any form and with reference to this project, Ammonia to be specific, 3 criteria must be looked at;

- a. The Hydrogen/Hydrogen-carrier production capacity of the location
- b. The strategy of the location
- c. The actual progressive actions of the location

This paper would help SABRI, the town of St. Anthony, and the province of Newfoundland and Labrador to evaluate its push for H₂ production and export while getting the necessary infrastructure ready across the island. After discussions with the Town Manager, there exist 2 options for any produced Hydrogen or Ammonia. Options suggested by the Town Manager were;

1. Revamping the old American wharf
2. Building a new facility to handle the Hydrogen/Ammonia.

The suggestions of the Town Manager after the initial meeting tie into criteria 2 and 3 listed above in relation to the export of Hydrogen or Ammonia that is produced at St. Anthony.

15. Finals

After several simulations, data analysis, comprehensive and extensive material investigation, data obtained for this project align well with established and existing knowledge, which are listed below;

- The location of St. Anthony has wind resource similar to Newfoundland, which is amongst the windiest locations on the globe.
- The 3 selected locations are the windiest spots in St. Anthony
- The available wind resource of the region is capable of generating power to replace the 6 MW standby diesel generator.
- Excess power produced can be used for the production of Hydrogen and Ammonia.
- Hydrogen and Ammonia production plants can operate at prevailing product cost in St. Anthony and selected locations.

There are barriers to the establishment of wind power project in St. Anthony but these barriers can be mitigated with appropriate steps and decisions. Sensitivity analysis and practical field data will be needed to improve the confidence level of the suggested projects.

16. Summary and Conclusion

St. Anthony, as a location, has several natural resources to generate enough revenue for the whole community. Wind resource is one surest way of transforming the ailing economy as this can generate the necessary life-saving opportunity for this community. The wind resource of this location compares favourably with other locations around the globe, which may not even have as much available wind [19], [32], [33]. With the right amount of investment, the wind resource can be used to replace the standby diesel generator, which contributes to GHG emissions of St. Anthony through power generation from the wind resource.

This document collected historical wind data and projected current wind data to ascertain how much power can be generated from the wind. It was emphatic to state that researchers in 2009 [4] studied the impact of a 5 MW wind farm on the grid in St. Anthony, but under the current leadership of SABRI and the town manager, a decision was made to fund research into how this wind resource or farm when developed can be transformational for the township of St. Anthony and surrounding communities in a bid to revive the economy of this region.

Historical wind speed averaged ranged between 6.84 m/s to 7.78 m/s collected at 50 meters height over a 30-year period ranging from 1983 to 2013, while recent wind data as obtained averaged between 8.83 m/s to 9.43 m/s indicated an overall increase in wind speed as at 2023 from global wind atlas. The wind power density of the studied locations was encouraging, ranging from 361 W/m² for 10-meter height to 1798 W/m² for 200-meter height. Inference was made that the wind power potential of these selected locations was well within 10% of wind power potential locations for the province of Newfoundland.

Production of power from the wind is very practical, as demonstrated through HOMER, and can be observed from the results that the 3 locations selected by SABRI can host wind power plants as these locations have great wind potential. This is corroborated by the researchers [4] as one of the sites, specifically Cape Norman, was the location for the establishment of the 5 MW wind farm whose effect on the grid was to be studied.

In this document, the wind resource was studied, and power generation was considered. It was found that the cost of power generated from these locations, which ranged between US \$0.23/kW to US \$ 0.27/kW, was well within the price range for most wind power plants, as referenced in [1], [2], [10], [29] just to cite a few. This paper went on to investigate the possibility of Hydrogen and Ammonia production from the power generated from the wind resource. It was evident through simulation and calculations that the LCOH and LCOA obtained in this paper were optimistic and encouraging. LCOH ranging between US \$ 3.902/kg to US \$ 9.87/kg was well with current rates for all studied references, with LCOA also showing promising figures for the quantities produced in this paper.

