FUELING CHANGE IN THE ARCTIC

The Arctic is changing, warming at twice the average global rate. Sustainable and clean renewable energy solutions are needed for Northern communities in order to protect people and nature.

Diesel fuel is the primary energy source for Arctic communities – a dependency that has high logistical and financial costs, negative impacts on the environment, and also hinders the self-sufficiency of northern communities.

Over the next five years, WWF-Canada's Arctic program will work to demonstrate that low-impact renewable energy from wind and solar is possible and can contribute to sustainability in northern Canadian communities and to a cleaner Arctic environment.

In the first phase of the Arctic Renewable Energy program, WWF-Canada, along with project partner Waterloo Institute for Sustainable Energy (WISE) performed pre-feasibility studies to predict what the use of renewable energy in northern community grids would look like.

The study has demonstrated how an initial investment in a mix of renewable energy in northern communities can lead to immense carbon dioxide (CO_2) emissions reduction and significant Operations and Maintenance (O&M) savings.

WWF'S OBJECTIVE:

To demonstrate that renewable energy is possible in the Canadian Arctic; we will work with partners to establish large-scale renewable-energy projects in at least three northern communities by 2020.

PRE-FEASIBILITY STUDY

A two-step procedure was adopted. In the first step of the study, Nunavut communities were analyzed based on high-level solar and wind profiles, size and energy consumption. Of the 25 communities, 13 were selected for further analysis.

In the second step of the study, the HOMER (Hybrid Optimization of Multiple Energy Resources) model was used to simulate renewable energy deployment in the 13 selected communities based on various assumptions and considerations. The simulation results were then ranked based on the following five criteria:

CRITERIA FOR SIMULATION RESULTS

REDUCTION IN CO2 EMISSIONS	Diesel fuel is dirty and has high emissions of climate change-causing CO_2. Replacing diesel with cleaner, habitat-friendly renewable energy results in reductions in CO_2 emissions. The study determined the maximum CO_2 emissions reduction in each community if renewable energy was mixed into the grid compared to the base case scenario of 100 per cent diesel fuel. Communities were ranked based on their potential for reducing CO_2 emissions.
O&M COST SAVINGS	Currently, all the communities in Nunavut use diesel generators for energy generation. The O&M costs, including transportation and fuel costs, for these generators are very high. The incorporation of renewable energy in the energy supply mix would reduce diesel requirements and associated O&M costs. The study found the maximum O&M cost reduction for each community, and then ranked them based on potential for savings achieved.
O&M COST SAVINGS EQUAL TO RE INSTALLATION COST	As mentioned previously, the study determined that we can achieve O&M cost savings when we integrate renewable energy into a community's energy plan. This ranking criterion is based on economic feasibility and the study sought to determine a condition where the renewable energy installation cost would be nearly equal to the O&M cost reduction achieved through renewable energy integration. This condition would allow the reallocation of money saved in O&M to the installation cost of the renewable energy equipment. The rankings were made on the basis of increasing O&M savings.
MAX RE PENETRATION	Here, the study determined the maximum feasible renewable energy penetration that could be achieved in a community. The higher the renewable energy penetration in a community, the lower the utilization of fossil fuel and in turn a reduction in CO_2 emissions. The communities were ranked based on the maximum feasible renewable energy penetration possible.
REPLACEMENT OF DIESEL GENERATORS	Diesel generators have a useful life and currently, many of northern generators are nearing the end of their useful life and need to be replaced in the near future. Every additional purchase of new diesel generators is costly and further increases the community's dependency on dirty fossil fuels. With that in mind, the study tried to find a feasible condition where regular energy demand could be met by the available diesel generators and by adding adequate capacity of RE wind and solar resources. The system also takes into consideration sufficient capacity of battery storage to ensure stable supply of energy at all times. This way the selected communities would save the costs of having to purchase new diesel generators. The ranking was based on the capacity and time line of avoiding new diesel generator purchases, and the cost of installing RE in ascending order.
RE INSTALLATION DESIGN COSTS	This is a well-established ranking method for RE integration pre-feasibility studies. The study determined the minimum amount of money required to design a diesel-free system, with associated RE and storage capacities. The communities were ranked based on ascending RE installation costs.

RESULTS

Based on how the 13 communities fared on each of the above mentioned criteria, we were able to determine the five communities that could have a strong business case for renewable energy deployment and could be most viable for a further detailed feasibility study.

◇ ***Sanikiluaq*** – Had the highest percentage of CO_2 emissions reduction (53.2%) and also the maximum savings on O&M costs (44.9%) when renewable energy was integrated into the energy plan. It can also have the highest feasible renewable energy penetration (52.1%) among all the communities.

◇ ***Iqaluit*** –Has very high potential for wind energy. Furthermore, when renewable energy is integrated into Iqaluit's energy plan we can achieve a very high percentage of CO_2 emissions reduction (42.29%), savings on O&M costs (25.21%) and feasible renewable energy penetration (41.5%).

◇ ***Rankin Inlet*** – Fourth highest in both reduction in CO_2 emissions (40.5%) and maximum feasible renewable energy penetration (40.6%), and the third highest O&M cost savings (27.79%).

◇ ***Arviat*** –Has been championing renewable energy for years. This, combined with the high CO_2 emissions reduction (34.99%) and O&M cost savings (20.29%) that can be achieved in this community, made Arviat a contender for a detailed feasibility study.

◇ ***Baker Lake*** – Ranked in the top five communities for all the above mentioned criteria. It had the 5th highest CO_2 emissions reduction (39.50%), O&M savings (24.87%) and max feasible RE penetration (40.3%)

Four of the five identified communities remain in the top five for all the criteria used in this study and in all of the five identified communities, at least 34% renewable energy mix, 20% operation and maintenance cost savings, and 34% reduction in CO2 emissions is achieved.

RENEWABLE ENERGY PENETRATION AND CO2 EMISSIONS REDUCTION POTENTIAL ASSOCIATED WITH MAX O&M COST SAVINGS

COMMUNITY	RE PENETRATION (%)	CO2 EMISSIONS REDUCTION (%)	MAX O&M SAVINGS (%)
Sanikiluaq	51.7	52.59	44.92
Hall Beach	36	37.03	27.82
Rankin Inlet	39.2	39.06	27.79
Iqaluit	39.3	40.08	25.21
Baker Lake	36.4	36.04	24.87
Kugaaruk	31.5	31.55	21.94
Clyde River	28.8	29.82	21.71
Cambridge Bay	30.1	30.96	21.33
Arviat	34.6	34.25	20.29
Cape Dorset	31	31.17	17.03
Igloolik	17	18.54	12.91
Qikiqtarjuaq	13.3	15.56	10.96
Pangnirtung	13.6	15.57	9.94

*see the pre-feasibility report for further details

NEXT STEPS

WWF-Canada and WISE will perform a detailed feasibility study on the selected five communities. WWF will then work with partners to support community pilot projects in at least two Nunavut communities by 2020.

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Appendix

The following were the assumptions that were used in the technical analysis:

- Discount Rate – 8%
- Project life – 25 years
- 40% increase in the peak load over the next 25 years (~1.41% annual increase)
- Operating reserve of 50% of wind energy generation, if selected
- Operating reserve of 25% of solar energy generation, if selected
- Operating reserve of 10% of peak load in all the cases
- Useful life of diesel generators vary from 72,000 hours to 160,000 hours, depending on the manufacturer
- Useful life of solar, wind, converter and battery are 25, 30, 15 and 15 years, respectively
- PV panel sets of 100 kW for all communities
- Wind turbine sizes are 100 kW @ 30 meter high except Iqaluit where 1.5 MW @ 80 meters is used due to large load

Experts' Group for the Renewable Energy Project

- WWF-Canada
- University of Waterloo (Waterloo Institute for Sustainable Energy)
- Pembina Institute
- Alaska Center for Energy and Power
- Borden Ladner Gervais
- Tugliq Energy Co.
- Qikiqtani Inuit Association

RENEWABLE ENERGY DEPLOYMENT IN CANADIAN ARCTIC

PHASE I: PRE-FEASIBILITY STUDIES

AND COMMUNITY ENGAGEMENT

REPORT FOR NUNAVUT

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Waterloo, Ontario, Canada, 2016

Executive Summary

Environmental degradation in the arctic, caused by climate change, is posing a threat to the wildlife present there by destroying their habitat. Though the arctic is mostly uninhabited, there are nearly 50 communities in the Canadian arctic, and a good portion of them use diesel generators as the only means to generate electricity. This not only adds to the carbon footprint, but also endangers the environment by elevating the risk of oil spills while transporting diesel to and storing it in these communities. In addition to the environmental risks, the cost of fossil fuel dependency is an economic problem in the North, as governments have to subsidize this fuel.

There are environmentally friendly and economic sources of energy for the arctic communities, which should help reduce their fossil fuel dependency. Thus, the Waterloo Institute of Sustainable Energy (WISE) of the University of Waterloo has been involved in a consortium, led by World Wildlife Fund (WWF) Canada, to perform studies, funded by WWF-Canada, on the communities of Nunavut to integrate Renewable Energy (RE) sources in their grids. The task is focused on gathering community size, load profile, transportation routing, high level data on solar and wind resources, etc., and use them to select 5 of the 25 communities from Nunavut for detailed feasibility studies for deployment of RE sources in some of these communities.

A two-step procedure has been adopted to determine the communities suitable for feasibility studies. In the first step, a pre-selection of 13 out of 25 communities in Nunavut is made based on high level data. In the second step, the HOMER software is used to simulate RE deployment in the pre-selected communities, based on various assumptions and considerations. The simulation results are ranked based on various predefined criteria, such as maximum Operation & Maintenance (O&M) savings and emission reductions, at minimum cost, resulting in the following final ranking of communities recommended for detailed feasibility studies:

1. Sanikiluaq
2. Iqaluit
3. Rankin Inlet
4. Baker Lake
5. Arviat

The result of this pre-feasibility study indicates that substantial reduction in CO_2 emission can be achieved at a relatively low initial investment costs, and at least 35% RE penetration can be achieved for all the top 5 communities in Nunavut at a minimum cost of 7.8 M$, except for Baker Lake (7.1%, 2.99 M$), while avoiding the purchase of a new diesel generator.

Feasibility studies are now being carried out for these communities. The analysis will be based on detailed low-level data and modeling of the selected communities, using the well-known mathematical programming tool GAMS (General Algebraic Modeling System). The results of the studies will yield the actual wind and solar plants and battery storage systems that should be deployed to maximize O&M savings and emission reductions, at minimum costs, in these communities.

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GLOSSARY

COE	Cost-of-Energy
CN	Canadian National railway
CWEEDS	Canadian Weather Energy and Engineering Datasets
GAMS	General Algebraic Modeling System
GHG	Green-house Gas
HOMER	Hybrid Optimization of Multiple Energy Resources
NASA	National Aeronautics and Space Administration
NEAS	Nunavut Eastern Arctic Shipping
NOAA	National Oceanic and Atmospheric Administration
NPC	Net Present Cost
NPV	Net Present Value
NRCAN	Natural Resources Canada
NREL	National Renewable Energy Laboratory
NSSI	Nunavut Sealink and Supply Inc.
NTCL	Northern Transportation Company Limited
NWT	Northwest Territories
O&M	Operation & Maintenance
QEC	Qulliq Energy Corporation
RE	Renewable Energy
RFP	Request for Proposal
SSE	Surface meteorology and Solar Energy
WISE	Waterloo Institute of Sustainable Energy
WWF	World Wildlife Fund

1 Introduction

Climate change is a predominant issue in the arctic, as is evidenced by the ever-decreasing mass of ice cover on the Arctic sea. This reduction is posing a threat to the wildlife in Arctic Canada. Hence, there is an urgent need to reduce the environmental impact of energy use in this region.

The Canadian Arctic, also called "Far North", is a part of Northern Canada, i.e., "The North", where The North politically refers to the territories of Yukon, NWT, and Nunavut. The Far North is subdivided into the eastern arctic, comprising Nunavut, Nunavik (part of Quebec), and Nunatsiavut (part of Newfoundland and Labrador), and the western arctic, i.e., the northernmost portion of NWT and a small part of Yukon (see Figure 1).

The pre-feasibility study presented in this report is focused on selecting communities for RE integration into the local grids, which are mostly dependent on diesel-based generation. The ge-

Figure 1: Canadian Arctic (the Far North) [1] (used with permission from Inuit Tapirit Kanatami).

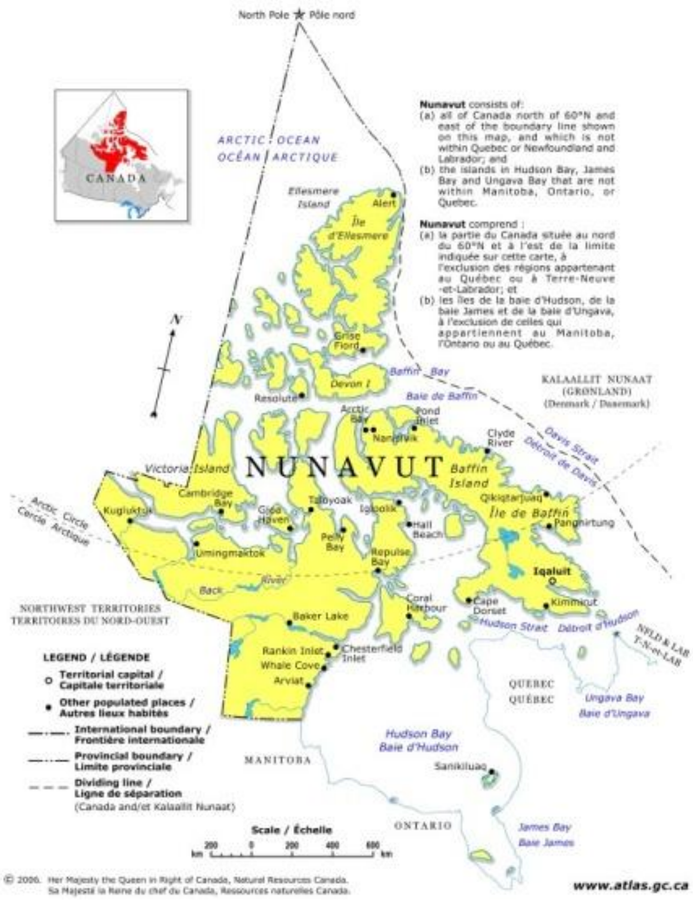

Figure 2: Communities of Nunavut (contains information licensed under the Open Government Licence of Canada [2]).

ographical region selected for this study comprises all 25 communities (Figure 2) in the territory of Nunavut. It is important to note that all communities in Nunavut are solely dependent on diesel for electricity generation; also worth mentioning that there is no territorial power grid and inter-community road access.

1.1 Motivation

It is well documented that the arctic habitat is continuously degrading due to the effect of climate change, endangering the wildlife prevalent there, particularly in the Canadian Arctic, associated with the loss of sea ice due to increased temperatures. In fact, the arctic has been found to be warming at least twice as fast as the rest of the planet, as reported by the National Oceanic and Atmospheric Administration (NOAA) of the US in their annual Arctic Report Card [3].

The communities in Nunavut use only diesel for electricity generation, and therefore the emission from the power plants in these communities are further disturbing the environment. The remoteness of these communities requires that fuel be transported by sea-barges and locally stored in storage tanks, and thus there is also a risk for oil spills, which can do extensive damage to the arctic environment. In addition, the cost of transporting diesel to all these remote communities is considerably high.

All the aforementioned factors, coupled with the fact that a majority of these communities have old diesel generators in operation that require replacement [4], is motivating the needs for alternate sources of electricity generation. RE sources, mainly solar and wind, are of particular interest for these communities, with well-designed RE implementation plans that have the potential for positive socio-economic-environmental effects as well. Building business cases for such plans is the ultimate objective of feasibility studies being carried out by WISE for the WWF. A total of 25 communities are in consideration here, for which performing RE feasibility studies would be too time consuming; thus, considering the urgency for replacement requirement of diesel generators in some communities, the present report concentrates on selecting 5-6 communities for detailed feasibility analyses, which will be used to identify 2-3 communities for possible RE deployment.

1.2 Objectives

The objectives of the present pre-feasibility study are as follows:

- Determine 5-6 communities suitable for feasibility studies that will be used to build business cases for RE deployment.

- Rank communities based on several criteria, such as project investment cost versus O&M savings or replacement of required diesel generators, at minimum costs.
- The primary target is to displace diesel fuel, not existing diesel capacity, by incorporating wind and solar plants and battery storage systems, so that local grids can be securely operated, as required by utility standards.

1.3 Content

The rest of this report is divided in 3 sections. Thus, Section 2 discusses the pre-selection process, where basic input data is considered for all 25 communities, describing the methodology adopted for pre-selection, and presenting the final list of the pre-selected communities for pre-feasibility ranking. Section 3 describes the ranking process of these pre-selected communities for the following feasibility studies, using the HOMER (Hybrid Optimization of Multiple Energy Resources [5]) software to determine optimal RE deployment for various battery storage system capacities. The techno-economic optimization results from HOMER are used to develop the ranking of the pre-selected communities based on certain pre-defined criteria, which basically consists of maximizing O&M savings and emission reductions, at minimum costs. Section 4 provides the conclusions to the pre-feasibility study and recommends a list of communities that should be considered for the feasibility study stage.

