FEASIBILITY STUDIES OF VARIABLE SPEED GENERATORS FOR CANADIAN ARCTIC COMMUNITIES

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Waterloo, Ontario, Canada, 2017

Executive Summary

Climate change is significant in the arctic regions of the world, causing environmental degradation, which consequently is destroying the habitat of the wildlife present there. A previous study of the Canadian regions of the arctic, commissioned by World Wildlife Fund (WWF) Canada and performed by the Waterloo Institute for Sustainable Energy (WISE) of the University of Waterloo, focused on determining the techno-economic feasibility of renewable energy (RE) integration. This study was performed for 5 communities of Nunavut and 1 from Northwest territories (NWT), which were selected through a pre-feasibility study performed on the region's 33 communities, 25 of which belong to the territory of Nunavut and 8 belonging to the Inuvik region of NWT. In these 6 communities, diesel generators are the only means to generate electricity, with this fossil-fuel not only adding to the carbon footprint, but also endangering the environment by elevating the risk of oil spills while transporting and storing it, as well as generating black carbon or soot, which has particularly negative impacts on arctic snow and ice. Moreover, the dependency on this fuel and its associated costs are an economic problem in the North, as governments subsidize it.

In order to reduce the diesel dependency, the previous study looked into developing business cases for diesel generator replacement with RE deployment, particularly of solar and wind, in these 6 communities, as this is both environmentally friendly and economic. The previous feasibility study was performed using an existing and tested optimization framework for optimum RE integration. Thus, a mathematical optimization model for RE integration and long-term planning, based on a long-term Generation Expansion Planning (GEP) approach, was developed; the model was built as a Mixed Integer Linear Programming (MILP) problem in the General Algebraic Modeling System (GAMS) environment, and was solved using the well established CPLEX solver from IBM. The study considered detailed parameters in its model, such as the diesel generator fuel curves, wind turbine power curves, and the capacity of RE equipment for various proper vendors, adequate forecast of demand for the planning horizon, wind speed, and solar radiation for the different locations. The optimization model considered a broad RE search space of 6 different wind turbines and 2 solar panels from various manufacturers, as well as a wide range of diesel generators to replace those at the end of their useful life.

In the present feasibility studies, the variable speed generator (VSG) developed by Innovus Power is considered, as the generator has unique fuel consumption characteristics and the ability to run at very low loading conditions of around 10% of its rated capacity; it also provides through its "PowerBridge" fast start up capability and a dump load to facilitate RE integration, as demonstrated by the results presented in this report. Therefore, this document presents a feasibility study considering Innovus' VSGs for the 6 selected arctic communities studied in the WWF report, to analyze the impact of this VSG's unique characteristics in the deployment of RE and diesel consumption in these communities. This is accomplished by incorporating in the optimization model used in the WWF study a model of the VSG, considering its fuel consumption and low loadability properties, as well as its PowerBridge. Simulations were performed to determine optimal RE deployment with VSGs replacing the new and/or fixed speed generators (FSG). The obtained results demonstrate the overall positive impact of the VSGs in costs and fuel consumptions, and show an increase in RE penetration and thus green-house gas (GHG) reductions with respect to the WWF feasibility results. The impact of VSG introduction in the 6 communities can be summarized as follows for each community:

1. The highest annual average RE penetration level obtained was 97.93% for the community of Arviat for the VSG-wind-solar hybrid model with PowerBridge, resulting in about 89% reduction in GHG emissions and fuel savings of $ 29.91 million (82.92% savings with respect to Business-as-Usual (BAU) costs) over a 20 year period.

2. The community of Sanikiluaq results show an annual average RE penetration of 93.19% for the VSG-solar-wind hybrid model with PowerBridge, with fuel savings of $ 20.24 million (79.25% savings with respect to BAU costs) in 20 years, and a reduction of GHG emissions of about 84.75%.

3. The results obtained for Rankin Inlet show an annual average RE penetration of 78.3% for the VSG-solar-wind hybrid model with PowerBridge, with 71.02% reduction in GHG emissions, and fuel savings of $ 63.26 million (68.85% savings with respect to BAU costs) over a 20-year horizon.

4. For Baker Lake, the results show an annual average RE penetration of 65.83% for the VSG-wind hybrid model with PowerBridge, with $ 25.04 million (60.06% savings with respect to BAU costs) in fuel savings in 20 years, and a reduction in GHG emissions of 59.68%.

5. For the community of Iqaluit, the simulations of VSGs, with or without PowerBridge, replacing all existing FSGs did not converge, given the large search space of VSGs (a minimum of 21 units) to completely replace all FSGs of the system, due to the available capacity of VSGs vis-á-vis the large capacity of existing FSGs. In this community, the diesel-wind-battery hybrid model, with VSGs without PowerBridge introduced as new

diesel generator purchases, is the best option, resulting in an annual average RE penetration of 31.82% and GHG reduction of 35.19%, with the highest fuel savings for all communities at $ 108.94 million over a 20-year period, which corresponds to 52.85% savings with respect to the BAU costs.

6. For Sachs Harbour, the VSG-wind hybrid model with PowerBridge yields the best results, with an annual average RE penetration and GHG reduction of 72.46% and 65.78%, respectively, and fuel savings of $ 3.27 million over a 20-year period, which corresponds to 62.40% savings with respect to the BAU costs.

The simulation results indicate that the deployment of VSGs in RE-diesel hybrid systems in any of the studied communities will always economically reduce the consumption of diesel. It can also be observed that, in general, with the introduction of VSGs with PowerBridge, there is no need for batteries. The results of this study show that adding VSGs in the generation portfolios for the communities studied can result in substantial reductions in GHG emissions, ranging from 59.68% to 89%, with annual average penetrations of RE from 31.82% to 97.93%, and a range of fuel savings of $ 3.27 million to $ 108.94 million over a 20-year period. Based on these results, projects deploying VSGs with PowerBridge should be pursued for Arviat and Sanikiluaq, and if possible, for Sachs Harbour and Rankin Inlet.

Acknowledgement

The authors would like to acknowledge all the support provided by Paul Pauze and Mark Preston from Innovus Power to successfully complete the work reported here.

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GLOSSARY

BAU	Business-as-Usual
CN	Canadian National railway
CWEEDS	Canadian Weather Energy and Engineering Datasets
DoD	Depth of Discharge
EWT	Emergya Wind Technologies
FSG	Fixed speed generator
GAMS	General Algebraic Modeling System
GEP	Generation Expansion Planning
GHG	Green-house Gas
ISR	Inuvialuit Settlement Region
MILP	Mixed Integer Linear Programming
NOAA	National Oceanic and Atmospheric Administration
NPC	Net Present Cost
NTPC	Northwest Territories Power Corporation
NWT	Northwest Territories
O&M	Operation & Maintenance
QEC	Qulliq Energy Corporation
RE	Renewable Energy
SOC	State of Charge
STC	Standard Testing Condition
VSG	Variable speed generator
WISE	Waterloo Institute for Sustainable Energy
WWF	World Wildlife Fund

Nomenclature

Indices

e_D	Existing diesel generators of different capacities and manufacturers
h	Hour
y	Year
n_B	New batteries from different manufacturers
n_V	New VSGs with capacities of 590 kW each
n_S	New solar panel sets from different manufacturers
n_W	New wind turbines of different capacities and manufacturers

Functions

$f(\cdot)$	General objective function
$F(\cdot)$	Fuel consumption curve of diesel generator
$g(\cdot)$	Inequality constraints
$h(\cdot)$	Equality constraints
$W(\cdot)$	Wind turbine power curve

Parameters

Cap^{FSG}	Existing diesel capacity including stand-by mode units [kW]
d	Discount rate [pu]
$Dcost$	Diesel cost [$/L]
df	Derating factor of solar PV panels [pu]
DoD^{Bat}	Depth-of-discharge (DOD) of a battery [pu]
GH^{life}	Useful life of new diesel generator [h]
GH^{remain}	Remaining life of existing diesel generator [h]
GT^{STC}	Incident solar radiation on the PV array at standard test conditions [kW/m^2]
HOM^{Bat}	Hourly O&M costs of battery [$/kWh]
HOM^{FSG}	Hourly Operation and Maintenance (O&M) costs of existing diesel generator [$/kWh]
HOM^{PB}	Hourly O&M costs of PowerBrdige [$/kWh]
HOM^{Sol}	Hourly O&M costs of solar panel set [$/kWh]
HOM^{VSG}	Hourly O&M costs of new diesel generator [$/kWh]
HOM^{Wnd}	Hourly O&M costs of wind turbine [$/kWh]
HY	Hours in a year (model specific) [h]
M	A very large number
ML^{FSG}	Minimum load operation of existing diesel generator [pu]
ML^{VSG}	Minimum load operation of new diesel generator [pu]

Nb	Number of batteries considered
NG	Number of new diesel generator (VSG) considered
NF	Number of existing diesel generator (FSG) considered
Ns	Number of solar panel sets considered
Nw	Number of wind turbines considered
p	Auxiliary set of parameters
PD	Power demand [kW]
PH	Project horizon [yr.]
SI	Solar insolation [kW/m^2]
T^{Dch}	Time duration a battery can discharge continuously at a fixed power [h]
T^{OM}	Percentage of hours per annum scheduled for maintenance [pu]
$Tcell$	Solar PV cell temperature in the current time step [°C]
$Tcell^{STC}$	Solar PV cell temperature under standard test conditions [°C]
UC^{Bat}	Unit cost of new batteries [$/kWh]
UC^{PB}	Unit cost of new PowerBridge module [$]
UC^{Sol}	Unit cost of solar panel sets [$/kW]
UC^{VSG}	Unit cost of new diesel generators [$/kW]
UC^{Wnd}	Unit cost of wind turbines [$/kW]
$Ucap^{Bat}$	Capacity of battery set [kWh]
$Ucap^{Sol}$	Capacity of solar panel set [kW]
$Ucap^{VSG}$	Capacity of new diesel generator unit [kW]
$Ucap^{Wnd}$	Capacity of wind turbine [kW]
WS	Wind speed [m/s]
α	Temperature coefficient of power for Solar PV panels [pu/°C]
β	Generation reserve margin [pu], assumed 10%
γ	Solar generation reliability co-efficient [pu], assumed 25%
ρ	Wind generation reliability coefficient [pu], assumed 50%
η^{Ch}	Efficiency of battery charging [pu]
η^{Dch}	Efficiency of battery discharging [pu]

Variables

Cap^{Bat}	Aggregate capacity of battery [kWh]
Cap^{Sol}	Aggregate capacity of solar PV [kW]
Cap^{VSG}	Aggregate capacity of new diesel generators [kW]
Cap^{Wnd}	Aggregate capacity of wind [kW]
$Capu^{VSG}$	Dummy variable to linearize a product [kW]
CC^{Bat}	Net present value (NPV) of battery capital cost [$]
CC^{PB}	NPV of total capital costs of purchasing PowerBridge [$]

CC^{Sol}	NPV of solar PV capital cost [$]
CC^{VSG}	NPV of total capital costs of purchasing new VSG [$]
CC^{Wnd}	NPV of wind capital cost [$]
DL^{PB}	Dump load using PowerBridge [kW]
FC^{FSG}	NPV of diesel fuel cost for FSGs [$]
FC^{VSG}	NPV of diesel fuel cost for VSGs [$]
$Fcon^{FSG}$	Hourly fuel consumption rate of existing diesel generators [L/kWh]
$Fcon^{VSG}$	Hourly fuel consumption rate of new diesel generators [L/kWh]
NCA^{Bat}	New capacity addition of battery [kW]
NCA^{Sol}	New capacity addition of solar PV [kW]
NCA^{VSG}	New capacity addition of diesel [kW]
NCA^{Wnd}	New capacity addition of wind [kW]
OMC^{Bat}	NPV of battery O&M cost [$]
OMC^{FSG}	NPV of total diesel O&M cost for FSGs [$]
OMC^{PB}	NPV of total O&M cost for PowerBridge [$]
OMC^{Sol}	NPV of solar PV O&M cost [$]
OMC^{VSG}	NPV of total diesel O&M cost for VSGs [$]
OMC^{Wnd}	NPV of wind O&M cost [$]
Pb^{Ch}	Battery charging power [kW]
Pb^{Dch}	Battery discharging power [kW]
Pd^{FSG}	Power generated by existing diesel generator [kW]
Pd^{VSG}	Power generated by new diesel generator [kW]
Ps^{Sol}	Power generated by solar PV [kW]
Pw^{Wnd}	Power generated by wind [kW]
SOC	Battery state-of-charge [kWh]
u^{BatPur}	Binary variable to denote purchase of battery
u^{Ch}	Binary variable to denote ON/OFF state of battery charging
u^{Dch}	Binary variable to denote ON/OFF state of battery discharging
u^{FSGop}	Binary variable to denote existing diesel generator ON/OFF state
u^{SolPur}	Binary variable to denote purchase of solar PV
u^{VSGop}	Binary variable to denote new diesel generator ON/OFF state
u^{VSGpur}	Binary variable to denote purchase of new diesel generator
u^{WndPur}	Binary variable to denote purchase of wind
x	Optimization variables
x_1, x_2, q, q_1, q_2	Auxiliary variables

1 Introduction

It is well documented that the gradually diminishing ice cover of the arctic sea due to increased temperatures, caused by climate change, is posing a threat to the wildlife in Arctic Canada. 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 [1].

The Canadian Arctic 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 the NWT and a small part of Yukon (see Figure 1). The latter, called the Inuvialuit Settlement Region (ISR), consists of 6 communities, and, along with Fort McPherson and Tsiigehtchic in the NWT, form the Inuvik Region.

A pre-feasibility study was undertaken to select the communities for detailed feasibility studies [3], which started with a pre-selection of the aforementioned 33 communities, based on certain parameters, to reduce the number of the communities to the most promising locations from the renewable energy (RE) integration perspective. The results of this pre-feasibility study

Figure 1: Canadian Arctic [2] (used with permission from Inuit Tapirit Kanatami).

Figure 2: Locations of the 6 selected communities for feasibility study.

yielded the selection of 5 communities in Nunavut and 1 in NWT, shown in Figure 2, for detailed RE integration feasibility studies [4]. These 6 communities are considered in the present study for introducing variable speed generators (VSGs), which have unique loadability and fuel consumption characteristics. Thus, results of incorporating VSGs, along with RE and fixed speed generator (FSG) power supply systems, in the considered communities are presented in this report.

All the communities considered in this study currently use only diesel for electricity generation, resulting in emission that are increasing the ill-effect of climate change in the region. Of particular concern is the emission of black carbon or soot, which when deposited on snow and ice, darkens the surface and thereby enhances the absorption of solar radiation and consequently increases the melt rates [5]. Moreover, the remoteness of these communities requires that fuel be transported by sea-barges and locally stored in storage tanks, and thus the cost of transporting diesel to all these remote communities is considerably high, plus there is a risk for oil spills, which can result in extensive damage to the arctic environment.

All the aforementioned factors, coupled with the fact that these communities, particularly the ones in Nunavut, have old diesel generators in operation that require replacement [6], is motivating the need to consider sources of electricity generation. RE sources, mainly solar and wind, are of particular interest for these communities, since well-designed RE implementation plans have the potential for positive socio-economic-environmental effects. Making business cases for the deployment of RE generation was the ultimate objective of the studies carried out for the WWF [4], while the present study focuses on analyzing the impact of VSGs on the proposed RE implementation plans for these communities.

1.1 Objectives

The primary objective of the present study is to displace diesel fuel by incorporating wind and solar plants along with VSG units, so that local grids can be cleanly and securely operated, as required by utility standards, at similar or even reduced costs than with the current diesel FSG only systems. This is accomplished by:

- Applying an existing feasibility study framework utilizing developed mathematical optimization models for long-term planning analyses for the integration of RE in the studied communities.
- Gathering and processing detailed specifications of various RE equipment, FSGs, VSGs, and demand, solar, wind, and temperature data to build a search space for the planning model.
- Presenting, analyzing and comparing long-term planning results to make suitable business cases for each community.

1.2 Content

The rest of this report is divided in 3 sections. Thus, Section 2 discusses the optimal RE integration model with VSGs replacing FSGs, explaining in detail the optimization framework and the developed mathematical model; it also contains a description of the input data needed for the model search space. Section 3 presents the community-wise results of the feasibility studies that consider VSGs in the optimal RE integration plan, along with observations, comparisons, and analyses of the planning results. The techno-economic optimization analyses to make business cases are based on the principle that the Net Present Cost (NPC) of the multi-year project should be less than or equal to the NPC of running the system on only FSGs over the same time period. Section 4 provides the conclusions of the study, and recommends the RE plans and VSG introduction strategy that could be implemented in the various considered communities as possible projects.

2 Optimal RE Integration Plan

The long-term planning approach for integration of RE described in this report is based on a GEP approach [7], with a suitable modified optimization framework. The optimization framework in Figure 3 [4], based on the approach proposed for northern communities in Ontario [8], was used to build the planning model for the feasibility study, considering VSGs as the new diesel generators.

