FUELLING CHANGE IN THE ARCTIC – PHASE II

Renewable energy solutions for the Canadian Arctic

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THE POWER OF RENEWABLES

WWF-Canada is committed to protecting Arctic ecosystems and species while building a sustainable northern economy for the people who live there. This is a time of dramatic flux, with the Arctic warming at twice the average global rate and sea-ice levels reaching record lows. Sustainable and clean renewable energy solutions are urgently needed to protect both people and nature.

In the Arctic, diesel fuel is the primary energy source. The dependency on diesel has high logistical and financial costs, negative impacts on the environment, and hinders the self-sufficiency of northern communities. Renewable energy from wind and solar has been proven reliable in remote northern communities, and can contribute to sustainability in Northern Canadian communities and a cleaner Arctic environment.

In the second phase of our Arctic Renewable Energy program, WWF-Canada commissioned the Waterloo Institute for Sustainable Energy (WISE) to perform in-depth feasibility analyses on the costs and economic benefits of renewable energy. The study focuses on the five communities identified in a pre-feasibility study as having the strongest business case for renewable energy deployment, and therefore the most viable for further study. Those five communities include Sanikiluaq, Iqaluit, Rankin Inlet, Arviat, and Baker Lake. (This report focuses on communities in Nunavut; we also analyzed a sixth community, Sachs Harbour in the Northwest Territories.)

While the Phase I pre-feasibility findings were encouraging, the results of these Phase II feasibility analyses exceeded expectations. Our research revealed that an initial investment in a mix of renewable energy in remote northern communities can lead to immense carbon dioxide (CO_2) emissions reductions, with renewable energy penetration averages reaching 80 per cent in some communities, and far greater than expected operations and maintenance (O&M) savings over the next 20 years, to the tune of $30 million in one community alone.

FEASIBILITY STUDY

For Phase II, WISE developed a customized mathematical model for each of the identified communities – using community-specific data and timelines, as well as different types of technology – to provide community-level simulation for each year in a 20-year period. This study considers more detailed parameters that were only broadly approximated in the pre-feasibility study, including diesel generator fuel curves, wind-turbine power curves and unit capacity of renewable-energy equipment. As a result, we now have a realistic picture of renewable energy penetration, costs and savings potential.

RESULTS

The simulation results indicate that the deployment of renewable-energy diesel-hybrid systems in all communities reduce the consumption of diesel. The addition of a battery energy-storage system will reduce fuel use, but it is overall a more expensive solution for some communities. The study also found that, in general, wind is the preferable renewable energy option in Nunavut, though in the communities of Iqaluit, Arviat and Sanikiluaq, the diesel-solar-wind-battery combination was found to be the most cost-effective.

The results of this feasibility study show that a substantial reduction in greenhouse gas (GHG) emissions, ranging from 26 per cent to 75 per cent, can be achieved, with higher-than-expected annual average penetration of renewable energy from almost 29 per cent to almost 82 per cent, and a range of savings of $9 million to $30 million over a 20-year period.

Results from 20-year simulations in identified communities:

BAKER LAKE	The highest annual average RE penetration level obtained was 81.6% for the community of Baker Lake for the diesel-wind-battery hybrid model, resulting in about 74.1% reduction in emissions and total savings of $13.4 million (approximately 29% of Business-as-Usual (BAU) costs) over a 20 year period.
SANIKILUAQ	The community of Sanikiluaq, which was ranked first in the pre-feasibility studies, resulted in an annual average RE penetration of 81.5% for the diesel-solar-wind-battery hybrid model, with savings of $ 10.2 million (approximately 39% of BAU costs) in 20 years, and a reduction of emissions of about 70%.
ARVIAT	The results obtained for Arviat showed an annual average RE penetration of 66.5% for the diesel-solar-wind-battery hybrid model, with 55% reduction in emissions, and a savings of $9.3 million (approximately 24% of BAU costs) over a 20-year horizon.
RANKIN INLET	The best scenario for Rankin Inlet is an annual average RE penetration of 53.3% in the Diesel-wind-battery hybrid model, with $26.8 million (27.2% of BAU costs) in savings in 20 years, and a reduction in emissions of 47%.
IQALUIT	The diesel-solar-wind-battery hybrid model is the best option for Iqaluit, resulting in an annual average RE penetration of 28.8% and GHG reduction of 26%, with the highest savings of all communities at $29.7 million over a 20-year period, which corresponds to 13.4% of the BAU costs.

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COMMUNITY OUTREACH

Arctic Renewable Energy Summit in Iqaluit, September, 2016

In September 2016, WWF-Canada convened an Arctic Renewable Energy Summit in Iqaluit in partnership with Indigenous and Northern Affairs Canada (INAC), the Government of Nunavut and Qulliq Energy Corporation. The summit brought together Canada's leading northern remote communities' renewable energy researchers, utilities, senior federal and territorial government officials, and representatives from Nunavut communities.