2 Pre-Selection of Communities

The pre-feasibility study for incorporating RE in the communities of Nunavut was initiated by performing a pre-selection of its 25 communities, based on certain parameters. The objective of this pre-selection was to reduce the number of the communities to a manageable list, where simulation of RE integration could be performed to rank these pre-selected communities based on a certain set of ranking criteria.

2.1 Basic Input Data

The following set of basic input parameters was gathered for each community under consideration:

- *Geographical Location*: The latitude and longitude was used to determine solar insolation, wind, and temperature profiles, when metered data was not available.
- *Flight Connections*: Air connection availabilities between communities and with big cities of neighbouring provinces/territories [6], by various airlines, were used to assess the cost involved in shipping smaller cargo to various communities from the purchase point. This was also used to estimate the cost of transporting technical personnel required for RE installation purposes.
- *Air Distance from Iqaluit and Yellowknife* [7]: The air-distance of a community from these two hubs was considered to determine the shortest and cheapest routing available for air-cargo and personnel required for RE installation.
- *Air-cargo and Sea-lift Rates*: These rates, coupled with the previous data set on flight connections and air-distances, helped to finalize the cheapest route to transport goods and personnel to/from communities, using the preferred/required modes of transport, as applicable (e.g. converters can be put in air-transport, whereas wind turbine blades and hubs will require sea-lift). Air cargo rates were obtained from [8], [9], [10], and [11]. The rates for sea-lift to/from the communities were available in the websites of The NEAS Group

(NEAS Inc, Nunavik Eastern Arctic Shipping, and Nunavut Eastern Arctic Shipping) [12], Nunavut Sealink and Supply Inc. [13], and Northern Transportation Company Limited (NTCL) [14]. NEAS transports to the communities from Valleyfield, Quebec, NSSI from Ste-Catherine, Quebec, and NTCL from Hay River Terminal, NWT.

- *Population, Growth, and Number of Household*: Present population (as of 2013) and its annual growth data, available in [15], and [16], helped in determining the size of the community. The number of households, retrieved from [17], helped in estimating the feasibility of rooftop solar PV penetration limit; however, at the pre-feasibility stage stage, only ground-mounted PV has been considered.

- *Electricity Rates*: The rates paid by the customers were divided into 2 groups: governmental and non-governmental, and domestic and commercial. Nunavut's electricity rates were provided by Qulliq Energy Corporation (QEC) [18], and these rates will be used to estimate the return-on-investment for RE projects in the feasibility studies, and were not used for the presented pre-feasibility results.

- *Energy Use, Costs and Greenhouse Gas (GHG) Emissions*: Energy use in the communities was categorized in three sectors: electricity, heating, and transport. The data for the electricity sector, obtained from Nunavut Energy [19], included annual energy consumption in kWh, the cost to generate this energy, and GHG emission resulting from it. For heating and transport, the data, on individual sectors, comprised of the amount of fuel consumed annually along with the associated costs and GHG emissions.

- *Solar PV, Wind, and Small Hydro Potential*: High level data for solar PV potential, on an annual energy generation capability per installed capacity (kWh/kW) basis, was obtained from photovoltaic and solar resource maps of Natural Resources Canada (NRCAN) [20]. Similarly, data on wind potential, i.e., annual average wind speed and wind energy, was obtained from the Wind Atlas Canada [21]. The potential of small hydro, as a run-of-the-river option, was determined from the water flow measurement with good granularity (at least daily values for a pre-feasibility study), which was available from the "Wateroffice" website of the Government of Canada [22].

Table 1: Parameters considered for pre-selecting communities and their corresponding ranges for assigning attributes.

Attributes	Parameters considered	Range division for defining attributes
L is of lowest merit, and *H* the highest	Wind speed (WS) [m/s]	$L < 4 \leq ML \leq 5 \leq MH \leq 6 \leq H$
	Solar energy (SE) [kWh/kW]	$L < 900 \leq ML \leq 1000 \leq MH \leq 1100 \leq H$
	Energy demand / person (EDpp) [MWh/pp]	NU: $L < 3 \leq ML \leq 4.5 \leq MH \leq 6 \leq H$
		NWT: $L < 13 \leq ML \leq 14 \leq MH \leq 15 \leq H$
	GHG emission / person (GHGpp) [tonnes/pp]	$L < 3 \leq ML \leq 5 \leq MH \leq 7 \leq H$
	Electricity rate (ER) [¢/kWh]	$L < 70 \leq ML \leq 85 \leq MH \leq 100 \leq H$
	Community size (CS)	$L < 4 \leq ML \leq 5 \leq MH \leq 6 \leq H$
L highest, *H* lowest	Air transport cost (TCA) [$/tonne]	$L < 35 \leq ML \leq 40 \leq MH \leq 45 \leq H$
	Sea transport cost (TCS) [$/tonne]	$L < 350 \leq ML \leq 375 \leq MH \leq 400 \leq H$

- *Existing Diesel and Natural Gas Generators*: The age of generators present in the communities of Nunavut and their rated capacities are obtained from a report by Opportunities North [23], and this data was used to assess the urgency of replacing existing gensets, which can be achieved by using RE.

2.2 Methodology

The first task was to gather all the information from various sources and compile them for comparative analysis. The next step was to define attributes to different ranges of a given parameter, in order to perform a qualitative comparison. For example, it was found that the wind speed data varies from 4.73 m/s to 7.71 m/s; hence, the ranges were divided in four categories, low (*L*), medium low (*ML*), medium high (*MH*), and high (*H*), as follows: $L <$ 4 m/s $\leq ML \leq$ 5 m/s $\leq MH \leq 6m/s \leq H$. This process of assigning attributes was confined to a certain set of input parameters, which were deemed to be important in the selection process; these parameters and their respective ranges for assigning attributes are shown in Table 1. Observe that the attributes for air and sea cargo rates are considered in the opposite order than the rest.

All these attributes were then cumulatively considered attaching weights to them, where the weights depend on the importance of the parameter in consideration (e.g. wind or solar characteristics have higher importance than community size). The cumulative attributes were finally sorted in descending order to determine the rank of the communities.

2.3 Pre-Selection List

The input data gathered during the pre-selection process, with the selected communities being identified (without ranking), was presented in tabular form during the "Expert Consortium Kick-off Meeting", held on November 13, 2015, in Toronto. The table is reproduced here in parts, with information for the different regions being presented as follows:

- The Kitikmeot region of Nunavut being shown in Tables 2, 3, 4, and 5.
- The Kivalliq region is presented in Tables 6, 7, 8, and 9.
- For the largest region in Nunavut, i.e., Qikiqtaaluk, Tables 10, 11, 12, and 13 present the input data used for pre-selecting its 13 communities.

Table 2: Location, flight connections, and air distance for the communities of the Kitikmeot region.

Community	**Location** Lat. & Long.	**Flight connections**	**Air Distance from** [km]	
			Iqaluit	Yellowknife
Cambridge Bay	69°07'02" N 105°03'11" W	Yellowknife (First Air & Canadian North); Rankin Inlet (Kivalliq Air)	1706.79	852.49
Gjoa Haven	68°37'33" N 95°52'30" W	Yellowknife (First Air); Cambridge Bay (Kenn Borek Air)	1327.42	1087.74
Kugaaruk	68°31'59" N 89°49'36" W	Yellowknife (First Air); Cambridge Bay (Kenn Borek & Kivalliq Air)	1088.27	1305.44
Kugluktuk	67°49'32" N 115°05'42" W	Yellowknife (First Air); Cambridge Bay (Kenn Borek Air)	2117.48	598.18
Taloyoak	69°32'13" N 93°31'36" W	Yellowknife (First Air); Cambridge Bay (Kenn Borek Air); Rankin Inlet (Kivalliq Air)	1263.48	1217.74

Table 3: Air and sea cargo rates and population for the communities of the Kitikmeot region.

Community	**Air Cargo rate: First Air** [Minimum cost, $ + $/kg]		**Sealift transport rates** [$/1000 kg]		**Population**		**No. of houses**
	Iqaluit	Yellowknife	NEAS NSSI	NTCL	2013	% change	
Camb. Bay	47 + 5.11	35 + 2.72	438.00	443	1658	1.01	540
Gjoa Haven	43 + 7.83	43 + 5.07	438.00	443	1386	3.27	230
Kugaaruk	48 + 8.87	43 + 6.4	388.43 [a]	NA	878	2.96	170
Kugluktuk	43 + 7.88	43 + 3.47	438.00	443	1547	2.02	430
Taloyoak	45 + 8.37	43 + 5.73	438.00	443	980	2.13	220

[a]Via Nanisivik, Canadian Coast Guard post.

Table 4: Electricity rates, annual energy consumption and associated costs, and GHG emissions for the communities of the Kitikmeot region.

Community	**Electricity rates** [a] [¢/kWh]				**Annual Energy use, Cost, and GHG emission**		
					Electricity	Heating	Transport
	D-NG	D-G	C-NG	C-G	[kWh; $; tonnes]	[Litres; $; tonnes]	
Cambridge Bay	76.06		66.07		9414003 5367272 7432	4662271 5239460 13157	3713399 4173243 9181
Gjoa Haven	89.45	92.28	85.96		5009314 3504488 3738	2080186 2514657 5870	1505793 2332352 3748
Kugaaruk	114.16		101.77		2653519 2282923 2010	1214378 1525259 3427	1189992 1897043 2967
Kugluktuk	93.32	98.68	87.19		5576589 4116493 3932	2690377 2998476 7592	1807449 2697608 4501
Taloyoak	98.36	106.46	96.78		3371214 2777233 2350	1416487 1717179 3997	1118463 1708319 2795

[a]D - Domestic; C - Commercial; G - Governmental; NG - Non-Governmental.

Table 5: Age and capacity of existing generators, and data on wind and solar potentials for the communities of the Kitikmeot region.

Community	Diesel generators [a]			Wind data				Solar data
	Installed	Cap.	Addns.	Speed	Energy	Weibull		Tilt = Lat.
	[Yr.]	[kW]	[Yr.]	[m/s]	[W/m^2]	[k]	[A]	[kWh/kW]
Cambridge Bay	1967	3110	1970	6.08	250.50	1.75	6.83	900-1000
Gjoa Haven	1977	1650	None	5.94	193.63	2.07	6.71	1000-1100
Kugaaruk	1974	835	None	6.30	238.13	2.01	7.11	1000-1100
Kugluktuk	1968	2220	1989	4.98	146.25	1.66	5.57	900-1000
Taloyoak	1972	1500	1986, 1993	5.46	163.13	1.91	6.16	900-1000

[a] As per the data gathered by Nov. 2015.

Table 6: Location, flight connections, and air distance for the communities of the Kivalliq region.

Community	Location Lat. & Long.	Flight connections	Air Distance from [km]	
			Iqaluit	Yellowknife
Arviat	61°06’29” N 94°03’25” W	Rankin Inlet (Skyward Aviation, Kivalliq & Calm Air); Winnipeg (Kivalliq & Calm Air)	1337.36	1073.63
Baker Lake	64°19’05” N 96°01’03” W	Rankin Inlet (Skyward Aviation, Kivalliq & Calm Air)	1330.14	933.66
Chesterfield Inlet	63°20’27” N 90°42’22” W	Rankin Inlet (Calm Air); Winnipeg (Kivalliq & Calm Air)	1095.93	1194.39
Coral Harbour	64°08’13” N 83°09’51” W	Iqaluit & Yellowknife (First Air); Rankin Inlet (Kivalliq Air)	715.42	1554.22
Rankin Inlet	62°48’35” N 92°05’58” W	Yellowknife & Iqaluit (Canadian-North & First); Winnipeg (First, Calm & Kivalliq Air)	1176.21	1134.19
Repulse Bay	66°31’19” N 86°14’06” W	Rankin Inlet (Kivalliq Air)	880.89	1406.73
Whale Cove	62°10’22” N 92°34’46” W	Rankin Inlet (Skyward Aviation, Kivalliq & Calm Air)	1219.96	1118.32

Table 7: Air and sea cargo rates and population for the communities of the Kivalliq region.

Community	Air Cargo rate: First Air [Minimum cost, $ + $/kg]		Sealift transport rates [$/1000 kg]		Population		No. of houses
	Iqaluit	Yellowknife	NEAS	NSSI	2013	% change	
Arviat	Calm Air cargo. [a]		343.36	361.43 255.72 [b]	2508	2.27	530
Baker Lake					2140	2.45	550
Chesterfield Inlet					393	1.73	110
Coral harbour	23.94 + 4.89	47 + 6.3			945	2.36	190
Rankin Inlet	23.94 + 3.38	35 + 3.27			2777	1.69	800
Repulse Bay	Calm Air cargo. [a]		365.13		1040	4.17	180
Whale Cove			343.36	361.43 255.72 [b]	463	3.39	100

[a]Calm Air provides matrix of cargo rates for all communities [9].
[b]Denotes rates from Churchill, Manitoba.

Table 8: Age and capacity of existing generators, and data on wind and solar potentials for the communities of the Kivalliq region.

Community	Diesel generators [a]			Wind data				Solar data
	Installed	Cap.	Addns.	Speed	Energy	Weibull		Tilt = Lat.
	[Yr.]	[kW]	[Yr.]	[m/s]	[W/m^2]	[(k)]	[(A)]	[kWh/kW]
Arviat	1971	2240	1979	7.55	419.63	1.96	8.62	1100-1200
Baker Lake	2003	2240	None	6.49	294.63	1.79	7.30	1100-1200
Chesterfield Inlet	1975	810	None	7.50	423.50	1.90	8.45	1100-1200
Coral Harbour	1988	1310	None	5.91	267.75	1.55	6.58	1100-1200
Rankin Inlet	1973	3550	1986, 1993	7.46	403.25	1.97	8.42	1100-1200
Repulse Bay	2000	990	None	6.71	299.13	1.93	7.57	1000-1100
Whale Cove	1991	750	None	7.71	429.63	2.04	8.70	1100-1200

[a]As per the data gathered by Nov. 2015.

Table 9: Electricity rates, annual energy consumption and associated costs, and GHG emissions for the communities of the Kivalliq region.

Community	**Electricity rates** [a] [¢/kWh]				**Annual Energy use, Cost, and GHG emission**		
					Electricity	Heating	Transport
	D-NG	D-G	C-NG	C-G	[kWh; $; tonnes]	[Litres; $; tonnes]	
Arviat	79.14		74.03		8028691 4993939 12373	2974762 3319307 8395	1410911 1593403 3463
Baker Lake	70.31		66.09		8938192 4761879 5472	4331683 4879176 12224	2184670 2545162 5542
Chesterfield Inlet	97.54		91.14		2002200 1497389 1307	819947 913085 2314	420826 471357 1028
Coral Harbour	94.66		87.11		3367600 2392802 2660	1380260 1554600 3895	1288046 1823065 3208
Rankin Inlet	62.23		55.04	60.64	17396062 8108206 13598	5598152 6238064 15798	14120218 21248477 36808
Repulse Bay	85.06		75.30		3584709 2374327 2603	1473913 1625892 4159	766633 835903 1878
Whale Cove	90.42	144.80	111.18	122.71	1754637 1692094 1479	688478 760008 1943	310521 342901 756

[a] D - Domestic; C - Commercial; G - Governmental; NG - Non-Governmental.

Table 10: Location, flight connections, and air distance for the communities of the Qikiqtaaluk region.

Community	**Location** Lat. & Long.	**Flight connections**	**Air Distance from** [km]	
			Iqaluit	Yellowknife
Arctic Bay	73°02'11" N 85°09'09" W	Iqaluit and Resolute Bay (First Air)	1227.9	1670.56
Cape Dorset	64°13'54" N 76°32'25" W	Iqaluit (First Air)	394.68	1869.24
Clyde River	70°28'26" N 68°35'10" W	Iqaluit (First Air)	748.28	2152.38
Grise Fiord	76°25'03" N 82°53'38" W	Iqaluit - Resolute Bay (First Air)-(Kenn Borek Air)	1499.93	1930.17
Hall Beach	68°46'38" N 81°13'27" W	Iqaluit (First Air); Rankin Inlet (Kivalliq Air)	794.92	1648.84
Igloolik	69°22'34" N 81°47'58" W	Iqaluit (First Air); Rankin Inlet (Kivalliq Air)	855.41	1637.91
Iqaluit	63°44'55" N 68°31'11" W	Ottawa, Montreal, and Yellowknife (First Air); Ottawa and Yellowknife (Canadian North)	NA	2261.43
Kimmirut	62°50'48" N 69°52'07" W	Iqaluit (First Air & (Kenn Borek Air)	120.67	2228.28
Pangnirtung	66°08'52" N 65°41'58" W	Iqaluit (First Air & Kenn Borek Air)	297.89	2320.19
Pond Inlet	72°41'57" N 77°57'33" W	Iqaluit [via Clyde River] (First Air)	1066	1870.57
Qikiqtarjuaq	67°33'29" N 64°01'29" W	Iqaluit (First Air & Kenn Borek Air)	470.62	2360.28
Resolute Bay	74°41'51" N 94°49'56" W	Iqaluit & Edmonton-Yellowknife (First Air)	1572.38	1558.5
Sanikiluaq	56°32'34" N 79°13'30" W	Montreal (Air Inuit)	993.83	2059.74

Table 11: Air and sea cargo rates and population for the communities of the Qikiqtaaluk region.