A multi-time-step mathematical optimization model is chosen here, incorporating various techno-economic considerations related to the integration of RE in diesel-based communities, to determine the optimal plan for suitable RE deployment, with VSGs as diesel generation options. The mathematical model is comprised of a cost-minimization objective function, that includes both existing and replacement diesel portfolios along with RE capital and operation and maintenance (O&M) costs, plus a set of suitable constraints associated with the equipment purchase plan and operating technical restrictions, including the secure hourly operation of the community

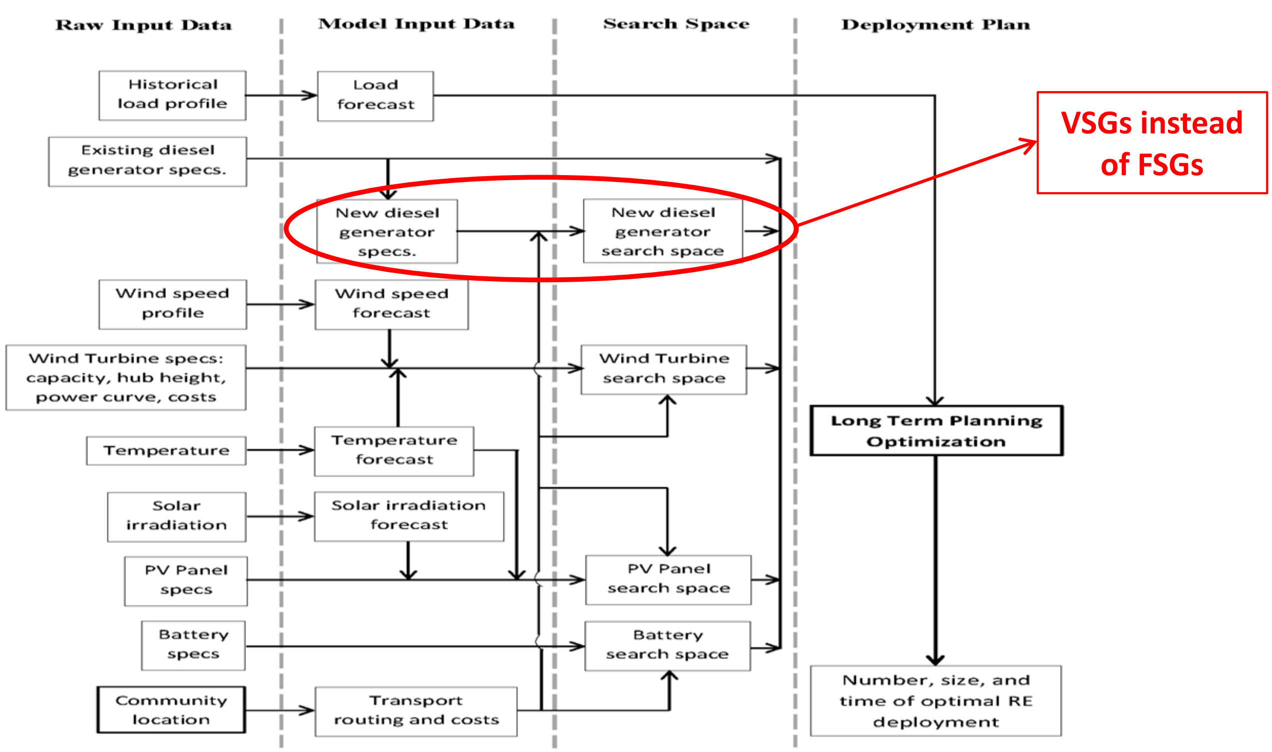


Figure 3: Optimization framework used for introducing VSGs in the presented feasibility studies.

grids.

2.1 Mathematical Model

Mathematical optimization is a technique to determine the best outcome (such as maximum profit or least cost) for a given mathematical model, satisfying a list of constraints represented by linear/non-linear relationships. This is performed by solving the following optimization problem:

$$\min_{x} \quad f(x, p) \tag{1}$$

$$\text{s.t.} \quad h(x, p) = 0 \tag{2}$$

$$g(x, p) \leq 0 \tag{3}$$

where $f(\cdot)$ is the objective function; $h(\cdot)$ and $g(\cdot)$ are the sets of equality and inequality constraints, respectively; x is the set of variables to be optimized, and p is a set of parameters. If at least one of the equations is non-linear, then this is a non-linear optimization problem, otherwise it is a linear problem. On the other hand, if all the variables in x are binaries or integers, the problem is an Integer Programming problem, and if some variables are continuous, whether bounded or unbounded, then the problem becomes an MILP problem. Thus, the mathematical model for the present microgrid planning problem is an MILP problem, since the variables associated with the hourly on/off status of the diesel generators, the unit purchase status for both diesel and RE equipment, and the charging and discharging status of batteries are binary in nature, while all other variables, such as generation power output and battery state-of-charge (SOC), are continuous variables.

2.1.1 Optimization Objective

The objective function of the proposed optimization model reflects the sum of total discounted costs, i.e., the NPC, of operating existing diesel equipment along with the purchase and operation of new VSG and RE equipment, as follows:

$$\begin{aligned} Z = & \underbrace{FC^{FSG} + OMC^{FSG}}_{FSG} + \underbrace{CC^{Sol} + OMC^{Sol}}_{Solar} + \underbrace{CC^{Wnd} + OMC^{Wnd}}_{Wind} \\ & + \underbrace{CC^{Bat} + OMC^{Bat}}_{Battery} + \underbrace{CC^{VSG} + FC^{VSG} + OMC^{VSG}}_{VSG} \end{aligned} \tag{4}$$

where the various parts of the equation represent the total costs of the different types of equipment considered. The notation used in this equation and all others in this document are defined in the

Nomenclature section at the beginning of the document.

The capital costs of VSG, solar, wind, and battery equipment are given by:

$$CC^{VSG} = \sum_{y=1}^{PH} \frac{\sum_{n_V=1}^{NG} UC^{VSG} \left(\sum_{h=1}^{HY} NCA_{n_V,y,h}^{VSG} \right)}{(1+d)^{y-1}} \tag{5a}$$

$$CC^{Sol} = \sum_{y=1}^{PH} \frac{\sum_{n_S=1}^{Ns} UC_{n_S}^{Sol} \left(\sum_{h=1}^{HY} NCA_{n_S,y,h}^{Sol} \right)}{(1+d)^{y-1}} \tag{5b}$$

$$CC^{Wnd} = \sum_{y=1}^{PH} \frac{\sum_{n_W=1}^{Nw} UC_{n_W}^{Wnd} \left(\sum_{h=1}^{HY} NCA_{n_W,y,h}^{Wnd} \right)}{(1+d)^{y-1}} \tag{5c}$$

$$CC^{Bat} = \sum_{y=1}^{PH} \frac{\sum_{n_B=1}^{Nb} UC_{n_B}^{Bat} \left(\sum_{h=1}^{HY} NCA_{n_B,y,h}^{Bat} \right)}{(1+d)^{y-1}} \tag{5d}$$

And the cost associated with the O&M of both existing FSGs and new VSGs are given by:

$$OMC^{FSG} = \sum_{y=1}^{PH} \frac{\sum_{h=1}^{HY} 30 \left(\sum_{e_D=1}^{Ned} HOM_{e_D}^{FSG} \; Pd_{e_D,y,h}^{FSG} \right)}{(1+d)^{y-1}} \tag{6}$$

$$OMC^{VSG} = \sum_{y=1}^{PH} \frac{\sum_{h=1}^{HY} 30 \left(\sum_{n_V=1}^{NG} HOM^{VSG} \; Pd_{n_V,y,h}^{VSG} \right)}{(1+d)^{y-1}} \tag{7}$$

where the factor 30 is associated with the time-step management of the project horizon as follows: The project horizon is $PH = 20$ years, with an hourly time-step for an average day of each month being used, which results in a total of $HY = 288$ hours in an average year. Hence, considering the averaging over a month, the factor of 30 is used, assuming 30 days in each month. The O&M costs of solar, wind and battery are given by the following expressions, respectively:

$$OMC^{Sol} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{n_S=1}^{Ns} HOM_{n_S}^{Sol} \; Cap_{n_S,y,h}^{Sol}}{(1+d)^{y-1}} \tag{8}$$

$$OMC^{Wnd} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{n_W=1}^{Nw} HOM_{n_W}^{Wnd} \, Cap_{n_W,y,h}^{Wnd}}{(1+d)^{y-1}} \tag{9}$$

$$OMC^{Bat} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{n_B=1}^{Nb} HOM_{n_B}^{Bat} \, Cap_{n_B,y,h}^{Bat}}{(1+d)^{y-1}} \tag{10}$$

The fuel cost associated with diesel generators is determined by computing the fuel consumption of individual generators from their respective fuel curves, and is given by:

$$FC^{FSG} = \sum_{y=1}^{PH} \frac{Dcost \sum_{h=1}^{HY} 30 \left(\sum_{e_D=1}^{Ned} Fcon_{e_D,y,h}^{FSG} \right)}{(1+d)^{y-1}} \tag{11}$$

$$FC^{VSG} = \sum_{y=1}^{PH} \frac{Dcost \sum_{h=1}^{HY} 30 \left(\sum_{n_V=1}^{NG} Fcon_{n_{VSG},y,h}^{VSG} \right)}{(1+d)^{y-1}} \tag{12}$$

where

$$Fcon_{e_D,y,h}^{FSG} = F_{e_D} \left(Pd_{e_D,y,h}^{FSG}, \; u_{e_D,y,h}^{FSGop} \right) \tag{13a}$$

$$Fcon_{n_V,y,h}^{VSG} = F^{VSG} \left(Pd_{n_V,y,h}^{VSG}, \; u_{n_V,y,h}^{VSGop} \right) \tag{13b}$$

denotes the fuel consumption of each existing FSGs and new VSGs based on their individual fuel consumption curves. The fuel curves are non-linear in nature, and thus these are made piece-wise linear here by using three data points of fuel consumption: at 100%, 85 % or 75% (depending on the manufacturer), and 50% of rated capacity for FSGs; and 100%, 50%, and 10% for VSGs.

2.1.2 Constraints

Supply-Demand Balance and Generation Adequacy Limit

The two most important operation and planning constraints are the supply-demand-balance and generation-adequacy. The first constraint matches the demand and supply of electrical energy at every time step, as follows:

$$\underbrace{\sum_{e_D=1}^{Ned} Pd^{FSG}_{e_D,y,h}}_{FSG} + \underbrace{\sum_{n_S=1}^{Ns} Ps^{Sol}_{n_S,y,h}}_{Solar} + \underbrace{\sum_{n_W=1}^{Nw} Pw^{Wnd}_{n_W,y,h}}_{Wind} + \underbrace{\sum_{n_B=1}^{Nb} \left(Pw^{Dch}_{n_B,y,h} - Pw^{Ch}_{n_B,y,h}\right)}_{Battery} + \underbrace{\sum_{n_V=1}^{NG} Pd^{VSG}_{n_V,y,h}}_{VSG} = PD_{y,h} \quad (14)$$

The second constraint represents the operating reserve in the system, based on the load at every time step of operation and the amount of intermittent generation from solar and wind, thus guaranteeing supply reliability, as follows:

$$\underbrace{\sum_{e_D=1}^{Ned} Cap^{FSG}_{e_D,y}}_{FSG} + \underbrace{\sum_{n_B=1}^{Nb} SOC_{n_B,y,h}}_{Battery} + \underbrace{\sum_{n_V=1}^{NG} Cap^{VSG}_{n_V,y,h}}_{VSG} \geq (1+\beta)PD_{y,h} + \gamma \underbrace{\sum_{n_S=1}^{Ns} Ps^{Sol}_{n_S,y,h}}_{Solar} + \rho \underbrace{\sum_{n_W=1}^{Nw} Pw^{Wnd}_{n_W,y,h}}_{Wind} \quad (15)$$

It should be mentioned that this equation is used for the studies where FSGs are replaced with VSGs at their end-of-life, and all new diesel generation required is supplied by VSGs.

Dynamic Addition of New Capacity

The commissioning of new VSG and RE capacity at a specified hour in the planning horizon is dynamically added to the generation portfolio using the following expressions for VSG, solar, wind, and battery, respectively:

$$Cap^{VSG}_{n_V,y,h+1} = Cap^{VSG}_{n_V,y,h} + NCA^{VSG}_{n_V,y,h} \quad (16)$$
$$Cap^{Sol}_{n_S,y,h+1} = Cap^{Sol}_{n_S,y,h} + NCA^{Sol}_{n_S,y,h} \quad (17)$$
$$Cap^{Wnd}_{n_W,y,h+1} = Cap^{Wnd}_{n_W,y,h} + NCA^{Wnd}_{n_W,y,h} \quad (18)$$
$$Cap^{Bat}_{n_B,y,h+1} = Cap^{Bat}_{n_B,y,h} + NCA^{Bat}_{n_B,y,h} \quad (19)$$

and, to sequentialize the hour and year indices:

$$Cap^{VSG}_{n_V,y+1,1} = Cap^{VSG}_{n_V,y,HY} + NCA^{VSG}_{n_V,y,HY} \quad (20)$$
$$Cap^{Sol}_{n_S,y+1,1} = Cap^{Sol}_{n_S,y,HY} + NCA^{Sol}_{n_S,y,HY} \quad (21)$$
$$Cap^{Wnd}_{n_W,y+1,1} = Cap^{Wnd}_{n_W,y,HY} + NCA^{Wnd}_{n_W,y,HY} \quad (22)$$
$$Cap^{Bat}_{n_B,y+1,1} = Cap^{Bat}_{n_B,y,HY} + NCA^{Bat}_{n_B,y,HY} \quad (23)$$

where the new capacity additions are as follows:

$$NCA^{VSG}_{n_V,y,h} = Ucap^{VSG}_{n_V}\ u^{VSGpur}_{n_V,y,h} \tag{24}$$

$$NCA^{Sol}_{n_S,y,h} = Ucap^{Sol}_{n_S}\ u^{SolPur}_{n_S,y,h} \tag{25}$$

$$NCA^{Wnd}_{n_W,N,h} = Ucap^{Wnd}_{n_W}\ u^{WndPur}_{n_W,y,h} \tag{26}$$

$$NCA^{Bat}_{n_B,N,h} = Ucap^{Bat}_{n_B}\ u^{BatPur}_{n_B,y,h} \tag{27}$$

Note here that addition of new capacity is allowed only in pre-defined windows of the project horizon. Thus, RE additions are allowed in the first 5 years only, to conform with the requirements of the possible projects, while considering the gestation period of individual technologies; for VSGs, the window is from the 3rd to the 10th year for a 20 yr project horizon.

Diesel Generation Limits

The maximum power generation for VSGs is limited by the rated capacity of the diesel generator:

$$Pd^{VSG}_{n_V,y,h} \leq Cap^{VSG}_{n_V,y,h}\ u^{VSGop}_{n_V,y,h} \tag{28}$$

where the right hand side of the expression is non-linear, being the product of a continuous and a binary variable. Therefore, a linearization technique is applied here to keep the model as an MILP [9], based on the following product of two variables:

$$q = x_1 x_2 \tag{29}$$

where x_1 is a bounded positive continuous variable, i.e., $0 \leq x_1 \leq x_1^{Max}$, and x_2 is a binary variable. A set of linear constraints are thus added to force q to take the value of x_1x_2, as follows:

$$q \leq x_1^{\text{Max}} x_2 \tag{30a}$$

$$q \leq x_1 \tag{30b}$$

$$q \geq x_1 - x_1^{\text{Max}}(1 - x_2) \tag{30c}$$

$$q \geq 0 \tag{30d}$$

To implement this method in the planning model, the positive continuous variable is defined as $x_1 = Cap^{VSG}_{n_V,y,h}$, with the upper limit assumed to be $x_1^{Max} = 5\ Ucap^{VSG}_{n_V}$, while the binary variable is defined as $x_2 = u^{VSGop}_{n_v,y,h}$. Thus, a new positive continuous variable is defined as $Capu^{VSG}_{n_V,y,h} = q$, resulting in the following set of equations that linearize and replace (28) in the model:

$$Pd^{VSG}_{n_V,y,h} \leq Capu^{VSG}_{n_V,N,h} \tag{31}$$

$$Capu^{VSG}_{n_V,y,h} \leq 5\ Ucap^{VSG}_{n_V}\ u^{VSGop}_{n_V,y,h} \quad (32)$$
$$Capu^{VSG}_{n_V,y,h} \leq Cap^{VSG}_{n_V,y,h} \quad (33)$$
$$Capu^{VSG}_{n_V,y,h} \geq Cap^{VSG}_{n_V,y,h} - 5\ UCap^{VSG}_{n_V}\left(1 - u^{VSGop}_{n_V,y,h}\right) \quad (34)$$
$$Capu^{VSG}_{n_V,y,h} \geq 0 \quad (35)$$

For existing FSGs, the maximum power generation linear constraint is as follows:

$$Pd^{FSG}_{e_D,y,h} \leq Cap^{FSG}_{e_D,y}\ u^{FSGop}_{e_D,y,h} \quad (36)$$

On the other hand, the following constraints for minimum generation of a diesel generator are incorporated to represent the minimum operating range of the generators:

$$Pd^{VSG}_{n_V,y,h} \geq ML^{VSG}\ Capu^{VSG}_{n_V,y,h} \quad (37)$$
$$Pd^{FSG}_{e_D,y,h} \geq ML^{FSG}_{e_D}\ Cap^{FSG}_{e_D,y}\ u^{FSGop}_{e_D,N,h} \quad (38)$$

Ramping and Turn ON/OFF Constraints and Costs

Given the 1 h time scale used for generation dispatch, these constraints and costs are not necessary in the present model, since the considered diesel units are able to turn ON/OFF in fractions of 1 h.