17. Reference

- [1] A. Kakavand, S. Sayadi, G. Tsatsaronis, and A. Behbahaninia, “Techno-economic assessment of green hydrogen and ammonia production from wind and solar energy in Iran,” *Int. J. Hydrog. Energy*, vol. 48, no. 38, pp. 14170–14191, May 2023, doi: 10.1016/j.ijhydene.2022.12.285.
- [2] R. Wiser et al., “Land-Based Wind Market Report: 2022 Edition; Executive Summary,” 2022.
- [3] D. R. MacFarlane et al., “A Roadmap to the Ammonia Economy,” *Joule*, vol. 4, no. 6, pp. 1186–1205, Jun. 2020, doi: 10.1016/j.joule.2020.04.004.
- [4] S. M. Islam, M. T. Iqbal, and J. E. Quaiocoe, “Grid Impact of a 5.25 MW Wind Farm near St. Anthony, Newfoundland,” *Wind Eng.*, vol. 33, no. 6, pp. 649–659, Dec. 2009, doi: 10.1260/0309-524X.33.6.649.
- [5] P. S.-L. Chen et al., “A review on ports’ readiness to facilitate international hydrogen trade,” *Int. J. Hydrog. Energy*, vol. 48, no. 46, pp. 17351–17369, May 2023, doi: 10.1016/j.ijhydene.2023.01.220.
- [6] C. E. R. Government of Canada, “CER – Provincial and Territorial Energy Profiles – Canada.” Accessed: Feb. 23, 2023. [Online]. Available: <https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-canada.html>
- [7] N. Mercer, G. Sabau, and A. Klinke, “‘Wind energy is not an issue for government’: Barriers to wind energy development in Newfoundland and Labrador, Canada,” *Energy Policy*, vol. 108, pp. 673–683, Sep. 2017, doi: 10.1016/j.enpol.2017.06.022.
- [8] B. A. Franco, P. Baptista, R. C. Neto, and S. Ganiha, “Assessment of offloading pathways for wind-powered offshore hydrogen production: Energy and economic analysis,” *Appl. Energy*, vol. 286, p. 116553, Mar. 2021, doi: 10.1016/j.apenergy.2021.116553.
- [9] N. D. Pawar et al., “Potential of green ammonia production in India,” *Int. J. Hydrog. Energy*, vol. 46, no. 54, pp. 27247–27267, Aug. 2021, doi: 10.1016/j.ijhydene.2021.05.203.
- [10] L. Aiche-Hamane, M. Belhamel, B. Benyoucef, and M. Hamane, “Feasibility study of hydrogen production from wind power in the region of Ghardaia,” *Int. J. Hydrog. Energy*, vol. 34, no. 11, pp. 4947–4952, Jun. 2009, doi: 10.1016/j.ijhydene.2008.12.037.
- [11] “Hydrogen-Insights-2021.pdf.”
- [12] “map of st anthony newfoundland - Google Search.” Accessed: Jun. 27, 2023. [Online]. Available: https://www.google.com/search?q=map+of+st+anthony+newfoundland&source=lmns&bih=643&biw=1366&client=firefox-b-d&hl=en&sa=X&ved=2ahUKEwji573orOP_AhUmD1kFHYDuAEIQ_AUoAHoECAEQAA
- [13] “Wind Energy & Hydrogen Export,” SABRI. Accessed: Jun. 27, 2023. [Online]. Available: <https://sabrnl.com/wind-energy/>
- [14] Eric R. Morgan, “Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind”, doi: 10.7275/11KT-3F59.
- [15] A. R. Dehghani-Sani et al., “Assessment of current developments and future prospects of wind energy in Canada,” *Sustain. Energy Technol. Assess.*, vol. 50, p. 101819, Mar. 2022, doi: 10.1016/j.seta.2021.101819.
- [16] E. Morgan, J. Manwell, and J. McGowan, “Wind-powered ammonia fuel production for remote islands: A case study,” *Renew. Energy*, vol. 72, pp. 51–61, Dec. 2014, doi: 10.1016/j.renene.2014.06.034.