Community	**Air Cargo rate: First Air** [Minimum cost, $ + $/kg]		**Sealift rates** [$/1000 kg]	**Population**		**No. of houses**
	Iqaluit	Yellowknife	NEAS & NSSI	2013	% change	
Arctic Bay	47 + 6.79	63 + 11.67	388.43	861	2.62	210
Cape Dorset	23.94 + 4.82	47 + 11.38	336.82	1491	2.02	390
Clyde River	53 + 9.66	78 + 14.51	388.43	1004	2.29	220
Grise Fiord	Kenn Borek Air: from Resolute Bay [24].		388.43	157	1.09	60
Hall Beach	47 + 6.47	62 + 11.35	365.13	851	3.22	170
Igloolik	47 + 6.47	62 + 11.35	365.13	1974	3.08	390
Iqaluit	35 + 4.84 (From Montreal & Ottawa)	40 + 5.0	297.14	7177	1.40	2560
Kimmirut	47 + 2.54	47 + 7.82	336.82	479	1.64	130
Pangnirtung	35 + 4.13	48 + 9.03	336.82	1611	2.22	430
Pond Inlet	60 + 10.98	85+15.81	388.43	1612	2.30	350
Qikiqtarjuaq	35 + 5.93	59 + 10.82	388.43	520	0.72	170
Resolute Bay	47 + 6.79	64 + 11.89	388.43	225	-0.85	70
Sanikiluaq	Air Inuit: from Montreal [25].		376.26	884	1.94	200

Table 12: Age and capacity of existing generators, and data on wind and solar potentials for the communities of the Qikiqtaaluk region.

Community	**Diesel generators** [a]			**Wind data**				**Solar data**
	Installed	Cap.	Addns.	Speed	Energy	Weibull		Tilt = Lat.
	[Yr.]	[kW]	[Yr.]	[m/s]	[W/m^2]	[(k)]	[(A)]	[kWh/kW]
Arctic Bay	1974	1070	None	4.95	164.13	1.51	5.49	900-1000
Cape Dorset	1964	1800	1973, 1992	6.79	359.25	1.7	7.61	1000-1100
Clyde River	1999	1350	None	6.46	293.63	1.78	7.26	900-1000
Grise Fiord	1963	Not Available		7.08 [b]	Not Available			800-900
Hall Beach	1974	1345	1993	6.01	226.5	1.84	6.77	1000-1100
Igloolik	1974	1740	2005	6.12	241.38	1.82	6.89	1000-1100
Iqaluit	1964	14900	2014	5.65	226.00	1.59	6.30	1000-1100
Kimmirut	1992	930	None	5.78	280.63	1.43	6.36	1000-1100
Pangnirtung	1971	2220	None	5.92	432.50	1.17	6.25	1000-1100
Pond Inlet	1992	2250	None	4.73	199.25	1.23	5.06	900-1000
Qikiqtarjuaq	1963	1305	1975, 1986	6.45	396.13	1.42	7.09	1000-1100
Resolute Bay	1971	2050	None	5.69	187.50	1.88	6.41	800-900
Sanikiluaq	2001	1200	None	7.69	407.25	2.14	8.68	1100-1200

[a] As per the data gathered by Nov. 2015.
[b] Wind speed measured from [26].

Table 13: Electricity rates, annual energy consumption and associated costs, and GHG emissions for the communities of the Qikiqtaaluk region.

Community	**Electricity rates** [a] [¢/kWh]				**Annual Energy use, Cost, and GHG emission**		
					Electricity	Heating	Transport
	D-NG	D-G	C-NG	C-G	[kWh; $; tonnes]	[Litres; $; tonnes]	
Arctic Bay	87.87		78.97		2694201 833259 2570	1338749 16157 3773	1536560 2335171 3856
Cape Dorset	68.59	71.87	64.47	71.87	6110277 3407697 4837	1330493 1439596 3755	1137756 1431160 2843
Clyde River	78.19	78.67	69.66		3681411 2125545 3197	1593433 1707242 4497	1406677 1952827 3746
Grise Fiord	92.09	110.79	105.92		1093204 806513 1166	569154 623002 1606	274039 378157 685
Hall Beach	89.03	92.32	85.91		3257607 2201664 2322	1290022 1397656 3640	1093848 1708287 2758
Igloolik	63.23		58.35		**unknown**	2620022 2805857 7394	1858221 2707218 4656
Iqaluit	60.29		50.68	52.04	56888646 24458774 38085	22446151 23635797 63343	35830881 34876372 90411
Kimmirut	103.74	103.51	87.70	88.13	2062661 1517785 2359	699306 749624 1973	362225 383811 887
Pangnirtung	65.74	70.13	58.66	64.26	6477118 3316528 4276	2001310 2152201 5648	1975768 2253920 4924
Pond Inlet	89.95	97.29	82.88		5993849 4105681 4707	2579698 2759564 7280	1824051 2761715 4556
Qikiqtarjuaq	77.92	88.71	74.06	88.71	2531400 1714261 1958	1008376 1037308 2846	806435 1067527 2004
Resolute Bay	101.35	103.15	96.81		3371214 2777233 2350	1901999 2167346 5367	2287347 3717131 5915
Sanikiluaq	82.25		79.01		3483467 2243977 2626	1217204 1278911 3435	861574 1087728 2240

[a] D - Domestic; C - Commercial; G - Governmental; NG - Non-Governmental.

COMMUNITIES	OVERALL RANK	WIND SPEED	SOLAR ENERGY	Tr. COST SEA	Tr. COST AIR	COMM. SIZE	ENERGY DEMAND	GHG EMISSION	ELECTR. RATE	REGION
Rankin Inlet	1	H	H	ML	L	H	H	ML	L	Kivalliq
Iqaluit	2	MH	MH	L	ML	H	H	MH	L	Qikiqtaaluk
Arviat	3	H	H	ML	L	H	ML	ML	ML	Kivalliq
Cape Dorset	4	H	MH	L	L	H	ML	ML	L	Qikiqtaaluk
Baker Lake	5	H	H	ML	L	H	ML	L	L	Kivalliq
Repulse Bay	6	H	MH	ML	L	H	ML	L	ML	Kivalliq
Sanikiluaq	7	H	H	ML	L	MH	ML	L	ML	Qikiqtaaluk
Chesterfield Inlet	8	H	H	ML	L	L	MH	ML	MH	Kivalliq
Coral Harbour	9	MH	H	ML	L	MH	ML	L	MH	Kivalliq
Whale Cove	10	H	H	ML	L	L	ML	ML	H	Kivalliq
Pangnirtung	11	MH	MH	L	ML	H	ML	L	L	Qikiqtaaluk
Igloolik	12	H	MH	ML	H	H	ML	MH	L	Qikiqtaaluk
Qikiqtarjuaq	13	H	MH	MH	ML	ML	MH	ML	ML	Qikiqtaaluk
Hall Beach	14	H	MH	ML	H	MH	ML	L	MH	Qikiqtaaluk
Clyde River	15	H	ML	MH	H	H	ML	ML	ML	Qikiqtaaluk
Cambridge Bay	16	H	ML	H	H	H	MH	ML	ML	Kitikmeot
Kugaaruk	17	H	MH	MH	H	MH	ML	L	H	Kitikmeot
Gjoa Haven	18	MH	MH	H	MH	H	ML	L	MH	Kitikmeot
Kimmirut	19	MH	MH	L	H	L	ML	ML	H	Qikiqtaaluk
Grise Fiord	20--21	MH	L	MH	H	L	H	H	H	Qikiqtaaluk
Resolute Bay	20--21	MH	L	MH	H	L	H	H	H	Qikiqtaaluk
Kugluktuk	22--23	ML	ML	H	MH	H	ML	L	MH	Kitikmeot
Pond Inlet	22--23	ML	ML	MH	H	H	ML	L	MH	Qikiqtaaluk
Taloyoak	24	MH	ML	H	H	MH	ML	L	H	Kitikmeot
Arctic Bay	25	ML	ML	MH	H	MH	ML	L	MH	Qikiqtaaluk

Figure 3: Overall ranking of all 25 communities in Nunavut to pre-select them for pre-feasibility studies.

2.4 Selected Communities for Pre-Feasibility Ranking

The overall ranking for all the communities in Nunavut is shown in Figure 3, along with the important parameters considered for the pre-selection process, and the region the ranked community belongs to. The first four parameters have been given twice the weight than the other parameters, because they have a large impact on possible RE deployment. Observe that none of the communities of the Kitikmeot region, which includes Cambridge Bay, feature in the top 15 rank; on the other hand, all the communities in the Kivalliq region ranks in the top 10. This regional disparity can be largely attributed to the vicinity of the Kivalliq region to the main sea

Table 14: Regional ranking of Nunavut's communities for selection for pre-feasibility studies.

Region	Rank	Community	Selected
Qikiqtaaluk	1	Iqaluit	✓
	2	Cape Dorset	
	3	Sanikiluaq	
	4	Pangnirtung	
	5	Igloolik	
	6	Qikiqtarjuaq	
	7	Hall Beach	
	8	Clyde River	
	9	Kimmirut	×
	10–11	Grise Fiord	
	10–11	Resolute Bay	
	12	Pond Inlet	
	13	Arctic Bay	

Region	Rank	Community	Selected
Kivalliq	1	Rankin Inlet	✓
	2	Arviat	
	3	Baker Lake	
	4	Repulse Bay	×
	5	Chesterfield Inlet	
	6	Coral Harbour	
	7	Whale Cove	
Kitikmeot	1	Cambridge Bay	✓
	2	Kugaaruk	
	3	Gjoa Haven	×
	4	Kugluktuk	
	5	Taloyoak	

connection points, i.e., Valleyfield in Quebec and Churchill in Manitoba, as RE equipment would require sea-lift transport. Hence, a better way was to do a regional ranking of the communities of Nunavut (as shown in Table 14), based on the results of Figure 3, to properly consider the merits of possible RE deployment in all regions. Thus, for each region, approximately 50% of the communities were selected for further study, stopping when there were some significant differences in some of the criteria illustrated in Figure 3 for the region. For example, for the Kivalliq region, the community of Baker Lake has better solar potential and similar electricity rates than Repulse Bay.

3 Communities Selection for Feasibility Study

The pre-feasibility study determines suitability of the communities for RE integration, and defines the final rankings of the communities for feasibility studies, based on more detailed ranking criteria for the group of communities selected in the previous stage. The HOMER software [5], developed by the US National Renewable Energy Laboratory (NREL), was used in the pre-feasibility study to determine the least-cost RE deployable option with and without battery storage systems.

3.1 Procedure

HOMER was used in this study as the main tool to simulate the RE integrated operation of the remote micro-grids, the generation planning of the communities. Certain operational constraints and various input requirements were carefully considered to simulate a realistic scenario. The results obtained were used to determine the best suited set of communities that deserve further in-depth analysis for developing business cases for possible deployment of RE. The simulation procedure adopted was as follows:

1. The base case, i.e., the first run, for any community was the case of “No RE”, considering the present scenario, which provided the basis for computing certain ranking criteria parameters, e.g. O&M cost and emission reduction.
2. The next run incorporated RE with no storage availability.
3. Further runs were based on increasing storage/battery capacities.
4. Increment of battery capacity was stopped based on the following stopping criteria:
   - Replacement of required new diesel generators by RE.
   - O&M costs when introducing RE (included batteries) was more than the base-case O&M costs, i.e., O&M savings becoming negative.
5. Battery and RE capacities were increased to determine the costs of a diesel free operation, if possible.

Communities were ranked to enable the selection of the top 5 for feasibility study, and for this purpose, the following array of ranking criteria was developed:

1. Replacement of new required diesel generators, considering emergency and stand-by generators.
2. Maximum savings on O&M costs (includes fuel, and O&M of RE equipments).
3. O&M savings equal to RE installation costs.
4. Maximum reduction in CO2 emissions.
5. Maximum RE penetration (as a percentage of total energy).
6. Diesel-free operation.

Some of these ranking criteria, such as the first three, are specific to the present study, as they portray the energy related requirements and conditions of the communities in consideration; the rest are well established ranking methods for RE integration pre-feasibility studies.

The first ranking criterion revealed a problem faced by the ageing generator fleet of Nunavut, and not so much for the generating stations in the Inuvik region; thus, this criterion was applied to rank the communities of Nunavut only. In addition to the age of generators, it was learned from discussions with personnel of Qulliq Energy [18], that they intend to equip all the communities with appropriate stand-by and emergency generators; it was also reported that not every community has sufficient number of generators with remaining operating life to fulfill these roles. This prompted the allocation of such generators wherever they were not existing in these roles, thereby reducing the number of available generators to supply demand, requiring the purchase of new generators to supply the energy demand. The simulation then tried to find a feasible condition where all the regular energy demand could be supplied by the existing available diesel generators, i.e., those not on stand-by or emergency mode, and the addition of adequate capacity of RE wind and solar resources, along with sufficient capacity of battery storage. This RE capacity replaced required new diesel generators, and the battery provided operating reserves traditionally obtained from diesel generators.

The second ranking criterion was applied to all the communities of the two regions in consideration. As all of the energy generated in these communities is from diesel generators, the cost of diesel itself, along with the transportation of it, is a point of concern. Hence, the incorporation of RE in the supply mix would reduce the diesel requirement and the associated O&M costs. The present study found the maximum O&M cost reduction point for each community, and then ranked them based on descending percentage points of savings achieved.

In the third ranking criterion, a condition was sought where the RE installation cost would be nearly equal to the O&M cost reduction. This condition allowed the reallocation of money saved in O&M to the installation cost of RE equipment.

The next two ranking criteria are well established, and self-explanatory as well. These two were considered in order to fulfill the ultimate goal of emission reduction and developing business cases for substantial RE deployment.

The last ranking criterion was considered to assess the possibilities and cost requirement of diesel-free operation.

A final ranking of 13 communities was prepared considering the rankings provided by all the criteria described earlier, and 5 were picked for the next phase, i.e., feasibility studies.

3.1.1 HOMER

HOMER was first released by NREL on February 2010, and after many upgrades, has become one of the most suitable simulation software for micro-grid modeling, particularly those with no transmission grid connection. The procedure performed using HOMER is the following:

- HOMER incorporates search spaces for fossil-fuel generator, solar, and wind capacities, along with storage capacities, if any.
- HOMER simulates all feasible cases of the search spaces given.
- If any search space combination is infeasible, HOMER stops simulation and does not provide any solution until the in-feasibility is removed.
- For all feasible solutions, HOMER lists the simulation results in ascending order of the Net Present Cost (NPC), even if there are stability issues as per the defined stability criteria. The task is then to choose the least cost solution which is free from stability issues.

3.1.2 Input Data Requirements

Different input data sets were required for HOMER simulation, some of whom were constant for all communities and some depended on the community in consideration. Some data was gathered from relevant authorities, such as utilities of the territories concerned, solar panel manufacturer (data obtained from Canadian Solar only), and others from the web. In some cases, assumptions had to be made, while keeping the scenario as realistic as possible.

3.1.3 Constraints

The following set of operating constraints was assumed for the pre-feasibility study:

- Capacity shortage was not allowed.
- Spinning reserves of 10% of the load at the current time step were considered.
- To account for the variability of the energy generated by renewable sources, further spinning reserves were used [27]:
  - 25% of solar power output at any given time step.
  - 50% of wind power output at any given time step.
- From reliability perspective, an additional operating reserve of 10% of the peak load was considered.

3.2 Input Data

The basic requirement for HOMER simulation is the system data set and operating conditions. The data assumed constant for all communities was the following:

- The simulation time step was 60 minutes, based on the available data provided by QEC.
- System economics:
  - Discount rate = 8%, and expected inflation rate = 2%.
  - Project life = 25 Yrs.

- System operation criteria:
  - Economic minimization.
  - Operation strategy of load following.
  - Allow system with multiple generators.
  - Allow generators to operate simultaneously.
  - Allow system with generator capacities less than peak load.
  - Allow diesel-off operation.

Several assumptions, apart from the one related to operational constraints, were made to perform the pre-feasibility study, as follows:

- The same linear relationship of fuel consumption rate with respect to rated capacity for all existing generators was used.
- Wind turbine sizes were considered to be 100 kW at 30m hub height, for all communities except Iqaluit, where 1.5 MW at 80m hub height turbine was used, due to the relatively larger load.
- PV panel sets of 100 kW for all communities in Nunavut.
- Useful life of solar, wind, converter, and battery were 25, 30, 15, and approximately 15 years, depending on energy use, respectively.
- Useful life of diesel generators varied from 72,000 hours to 160,000 hours, depending on the manufacturer, for the communities of Nunavut.