Diesel Generator Life

The useful life of new VSGs and the remaining life of existing FSGs, in hours, are incorporated in the model using the following two expressions, respectively:

$$\sum_{y=1}^{PH}\sum_{h=1}^{HY} 30\ u^{VSGop}_{n_V,y,h} \leq GH^{life}_{n_V} \quad (39)$$
$$\sum_{y=1}^{PH}\sum_{h=1}^{HY} 30\ u^{FSGop}_{e_D,y,h} \leq GH^{remain}_{e_D} \quad (40)$$

Annual O&M Time Availability

All the diesel generators are to be scheduled for annual maintenance, and thus this constraint is imposed on both existing and new units to make them available for scheduled maintenance:

$$\sum_{h=1}^{HY} u^{FSGop}_{e_D,y,h} \leq 288(1 - T^{OM}) \quad (41)$$

$$\sum_{h=1}^{HY} u_{n_V,y,h}^{VSGop} \leq 288(1 - T^{OM}) \tag{42}$$

PowerBridge Model

The PowerBridge component is integrated with the VSG for studies where FSGs are wholly replaced with VSGs after 2 years, in which case the capital cost is modeled as follows:

$$CC^{PB} = \sum_{y=1}^{PH} \frac{\sum_{n_V=1}^{NG} UC^{PB} \left(\sum_{h=1}^{HY} u_{n_V,y,h}^{VSGpur} \right)}{(1+d)^{y-1}} \tag{43}$$

This component is included in the objective function whenever PowerBridge is considered, replacing batteries, since RE excess energy is assumed to be dumped in the PowerBridge dump load instead of stored in batteries. This modifies equation (4) as follows:

$$\begin{aligned} Z = \underbrace{FC^{FSG} + OMC^{FSG}}_{FSG} + \underbrace{CC^{Sol} + OMC^{Sol}}_{Solar} + \underbrace{CC^{Wnd} + OMC^{Wnd}}_{Wind} \\ + \underbrace{CC^{PB} + OMC^{PB}}_{PowerBridge} + \underbrace{CC^{VSG} + FC^{VSG} + OMC^{VSG}}_{VSG} \end{aligned} \tag{44}$$

where the O&M cost of PowerBridge is given by:

$$OMC^{PB} = \sum_{y=1}^{PH} \frac{\sum_{h=1}^{HY} 30 \left(\sum_{n_V=1}^{NG} HOM^{PB} \, Cap_{n_V,y,h}^{VSG} \right)}{(1+d)^{y-1}} \tag{45}$$

A provision of load dumping is part of the PowerBridge operation, and thus, its inclusion in the system enables excess RE generation to be dumped instead of stored in batteries. This is incorporated in the supply demand balance constraint, i.e., equation (14), as follows:

$$\underbrace{\sum_{e_D=1}^{Ned} Pd_{e_D,y,h}^{FSG}}_{FSG} + \underbrace{\sum_{n_S=1}^{Ns} Ps_{n_S,y,h}^{Sol}}_{Solar} + \underbrace{\sum_{n_W=1}^{Nw} Pw_{n_W,y,h}^{Wnd}}_{Wind} + \underbrace{\sum_{n_V=1}^{NG} Pd_{n_V,y,h}^{VSG}}_{VSG} = PD_{y,h} + \underbrace{\sum_{n_V=1}^{NG} DL_{n_V,y,h}^{PB}}_{PowerBridge} \tag{46a}$$

$$DL_{n_V,y,h}^{PB} \leq Cap_{n_V,y,h}^{VSG} \tag{46b}$$

and the adequacy constraint is also modified to omit the battery and incorporate hourly availability of FSGs, since these genertaors are replaced with VSGs after 2 years in these studies:

$$\underbrace{\sum_{e_D=1}^{Ned} Cap^{FSG}_{e_D,y} u^{FSGop}_{e_D,y,h}}_{FSG} + \underbrace{\sum_{n_V=1}^{NG} Cap^{VSG}_{n_V,y,h}}_{VSG} \geq (1+\beta)PD_{y,h} + \gamma \underbrace{\sum_{n_S=1}^{Ns} Ps^{Sol}_{n_S,y,h}}_{Solar} + \rho \underbrace{\sum_{n_W=1}^{Nw} Pw^{Wnd}_{n_W,y,h}}_{Wind} \tag{47}$$

Wind Power Generation

Non-linear wind-power curves of individual wind turbines are linearized using the piece-wise linearization approach using 5 data-points, and the wind generation at every time-step is computed using the hourly wind speed data at each location. This equality constraint is expressed as follows:

$$Pw^{Wnd}_{n_W,y,h} = W_{n_W}\left(Cap^{Wnd}_{n_W,y,h},\ WS_h\right) \tag{48}$$

Solar Power Generation

The generation of solar power depends primarily on the local solar insolation and temperature. Thus, the power of a solar panel set is computed using the temperature coefficient of solar cells as well as their derating factor, as follows:

$$Ps^{Sol}_{n_S,y,h} = Cap^{Sol}_{n_S,y,h}\, df^{Sol} \left(\frac{SI_h}{GT^{stc}}\right)[1 + \alpha\,(Tcell_h - Tcell^{stc})] \tag{49}$$

Battery SOC

The SOC of a battery-bank varies dynamically as the batteries charge or discharge and when a new battery is added to the bank. The following two equations take care of this constraint, while considering the sequence of hour and year indices:

$$SOC_{n_B,y,h+1} - SOC_{n_B,y,h} = \eta^{Ch}\ Pb^{Ch}_{n_B,y,h} - \frac{\eta^{Dch}}{Pb^{Dch}_{n_B,y,h}} + 0.8\ NCA^{Bat}_{n_B,y,h} \tag{50}$$

$$SOC_{n_B,y+1,1} - SOC_{n_B,y,HY} = \eta^{Ch}\ Pb^{Ch}_{n_B,y,HY} - \frac{\eta^{Dch}}{Pb^{Dch}_{n_B,y,HY}} + 0.8\ NCA^{Bat}_{n_B,y,HY} \tag{51}$$

The upper limit of SOC is simply the fully charged capacity of the battery-bank, but the lower limit is of importance to control the depth-of-discharge (DoD) of the battery-bank. The SOC is thus constrained as follows:

$$SOC_{n_B,y,h} \leq Cap^{Bat}_{n_B,y,h} \tag{52}$$

$$SOC_{n_B,y,h} \geq DoD^{Bat}\, Cap^{Bat}_{n_B,y,h} \tag{53}$$

Battery Charging/Discharging and Life

The maximum discharging capacity of a battery is constrained by the power that the battery can discharge continuously for a given duration until it reaches its DoD, and the charging rates can be kept the same to the discharging rates, thus yielding the following maximum charging and discharging limits:

$$Pb^{Dch}_{n_B,y,h} \leq \left(\frac{1 - DoD^{Bat}}{T^{Dch}}\right) Cap^{Bat}_{n_B,y,h} \tag{54}$$

$$Pb^{Ch}_{n_B,y,h} \leq \left(\frac{1 - DoD^{Bat}}{T^{Dch}}\right) Cap^{Bat}_{n_B,y,h} \tag{55}$$

The following lower limits are imposed to ensure a minimum charging/discharging power at a given hour, so that these values are greater than zero when the operating state is ON (i.e., binary variable = 1):

$$Pb^{Dch}_{n_B,y,h} \geq u^{Dch}_{n_B,y,h} \tag{56}$$

$$Pb^{Ch}_{n_B,y,h} \leq u^{Ch}_{n_B,y,h} \tag{57}$$

If these minimum limits are not included, then solutions with zero charge/discharge values can be obtained, while the binary state of the operation is ON.

Since both charging and discharging of a battery cannot occur at the same moment, the following complementary constraint is imposed:

$$Pb^{Ch}_{n_B,y,h}\, Pb^{Dch}_{n_B,y,h} = 0 \tag{58}$$

This is a non-linear equation, since it is a product of two continuous variables, which is linearized using the following approach: Let there be two binary variables q_1 and q_2, and a very large number M, then the following set of equations allow to linearize the product [10]:

$$x_1 \leq M\, q_1 \tag{59a}$$

$$x_2 \leq M\, q_2 \tag{59b}$$

$$q_1 + q_2 \leq 1 \tag{59c}$$

Hence, (58) is replaced by:

$$Pb_{n_B,y,h}^{Dch} \leq u_{n_B,N,h}^{Dch} M \tag{60}$$

$$Pb_{n_B,y,h}^{Ch} \leq u_{n_B,y,h}^{Ch} M \tag{61}$$

$$u_{n_B,y,h}^{Ch} + u_{n_B,y,h}^{Dch} \leq 1 \tag{62}$$

Finally, the battery life is computed as follows:

$$\sum_{y=1}^{PH} \sum_{h=1}^{HY} \left(Pb_{n_B,y,h}^{Dch} + Pb_{n_B,y,h}^{Ch} \right) \leq 3000 \sum_{y=1}^{PH} \sum_{h=1}^{HY} NCA_{n_B,y,h}^{Bat} \tag{63}$$

assuming a typical Li-ion battery with 3000 cycles of fully charging and discharging.

Forceful Inclusion of RE

If the inclusion of any RE technology increases the NPC of the project, then the optimal planning result excludes RE. In this case, the RE technology is forced into the optimal planning solution to understand its economic impact. This is accomplished in this model by adding a constraint that states that the technology in consideration should be generating a minimum of 1% of the total annual energy demand, as follows:

$$\sum_{n_S=1}^{Ns} \sum_{h=1}^{HY} Ps_{n_S,y,h}^{Sol} \geq 0.01 \sum_{h=1}^{HY} load_{y,h} \tag{64}$$

$$\sum_{n_W=1}^{Nw} \sum_{h=1}^{HY} Pw_{n_W,y,h}^{Wnd} \geq 0.01 \sum_{h=1}^{HY} load_{y,h} \tag{65}$$

For the inclusion of batteries, the constraint enforces a purchase of at least one unit size of the device, as follows:

$$\sum_{n_B=1}^{Nb} \sum_{y=1}^{PH} \sum_{h=1}^{HY} u_{n_B,y,h}^{BatPur} \geq 1 \tag{66}$$

2.1.3 Final Model

The resulting MILP optimization model when PowerBridge is not considered, i.e., for the studies where FSGs are replaced by VSGs at their end-of-life and all new diesel generation requirements are met with VSGs, is comprised of equations (4) to (27), (31) to (42), (48) to (57), and (60) to

(63), with equations (64) to (66) being optional, as required. If PowerBridge is considered, i.e., for the studies where all FSGs are replaced after 2 years by VSGs, then (4), (14), and (15) are replaced by (44) to (47), and all the battery related equations, i.e., (5d), (10), (19), (23), (27), (50) to (57), and (60) to (63), are removed from the model. These model were solved in the GAMS environment [11], using the CPLEX solver [12], on an Intel(R) Xeon(R) CPU L7555, 1.87 GHz 4-processor server.

2.2 Input Data

Various sets of input data are required for the simulations, some of which are constant for all communities and some are specific to the community in consideration. The details of the important input data used for the studies presented here are discussed next. In order to keep the report at a reasonable length, only sample graphics and/or tables for some communities are included here, with all the rest being made available in the Appendix.

2.2.1 Load Profiles

Load data was made available by the respective territorial utilities, i.e., Qulliq Energy Corporation (QEC) for the communities of Nunavut [13], and Northwest Territories Power Corporation (NTPC) for the community of Sachs Harbour of NWT [14]. QEC provided the maximum and minimum monthly load values and the monthly energy generation for a 2 year period between 2013 and 2015, which was then synthesized to represent an hourly load profile for the communities, so that the peak load appeared between 1 and 4 pm, the average load was present 50% of the time, and the rest was considered to be minimum load, enforcing the total energy consumed in a month. On the other hand, NTPC provided per-minute load data for the year of 2012 for the community of Sachs Harbour, that was then averaged to represent an hourly load profile. As described in Section 2.1.1, the load and RE data was averaged per day over a month, so that simulations could be carried out in a timely fashion; the resulting load profiles for the first year of the simulation are shown in Figures 4 and 5 for the communities of Sanikiluaq and Sachs Harbour, respectively, while the rest are shown in Appendix A.1.

2.2.2 RE Resource Profiles

Detailed raw data on solar, wind, and temperature profiles for the years of 2010 to 2014, for the communities considered, from Environment Canada's Canadian Weather Energy Engineering Dataset (CWEEDS) [15], were gathered and processed to obtain the required hourly profiles of

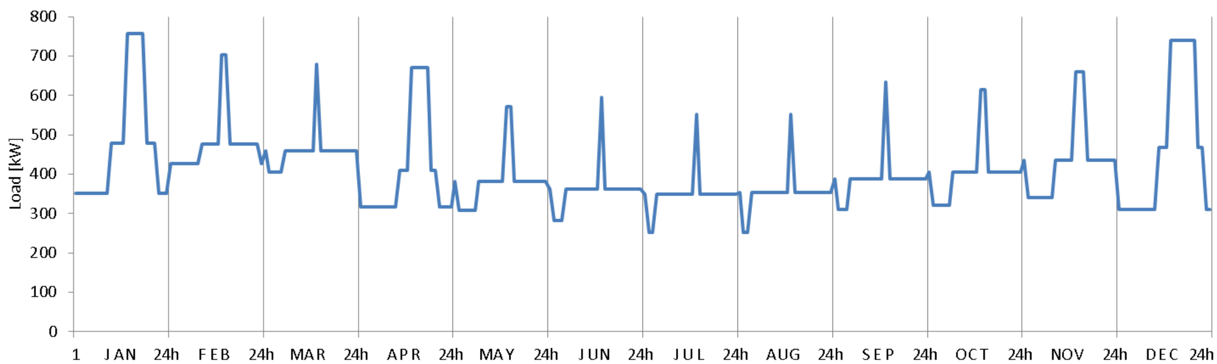


Figure 4: Daily average hourly load profile per month for Sanikiluaq, NU.

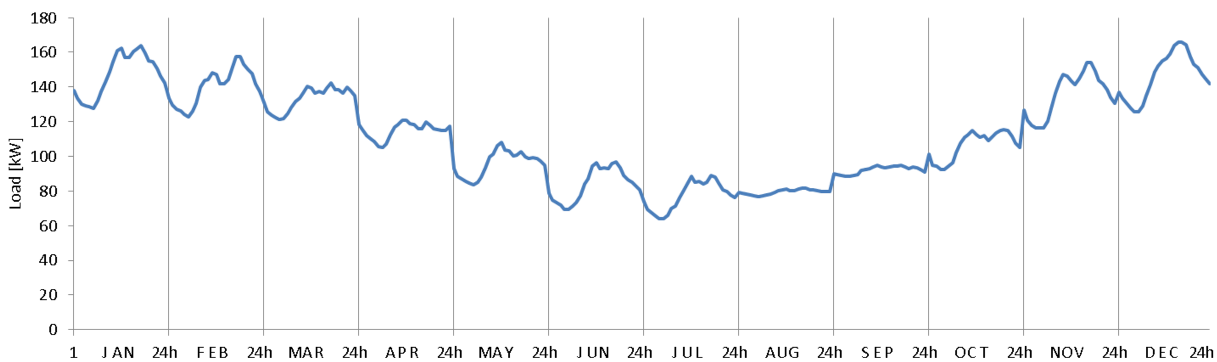


Figure 5: Daily average hourly load profile per month for Sachs Harbour, NWT.

daily averages per month. Solar, wind, and temperature profiles of Sanikiluaq and Sachs Harbour are shown in Figures 6 and 7, respectively, and the rest are presented in Appendix A.2.

2.2.3 Existing Fixed-Speed Diesel Generators

A complete list of all existing FSGs in the 6 communities in consideration is presented in Table 1, along with their capacities, remaining life, manufacturers, and model numbers. This information was used to find the data-sheets of these generators in order to obtain their fuel consumption curves. The fuel curves of 2 of the generators are shown in Figure 8, and the fuel curves of rest of the existing generators are presented in Appendix A.3. Note that the fuel curves are non-linear in nature, and thus, to keep the model linear, the points shown in the figures are the 3 data-points used to piece-wise linearize these curves.