- [17] J. Ikäheimo, J. Kiviluoma, R. Weiss, and H. Holttinen, “Power-to-ammonia in future North European 100 % renewable power and heat system,” *Int. J. Hydrog. Energy*, vol. 43, no. 36, pp. 17295–17308, Sep. 2018, doi: 10.1016/j.ijhydene.2018.06.121.
- [18] T. R. Ayodele and J. L. Munda, “Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa,” *Int. J. Hydrog. Energy*, vol. 44, no. 33, pp. 17669–17687, Jul. 2019, doi: 10.1016/j.ijhydene.2019.05.077.
- [19] G. Correa, F. Volpe, P. Marocco, P. Muñoz, T. Falagüerra, and M. Santarelli, “Evaluation of levelized cost of hydrogen produced by wind electrolysis: Argentine and Italian production scenarios,” *J. Energy Storage*, vol. 52, p. 105014, Aug. 2022, doi: 10.1016/j.est.2022.105014.
- [20] Y. Wang, S. Zheng, J. Chen, Z. Wang, and S. He, “Ammonia (NH₃) Storage for Massive PV Electricity,” *Energy Procedia*, vol. 150, pp. 99–105, Sep. 2018, doi: 10.1016/j.egypro.2018.09.001.
- [21] “2012 BILL 61.” Accessed: Oct. 26, 2023. [Online]. Available: <https://www.assembly.nl.ca/business/bills/Bill1261.htm>
- [22] M. Scobie, “Policy coherence in climate governance in Caribbean Small Island Developing States,” *Environ. Sci. Policy*, vol. 58, pp. 16–28, Apr. 2016, doi: 10.1016/j.envsci.2015.12.008.
- [23] Z.-Y. Zhao, R.-D. Chang, and Y.-L. Chen, “What hinder the further development of wind power in China?—A socio-technical barrier study,” *Energy Policy*, vol. 88, pp. 465–476, Jan. 2016, doi: 10.1016/j.enpol.2015.11.004.
- [24] S. Diaf and G. Notton, “Technical and economic analysis of large-scale wind energy conversion systems in Algeria,” *Renew. Sustain. Energy Rev.*, vol. 19, pp. 37–51, Mar. 2013, doi: 10.1016/j.rser.2012.11.026.
- [25] “Electrolysers-Brochure-Rev-D.pdf.”
- [26] “Canada Inflation Rate and CPI - July 2023 Update | WOWA.ca.” Accessed: Aug. 27, 2023. [Online]. Available: <https://wowa.ca/inflation-rate-canada-cpi>
- [27] “Policy interest rate.” Accessed: Aug. 27, 2023. [Online]. Available: <https://www.bankofcanada.ca/core-functions/monetary-policy/key-interest-rate/>
- [28] “Executive summary – Global Hydrogen Review 2021 – Analysis,” IEA. Accessed: Oct. 29, 2023. [Online]. Available: <https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary>
- [29] “Making the breakthrough: Green hydrogen policies and technology costs”.
- [30] R. Nayak-Luke, R. Bañares-Alcántara, and I. Wilkinson, “‘Green’ Ammonia: Impact of Renewable Energy Intermittency on Plant Sizing and Levelized Cost of Ammonia,” *Ind. Eng. Chem. Res.*, vol. 57, no. 43, pp. 14607–14616, Oct. 2018, doi: 10.1021/acs.iecr.8b02447.
- [31] H. Zhao, L. M. Kamp, and Z. Lukszo, “The potential of green ammonia production to reduce renewable power curtailment and encourage the energy transition in China,” *Int. J. Hydrog. Energy*, vol. 47, no. 44, pp. 18935–18954, May 2022, doi: 10.1016/j.ijhydene.2022.04.088.
- [32] M. A. Delucchi and M. Z. Jacobson, “Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies,” *Energy Policy*, vol. 39, no. 3, pp. 1170–1190, Mar. 2011, doi: 10.1016/j.enpol.2010.11.045.
- [33] M. H. Soulouknga, S. Y. Doka, N.Revanna, N.Djongyang, and T.C.Kofane, “Analysis of wind speed data and wind energy potential in Faya-Largeau, Chad, using Weibull distribution,” *Renew. Energy*, vol. 121, pp. 1–8, Jun. 2018, doi: 10.1016/j.renene.2018.01.002.