The capital and O&M costs for both RE and new diesel generators were determined considering the transportation and installation costs for each community; no Balance-of-Plant (BoP) costs were considered in the present studies. The basic equipment costs for all types of equipments considered in the study was retrieved from Lazard's LCOE Analysis, Version 8.0 [28], and the cost of transporting the equipment from the purchase point to the shipping dock (at Valleyfield or Churchill or Hay River Terminal) was estimated from Canadian National (CN) railways' site [29]. The purchase points for various equipments, except solar PV, were assumed to be Toronto; Solar PV equipment was assumed to be purchased from Canadian Solar [30], and

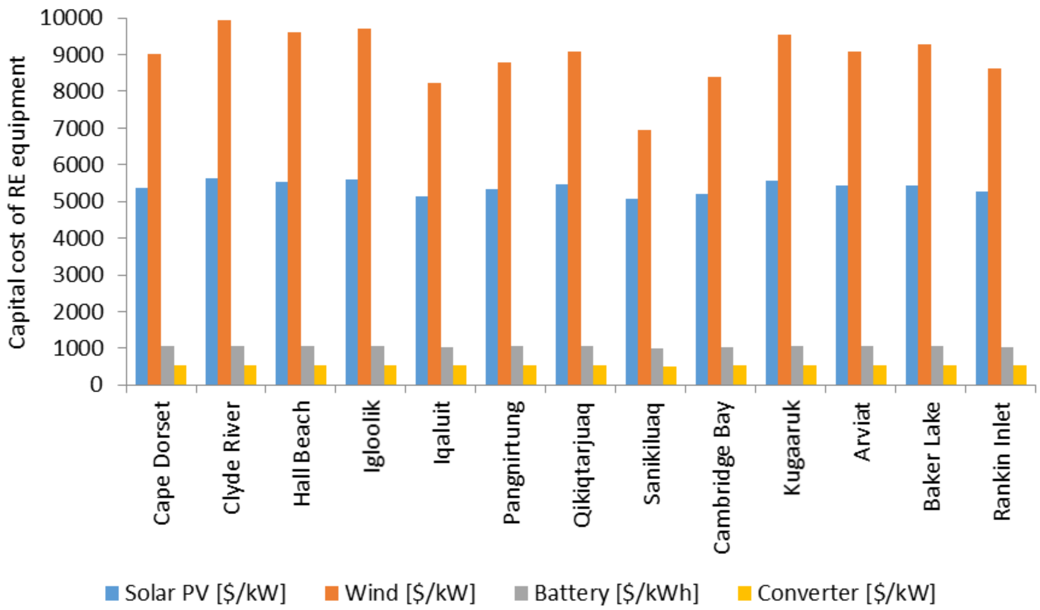

Figure 4: Capital cost, including transportation and installation, of RE equipment at the communities.

thus the base purchase point for all the communities was considered to be their manufacturing location, i.e., Guelph, Ontario.

The project management cost associated with the purchase to installation aspect of these equipment was assumed to be 6–8% of the combined equipment plus transportation costs, varying based on the travel distance. Similarly, 10%, 15%, and 8–10% were assumed for the costs related to spare parts, contingency, and logistics (data extrapolated from [31]), respectively. The final capital cost of RE equipment, varying with destination community, is shown in Figure 4.

It should be mentioned that, for feasibility studies, these assumptions will be revised, while including more details and consideration (e.g., different wind turbine sizes and curves, different non-linear fuel consumption curves for the diesel generators, BoP costs).

Details of a set of important input data used to run simulations in HOMER are presented next. In order to keep the report at a readable length, only some sample graphics and/or tables are included here for some communities.

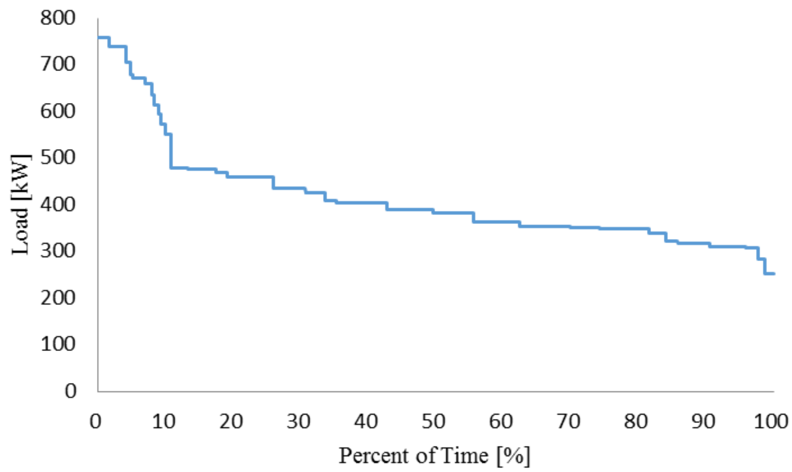

Figure 5: Load duration curve of the top ranked community, i.e., Sanikiluaq, Nunavut.

3.2.1 Load Profile

Load data, made available by QEC, consists of the maximum and minimum monthly values along with the monthly energy generation; this was then synthesized to represent an hourly load profile for these communities. A 10% hourly variation in the synthesized input load profile was implemented by HOMER, resulting in nearly 40% increase in peak load over 25 years (amounting to 1.41% annual increase); however, in the simulation, only the maximum annual load profile for all years was considered, since HOMER does not allow year by year increase as an input. The load duration curve for the top ranked community (Sanikiluaq) is shown in Figure 5.

3.2.2 Solar Insolation Profile

The hourly solar insolation profile was derived from Canadian Weather Energy and Engineering Datasets (CWEEDS) [32], for the communities of Baker Lake, Cambridge Bay, Clyde River, Hall Beach, Iqaluit, and Rankin Inlet. Solar insolation for rest of the communities was obtained from the database of NASA SSE (Surface meteorology and Solar Energy [33]) by HOMER. Figures 6 and 7 depict the solar insolation of two communities, showing the different granularities between the two datasets.

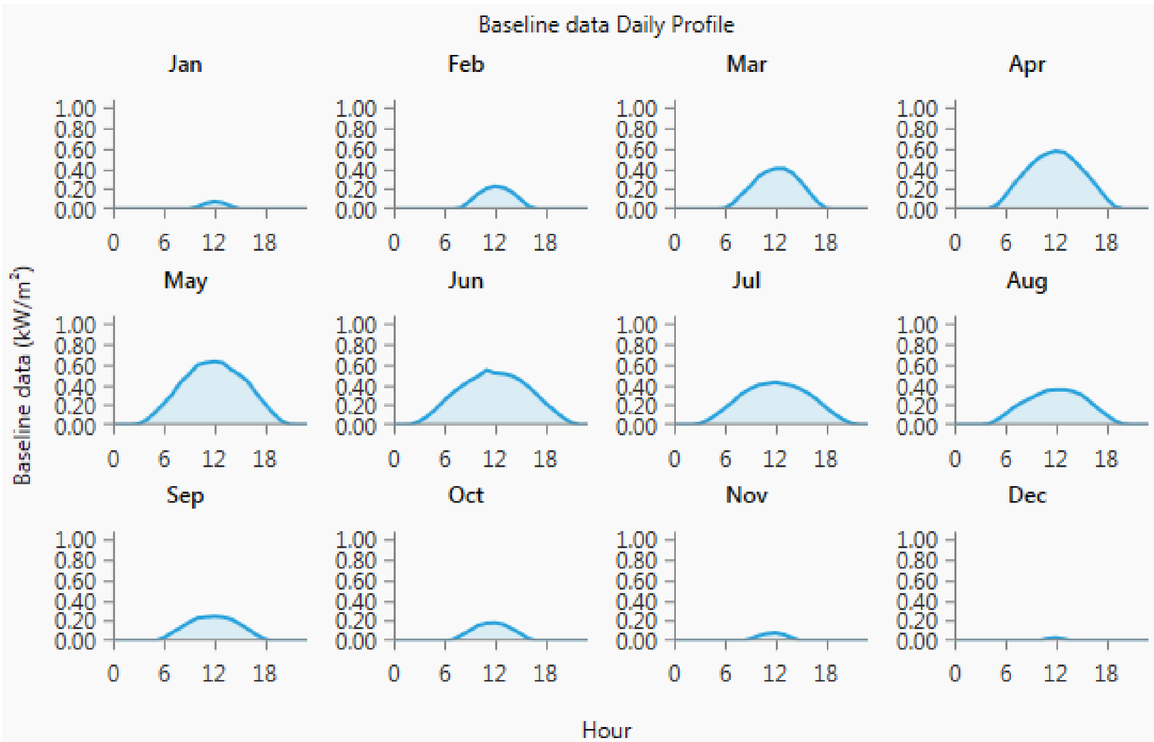

Figure 6: Average daily solar insolation profile for every month for Baker Lake, Nunavut, obtained from CWEEDS [32].

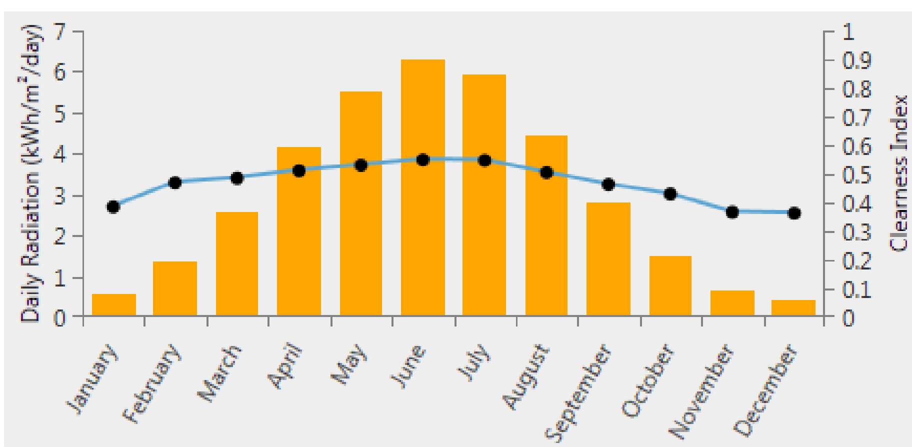

Figure 7: Average monthly solar insolation profile for Sanikiluaq, Nunavut, obtained from NASA SSE [33].

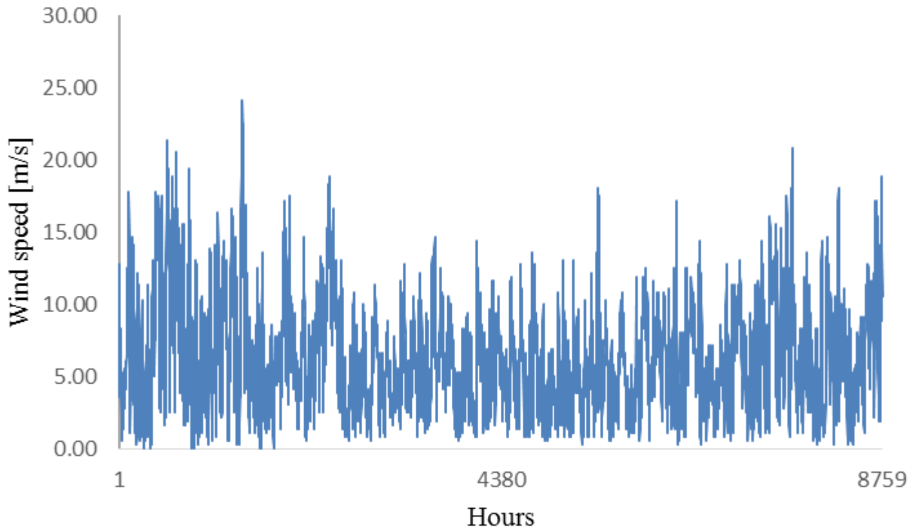

Figure 8: Hourly wind speed for Baker Lake, Nunavut, obtained from Environment and Climate Change, Canada [34].

3.2.3 Wind Speed Profile

The hourly wind profile was calculated using data obtained from the database of Environment and Climate Change, Canada [34]. Although data was available for all the communities in consideration for this pre-feasibility study, the data was sparse, i.e., less than 40% of hourly data over a year, for the communities of Igloolik and Sanikiluaq. Hence, HOMER's inbuilt dataset, obtained from NASA SSE, was used for these 2 communities. The wind profile of Baker Lake, Nunavut, obtained from [34], is shown in Figure 8.

3.2.4 Temperature Profile

Temperature profiles of all the communities were available in HOMER's database, obtained from NASA SSE. These profiles were utilized to implement the effect of temperature on solar cell and wind turbine output.

3.2.5 Existing Diesel Generators

All the communities considered in this study generate electricity using diesel generators only, except Inuvik, which has a couple of natural gas based generators as well. The size of these generators varied from 165 kW to 5 MW, and age varied from less than a year old to more than 40 years old; details of all these generators are provided in the result section. As mentioned earlier, the same linear fuel curve was used for all generators; fuel curves of individual generators for the selected communities will be considered in the feasibility study.

3.2.6 Solar PV

Solar PV panel sets of 100 kW capacity were considered as the unit-size for PV plants for all the communities. The panels technical characteristics, which include the temperature effect as well, were obtained from the technical manuals of panels manufactured by Canadian Solar [30]. The panel tilt was assumed to be equal to the latitude of the location it would be installed. In the feasibility stage, other tilt angles (e.g., vertical) will also be considered along with panels manufactured by other companies.

3.2.7 Wind Turbine

Generic wind turbines of 100 kW capacity and 30m hub height had been considered for all communities except Iqaluit, where a 1.5 MW turbine with 80m hub height was considered, due to the community's relatively high load; the power curves for these turbines are embedded in HOMER. In the feasibility study, different manufacturer's wind turbine of various sizes, along with their corresponding power curves will be considered.

3.2.8 Battery

Only lead acid batteries were considered at this stage, as they are the cheapest available. During feasibility studies, other battery designs (e.g., Lithium ion) will be incorporated, and the possibility of hydrogen storage systems for long-term seasonal solar energy storage will be considered.

3.3 Results

In this section, the results for the base case and the 6 different ranking criteria stated in Section 3.1 are presented and discussed. Plots depicting the results of the various HOMER simulations used to obtain the various rankings are presented in the Appendix, for the select 5 communities of Nunavut. It is worth mentioning here that the existing diesel generators were modeled with zero capital costs, as these costs are not incurred during the time-line of the project. The omission of this capital cost from the simulations resulted in a lower than expected value of cost-of-energy (COE), and thus these values are not presented in this report.

3.3.1 Base Case

The first run of HOMER simulations, termed the base-case scenario, yielded the NPV of O&M costs (including fuel cost) along with the annual CO_2 emissions, which provided the basis for O&M cost and emission reduction with RE integration for each community. The base case also determines the time line of new diesel generator purchase, based on the peak load, while considering the N – 1 contingency of the largest generator. If the stand-by and/or emergency units were not mentioned in the data set provided by QEC, then these were chosen based on the following criteria:

- Largest available generator as the stand-by.
- Generator with capacity approximately 25% of peak load as emergency unit.

Simulations were thus performed removing the emergency/stand-by units from the inventory.

Details of available generators, with their remaining useful life and new required generator capacities, if any, for all communities in Nunavut, are shown in Figures 9 and 10, along with the peak load from 2015 data and the peak estimated by HOMER. Observe that the largest requirement of a new generator (for 2015) is in the community of Cape Dorset (1,423 kW), which is consistent with QEC's Request for Proposal (RFP) to build a new power plant at this community, with an array of new generators. Furthermore, the communities of Arviat, Clyde River, Igloolik, Iqaluit, Kugaaruk, Qikiqtarjuaq, and Sanikiluaq do not require new diesel generators for 2015.

Community	Apr`14 - Mar`15		Diesel Generators			NPV of O&M Costs	Annual CO2 Emissions	New Generator Requirement [kW]	
	Annual Energy Demand	Peak Load	Capacity	Engine Life	Remaining			N-1 Contingency	
	[kWh]	[kW]	[kW (Yr.)]	[h] (as of 31 Mar. 2015)		[M$]	[tonnes/yr]	**2015**	**HOMER**
Arviat	8,852,004	1,734	800 (14)	100,000	97,549	49.21	6,482.05	None	355
		[2,465] [a]	550 (10)	100,000	83,972				
			960 (94)	100,000	6,702				
			800 (05)	100,000	79,250				
Baker Lake	8,901,168	2,188	800 (94) [b]	100,000	-2	54.18	6,350.84	718	1,644
		[3,114]	920 (05)	100,000	56,611				
			1,150 (05)	100,000	49,908				
			550 (11)	100,000	88,626				
Cambridge Bay	11,095,327	2,091	1,100 (10)	100,000	81,142	83.85	8,131.33	441	1,286
		[2,936]	550 (07)	100,000	81,757				
			720 (92)	100,000	-1,612				
			1,100 (10)	100,000	85,828				
Cape Dorset	6,203,140	1,423	540 (76)	100,000	-45,209	48.13	4,696.61	1,423	1,956
		[1,956]	720 (95)	100,000	-4,581				
			1,000 (02)	72,000	27,682				
			320 (08) [c]	72,000	71,999				
			1,000 (92)	100,000	963,779				
Clyde River	3,801,055	810	540 (11)	72,000	59,836	30.78	2,838.11	480	821
		[1,151]	480 (94)	100,000	-7,306				
			330 (06)	72,000	42,496				
			330 (00)	NA	NA				
			2X540 (06)	NA	NA				
			540 (00)	NA	NA				
Hall Beach	3,317,573	694	165 (83)	90,000	37,894	30.58	2,480.59	199	486
		[981]	550 (11)	100,000	89,685				
			330 (09)	72,000	50,134				
			480 (93)	100,000	-16,075				
			330 (99)	NA	NA				
			330 (08)	NA	NA				
			270 (82)	NA	NA				
Igloolik	6,608,037	1,427	850 (13)	100,000	95,550	49.08	4,566.02	None	442
		[1,962]	480 (93)	100,000	20,322				
			720 (95)	100,000	3,396				
			320 (06)	72,000	41,246				
			540 (85)	NA	NA				

a [·]: HOMER estimated future peak load.
b in **Red**: Generators not used in pre-feasibility due to overuse.
c in **Green**: Generators kept for stand-by and/or emergency use.

Figure 9: Base-case results for 7 communities of Nunavut along with new generator requirements.