It is preferable to have some generators of a community in a stand-by mode, but, as mentioned

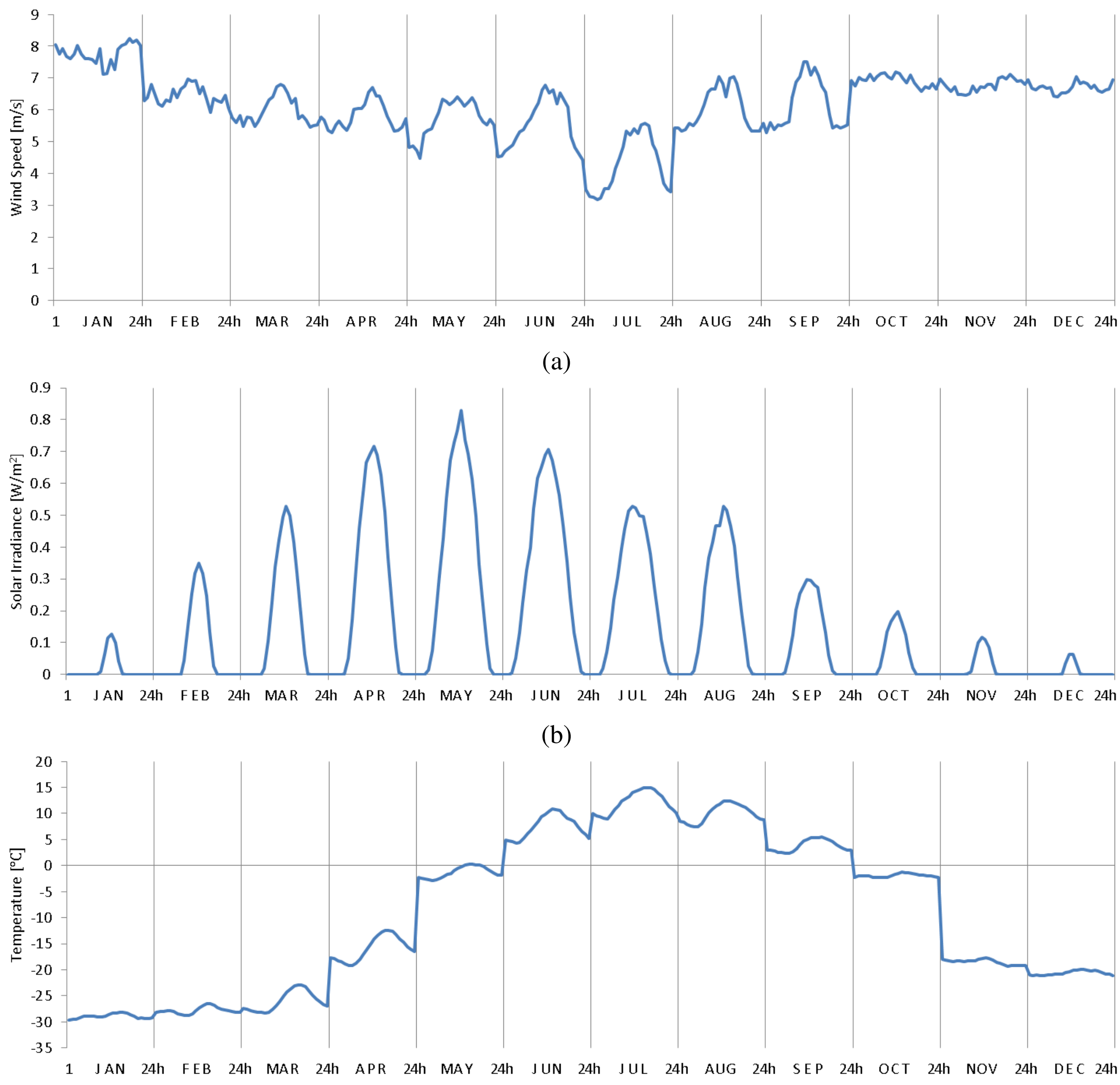
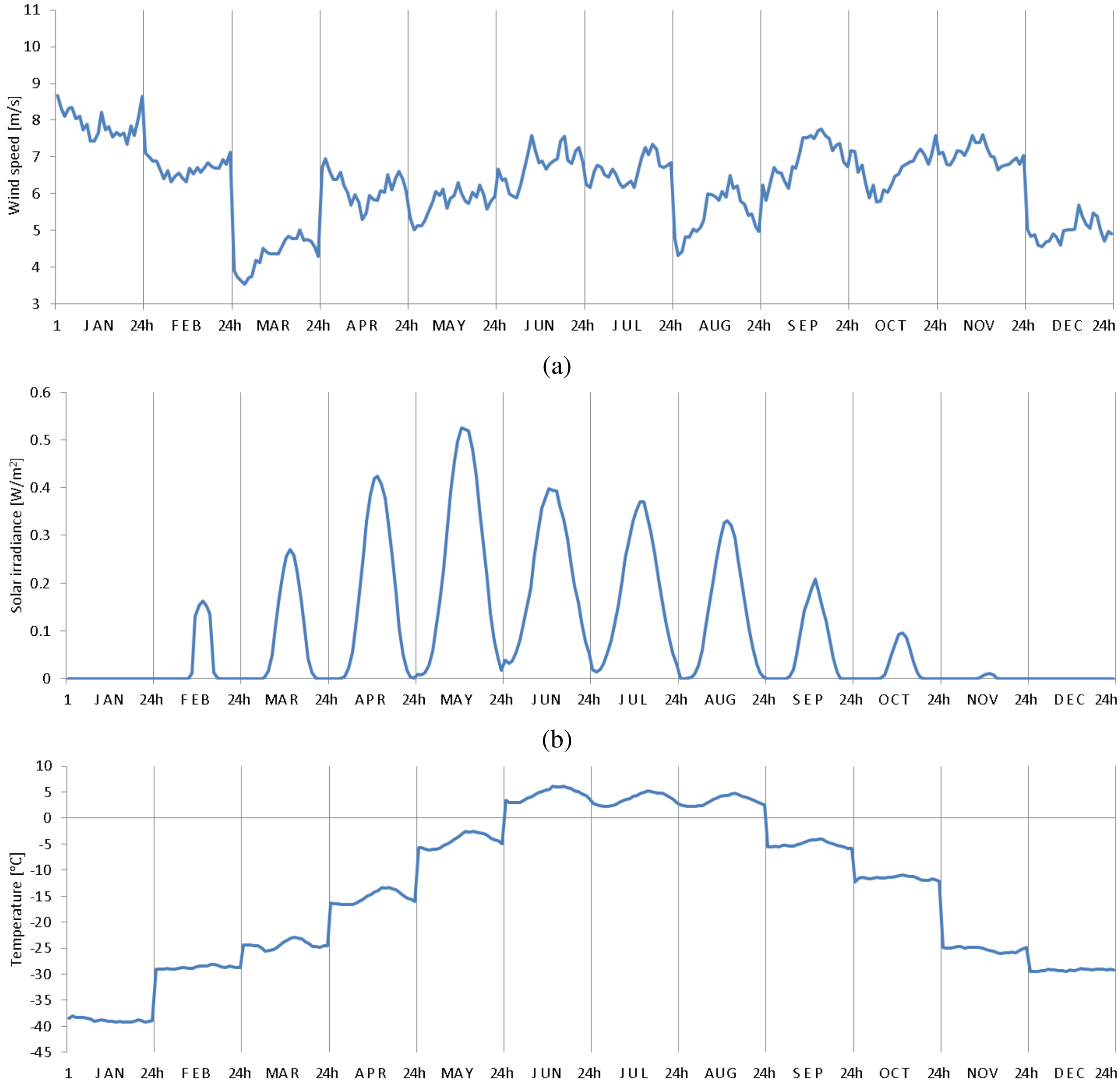


Figure 6: Daily average hourly profiles per month of (a) wind speed at 21m hub height, (b) solar insolation, and (c) temperature for the community of Sanikiluaq, NU.



(a)

(b)

(c)

Figure 7: Daily average hourly profiles per month of (a) wind speed at 21m hub height, (b) solar insolation, and (c) temperature for the community of Sachs Harbour, NWT.

Table 1: List of existing diesel generators in the 6 communities.

Community	**Capacity** [kW]	**Remaining Life** [h]	**Model**	**Community**	**Capacity** [kW]	**Remaining Life** [h]	**Model**
Arviat	550	83,972	Cat.[a] D3508B	Rankin Inlet	850	98,509	Cat. D3516
	800	79,250	Cat. D3512B		1,450	90,118	EMD 8V710
	800	97,549			1,650	84,897	Cat. D3606
	960	6,702	Cat. D3516B		2,150	64,286	EMD 12V710
Baker Lake	550	88,626	Cat. D3508B	Sanikiluaq	330	35,339	DD Series 60
	920	56,611	Cat. D3512BHD		330	standby and/or emergency	
	1,150	49,908	Cat. D3516BHD		330		
Iqaluit	330	50,534	DD[b] Series 60		330		
	2,000	27,884	Wrt. [c] 12V200		500[d]	100,000	Cat. D3508B
	2,300	7,554	EMD 20V645		540	64,696	DD Series 2000
	4,300[d]	40,678	Wrt. 12V32		550	50,000	Cat. D3508B
	5,250	151,882		Sachs Harbour	175	81,402	Cat. D3406
	5,250	153,700			300	40,227	Cat. D3412
					320[d]	7,046	DD Series 60

[a]Caterpillar
[b]Detroit Diesel
[c]Wartsilla
[d]Reduced capacity due to ageing

by QEC, such an option is only available in some communities. Nevertheless, existing generators in all the 5 selected communities of Nunavut were assigned as rotating stand-by mode operation during the simulations, as shown in Table 2. Since Sachs Harbour's peak load is less than 300 kW, it is possible to keep at least 1 of its 3 generators in stand-by mode.

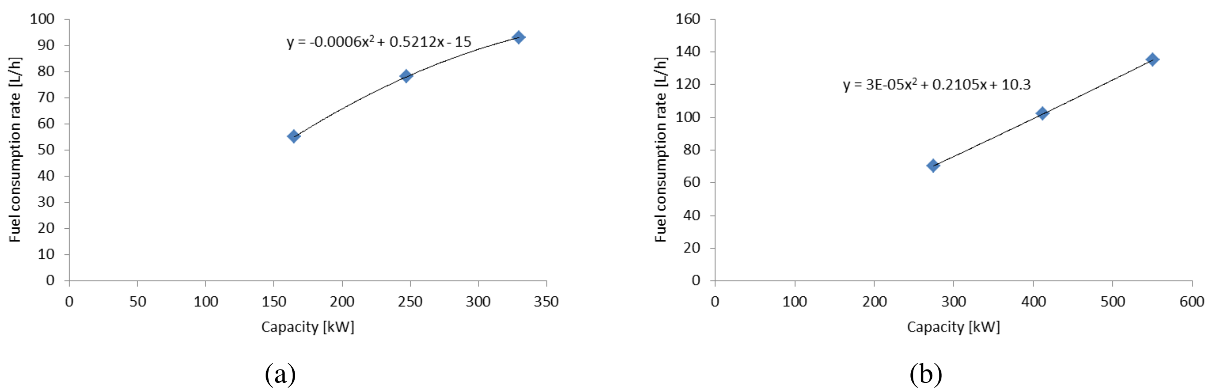


Figure 8: Fuel consumption curves for (a) DD 60 and (b) Cat. D3508 diesel generators.

Table 2: Stand-by mode operations of existing diesel generators used in simulations.

Community	Generator	Year of Project Horizon																			
	kW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Arviat	550				•				•				•				•				•
	800			•				•				•				•				•	
	800		•				•				•				•				•		
	960	•				•				•				•				•			
Baker Lake	550			•			•			•			•			•			•		
	920		•			•			•			•			•			•			•
	1,150	•			•			•			•			•			•			•	
Iqaluit	330																				
	2,000	•			•			•			•			•			•			•	
	2,300		•			•			•			•			•			•			•
	4,300			•			•			•			•			•			•		
	5,250		•		•		•		•		•		•		•		•		•		
	5,250	•		•		•		•		•		•		•		•		•		•	
Rankin Inlet	850				•				•				•				•				•
	1,450			•				•				•				•				•	
	1,650		•				•				•				•				•		
	2,150	•				•				•				•				•			
Sanikiluaq	330		•		•		•		•		•		•		•		•		•		•
	330		•		•		•		•		•		•		•		•		•		•
	330	•		•		•		•		•		•		•		•		•		•	
	330	•		•		•		•		•		•		•		•		•		•	
	500	•		•		•		•		•		•		•		•		•		•	
	540	•		•		•		•		•		•		•		•		•		•	
	550		•		•		•		•		•		•		•		•		•		•
Sachs Harbour	175	•			•			•			•			•			•			•	
	300		•			•			•			•			•			•			•
	320			•			•			•			•			•			•		

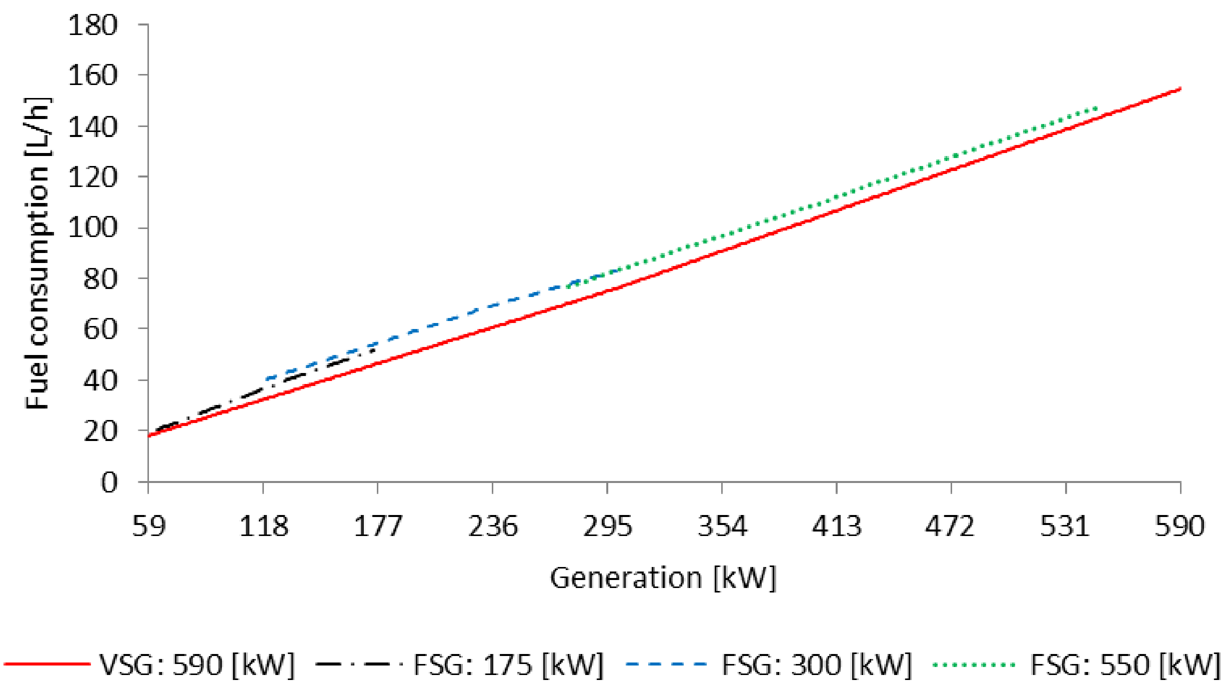


Figure 9: Comparison of fuel consumption and loadability of VSG versus similar capacity FSGs.

2.2.4 New Variable Speed Diesel Generators

The 590 kW VSGs from Innovus Power have unique characteristics of low loadability and fuel consumption, as shown in Figure 9, where the fuel curves are compared with three other comparable capacity FSGs. This unique characteristic is enhanced by adding the PowerBridge, which is designed as an energy buffer and stabilizing load system that allows managing excess RE generation. Another aspect of the PowerBridge is its capability to allow fast ramping up and down of the generator engine using ultra-capacitors; however, this is not required in the present studies, since ramping constraints, start up and shut down costs, and minimum uptime and downtime constraints are unnecessary for the time interval of 1 h used here, as mentioned in Section 2.1.2, in which generators can be assumed to start up and shut down instantaneously.

2.2.5 General Considerations

The data assumed constant for all communities are the following:

- The simulation time steps of the multi-time step model are 1 h for an average of 24 h ×

12 months = 288 h/year for a 20-year horizon.

- Discount rate of $d = 0.08$ (8%).
- System operation criteria:
  - Economic minimization.
  - Operation strategy of load following.
  - Operating reserves of $\gamma = 0.5$ (50%) for wind, and $\rho = 0.25$ (25%) for solar power generated at every time step [16], [17].
- Generation reserve margin for demand of $\beta = 0.1$ (10%).
- Minimum loading of a diesel generator is $ML = 0.4$ (40%) of the rated capacity for the existing units, and $ML = 0.1$ (10%) for the new VSGs purchased.
- Minimum percent of time per year a diesel generator must be off-line for maintenance is $T^{OM} = 0.1$ (10%).
- Useful life of diesel generators is considered to be in the range of GH^{life} = 72,000 to 100,000 h.
- Temperature at Standard Test Conditions (STC) for PV cell is $Tcell^{STC} = 25°C$.
- The solar radiation incident on the PV cell at STC is $GT^{STC} = 1$ kW/m^2.
- Derating factor of solar PV cell is assumed to be $df^{sol} = 0.98$ (98%).
- Charging and discharging efficiencies of a battery are assumed to be $\eta^{Ch} = \eta^{Dch} = 0.95$ (95%).
- Depth-of-Discharge of a battery is assumed to be $DoD = 0.2$ (20%).
- Number of hours a battery can discharge continuously at peak power is assumed to be $T^{Dch} = 4$ h.