The Arctic Renewable Energy Summit also acted as a platform for describing existing Arctic renewable energy successes, with examples from communities in Alaska and Russia, and from the mining industry in the Canadian Arctic. The summit drew key insights and takeaways from these success stories and identified their applicability to remote communities in Northern Canada.

NEXT STEPS

WWF-Canada is committed to seeing renewable energy deployed in remote northern communities, beginning with Arviat and two other communities yet to be determined.

Arviat is one of five Nunavut communities determined by WWF-Canada and WISE as a cost-effective and carbon-effective candidate for the deployment of renewable energy, with a special emphasis on wind energy. In a letter to Arctic Renewable Energy Summit organizers, the Hamlet of Arviat expressed its interest and support for increasing the use of renewable energy in Nunavut. As an immediate next step, WWF-Canada will assist the Hamlet of Arviat in developing and implementing a comprehensive wind resource assessment plan to support future wind project development in the community. WWF-Canada, in partnership with the Alaska Center for Energy & Power (ACEP), will assess available data from a variety of sources to determine potential sites for wind energy development based on computer modelling. These potential sites will then be shared with communities to account for traditional knowledge about species, habitat and community uses. This combined information will form the basis for a deployment plan to share with stakeholders in Arviat.

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RENEWABLE ENERGY DEPLOYMENT IN CANADIAN ARCTIC

PHASE II: FEASIBILITY STUDIES

REPORT ON SELECTED COMMUNITIES OF NUNAVUT AND NORTHWEST TERRITORIES

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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 portion of the Canadian regions of the arctic that this study focuses on has about 33 communities, of which 25 belongs to the territory of Nunavut and 8 belongs to the Inuvik region of Northwest Territories (NWT). Diesel generators are the only means to generate electricity in these communities, except Inuvik where there are a couple of natural gas based generators along with diesel. The use of fossil-fuel 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, as well as the generation of black carbon or soot, which has particularly negative impacts on arctic snow and ice. Moreover, the dependency on diesel and its associated costs are an economic problem in the North, as governments subsidize this fuel.

In order to reduce the diesel dependency, these communities should look into environmentally friendly and economic sources of energy, such as solar and wind. 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 on the communities of Nunavut and the Inuvik region of the NWT to integrate Renewable Energy (RE) sources in their grids. The current task is focused on developing a business case for diesel generator replacement with RE deployment in 5 communities of Nunavut and 1 of NWT, of the total 33 communities, by studying the techno-economic feasibility of RE integration. The final objective is to initiate pilot projects in some of the identified communities based on the feasibility studies presented in this report.

The selection of the 5 communities of Nunavut and 1 from NWT was done in a pre-feasibility study, initializing with a pre-selection of 13 out of 25 Nunavut communities and 4 out of 8 communities from the Inuvik region of NWT, using high-level data of wind speed and solar insolation, community size, their location and associated transportation costs, and energy demand. HOMER was used for RE integration analyses, for a 25-year planning horizon, considering hourly wind and solar profiles, existing diesel generator portfolio, and other data used in the pre-selection process. The results were used to rank the communities using a set of predefined ranking criteria, and the results were presented to the respective group of stakeholders of the two territories in consideration, who provided feedback that was used to select the final communities for the studies discussed in this report.

Feasibility studies were performed on the 6 selected communities using an existing and tested optimization framework of optimum RE integration. A mathematical optimization model of 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 simulation results obtained using this model are better than those obtained in the pre-feasibility studies, in terms of higher RE penetration and larger savings potential. This can be attributed to the fact that the current studies have considered more detailed parameters in its model, which were broadly approximated in the pre-feasibility studies, such as the diesel generator fuel curves, wind turbine power curves, and unit capacity of RE equipment. The feasibility studies model also incorporated a broader RE search space of 6 different wind turbines and 2 solar panels from various manufacturers, as well as a wider range of diesel generators for replacing old ones at the end of their useful life. Furthermore, one of the most important factors that has impacted the simulation outcome in the feasibility stage, is the consideration of load growth over the project horizon, which HOMER could not properly handle in the pre-feasibility studies simulations. The best case results obtained for a 20-year horizon from the simulations in the feasibility studies are the following:

1. The highest annual average RE penetration level obtained was 81.59% for the community of Baker Lake for the diesel-wind-battery hybrid model, resulting in about 74.12% reduction in emissions and total savings of \$ 13.4 million (approximately 29% of Business-as-Usual (BAU) costs) over a 20 year period.

2. The community of Sanikiluaq, which was ranked first in the pre-feasibility studies, resulted

in an annual average RE penetration of 81.48% for the diesel-solar-wind-battery hybrid model, with savings of $ 10.2 million (approximately 39.02% of BAU costs) in 20 years, and a reduction of emissions of about 70%.