Community	Apr`14 - Mar`15		Diesel Generators			NPV of O&M Costs	Annual CO2 Emissions	New Generator Requirement [kW]	
	Annual Energy Demand	Peak Load	Capacity	Engine Life	Remaining			N-1 Contingency	
	[kWh]	[kW]	[kW(Yr.)]	[h] (as of 31 Mar. 2015)		[M$]	[tonnes/yr]	2015	HOMER
Iqaluit	26,254,474	9,813	2,300 (74)	100,000	7,554	382.01	40,856.84	None	2,445
		[14,075] [a]	3,300 (92) [b]	120,000	-130				
			3,000 (93)	100,000	-4,634				
			2,000 (96)	100,000	27,884				
			4,300 (00)	135,000	40,678				
			330 (03)	72,000	50,534				
			5,250 (13)	160,000	153,700				
			5,250 (13)	160,000	151,882				
			320 (10) [c]	100,000	95,304				
			2,000 (12)	NA	NA				
			2,000 (12)	NA	NA				
Kugaaruk	2,801,331	734	400 (04)	72,000	36,487	34.06	2,155.37	None	63
		[1,013]	550 (09)	100,000	80,043				
			550 (09)	100,000	77,716				
Pangnirtung	6,459,355	1,415	550 (16) [d]	100,000	100,000	50.46	4,857.81	None	None
		[2,012]	550 (16)	100,000	100,000				
			550 (16)	100,000	100,000				
			550 (16)	100,000	100,000				
			550 (16)	100,000	100,000				
			550 (16)	100,000	100,000				
Qikiqtarjuaq	2,809,200	495	330 (97)	100,000	46,848	25.63	2,136.28	165	374
		[704]	450 (04)	90,000	37,784				
			540 (88) [e]	90,000	1,680				
			165 (70)	NA	NA				
Rankin Inlet	17,777,180	3,122	950 (93)	100,000	-1,719	118.77	13,001.05	22	1,351
		[4,451]	1,650 (11)	100,000	84,897				
			1,450 (06)	120,000	90,118				
			2,150 (03)	120,000	64,286				
			850 (09)	100,000	98,509				
Sanikiluaq	3,624,377	758	550 (15)	100,000	100,000	33.22	2,687.95	None	242
		[1,072]	500 (08)	100,000	64,696				
			330 (05)	72,000	35,339				
			2X330 (00)	NA	NA				
			330 (05)	NA	NA				
			540 (00)	NA	NA				

a [·]: HOMER estimated future peak load.
b in **Red**: Generators not used in pre-feasibility due to overuse.
c in **Green:** Generators kept for stand-by and/or emergency use.
d in **Blue**: New generators.
e: Not considered due to small remaining life.

Figure 10: Base-case results for remaining 6 communities of Nunavut along with new generator requirements.

Considering the load growth corresponding to the HOMER estimated peak load, all except Clyde River and Qikiqtarjuaq require new generators. Note also that all communities, except Pangnirtung, require a new generator during the project lifetime, which can be attributed to the fact that the Pangnirtung's power plant was destroyed in a recent fire, and thus this community is now getting a new plant with 6 generators, each of 550 kW, with 2 kept as emergency and stand-by. It should be mentioned that Qikiqtarjuaq's new generator requirement has been computed ignoring the 540 kW generator as it has only 1,680 hours of useful life remaining, and therefore will require replacement in the early years of the project. Observe that both maximum energy demand and peak load are for Iqaluit, which justifies the fact that annual CO_2 emission and NPV of O&M costs are also maximum for Iqaluit, and that the minimum annual CO_2 emissions and NPV of O&M costs are for the community of Qikiqtarjuaq.

3.3.2 First Ranking Criterion

The first ranking criterion consists of replacing new required diesel generators using RE deployment to reduce dependency on fossil fuels, since new generator is required for those communities in the base-case scenario, as explained in Section 3.3.1. The resulting ranking obtained from the HOMER simulations is shown in Figure 11, and is based on the capacity (larger) and time line (earlier) of avoiding new diesel generator purchases, and the cost of installing RE in ascending order.

In this case, the communities of Arviat and Baker Lake take the top two positions, out of which Baker Lake is the earliest to avoid new generation purchase. Substantial O&M savings occur for Ranking Inlet, Clyde River, and Cambridge Bay, while the community of Qikiqtarjuaq is the most expensive in terms of deploying RE. Observe that apart from Arviat, Cape Dorset, Kugaaruk, and Qikiqtarjuaq, all other communities avoid new diesel generator purchase with RE deployment and O&M savings. Interestingly, Pangnirtung, the community with all new generators, can also reduce the need for a new generator (5 instead of 6) by integrating RE.

Community (Alphabetical)	Gen. Cap. Removed	Installation Costs (NPV)	O&M Savings	RE and Associated CAPACITIES				RE Penetration	CO2 Reduction	Rankings based on	
				Battery	PV	Wind	Converter			Gen. Cap. Removed	Installation Costs of RE
	[kW]	[M$]	[%]	[kWh]	[kW]	[kW]	[kW]	[%]	[%]	(Descend)	(Ascend)
Arviat	**1,400**	15.058	-0.32	**3,500**	500	1,100	1,000	35.1	34.99	2	6
Baker Lake	**1,200**	2.989	7.94	**0**	500	0	500	7.1	7.31	5	2
Cambridge Bay	**780**	19.931	20.62	**4,300**	1,200	1,000	1,600	28.8	29.63	7	7
Cape Dorset	**1,400**	34.635	-18.56	**21,600**	1,100	600	1,100	37.0	37.32	3	10
Clyde River	**520**	7.691	21.71	**1,460**	500	300	600	28.7	29.82	9	3
Igloolik	**840**	8.771	12.91	**2,400**	1,000	0	1,100	17.0	18.54	6	5
Kugaaruk	**1,300**	29.220	-28.24	**18,600**	600	600	600	42.7	42.83	4	8
Pangnirtung	**550**	7.946	9.94	**2,500**	900	0	1,000	13.6	15.57	8	4
Qikiqtarjuaq	**400**	43.103	-151.84	**37,000**	700	0	500	20.6	21.89	11	11
Rankin Inlet	**2,300**	32.524	27.79	**7,000**	1,300	2,000	2,200	39.2	39.06	1	9
Sanikiluaq	**460**	1.402	10.53	**300**	100	100	100	11.5	11.37	10	1

Figure 11: Ranking of relevant communities of Nunavut based on replacement of new required diesel generators.

RANK	Max. O&M Savings	Community	RE & Associated CAPACITIES				RE Penetration	CO2 Reduction	Installation Costs (NPV)
			Battery	PV	Wind	Converter			
	[%]		[kWh]	[kW]	[kW]	[kW]	[%]	[%]	[M$]
1	44.92	Sanikiluaq	2,500	400	600	700	51.7	52.59	7.795
2	27.82	Hall Beach	1,300	400	400	500	36.0	37.03	7.726
3	27.79	Rankin Inlet	7,000	1,300	2,000	2,200	39.2	39.06	32.524
4	25.21	Iqaluit	21,500	2,000	6,000	5,500	39.3	40.08	84.715
5	24.87	Baker Lake	3,500	600	900	1,000	36.4	36.04	15.873
6	21.94	Kugaaruk	1,500	500	300	600	31.5	31.55	7.573
7	21.71	Clyde River	1,460	500	300	600	28.8	29.82	7.691
8	21.33	Cambridge Bay	4,500	1,200	1,100	1,600	30.1	30.96	20.978
9	20.29	Arviat	3,500	500	1,100	900	34.6	34.25	15.058
10	17.03	Cape Dorset	3,500	500	700	900	31.0	31.17	13.160
11	12.91	Igloolik	2,400	1,000	0	1,100	17.0	18.54	8.771
12	10.96	Qikiqtarjuaq	1,100	400	0	500	13.3	15.56	3.620
13	9.94	Pangnirtung	2,500	900	0	1,000	13.6	15.57	7.946

Figure 12: Ranking of Nunavut communities based on maximum O&M savings.

3.3.3 Second Ranking Criterion

The rankings here are based on maximum O&M savings achieved, and is shown in Figure 12. Note that Sanikiluaq, Hall Beach, and Ranking Inlet are the 3 most preferred communities for RE integration, with more than 27% savings, with Sanikiluaq ahead at 45% savings. Iqaluit and Baker Lake follow in the top 5 with 25% savings in their corresponding O&M costs. Among these top 5 communities, RE deployment in Iqaluit is the most expensive, while Hall Beach is the cheapest. It was found that a minimum of 400 kW of solar PV, 400 kW of wind, 500 kW converter, and 1.3 MWh of battery would be required by these 5 communities, and Iqaluit requires the maximum capacities of all RE related equipment, which can be attributed to its large 26 GWh energy demand and more than 9 MW of peak load. Rankin Inlet, with the second highest energy demand in the base scenario, comes second in terms of RE related capacities. A point to note, for the top 4, is that the O&M savings achieved (in M$) are more than the RE installation costs incurred.

3.3.4 Third Ranking Criterion

The third ranking criterion is based on economic criteria, and the ranking of Nunavut communities is shown in Figure 13. The rankings are made on the basis of decreasing O&M savings and it can be observed that Sanikiluaq, Rankin Inlet, Hall Beach, and Iqaluit take the top 5 spots with various battery capacities. It was found that increasing battery capacities for Hall Beach and Rankin Inlet yield higher O&M savings, as these haven't reached their corresponding maximum O&M savings points. The ranking has more than one entry for a particular community, indicating that the O&M savings and RE installation costs crisscrossed each other as battery capacity varied, as shown in Figure 20 in the Appendix Section A.2 for Iqaluit.

An additional ranking was made on the basis of ascending RE installation costs, finding that the ranking almost reverses in comparison with descending O&M savings. This emphasizes the need for high RE deployment investments to achieve any substantial improvement over the base-case scenario.

Community (Alphabetical)	(NPV)O&M Savings [$]	Installation Costs (NPV) [$]	O&M Savings [%]	RE and Associated CAPACITIES Battery [kWh]	PV [kW]	Wind [kW]	Converter [kW]	RE Penetration [%]	CO2 Reduction [%]	Rankings based on O&M Savings % (Descend)	Rankings based on Installation Costs of RE (Ascend)
Arviat	837,705	907,600	1.70	0	0	100	0	2.6	2.46	16	3
Baker Lake	3,648,351	4,047,500	6.73	1,000	500	0	500	7.1	7.36	14	8
Cambridge Bay	6,198,906	5,879,400	7.39	1,500	600	100	700	8.3	9.07	13	9
Cape Dorset	580,989	591,400	1.21	0	100	0	100	0.6	1.41	18	1
Clyde River	3,053,834	3,087,000	9.92	800	200	100	200	11.3	13.49	8	7
Hall Beach	2,429,447	2,374,200	7.95	700	100	100	200	9.8	11.27	11	6
Hall Beach	8,332,737	7,940,400	27.25	1,500	400	400	500	36.2	37.25	3	12
Igloolik	735,488	721,800	1.50	100	100	0	100	1.7	1.66	17	2
Iqaluit	36,739,335	37,081,000	9.62	12,500	2,000	1,500	3,000	13.5	14.99	9	16
Iqaluit	96,285,121	84,714,992	25.21	21,500	2,000	6,000	5,500	39.3	40.08	4	17
Iqaluit	93,116,687	90,651,504	24.28	25,000	0	7,500	5,500	41.4	42.25	5	18
Kugaaruk	6,285,116	6,138,500	18.45	1,100	500	200	500	25.9	25.84	7	10
Kugaaruk	7,471,944	7,572,900	21.94	1,500	500	300	600	31.5	31.55	6	11
Pangnirtung	1,944,607	1,863,800	3.85	100	300	0	300	4.7	4.57	15	5
Qikiqtarjuaq	1,898,300	1,730,400	7.41	500	200	0	200	6.7	9.22	12	4
Rankin Inlet	11,197,390	12,392,600	9.43	4,000	500	600	800	13.8	14.79	10	14
Rankin Inlet	33,006,219	32,523,800	27.79	7,000	1,300	2,000	2,200	39.2	39.06	2	15
Sanikiluaq	11,292,466	11,537,900	33.99	10,000	400	600	700	52.1	53.06	1	13

Figure 13: Ranking of Nunavut communities based on near equal values for O&M savings and RE installation costs.

RANK	Max. CO2 Reduction	Community	RE and Associated CAPACITIES				RE Penetration	O&M Savings	Installation Costs (NPV)
			Battery	PV	Wind	Converter			
	[%]		[kWh]	[kW]	[kW]	[kW]	[%]	[%]	[M$]
1	53.06	Sanikiluaq	7,500	400	600	700	52.1	37.79	10.290
2	42.83	Kugaaruk	18,600	600	600	600	42.7	-28.24	29.220
3	42.29	Iqaluit	30,000	0	7,500	6,000	41.5	22.88	95.806
4	40.50	Rankin Inlet	15,000	1,300	2,100	2,200	40.6	20.97	41.737
5	39.50	Baker Lake	12,500	600	1,000	1,300	40.3	7.62	26.495
6	37.32	Cape Dorset	21,600	1,100	600	1,100	37.0	-18.56	34.635
7	37.31	Hall Beach	2,000	400	400	500	36.2	37.31	8.476
8	34.99	Arviat	12,500	500	1,100	1,000	35.1	-0.32	19.945
9	30.98	Cambridge Bay	10,000	1,200	1,100	1,600	30.1	13.59	26.671
10	30.08	Clyde River	2,000	500	300	700	28.9	19.87	8.324
11	21.89	Qikiqtarjuaq	37,000	700	0	500	20.6	-151.84	43.103
12	18.54	Igloolik	2,400	1,000	0	1,100	17.0	12.91	8.771
13	15.64	Pangnirtung	5,000	900	0	1,000	13.6	4.10	10.561

Figure 14: Ranking of Nunavut communities based on maximum CO_2 reduction.

3.3.5 Fourth and Fifth Ranking Criteria

These two ranking criteria are maximum reduction in CO_2 and maximum penetration of RE, which are similar, as increasing RE penetration results in more emission reductions. The rankings based on maximum emission reduction and maximum RE penetration for the communities of Nunavut are shown in Figures 14 and 15, respectively.

Observe that the same set of communities of Nunavut rank in the top 5 for these 2 ranking criteria, maintaining their respective positions, with solar, wind, and converter capacities remaining the same. It was found that, except Rankin Inlet and Hall Beach, all other communities have the same optimal point for maximum emission reduction and maximum RE penetration, which

RANK	Max. RE Penetration	Community	RE and Associated CAPACITIES				CO2 Reduction	O&M Savings	Installation Costs (NPV)
			Battery	PV	Wind	Converter			
	[%]		[kWh]	[kW]	[kW]	[kW]	[%]	[%]	[M$]
1	52.1	Sanikiluaq	7,500	400	600	700	53.06	37.79	10.290
2	42.7	Kugaaruk	18,600	600	600	600	42.83	-28.24	29.220
3	41.5	Iqaluit	30,000	0	7,500	6,000	42.29	22.88	95.806
4	40.6	Rankin Inlet	10,000	1,300	2,100	2,200	40.49	25.99	36.517
5	40.3	Baker Lake	12,500	600	1,000	1,300	39.50	7.62	26.495
6	37.0	Cape Dorset	21,600	1,100	600	1,100	37.32	-18.56	34.635
7	36.2	Hall Beach	1,500	400	400	500	37.25	27.25	7.940
8	35.1	Arviat	12,500	500	1,100	1,000	34.99	-0.32	19.945
9	30.1	Cambridge Bay	10,000	1,200	1,100	1,600	30.98	13.59	26.671
10	28.9	Clyde River	2,000	500	300	700	30.08	19.87	8.324
11	20.6	Qikiqtarjuaq	37,000	700	0	500	21.89	-151.84	43.103
12	17.0	Igloolik	2,400	1,000	0	1,100	18.54	12.91	8.771
13	13.6	Pangnirtung	5,000	900	0	1,000	15.64	4.10	10.561

Figure 15: Ranking of Nunavut communities based on maximum RE penetration.

was expected. Note that these two rankings do not correspond to maximum O&M savings, as it is evident from the ranking results with respect to maximum O&M savings. However, the rankings are similar with almost the same set of communities at the top, except for Kugaaruk at the expense of Hall Beach, which shows negative O&M savings, indicating that substantial investment in RE is needed to increase emission reduction.

3.3.6 Sixth Ranking Criteria

The minimum amount of money required to design a diesel-free system, with associated RE and storage capacities, is presented in Table 15, for those communities of Nunavut where this could

Table 15: Minimum cost and RE capacities required to achieve diesel-free operation in Nunavut.

Community	Installation Costs of RE	Battery	Solar PV	Wind	Converter	COE
	[M$]	[MWh]	[MW]			[$/kWh]
Sanikiluaq	72.1	23	5	5	1.3	2.01
Baker Lake	293	75	10	17	2.5	3.68
Arviat	341	15	19	25	5.0	3.75
Kugaaruk	403	84	0	32	5.0	16.11
Igloolik	415	69	7	31	9.2	7.22
Cape Dorset	442	67	24	27	3.4	7.39
Rankin Inlet	744	75	73	33	5.2	4.04
Qikiqtarjuaq	880	78	100	32	3.0	28.52

Table 16: Communities that did not achieve diesel free operation in HOMER.

Community	RE Saturation	RE Install. Costs	Battery	Solar PV	Wind	Converter	COE
	[%]	[M$]	[MWh]	[MW]			[$/kWh]
Cambridge Bay	87	573	49.5	47	32.7	2.7	5.09
Clyde River	85	1070	57.5	87.7	32.8	1.4	21.84
Hall Beach	96	529	12	15.3	32.8	1.1	17.63
Iqaluit	72	1990	164	300	33	10.7	33.6
Pangnirtung	73	1040	99.4	121	32	8.4	15.29
Inuvik	43	635	100	50	32	11	2.41

be achieved. The communities are ranked based on ascending RE installation costs, resulting in Sanikiluaq, Baker Lake, and Arviat in the top 3 positions. Observe the significantly lower cost requirement (72 M$) for Sanikilauq to go diesel free, compared to all other communities, due to its significant RE resource.