An important factor is the cost of diesel, which was computed using consumption data from QEC and fuel costs from Nunavut Energy [18]. This results on the price of diesel in the selected communities varying from 1.4 $/L to 2.4 $/L, which was assumed to be unsubsidized, as the cost data reflects the payments made by government. On the other hand, fuel-pump level data from various sources, particularly online sources, present a seemingly subsidized rate in the range of 1.01 $/L to 1.72 $/L, with Iqaluit having 1.3 $/L. The current study has been based on the costs paid by government, as it focuses on savings over unsubsidized costs of diesel, since the point of view of the studies is from the main payee, i.e., territorial governments. The rest of the dataset input is presented next.

2.2.6 Search Space

Simulation search spaces for diesel, wind, solar, and battery have been defined for each community based on their load profiles and existing generation capacities.

Diesel

New diesel generators are all considered to be 590 kW VSGs from Innovus Power.

Solar

The search space for solar PV is comprised of panel sets from 2 manufacturers, Canadian Solar and First Solar, with comparable unit prices. The temperature coefficient for power generation of Canadian Solar panels is $\alpha = -0.0041 pu/^{\circ}$C, and that for First Solar panels is $\alpha = -0.0029 pu/^{\circ}$C, while the unit panelset capacities are $Ucap = 9.6$ kW and 10 kW, respectively.

Wind

There are a large number of wind turbines available today, but only a few of them are suitable for the arctic environment. Thus, the search space considered includes turbines that are either tested in such an environment, like Alaska or Yukon, or manufacturers that claim that their turbines are operable in the arctic conditions. In view of this, this study shortlisted 7 turbines for consideration, as follows:

1. NPS100 (tested in Alaska): 100 kW turbine with 21 m hub height from Northern Power Systems.
2. nED100 (no tested in arctic climate): 100 kW turbine with 24 m hub height from Norvento.
3. EWT250 (tested in Alaska): 250 kW turbine with 52 m hub height from Emergya Wind Technologies (EWT) B.V.
4. EWT500 (tested in Alaska): 500 kW turbine with 54 m hub height from EWT B.V.
5. EWT900 (tested in Alaska): 900 kW turbine with 50 m hub height from EWT B.V.
6. En70 (tested in Yukon): 2300 kW turbine with 75 m hub height from Enercon.
7. EW50 (tested in Alaska): 50 kW turbine with 31 m hub height from Entegrity.

The search space for each community is presented in Table 3, and the wind power curves are presented in the Appendix A.4.

Battery

Li-ion batteries are considered in the presented studies as energy storage systems, as their operating characteristics and O&M handling and costs are adequate. This once costly battery's capital cost has decreased considerably in the last couple of years, and is forecasted to reduce further with the announcement of Tesla's Gigafactory project. In view of this, Li-ion batteries have been chosen for these studies, and only Canadian Solar has been selected as the supplier, as it is more cost-effective over similar batteries from Tesla, and the company indicates that these

Table 3: Wind turbine search space.

n_W	**Arviat**	**Baker Lake**	**Iqaluit**	**Rankin Inlet**	**Sanikiluaq**	**Sachs Harbour**
1	NPS100	NPS100	NPS100	NPS100	NPS100	NPS100
2	nED100	nED100	nED100	nED100	nED100	nED100
3	EWT250	EWT250	EWT250	EWT250	EWT250	EWT250
4	EWT500	EWT500	EWT500	EWT500	-	EW50
5	-	EWT900	EWT900	EWT900	-	-
6	-	-	En70	-	-	-

are appropriate for northern climates. The study considered $Ucap^{Bat}$ = 100 kWh as the unit size of a battery bank with 20 kW as the peak discharge power.

Diesel and RE Equipment Costs

The capital and O&M costs for both RE and new diesel generators were determined considering the transportation and installation costs for each community. The basic equipment costs for all types of equipments considered in the study was retrieved from Lazard's LCOE Analysis, Version 8.0 [19], 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 [20]. For the VSGs, the capital costs were determined by adding 15% to the final capital cost of a comparable size new diesel generator, as indicated by Innovus Power. The PowerBridge cost provided by Innovus Power adds \$100k to the base cost of the VSG.

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 distance traveled. Similarly, 10%, 15%, and 8–10% were assumed for the costs related to spare parts, contingency, and logistics (data extrapolated from [8]), respectively. The final capital costs of RE equipment and diesel generators, varying with destination community, are shown in Table 4. Note that the wind turbine cost per kW increases as turbine capacity decrease, and for solar panels, the ones made by First Solar have the lower cost. In Table 5, various cost components to compute the final capital cost of a wind turbine is shown, for the communities of Sanikiluaq and Baker Lake, to illustrate the procedure used to calculate the equipment costs.

The O&M costs of RE equipment were considered as a range of percentage values of the final computed capital costs of the equipment as follows: 2.5% to 5% for wind, 1.5% to 3% for solar, and 2% to 5% for battery. The costs vary based on the fact that tools required, spare parts, and sometimes maintenance personnel are not available 24/7 in all the communities and are flown in from their bases in one of the 3 regional offices of QEC; thus, for the simulation, Iqaluit and Rankin Inlet were considered to be the locations at which maintenance stores and

Table 4: Community-wise capital costs of RE equipment and VSG.

Community	**Wind**		**Solar**		**Battery**	**VSG**	**VSG with PowerBridge**
	low	high	low	high			
	$/kW	$/kW	$/kW	$/kW	$/kWh	$/kW	$/kW
Arviat	8,715	9,076	5,424	5,507	1,594	835	1004
Baker Lake	9,295	10,971	5,439	5,574	1,627	845	1014
Iqaluit	8,076	10,235	5,142	5,277	1,577	880	1049
Rankin Inlet	8,612	9,459	5,254	5,391	1,572	817	986
Sanikiluaq	7,943	8,614	5,082	5,211	1,504	837	1006
Sachs Harbour	10,183	11,537	5,540	5,644	1,548	914	1083

Table 5: Components of capital cost of NPS100 wind turbine (all values in $/kW).

Community	**Equipment Cost**	**Transportation**		**Installation**			**Equipment + Transport + Installation Cost**
		Road	Sea	Personnel	Technical	Crane	
Sanikiluaq	3,000	89	94	911	120.69	1500	5,714.69
Baker Lake	3,000	89	116	1,452	142.76	1,700	6,499.76

Community	**Overhead**				**Final Costs**
	Proj. Mgt.	Spare	Contingency	Logistics	
Sanikiluaq	342.88	571.47	857.20	457.18	7,943.42
Baker Lake	519.98	649.98	974.96	649.98	9,294.66

people are based, resulting in the O&M costs depicted in Table 6. For the VSGs, the O&M costs were estimated to be 15% lower than that of similar capacity new FSG, as indicated by Innovus Power.

Table 6: Range of the O&M costs of diesel and RE equipment (all values in $/kWh) [19].

Community	**Wind**		**Solar**		**Battery**	**Diesel Generator**		
						Existing FSG		New VSG
	low	high	low	high		low	high	
Arviat	0.0398	0.0414	0.0155	0.0157	0.0073	0.0225	0.0256	0.0168
Baker Lake	0.0531	0.0626	0.0186	0.0191	0.0093	0.0257	0.0291	0.0196
Iqaluit	0.0231	0.0292	0.0088	0.0090	0.0036	0.0171	0.0194	0.01275
Rankin Inlet	0.0295	0.0324	0.0120	0.0123	0.0054	0.0197	0.0223	0.0147
Sanikiluaq	0.0363	0.0393	0.0145	0.0149	0.0069	0.0218	0.0248	0.0163
Sachs Harbour	0.0581	0.0659	0.0190	0.0193	0.0088	0.0260	0.0295	0.0194

3 Feasibility Analysis

The feasibility study performed for WWF was based on the following seven case studies [4]:

1. NoRE: Only diesel generation.
2. S: Only solar energy with diesel.
3. W: Only wind energy with diesel.
4. SW: Both solar and wind energy with diesel.
5. SB: Solar with diesel plus battery storage.
6. WB: Wind with diesel plus battery storage.
7. SWB: Both solar and wind with diesel plus battery storage.

The simulation results based on these case studies for each community are shown in Table 7 for the Business-as-Usual (BAU) case, i.e., only FSG equipment, and in Figure 10 for the optimal RE integration case.

The deployment of VSGs was considered with two different strategies: replacement of existing end-of-life FSGs with VSGs (VSG+FSG), and operation with only VSGs, with POwerBridge

Table 7: Feasibility study results for the BAU case [4]

Communities	Arviat	Baker Lake	Iqaluit	Rankin Inlet	Sanikiluaq	Sachs Harbour
Total NPC [M$]	38.65	45.88	221.42	98.81	26.46	5.52
NPC of Fuel [M$]	36.07	41.69	206.12	91.88	25.54	5.24

Communities	Best Case Scenario	Annual RE Penetration		GHG Reduction over 20 yr [%]	Savings over 20 yr		Total RE Investment Required [M$]
		Average [%]	Maximum [%]		Cost [M$]	Fuel [M$]	
Arviat	SWB	66.49	72.96	60.40	9.32	19.63	10.80
Baker Lake	WB	81.59	89.03	74.12	13.39	28.83	18.41
Iqaluit	SWB	28.82	31.01	26.17	29.70	72.61	45.22
Rankin Inlet	WB	53.32	57.48	48.35	26.83	42.88	20.37
Sanikiluaq	SWB	81.48	87.92	74.24	10.32	17.75	7.62
Sachs Harbour	SW	38.99	42.15	35.41	0.44	1.57	0.98

Figure 10: Optimal solutions obtained in the WWF studies for RE integration [4].

Table 8: VSG+FSG strategy compared with respect to BAU.

Communities	Arviat	Baker Lake	Iqaluit	Rankin Inlet	Sanikiluaq	Sachs Harbour
Total NPC [M$] (% savings)	38.07 (1.50%)	43.07 (6.12%)	180.84 (18.33%)	91.33 (7.57%)	26.34 (0.45%)	5.01 (9.24%)
NPC of Fuel [M$] (% savings)	34.88 (3.30%)	39.93 (4.22%)	176.65 (14.30%)	85.71 (6.72%)	25.16 (1.49%)	4.36 (16.79%)
No. of VSGs	3	2	8	6	1	1

Table 9: VSG-2yr with no PowerBridge compared with respect to BAU.

Communities	Arviat	Baker Lake	Iqaluit	Rankin Inlet	Sanikiluaq	Sachs Harbour
Total NPC [M$] (% savings)	39.03 (-0.98%)	44.73 (2.51%)	NA	92.96 (5.92%)	26.62 (-0.61%)	5.04 (8.70%)
NPC of Fuel [M$] (% savings)	35.49 (1.61%)	40.23 (3.50%)	NA	86.88 (5.44%)	25.03 (2.00%)	4.01 (23.47%)
Min. no. of VSGs	4	5	21	7	2	2

for RE integration, from the 3rd year of the project horizon (VSG-2yr), with standby and emergency generation being provided by existing FSGs. Simulations were performed for the NoRE case with the two VSG strategies, and the results with their respective savings with respect to BAU are presented in Tables 8 and 9. Note that for Iqaluit in Table 9 no solutions were obtained, due to the large search space of 21 VSGs, which made the simulation computationally infeasible. The number of VSGs required was arrived at by the fact that any lesser number resulted in an infeasible solution due to the supply-demand-balance and/or the adequacy constraint.

Simulations were then performed for all the case studies of RE integration and the two VSG deployment strategies for the community of Arviat, with no PowerBridge in this case, and it was found that the optimal RE mix remained the same that of the WWF results, i.e., SWB, as shown in Figures 11 and 12. Based on this observation, simulations for the other communities were carried out for the VSG+FSG strategy with the optimal RE mix obtained from the WWF study. For the VSG-2yr with PowerBridge approach, the optimization model yielded the optimal mix of RE with no battery. The results of these simulations are presented in Figure 13.

RE mix	VSG strategy	Total NPC [M$]	Fuel NPC [M$]	Capacity additions (year) [kW(yr.)]			
				D / VSG	S	W	B
SWB	FSG only	29.34	16.44	520(2) + 800(2) + 1000 (2)	80 (2) + 10(5)	750 (3)	220 (2,3,5)
	VSG+FSG	25.99	18.84	**2 X 590(2)**	40(2) + 230(3) + 340(4) + 10(5)	250(3)	400 (2,3,5,6,9)
	VSG-2yr	26.47	17.95	**2 X 590(2) + 590(10)**	--	750(3)	100 (2,3)
		29.42	19.64	**2 X 590(2) + 590(10)**	10(2)	750(3)	60 (2,3)
W	FSG only	29.40	20.43	800(3) + 1000(3)	--	750(3)	--
	VSG+FSG	27.97	19.35	**3 X 590(2)**	--	750(3)	--
	VSG-2yr	28.60	19.60	**3 X 590(2) + 590(10)**	--	750(3)	--
SW	FSG only	29.54	20.02	520(3) + 800(3) + 1000(3)	80(2) + 10(4) + 20(5)	750(3)	--
	VSG+FSG	27.08	21.78	**590(7)**	20(2) + 50(4) + 30(5)	250(3) + 250(5)	--
	VSG-2yr	28.70	19.83	**3X590(2)**	10(2) + 10(3) +10(5)	500(3) +250(4)	--

Figure 11: Optimal solutions obtained for SWB, W, and SW cases and the two VSG deployment strategies with no PowerBridge for the community of Arviat.

RE mix	VSG strategy	Total NPC [M$]	Fuel NPC [M$]	Capacity additions (year) [kW(yr.)]			
				D / VSG	S	W	B
WB	FSG only	30.77	20.51	520(3) + 1000(3)	--	750(3)	220 (2,3,4)
	VSG+FSG	25.54	17.80	**2X590(2)**	--	500 (3)	500 (2,3)
	VSG-2yr	26.53	17.61	**2X590(2)**	--	500(3) +250(5)	400 (2,3, 4,5,7,15)
S	FSG only	41.24	32.80	520(3) + 800(8) + 1000(3)	140(2) + 890(3) + 20(4)	--	--
	VSG+FSG	37.44	31.77	**2 X 590(2)**	900(5)	--	--
	VSG-2yr	38.24	34.43	**3 X 590(2) + 590(3)**	40(2) + 20(3) + 10(5)	--	--
SB	FSG only	43.62	30.07	520(10) + 1000(3)	880(2) + 70(3) + 190(4) + 450(5)	--	440(2)
	VSG+FSG	37.59	28.48	**2 X 590(2)**	550(2)	--	580 (20)
	VSG-2yr	40.83	22.27	**2 X 590(2) + 590(3)**	1510(2)	--	2080 (2,3,4,5,6 ,8)

Figure 12: Optimal solutions obtained for WB, S, and SB cases and the two VSG deployment strategies with no PowerBridge for the community of Arviat.

Community	RE Mix	VSG Strategy	Total NPC [M$]	Fuel NPC [M$]	Capacity additions [kW]				GHG Redn.* [%]	RE penetration [%]		BAU-LCOE** [$/kWh]	El. Rate [$/kWh]	nLCOE*** [$/kWh]
					D / VSG	S	W	B		Max.	Av.			
ARVIAT	SWB	FSG Only	29.34	16.44	2320	9X10	4X250	220	60.40	72.96	66.49	0.86	0.74 - 0.79	0.81
		VSG+FSG	26.00	18.84	**2X590**	62X10	1X250	400	30.22	26.59	24.54			0.74
	SW	VSG-2yr	22.88	6.16	**3X590**	12X10	7X250	--	89.00	99.37	97.93			0.65
BAKER LAKE	WB	FSG Only	32.49	12.86	1000	--	6X250	980	74.12	89.03	81.59	0.97	0.66 - 0.70	0.82
		VSG+FSG	30.56	15.06	**1X590**	--	4X250	900	61.02	72.87	67.33			0.92
	SW	VSG-2yr	27.52	16.65	**3X590**	0	4X250	--	59.68	70.25	65.83			0.75
IQALUIT	SWB	FSG Only	191.72	133.51	6320	74X9.6	18X250	1050	26.17	31.00	28.82	0.78	0.52 - 0.60	0.76
		VSG+FSG	174.40	97.18	**9X590**	0	29X250	340	35.19	41.95	31.82			0.72
	SW	VSG-2yr												
RANKIN INLET	WB	FSG Only	71.98	49.01	1800	--	6X250	900	48.35	57.48	53.32	1.09	0.55 - 0.62	0.99
		VSG+FSG	58.00	32.32	**3X590**	--	8X250	1060	64.68	76.84	71.36			0.83
	SW	VSG-2yr	50.09	28.62	**4X590**	5X9.6	9X250	--	71.02	83.17	78.30			0.75
SANIKILUAQ	SWB	FSG Only	16.13	7.80	840	25X9.6	2X250	400	74.24	87.92	81.48	1.31	0.79 - 0.82	1.21
		VSG+FSG	14.67	10.38	**2X590**	29X9.6	2X250	320	40.33	48.92	42.03			1.07
	SW	VSG-2yr	11.61	5.30	**1X590**	14X9.6	3X250	--	84.75	95.08	93.19			0.97
SACHS HARBOUR	SW	FSG Only	5.08	3.67	495	2X9.6	2X50	--	35.41	42.15	38.99	1.97	0.29 - 1.96	1.22
		VSG+FSG	5.04	3.24	**2X590**	1X9.6	2X50	--	29.72	35.27	32.75			1.00
		VSG-2yr	4.61	1.97	**1X590**	0	5X50	--	65.78	76.02	72.46			0.95

* with respect to BAU results.