Nomenclature

ASL = Ammonia synthesis loop
 AST = Ammonia storage tank
 ASU = Air separation unit
 BES = Battery energy storage
 C = Capital cost
 CRF = Capital recovery factor
 Ca = Annualized cost
 CBES = Capital cost of battery energy system
 CCEW = Cost of civil and earth works
 CEP = Cost of energy project
 CLCOE = Levelized cost of energy
 CMISC = Miscellaneous cost for project
 CNPV = Cost of Net Present value
 CTC = cost of tower and conversion system
 CRI = Cost of rectifier and inverter
 CWEP = Cost of Wind Energy Project
 d = Discounted rate
 E = energy produce
 f = fractional percentage of cost
 ESC = Escalated
 e_{om} = escalation ratio for operation and maintenance
 m_o = inceptive year operation and maintenance
 om = operation and maintenance
 PR = Power rating
 WT = Wind turbine
 S = Specific cost
 K = Recovery cost
 TCS = Tower and control system
 RI = Rectifier and inverter
 CEW = Civil and Earth works
 MISC = Miscellaneous
 WES = Wind energy system
 H = Observed height
 Hr = Reference height
 HST = Hydrogen storage tank
 M = Total mass (kg)
 m = mass flow rate (kg/h)
 P = Power generated (kW)
 Rec = rectifier
 $\eta_{s,C}$ = Isentropic efficiency
 η = efficiency
 P_c = Power required for compression (kW)
 Q = Volumetric flow rate (m^3/h)
 T_{suc} = Suction temperature (K)
 Z_{suc} = Compressibility factor for suction
 Z_{dis} = Compressibility factor for discharge
 P_{dis} = Discharge pressure (bar)

P_{suc} = Suction pressure (bar)
 P_{HST} = System power consumption by hydrogen storage (kW)
 P_{ASU} = System power consumption by air separation unit (kW)
 P'_{HST} = Specific power consumption by hydrogen storage tank (kWh/tNH₃)
 P'_{ASU} = Specific power consumption by Air separation unit (kWh/tNH₃)
 WDU = Water desalination unit
 α = roughness partner
 GHG = Greenhouse gases
 γ = Specific heat ratio
 a, b = constants
 N = Number of compression stages
 EZ = Electrolyser
 INS = installation
 STK = electricity stake
 ST = Storage tank
 G = Capacity of electrolysis

Appendix
Wind speed calculated using power log

		Cape Norman						American drive and Cremaillere						
		Small		Normal			Huge							
M	α	30	40	50	60	70	80	α	30	40	50	60	70	80
Jan	0.659	6.61	7.99	9.25	10.43	11.55	12.61	0.644	5.74	6.91	7.98	8.97	9.91	10.80
Feb	0.656	6.40	7.72	8.94	10.07	11.15	12.17	0.642	5.62	6.76	7.80	8.77	9.68	10.55
Mar	0.651	6.12	7.37	8.54	9.62	10.63	11.60	0.637	5.39	6.47	7.46	8.38	9.24	10.06
Apr	0.639	5.48	6.58	7.59	8.53	9.41	10.25	0.628	4.94	5.92	6.81	7.64	8.41	9.15
May	0.630	5.05	6.05	6.96	7.81	8.60	9.36	0.615	4.41	5.27	6.04	6.76	7.43	8.07
Jun	0.626	4.88	5.84	6.72	7.53	8.30	9.02	0.610	4.20	5.01	5.74	6.42	7.05	7.65
Jul	0.625	4.80	5.75	6.61	7.41	8.16	8.87	0.605	4.02	4.78	5.47	6.11	6.71	7.27
Aug	0.622	4.69	5.61	6.44	7.21	7.94	8.63	0.610	4.20	5.00	5.73	6.40	7.04	7.63
Sep	0.631	5.09	6.11	7.03	7.89	8.69	9.46	0.625	4.81	5.76	6.62	7.42	8.17	8.88
Oct	0.642	5.62	6.76	7.80	8.77	9.68	10.55	0.627	4.94	5.91	6.80	7.62	8.40	9.13
Nov	0.649	6.00	7.23	8.36	9.41	10.40	11.34	0.638	5.42	6.51	7.50	8.42	9.29	10.12
Dec	0.657	6.49	7.84	9.08	10.24	11.33	12.37	0.645	5.83	7.01	8.10	9.11	10.06	10.97