All other communities that failed to achieve diesel-free operation are depicted in Table 16. For these cases, HOMER could not find an optimal result that would allow the total elimination of diesel generation

4 Conclusions and Recommendations

The final ranking of the communities, for the two regions, can be derived from the rankings for the different criteria discussed in Section 3, except the sixth one, due to the high RE installation costs. Hence, the top 5 positions for the communities in Nunavut that are deemed suitable for feasibility studies are:

1. Sanikiluaq
2. Iqaluit
3. Rankin Inlet
4. Baker Lake
5. Arviat

For the last position, the communities of Kugaaruk, Hall Beach, and Arviat could be selected. However, QEC recommended selecting Arviat as the 5^{th} community.

The result of this pre-feasibility study indicates that substantial reduction in CO_2 emission can be achieved at a relatively low initial investment cost, and at least 35% RE penetration can be achieved for all the top 5 communities in Nunavut at a minimum cost of 7.8 M$, except for Baker Lake (7.1%, 2.99 M$), while avoiding the purchase of a new diesel generator.

A APPENDIX

Simulation results of the communities selected for feasibility studies are presented here.

A.1 Sanikiluaq, NU

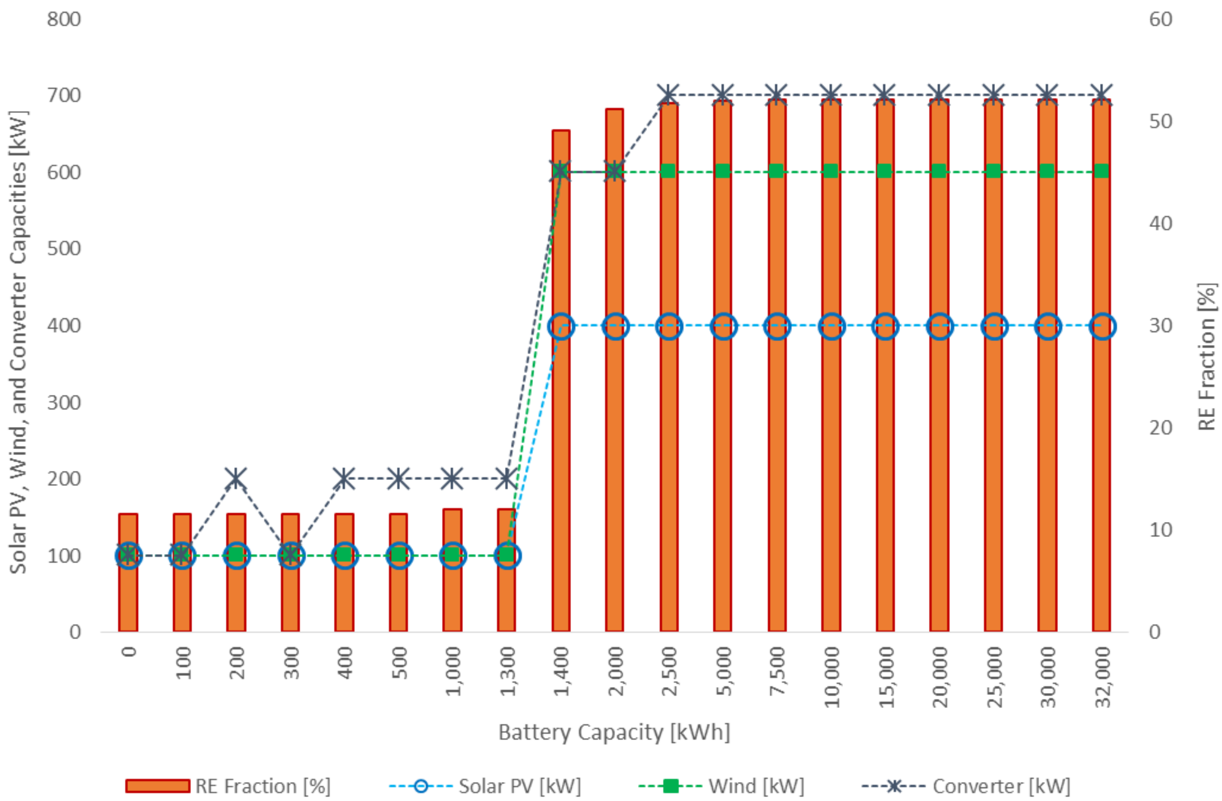

Figure 16: Solar, wind, and converter capacities versus battery capacity for Sanikiluaq, Nunavut.

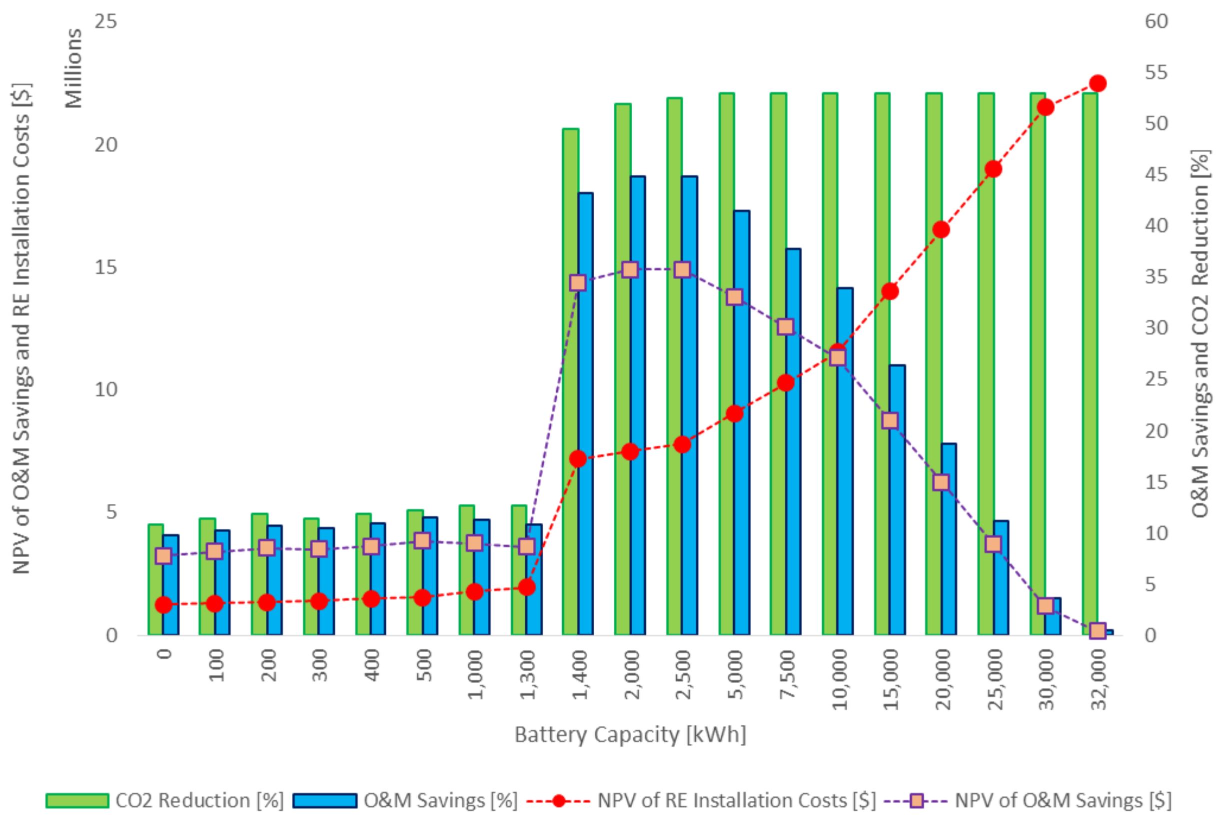

Figure 17: O&M savings, RE installation costs, and CO_2 reductions versus battery capacity for Sanikiluaq, Nunavut.

Figure 18: Percentage share of energy generation by diesel generators and RE sources versus battery capacity for Sanikiluaq, Nunavut.

A.2 Iqaluit, NU

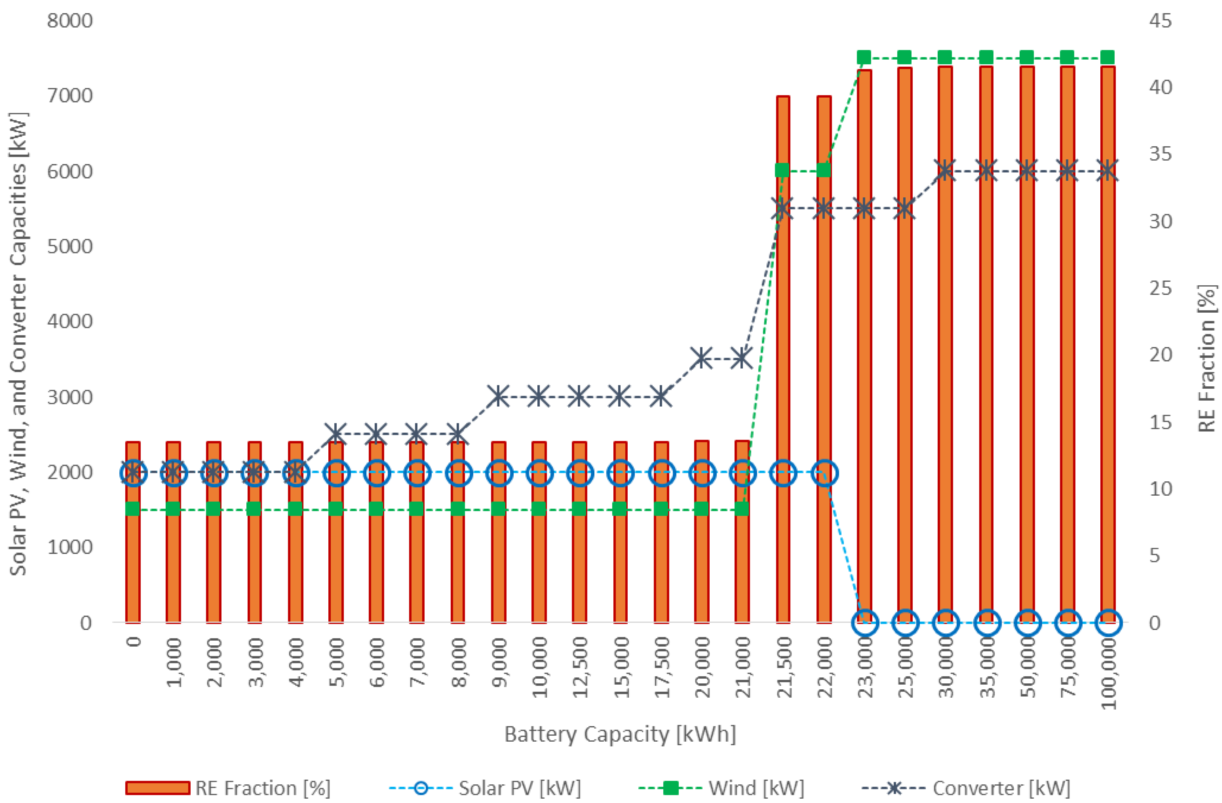

Figure 19: Solar, wind, and converter capacities versus battery capacity for Iqaluit, Nunavut.

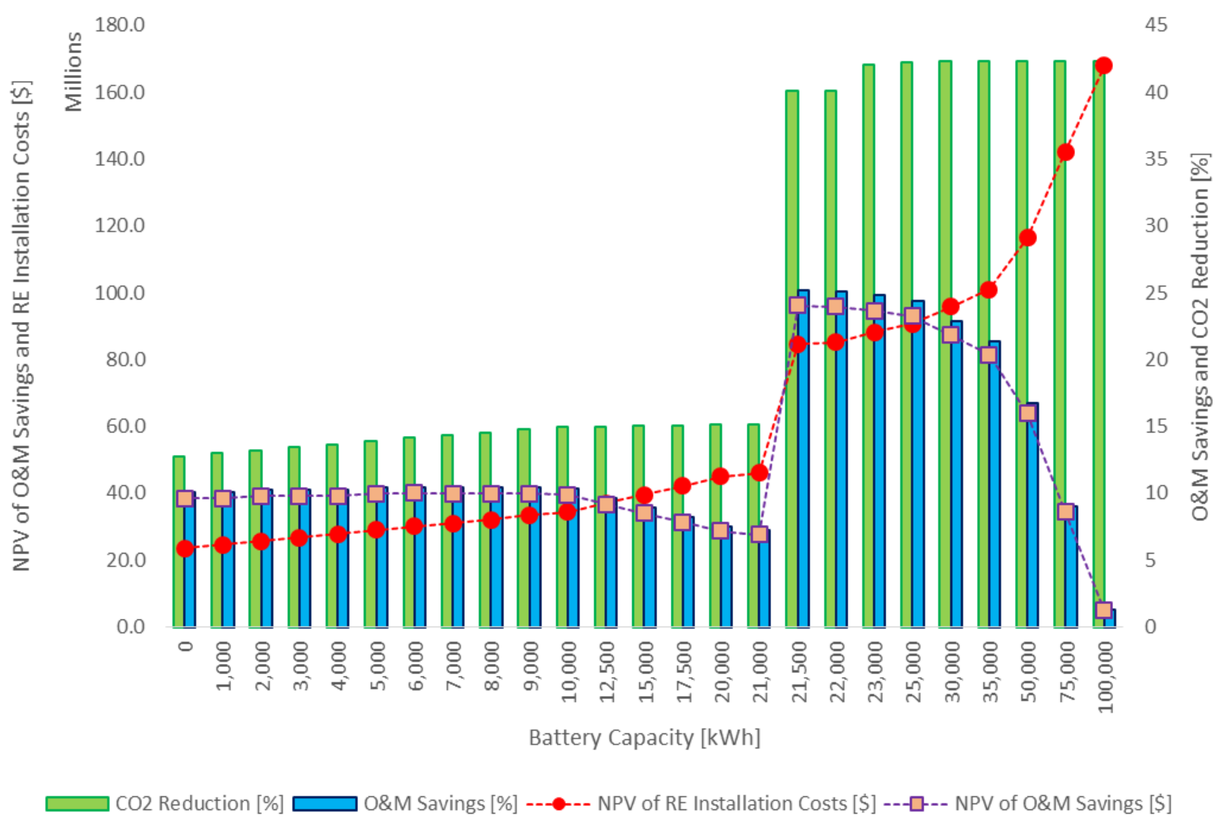

Figure 20: O&M savings, RE installation costs, and CO_2 reductions versus battery capacity for Iqaluit, Nunavut.

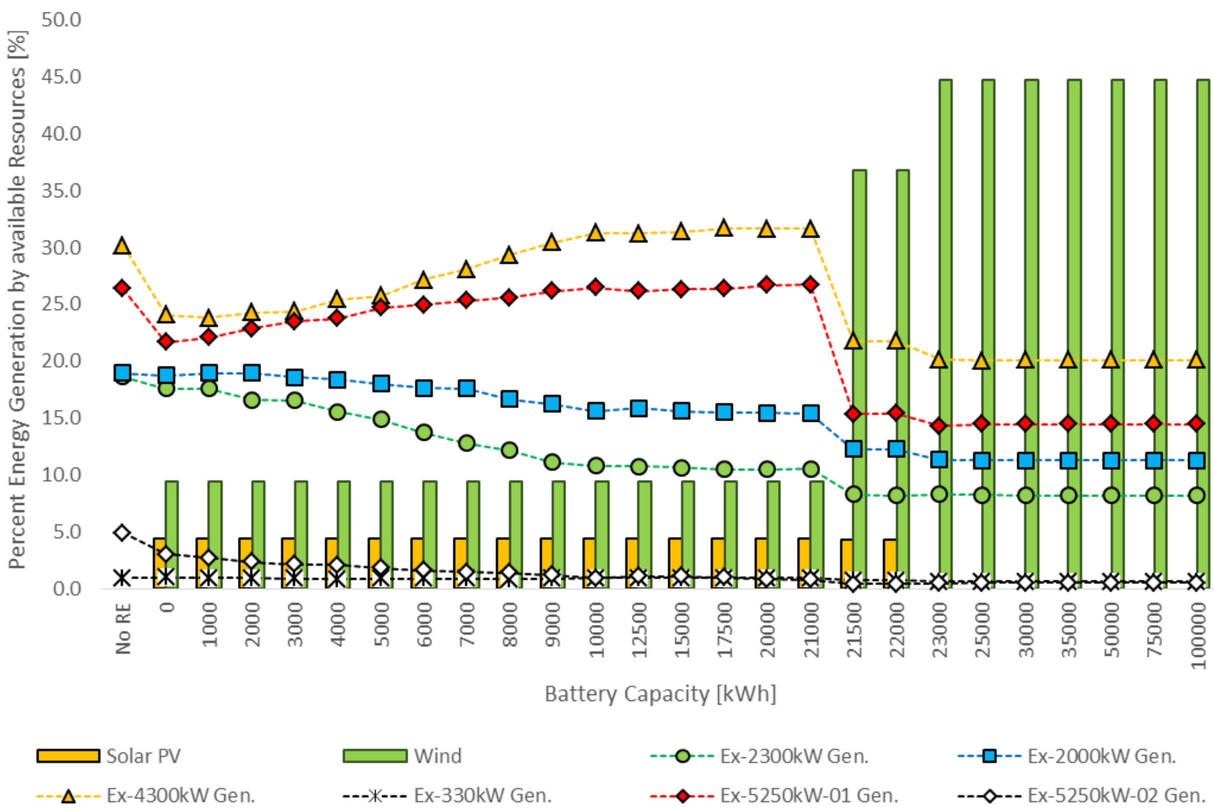

Figure 21: Percentage share of energy generation by diesel generators and RE sources versus battery capacity for Iqaluit, Nunavut.