** BAU-LCOE estimated considering the depreciated values of the existing FSGs (provided by Innovus) and overhead costs (e.g. salaries, travel, office expenditures), assumed to be same percentage of total BAU cost for each community as per QEC's 2014 Annual Report.

**** nLCOE computed for energy generation from new capacities only, assuming same net overhead costs as BAU.

Figure 13: Comparison of community-wise optimal RE integration plan and operational savings obtained for two VSG deployment strategies.

Table 10: Depreciated costs of FSGs sold after 2 years.

Community	**Capacity** [kW]	**Purchase Year**	**Sold at** [$]	**Community**	**Capacity** [kW]	**Purchase Year**	**Sold at** [$]
Arviat	800	2005	367,609	Sanikiluaq	330	2005	95,627
Baker Lake	920	2005	358,984		500	2015	295,058
Rankin Inlet	1450	2006	869,420		540	2008	205,384
	1650	2011	1,115,985		550	2000	162,233
Sachs Harbour	300	NA	76,625				

Observe in Figure 13 that, similarly to the VSG deployment for the BAU scenario, the VSG-2yr strategy did not converge for the community of Iqaluit, due to the large search space of VSGs along with wind, and solar equipment. Note also that the VSG-2yr with PowerBridge strategy yields the best performance metrics, such as increased GHG reductions, increased RE penetration, and most significantly a reduction of the new LCOE to values below present subsidized electricity rates for some communities. Observe that the VSG-2yr results in substantially increased RE installed capacities and also significant reduction in GHG emissions for all communities, except Baker Lake, while removing the requirement of battery storage. The different outcome for the community of Baker Lake can be attributed to various causes, such as the transportation costs, demand levels, and RE resource profiles.

The levelized cost of energy (LCOE) in Figure 13 is computed using the depreciated costs of existing FSGs, shown in Table 10, which was provided by Innovus Power, and excludes standby and emergency FSGs. Observe that the LCOEs in the BAU case are all higher than the reported electricity rates of each community, indicating that subsidies are required to reduce the burden on consumers. The new computed LCOEs for the RE cases continually decline as VSGs replace all FSGs, due to the better fuel consumption characteristics of VSGs, and the PowerBridge advantages.

The low loadability of 10% of rated capacity of the VSG plus the PowerBridge allow better integration of renewables, as shown in Figure 14, where the power demand and output for all generation equipment are depicted for Rankin Inlet with the VSG-2yr strategy. Note in the final zoomed-out graph that the low-loading capability of VSGs (near 60 kW), coupled with the dump load of the PowerBridge, allows excess power output from wind generator without the need of curtailment.

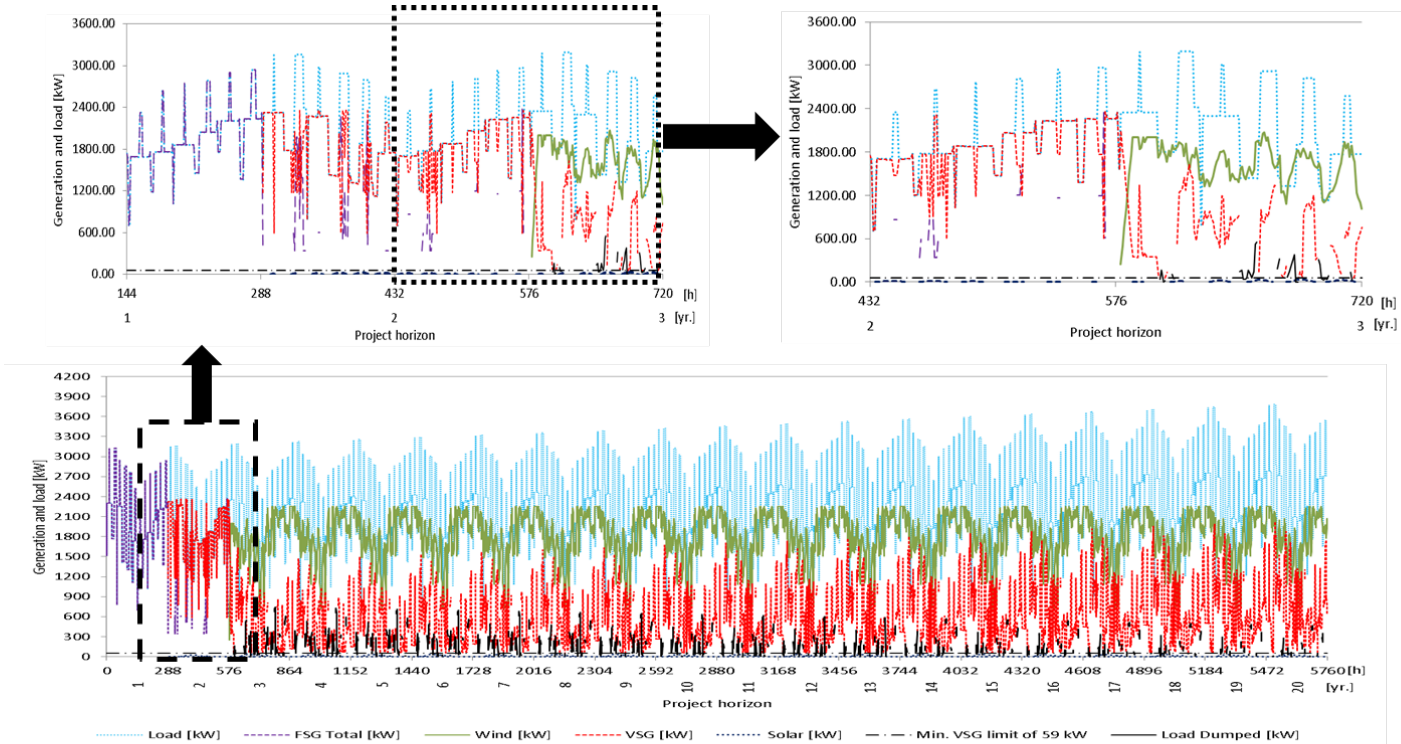


Figure 14: Load profile and power generation from all equipment at Rankin Inlet in the WB scenario with VSG-2yrs strategy.

4 Conclusions and Recommendations

The impact of VSG introduction in the 6 communities can be summarized as follows for each community:

1. The highest annual average RE penetration level obtained was 97.93% for the community of Arviat for the VSG-wind-solar hybrid model with PowerBridge, resulting in about 89% reduction in GHG emissions and fuel savings of \$ 29.91 million (82.92% savings with respect to Business-as-Usual (BAU) costs) over a 20 year period.

2. The community of Sanikiluaq results show an annual average RE penetration of 93.19% for the VSG-solar-wind hybrid model with PowerBridge, with fuel savings of \$ 20.24 million (79.25% savings with respect to BAU costs) in 20 years, and a reduction of GHG emissions of about 84.75%.

3. The results obtained for Rankin Inlet show an annual average RE penetration of 78.3% for the VSG-solar-wind hybrid model with PowerBridge, with 71.02% reduction in GHG emissions, and fuel savings of \$ 63.26 million (68.85% savings with respect to BAU costs) over a 20-year horizon.

4. For Baker Lake, the results show an annual average RE penetration of 65.83% for the VSG-wind hybrid model with PowerBridge, with \$ 25.04 million (60.06% savings with respect to BAU costs) in fuel savings in 20 years, and a reduction in GHG emissions of 59.68%.

5. For the community of Iqaluit, the simulations of VSGs, with or without PowerBridge, replacing all existing FSGs did not converge, given the large search space of VSGs (a minimum of 21 units) to completely replace all FSGs of the system, due to the available capacity of VSGs vis-á-vis the large capacity of existing FSGs. In this community, the diesel-wind-battery hybrid model, with VSGs without PowerBridge introduced as new diesel generator purchases, is the best option, resulting in an annual average RE penetration of 31.82% and GHG reduction of 35.19%, with the highest fuel savings for all communities at \$ 108.94 million over a 20-year period, which corresponds to 52.85% savings with respect to the BAU costs.

6. For Sachs Harbour, the VSG-wind hybrid model with PowerBridge yields the best results, with an annual average RE penetration and GHG reduction of 72.46% and 65.78%, respectively, and fuel savings of \$ 3.27 million over a 20-year period, which corresponds to 62.40% savings with respect to the BAU costs.

The simulation results indicate that the deployment of VSGs in RE-diesel hybrid systems in any of the studied communities will always economically reduce the consumption of diesel. It can also be observed that, in general, with the introduction of VSGs with PowerBridge, there is no need for batteries. The results of this study show that adding VSGs in the generation portfolios for the communities studied can result in substantial reductions in GHG emissions, ranging from 59.68% to 89%, with annual average penetrations of RE from 31.82% to 97.93%, and a range of fuel savings of $ 3.27 million to $ 108.94 million over a 20-year period. Based on these results, projects deploying VSGs with PowerBridge should be pursued for Arviat and Sanikiluaq, and if possible, for Sachs Harbour and Rankin Inlet.

A APPENDIX

A.1 Load Profiles for the rest of the Communities

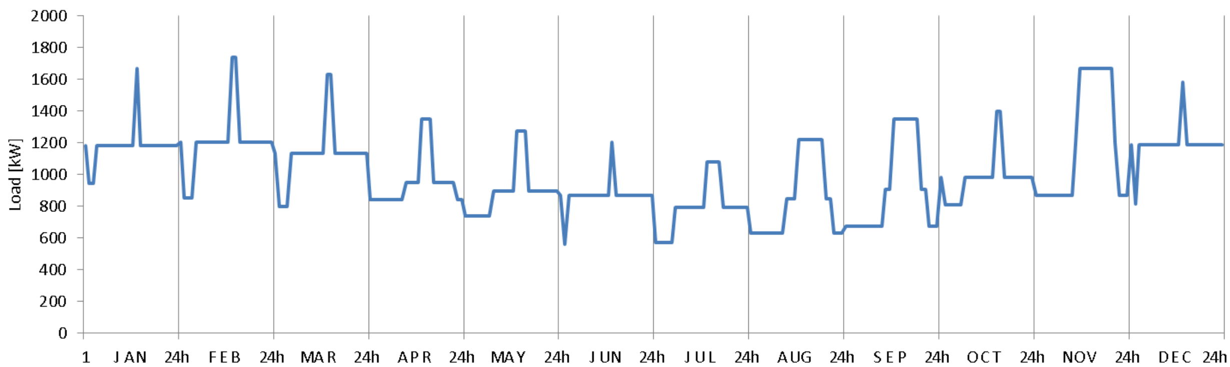


Figure 15: Daily average hourly load profile per month for Arviat, NU.

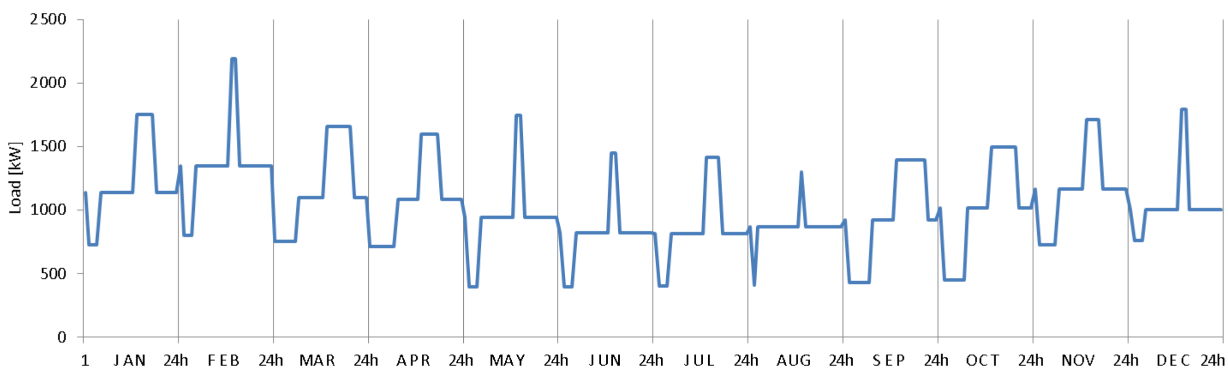


Figure 16: Daily average hourly load profile per month for Baker Lake, NU.

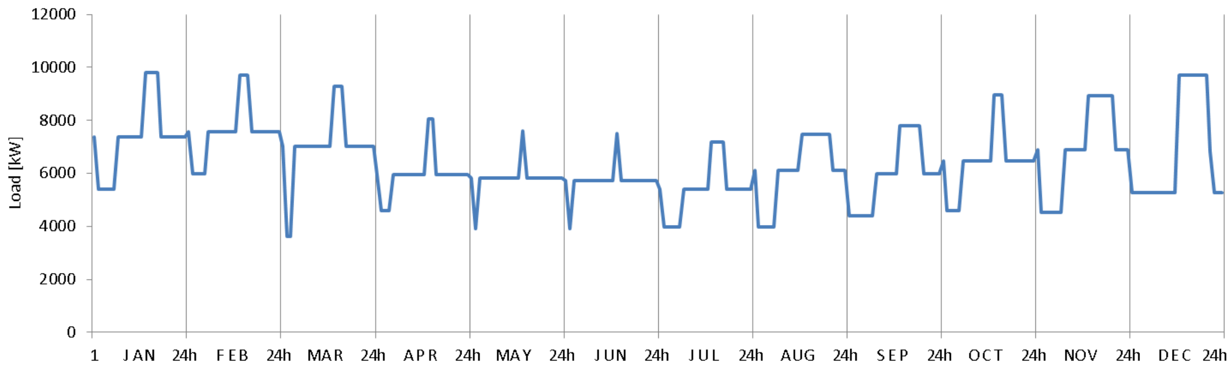


Figure 17: Daily average hourly load profile per month for Iqaluit, NU.