A.3 Rankin Inlet, NU

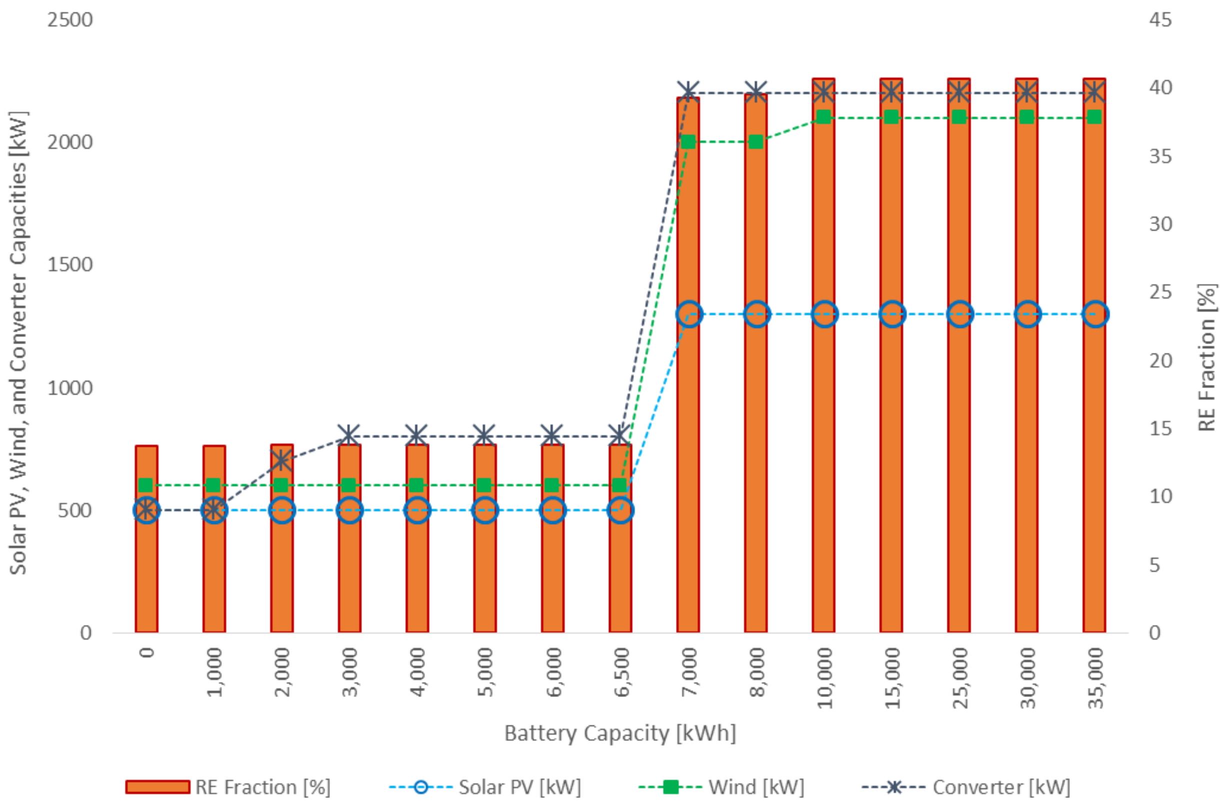

Figure 22: Solar, wind, and converter capacities versus battery capacity for Rankin Inlet, Nunavut.

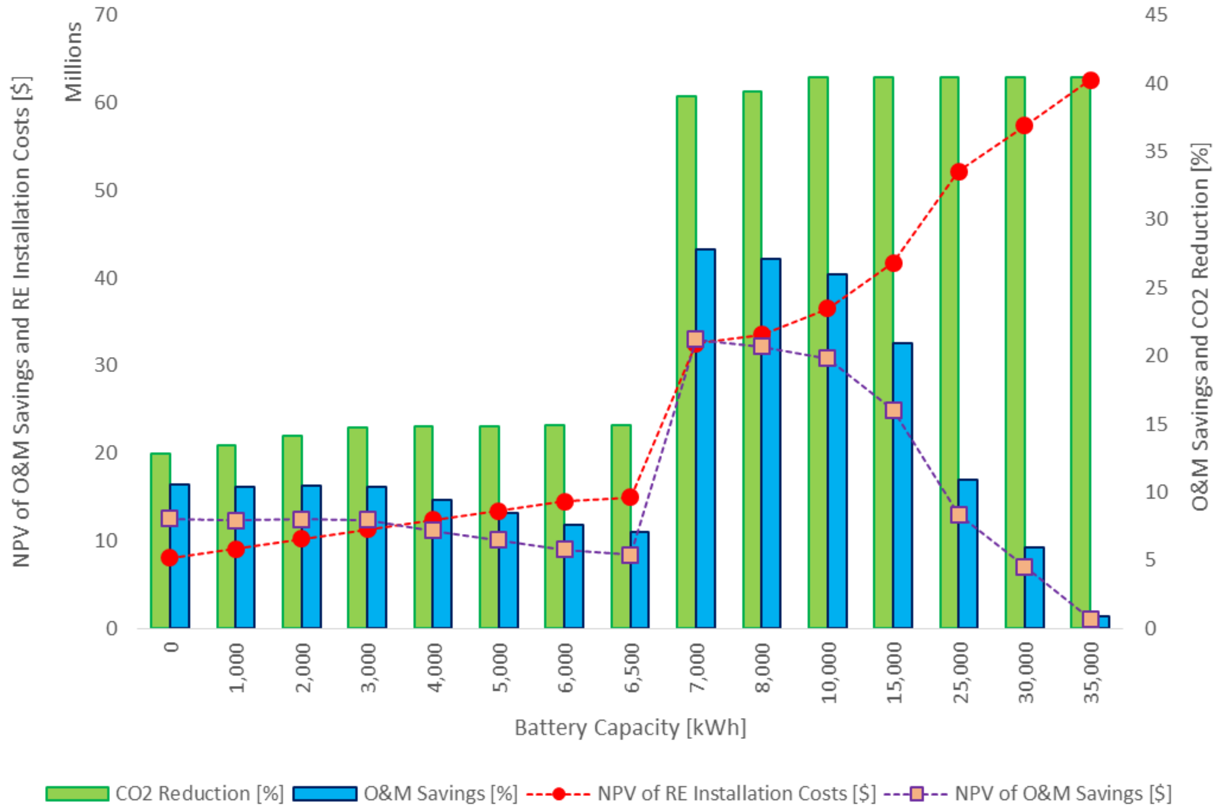

Figure 23: O&M savings, RE installation costs, and CO_2 reductions versus battery capacity for Rankin Inlet, Nunavut.

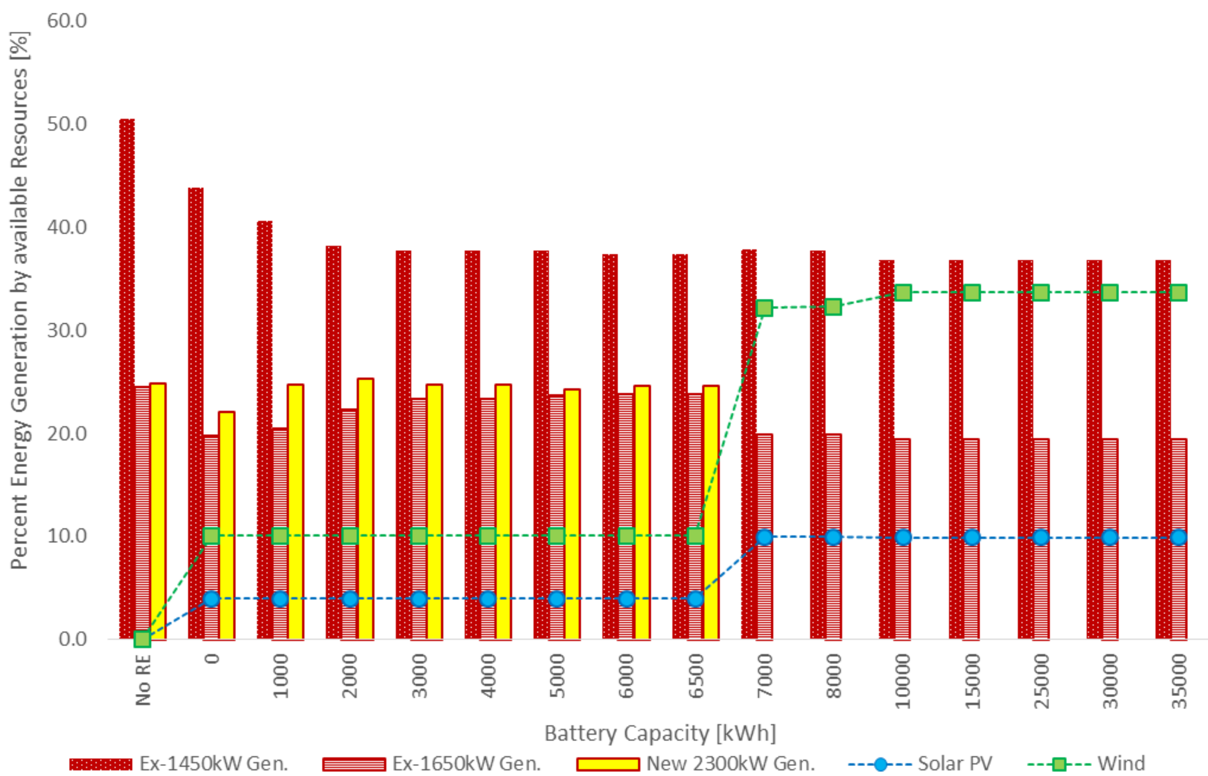

Figure 24: Percentage share of energy generation by diesel generators and RE sources versus battery capacity for Rankin Inlet, Nunavut.

A.4 Baker Lake, NU

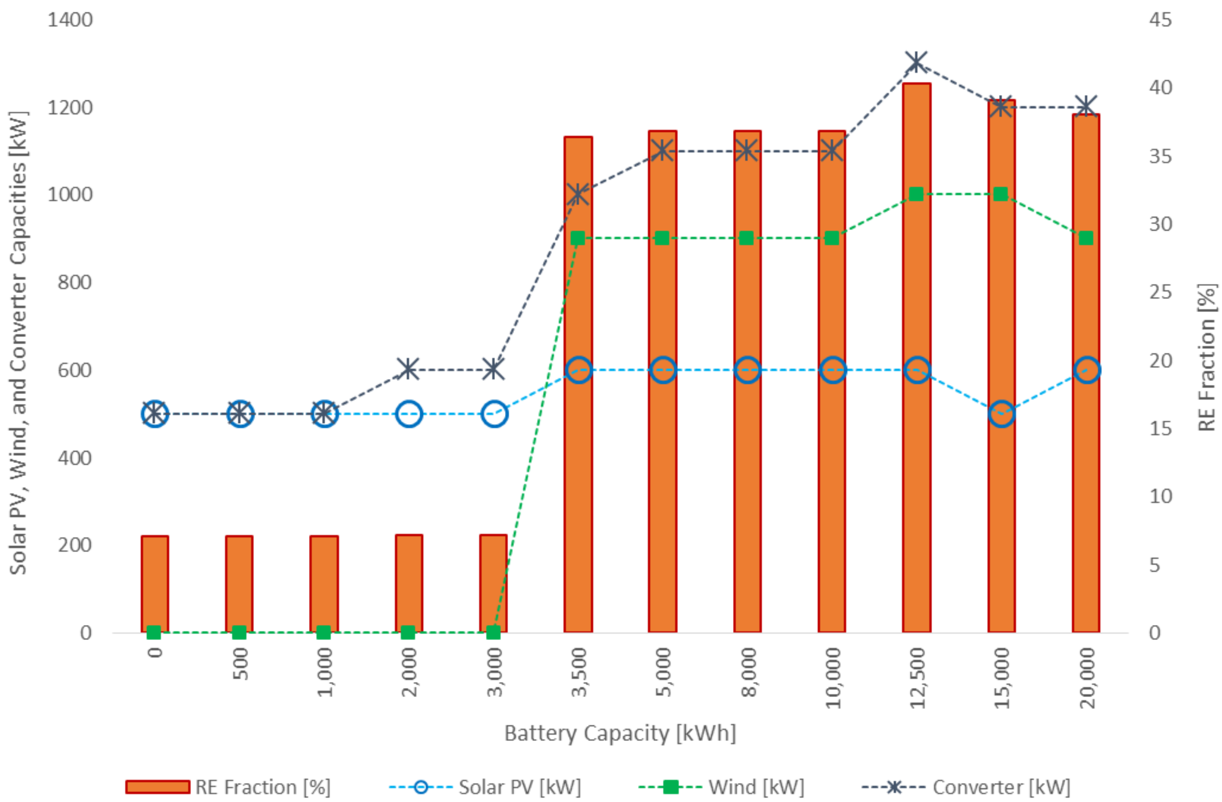

Figure 25: Solar, wind, and converter capacities versus battery capacity for Baker Lake, Nunavut.

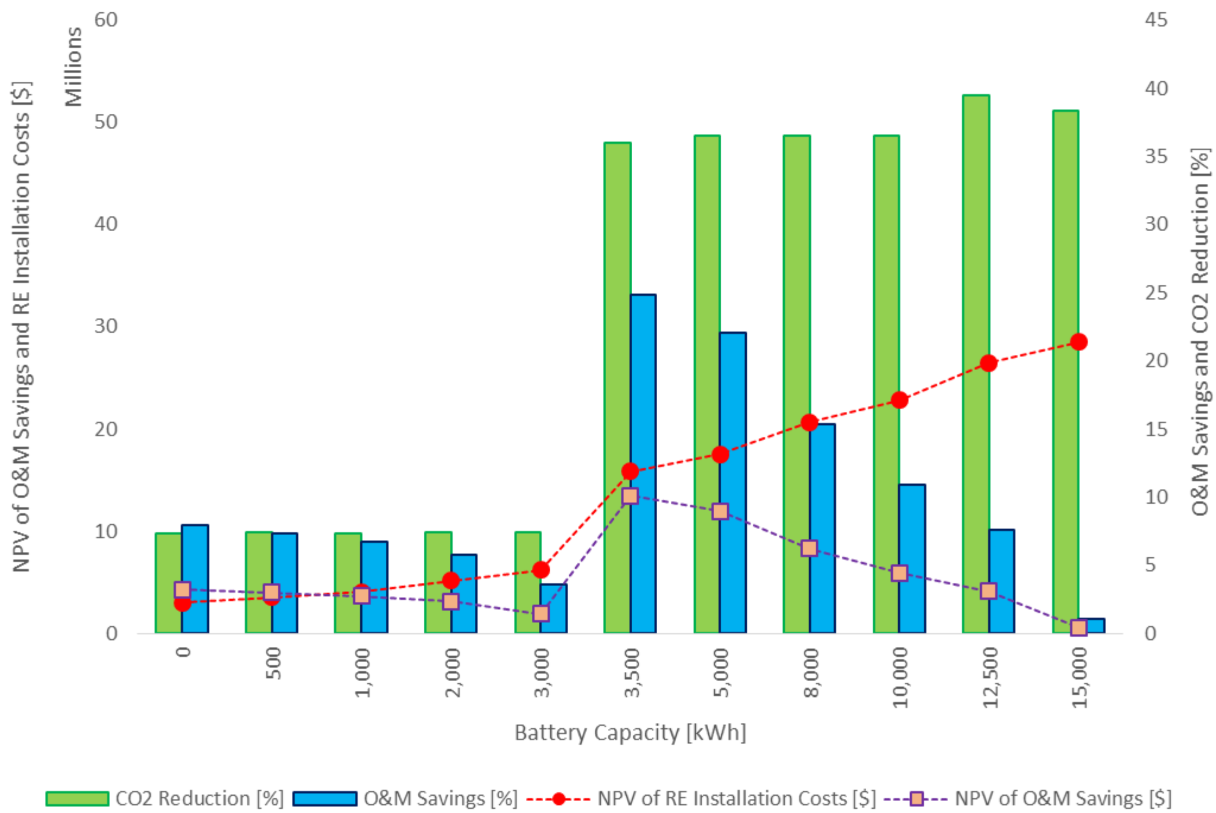

Figure 26: O&M savings, RE installation costs, and CO_2 reductions versus battery capacity for Baker Lake, Nunavut.

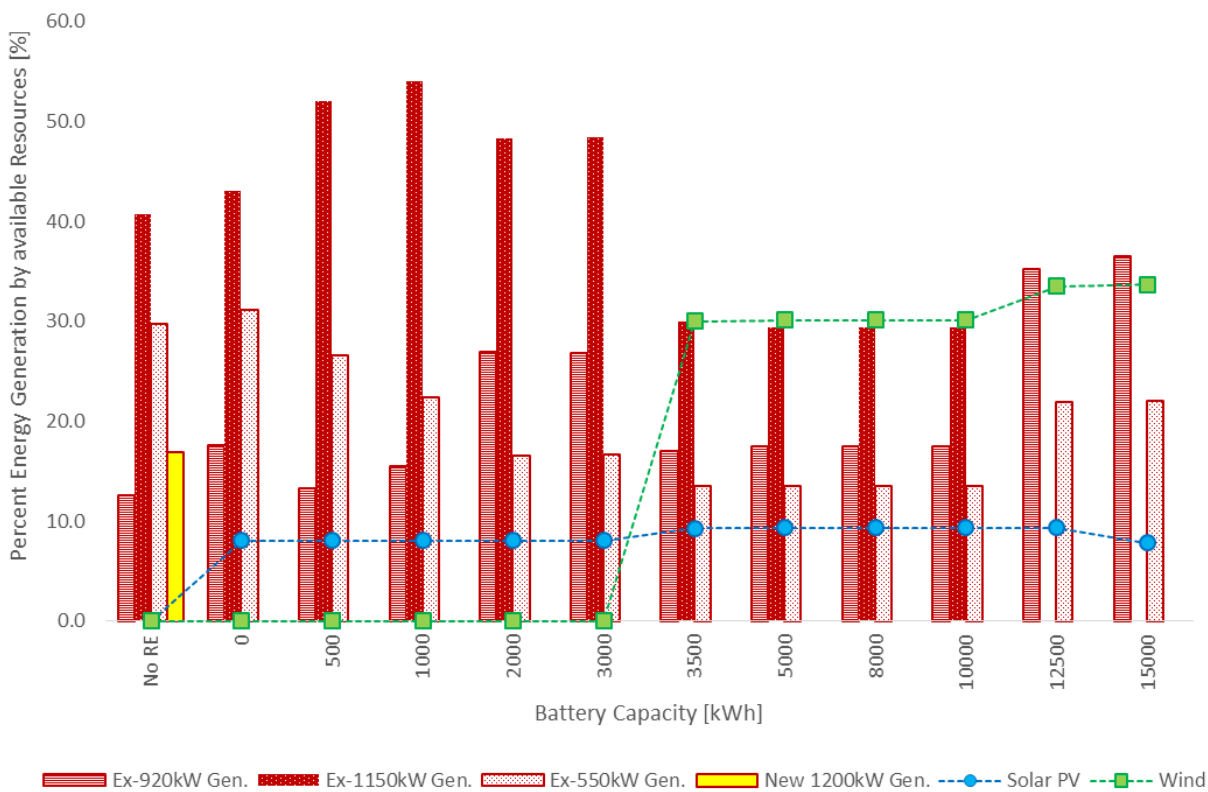

Figure 27: Percentage share of energy generation by diesel generators and RE sources versus battery capacity for Baker Lake, Nunavut.

A.5 Arviat, NU

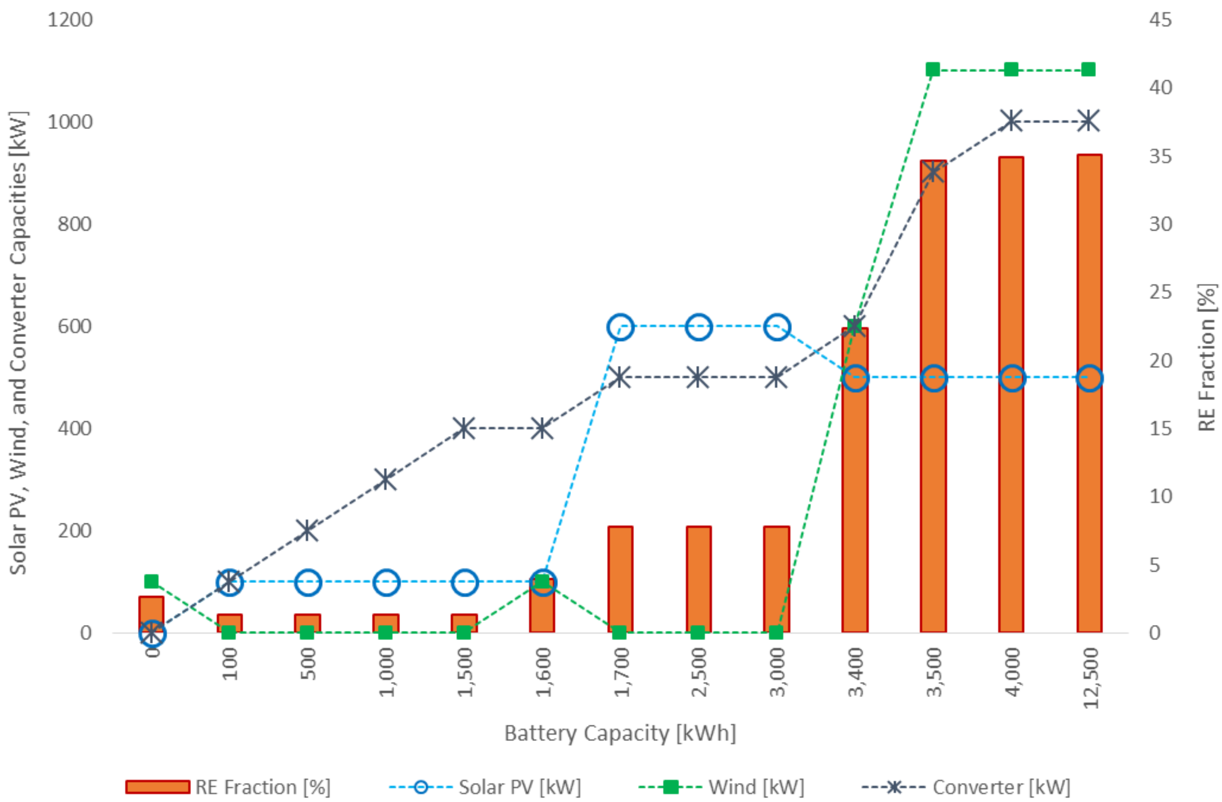

Figure 28: Solar, wind, and converter capacities versus battery capacity for Arviat, Nunavut.

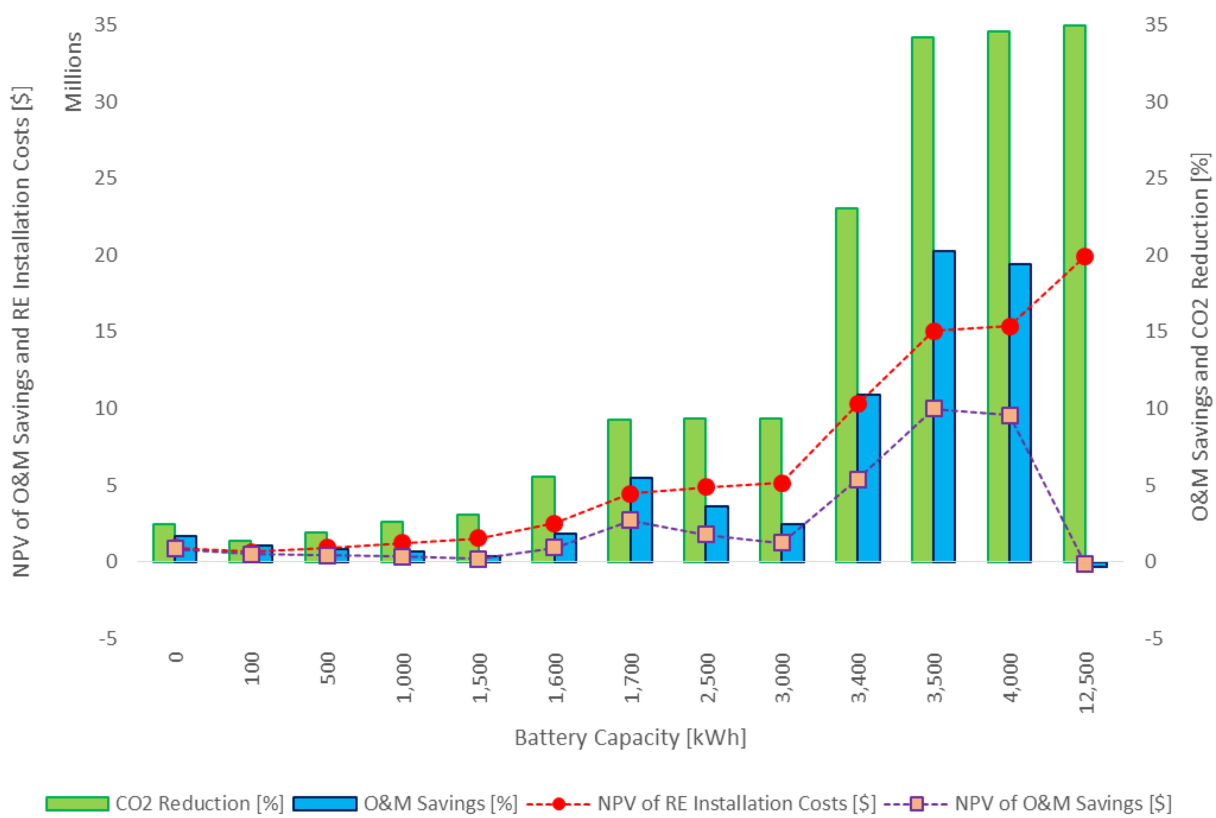

Figure 29: O&M savings, RE installation costs, and CO_2 reductions versus battery capacity for Arviat, Nunavut.

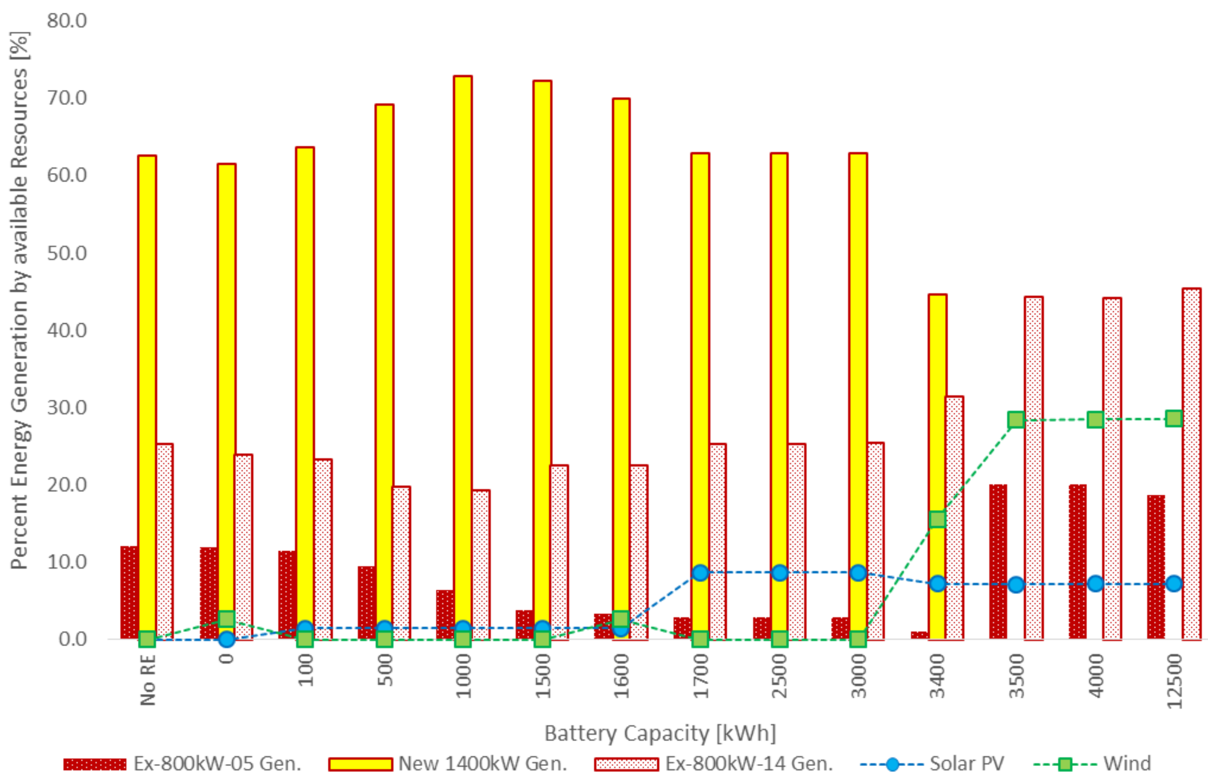

Figure 30: Percentage share of energy generation by diesel generators and RE sources versus battery capacity for Arviat, Nunavut.

REFERENCES

[1] Inuit Tapirit Kanatami. [Online]. Available: https://www.itk.ca/about-inuit/inuit-regions-canada

[2] Open Government Licence, Govt. of Canada. [Online]. Available: http://open.canada.ca/en/open-government-licence-canada

[3] M. Jeffries, J. Richter-Menge, and J. E. Overland, "Arctic Report Card: Update for 2015," Tech. Rep., 2015. [Online]. Available: http://www.arctic.noaa.gov/reportcard

[4] Nunavut's power generators need replacing, says Senate report. Canadian Broadcasting Corporation (CBC) News. [Online]. Available: http://www.cbc.ca/news/canada/north/nunavut-s-power-generators-need-replacing-says-senate-report-1.3119766

[5] HOMER Energy LLC. [Online]. Available: http://www.homerenergy.com/

[6] Explore Nunavut. [Online]. Available: http://www.explorenunavut.com/index.php

[7] Distance Calculator from Globefeed.com. [Online]. Available: http://distancecalculator.globefeed.com/Canada_Distance_Calculator.asp

[8] Domestic Cargo Rates by Community: First Air. [Online]. Available: https://firstair.ca/flying/tariffs/domestic-cargo-rates/

[9] Calm Air Cargo Rates eff. 01 May 2015. [Online]. Available: http://www.calmair.com/pdf_files/CalmAir_CargoRates_Effective_May_1_2015.pdf

[10] Kivalliq Air. [Online]. Available: http://www.kivalliqair.com/

[11] Skyward Aviation. [Online]. Available: http://www.skywardaviation.com/index.php

[12] The NEAS Group. [Online]. Available: http://www.neas.ca/pdf/freight_nunavut.pdf

[13] Nunavut Sealink and Supply Inc. [Online]. Available: http://www.arcticsealift.com/subsections/987/nunavut-rates-and-conditions.html

[14] Northern Transportation Company Limited. [Online]. Available: http://www.ntcl.com/

[15] Community Information, Department of Executive and Intergovernmental Affairs, Government of Nunavut. [Online]. Available: http://www.gov.nu.ca/eia/information/community-information

[16] Population Data, Nunavut Bureau of Staistics. [Online]. Available: http://www.stats.gov.nu.ca/en/Population.aspx

[17] Individual Factsheets: Nunavut Housing Needs Survey (NHNS). [Online]. Available: http://www.stats.gov.nu.ca/en/factsheets.aspx

[18] Qulliq Energy Corporation. [Online]. Available: http://www.qec.nu.ca/home/

[19] IKUMMATIIT: Energy Secretariat, Department of Economic Development and Transportation, Government of Nunavut. [Online]. Available: http://www.nunavutenergy.ca/communities

[20] Photovoltaic and Solar Resource Maps: Natural Resources Canada. [Online]. Available: https://pv.nrcan.gc.ca/

[21] Wind Atlas Canada: EOLE Wind Energy Project, Environment Canada. [Online]. Available: https://www.windatlas.ca/en/maps.php

[22] Wateroffice, Government of Canada. [Online]. Available: https://wateroffice.ec.gc.ca/

[23] "Ageing power plants a worry: Opportunities North," Northern News Services Online, June 2015. [Online]. Available: http://www.nnsl.com/business/pdfs/OPPS/oppsB_power.pdf

[24] Kenn Borek Air. [Online]. Available: http://www.borekair.com/about-us.php

[25] Air Inuit. [Online]. Available: http://www.airinuit.com/

[26] Climate Grise Fiord Airport. Meteoblue. [Online]. Available: https://www.meteoblue.com/en/weather/forecast/modelclimate/grise-fiord-airport_canada_6295841

[27] Omar Hafez, "Some Aspects of Microgrid Planning and Optimal Distribution Operation in the Presence of Electric Vehicles," Master's thesis, University of Waterloo, 2011.

[28] (2014) Levelized Cost of Energy Analysis. Lazard. [Online]. Available: https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf

[29] Prices, Tariffs, and Transit Times. Canadian National Railway Company. [Online]. Available: https://ecprod.cn.ca/velocity/POWCarloadFrontend/public/english/GetCarloadPrice?s_icid=CarloadPrice-feature-rght-getcarloadprice

[30] Canadian Solar. [Online]. Available: http://www.canadiansolar.com/

[31] Mariano Arriaga Marín, "Long-Term Renewable Energy Generation Planning for Off-grid Remote Communities," Ph.D. dissertation, University of Waterloo, 2015.

[32] Canadian Weather Energy and Engineering Datasets, Govt. of Canada. [Online]. Available: ftp://ftp.tor.ec.gc.ca/Pub/Engineering_Climate_Dataset/Canadian_Weather_Energy_Engineering_Dataset_CWEEDS_2005/ZIPPED%20FILES/ENGLISH/

[33] NASA Surface meteorology and Solar Energy. [Online]. Available: https://eosweb.larc.nasa.gov/cgi-bin/sse/homer.cgi?email=skip@larc.nasa.gov

[34] Environment and Climate Change, Govt. of Canada. [Online]. Available: http://climate.weather.gc.ca/index_e.html#access