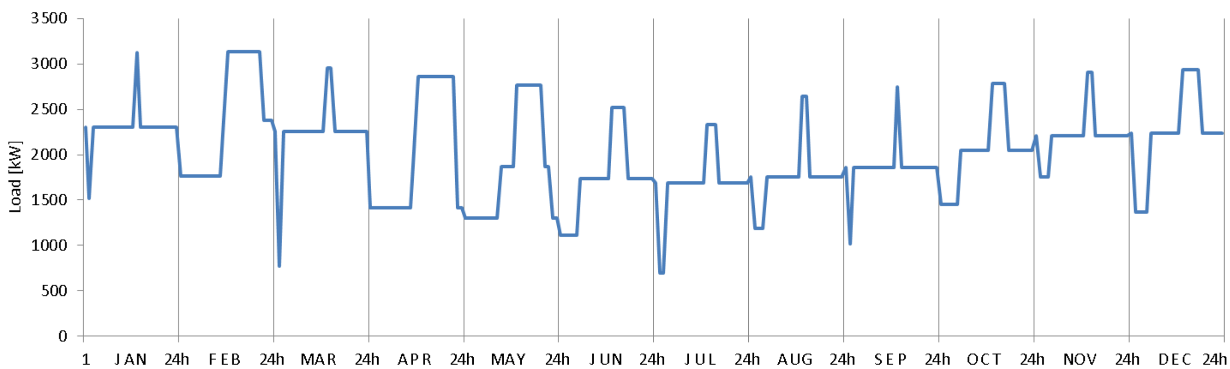
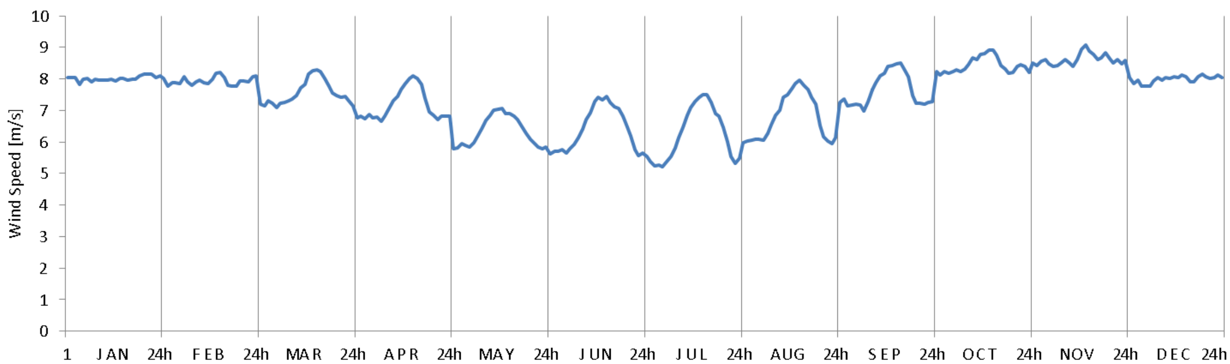
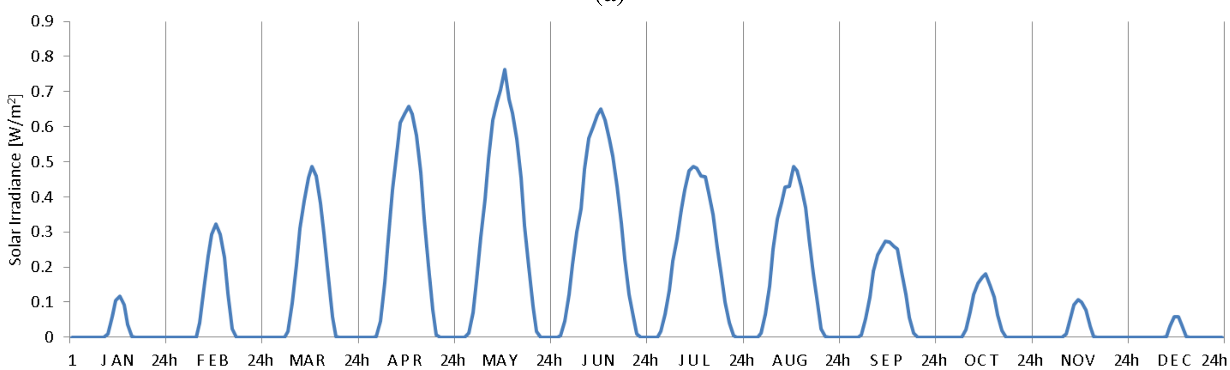


Figure 18: Daily average hourly load profile per month for Rankin Inlet, NU.

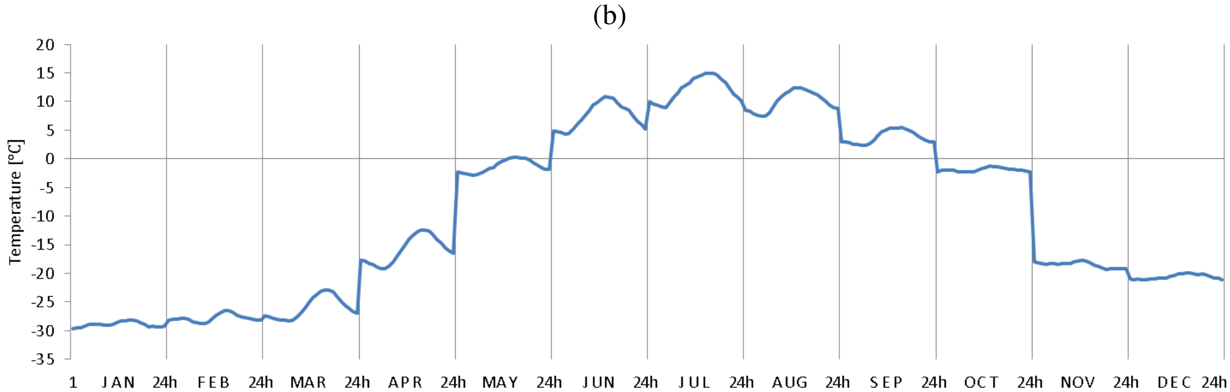
A.2 RE Resource Profiles for the rest of the Communities



(a)

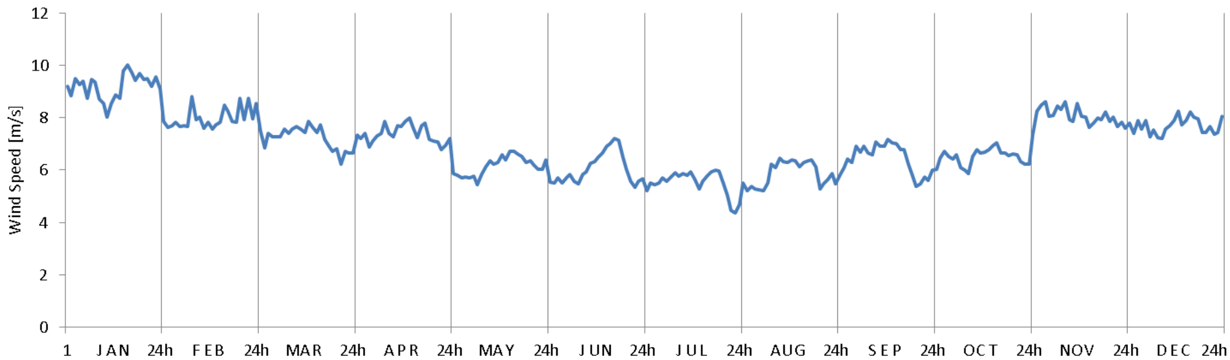


(b)

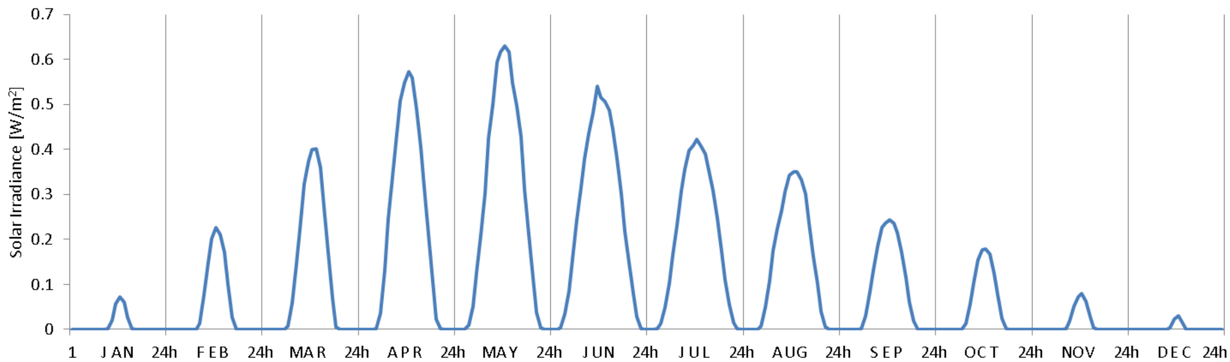


(c)

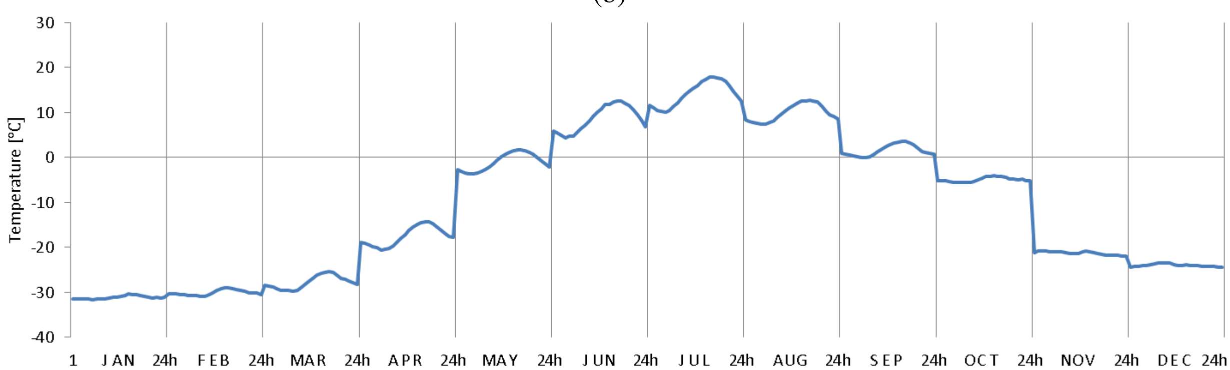
Figure 19: Daily average hourly profiles per month of (a) wind speed at 50m hub height, (b) solar insolation, and (c) temperature for the community of Arviat, NU.



(a)



(b)



(c)

Figure 20: Daily average hourly profiles per month of (a) wind speed at 21m hub height, (b) solar insolation, and (c) temperature for the community of Baker Lake, NU.

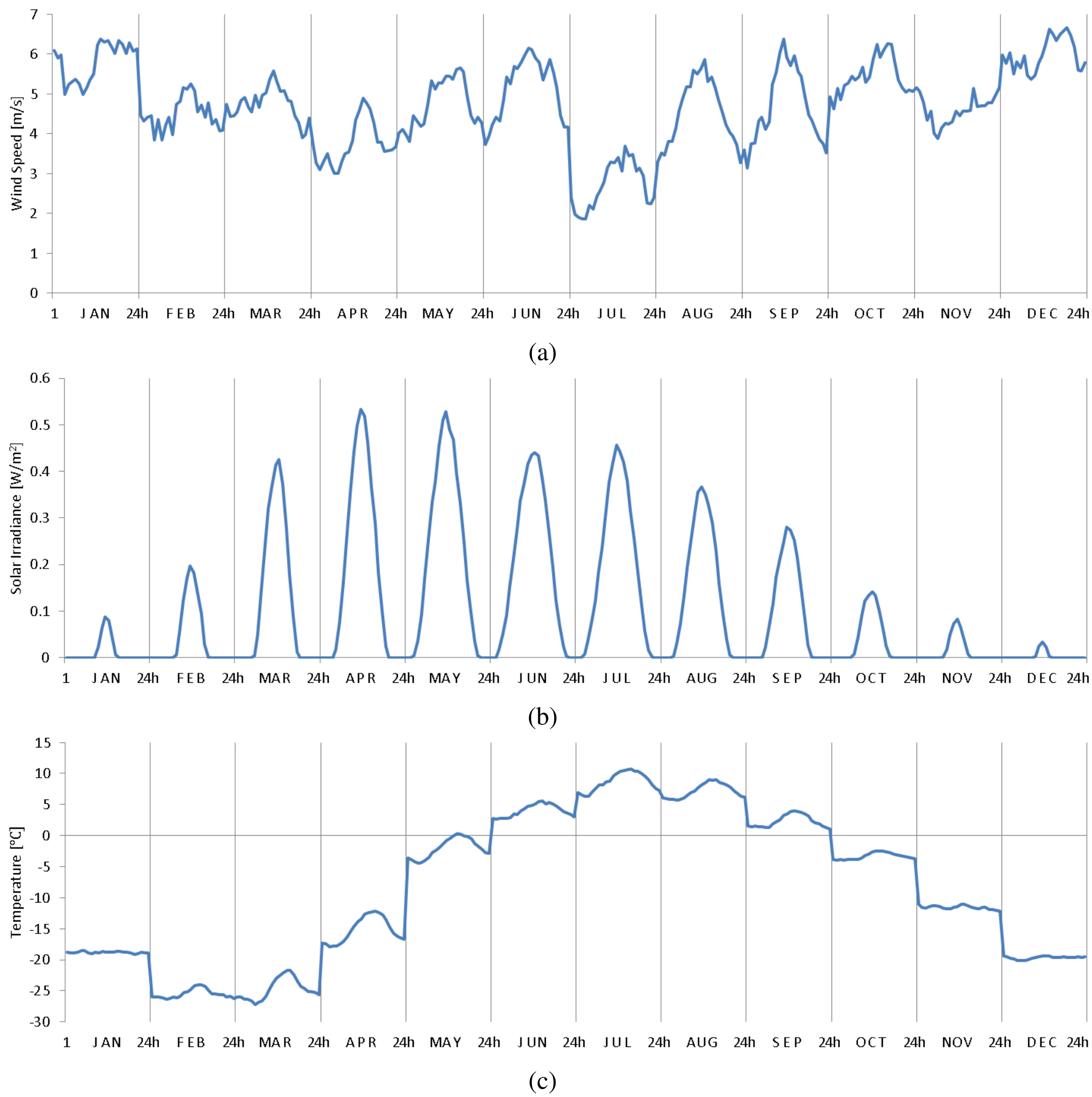


Figure 21: Daily average hourly profiles per month of (a) wind speed at 50m hub height, (b) solar insolation, and (c) temperature for the community of Iqaluit, NU.

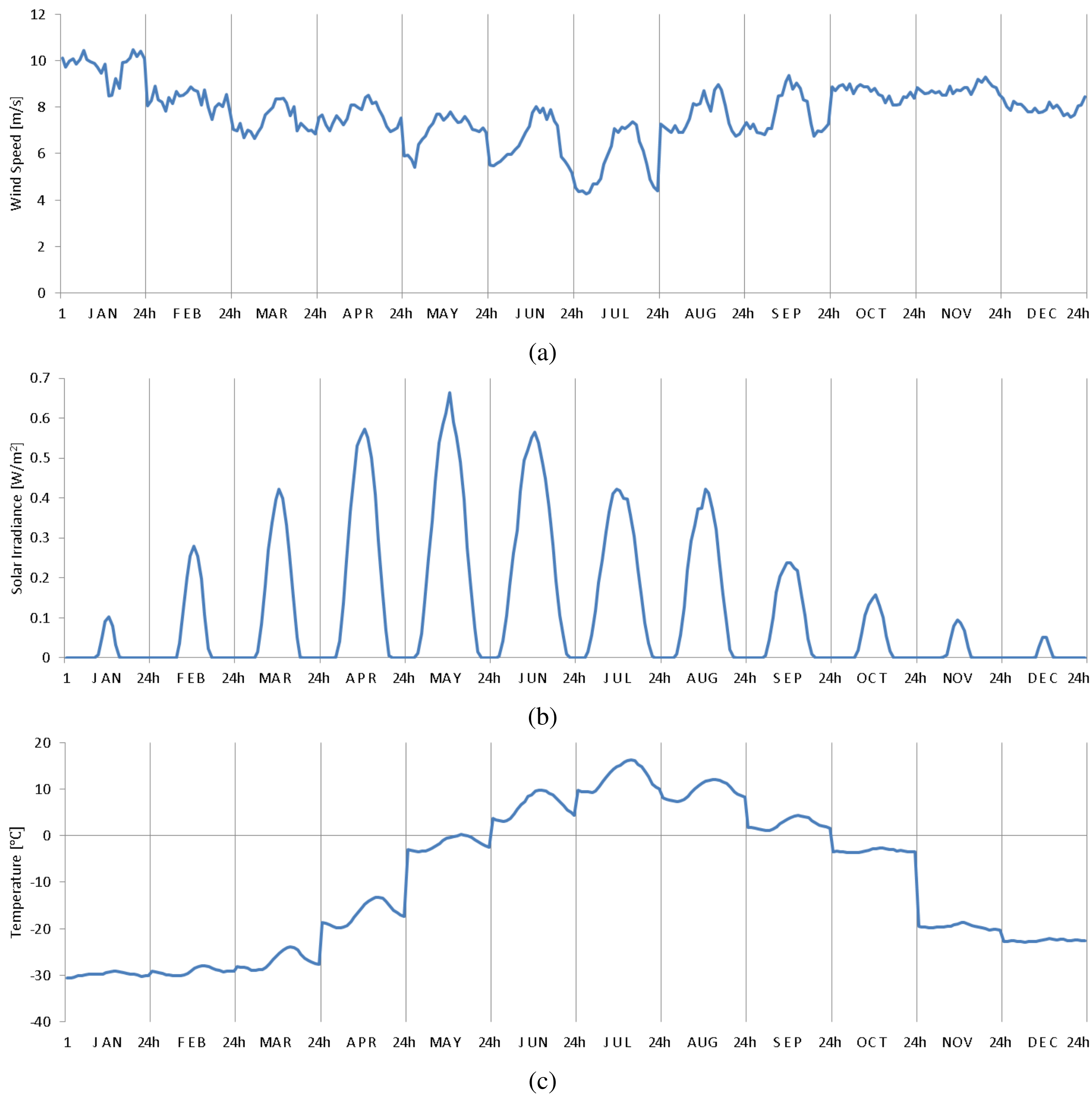


Figure 22: Daily average hourly profiles per month of (a) wind speed at 50m hub height, (b) solar insolation, and (c) temperature for the community of Rankin Inlet, NU.

A.3 Fuel Curves of Existing Diesel Generators

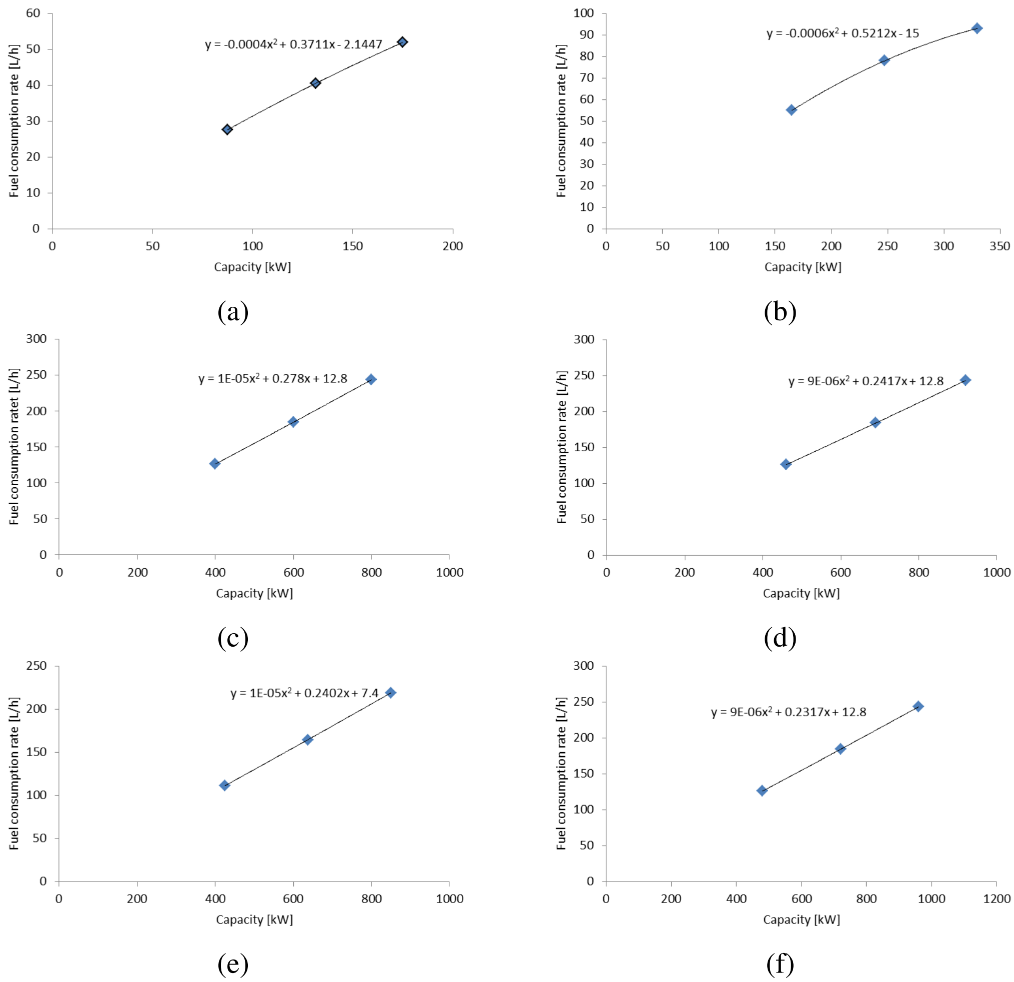


Figure 23: Fuel consumption curves for Caterpillar (a) D3406 175 kW, (b) D3412 300 kW, (c) D3512B 800 kW, (d) D3512BHD 920 kW, (e) D3516 850 kW, and (f) D3516B 960 kW diesel generators [21].

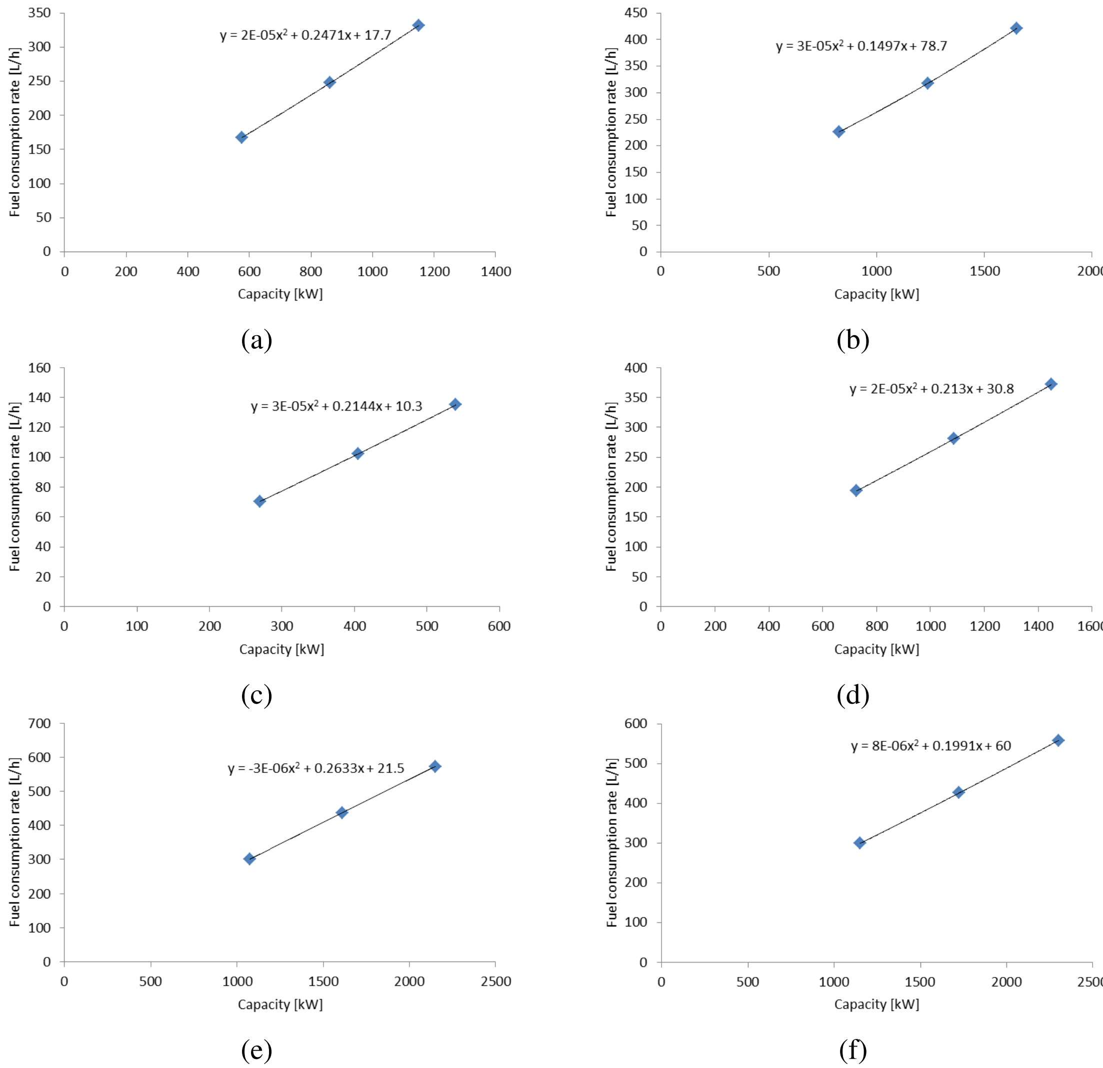
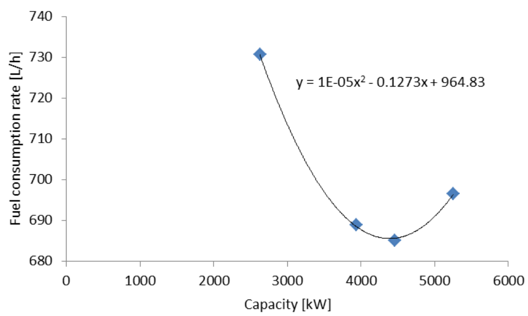
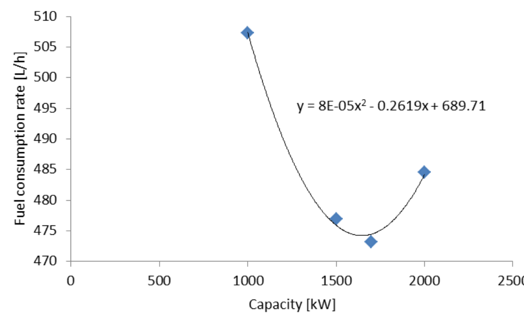


Figure 24: Fuel consumption curves for (a) Cat. D3516BHD 1150 kW, (b) Cat. D3606 1650 kW, (c) DD2000 540 kW, (d) EMD 8V710 1450 kW, (e) EMD 12V710 2150 kW, and (f) EMD 20V645 2300 kW diesel generators [21], [22].



(a)



(b)

Figure 25: Fuel consumption curves for Wartsilla (a) 12V32 5250 kW, and (b) 12V200 2000 kW diesel generators [23].

A.4 Power Curves of Wind Turbines

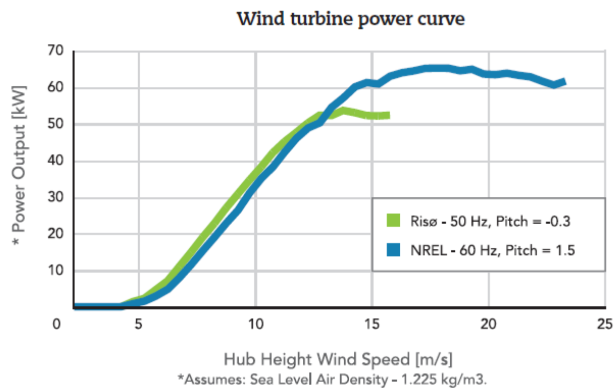
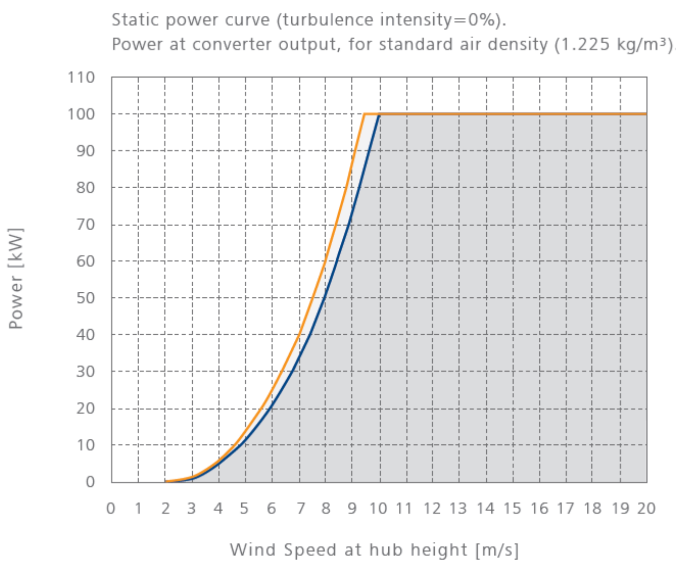


Figure 26: Wind power curve for 50 kW Entegrity EW50 turbine [24].



Wind speed [m/s]	Power [kW] Ø22	Power [kW] Ø24
2	0.0	0.0
3	0.8	0.5
4	4.9	5.2
5	11.5	13.2
6	21.0	24.2
7	34.2	39.3
8	51.8	59.3
9	74.0	84.3
10	100.0	100.0
11	100.0	100.0
12	100.0	100.0
13	100.0	100.0
14	100.0	100.0
15	100.0	100.0
16	100.0	100.0
17	100.0	100.0
18	100.0	100.0
19	100.0	100.0
20	100.0	100.0

Figure 27: Wind power curve for 100 kW Norvento nED100 turbine [25].

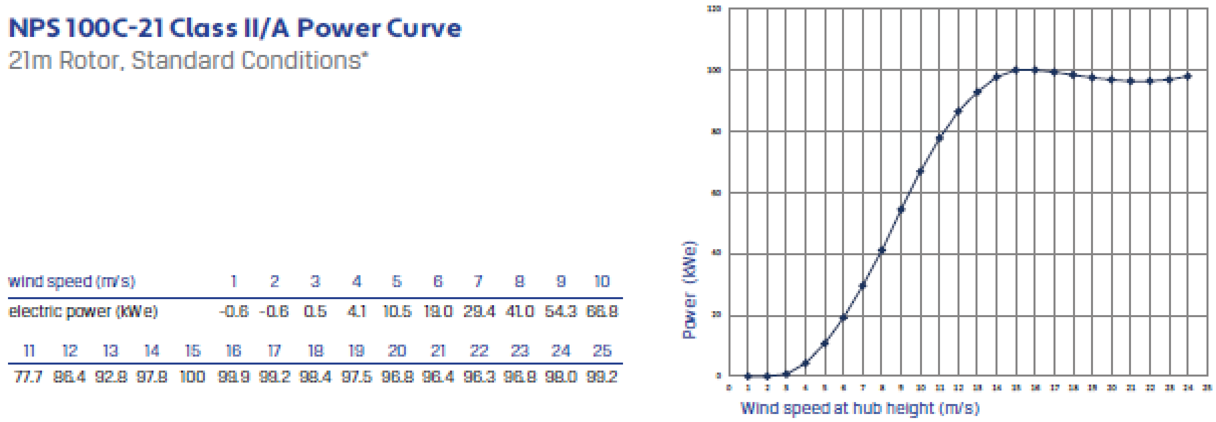
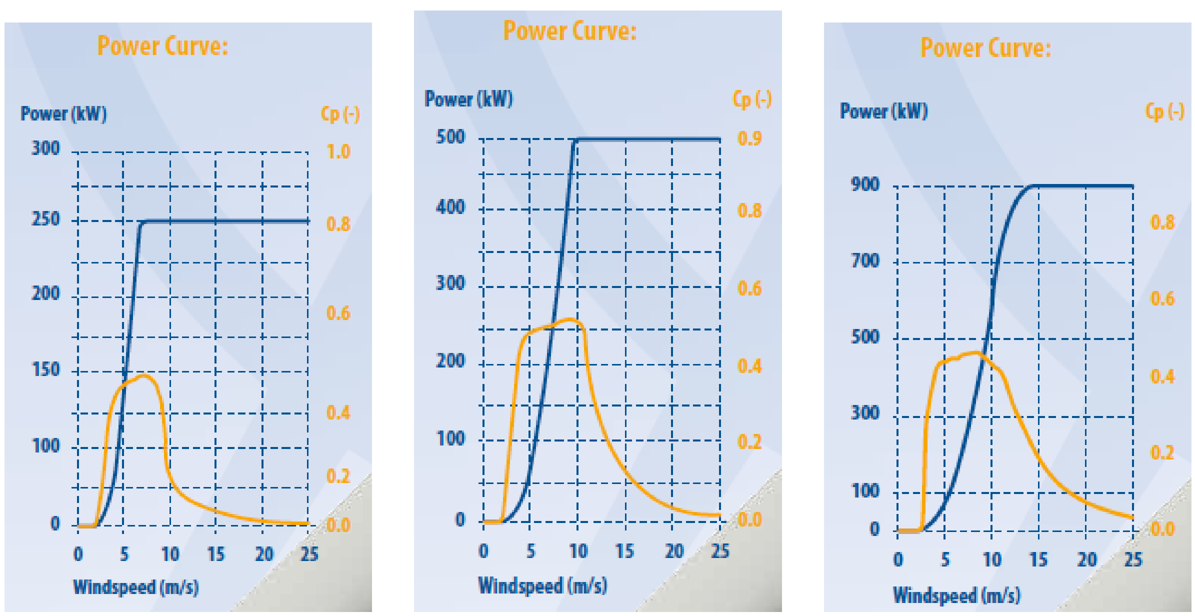
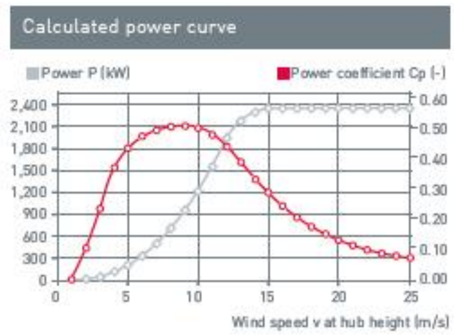


Figure 28: Wind power curve for 100 kW Northern Power Systems NPS100 turbine [26].



(a) (b) (c)

Figure 29: Wind power curves for EWT (a) 250 kW, (b) 500 kW, and (c) 900 kW turbines [27].



Wind (m/s)	Power P (kW)	Power-coefficient Cp (-)
1	0.0	0.00
2	2.0	0.10
3	18.0	0.27
4	56.0	0.36
5	127.0	0.42
6	240.0	0.46
7	400.0	0.48
8	626.0	0.50
9	892.0	0.50
10	1,223.0	0.50
11	1,590.0	0.49
12	1,900.0	0.45
13	2,080.0	0.39
14	2,230.0	0.34
15	2,300.0	0.28
16	2,310.0	0.23
17	2,310.0	0.19
18	2,310.0	0.16
19	2,310.0	0.14
20	2,310.0	0.12
21	2,310.0	0.10
22	2,310.0	0.09
23	2,310.0	0.08
24	2,310.0	0.07
25	2,310.0	0.06

$\rho = 1.225\ kg/m^3$

Figure 30: Wind power curve for 2300 kW Enercon En-70 E4 turbine [28].

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