3. The results obtained for Arviat showed an annual average RE penetration of 66.49% for the diesel-solar-wind-battery hybrid model, with 55% reduction in emissions, and a savings of $9.32 million (approximately 24% of BAU costs) over a 20-year horizon.
4. The best scenario for Rankin Inlet is an annual average RE penetration of 53.32% in the diesel-wind-battery hybrid model, with $26.83 million (27.15% of BAU costs) in savings in 20 years, and a reduction in emissions of 47%.
5. The diesel-solar-wind-battery hybrid model is the best option for Iqaluit, resulting in an annual average RE penetration of 28.82% and GHG reduction of 26%, with the highest savings of all communities at $29.7 million over a 20-year period, which corresponds to 13.4% of the BAU costs.
6. For Sachs Harbour, the diesel-wind-solar hybrid model is the best case, resulting in an annual average RE penetration and GHG reduction of 38.99% and 35.41%, respectively, with total savings of $0.44 million over a 20-year period, which corresponds to 7.97% of the BAU costs.

The simulation results indicate that the deployment of RE-diesel hybrid systems in any community will always economically reduce the consumption of diesel. The addition of battery energy storage system will reduce fuel use, but it is an overall more expensive solution for some communities. It is also observed that in general wind is the preferable RE option, and in some cases the introduction of solar increases the project net present cost (NPC) with reduction in RE penetration; however, in the communities of Arviat and Sanikiluaq, the diesel-solar-wind-battery option was the most cost-effective. The results of this feasibility study show that a substantial reduction in greenhouse gas (GHG) emissions, ranging from 26% to 74%, can be obtained, with higher than expected annual average penetrations of RE from 28% to 81.6%, and a range of savings of $0.5 million to $29.7 million over a 20-year period. Based on these results, pilot projects should be pursued for Baker Lake and Sanikiluaq, and if possible, for Arviat or Rankin Inlet.

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Table of Contents

List of Figures

List of Tables

GLOSSARY

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

Nomenclature

The main notations used throughout the report are stated below for quick reference.

Indices

e_D	Existing diesel generators of different capacities and manufacturers
h	Hour
y	Year
n_B	New batteries from different manufacturers
n_D	New diesel generators of different capacities
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^{ExDsl}	Existing diesel capacity including stand-by mode units [kW]
d	Discount rate [%]
$Dcost$	Diesel cost [$/L]
df	Derating factor of solar PV panels [%]
DoD^{Bat}	Depth-of-discharge (DOD) of a battery [%]
GH^{life}	Useful life of new diesel generator [hr.]
GH^{remain}	Remaining life of existing diesel generator [hr.]
GT^{STC}	Incident solar radiation on the PV array at standard test conditions [kW/m^2)]
HOM^{ExDsl}	Hourly Operation and Maintenance (O&M) costs of existing diesel generator [$/kWh]
HOM^{NewDsl}	Hourly O&M costs of existing diesel generator [$/kWh]

HOM^{Sol}	Hourly O&M costs of solar panel set [\$/kWh]
HOM^{Wnd}	Hourly O&M costs of wind turbine [\$/kWh]
HOM^{Bat}	Hourly O&M costs of battery [\$/kWh]
HY	Hours in a year (model specific) [hr.]
M	A very large number
ML^{ExDsl}	Minimum load operation of existing diesel generator [%]
ML^{NewDsl}	Minimum load operation of new diesel generator [%]
Nb	Number of batteries considered
Nd	Number of new diesel generator considered
Ned	Number of existing diesel generator considered
Ns	Number of solar panel sets considered
Nw	Number of wind turbines considered
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 [hr.]
T^{OM}	Percentage of hours per annum scheduled for maintenance [%]
$Tcell$	Solar PV cell temperature in the current time step [°C]
$Tcell^{STC}$	Solar PV cell temperature under standard test conditions [°C]
UC^{NewDsl}	Unit cost of new diesel generators [\$/kW]
UC^{Sol}	Unit cost of solar panel sets [\$/kW]
UC^{Wnd}	Unit cost of wind turbines [\$/kW]
UC^{Bat}	Unit cost of new batteries [\$/kWh]
$Ucap^{NewDsl}$	Capacity of new diesel generator unit [kW]
$Ucap^{Sol}$	Capacity of solar panel set [kW]
$Ucap^{Wnd}$	Capacity of wind turbine [kW]
$Ucap^{Bat}$	Capacity of battery set [kWh]
WS	Wind speed [m/s]
α	Temperature coefficient of power for Solar PV panels [%/°C]
β	Generation reserve margin [%]

η^{Ch}	Efficiency of battery charging [%]
η^{Dch}	Efficiency of battery discharging [%]

Variables

Cap^{Bat}	Aggregate capacity of battery [kWh]
Cap^{NewDsl}	Aggregate capacity of new diesel generators [kW]
Cap^{Sol}	Aggregate capacity of solar PV [kW]
Cap^{Wnd}	Aggregate capacity of wind [kW]
$Capu^{NewDsl}$	Dummy variable to linearize a product [kW]
CC^{Bat}	Net present value (NPV) of battery capital cost [$]
CC^{NewDsl}	NPV of total capital costs of purchasing new diesel [$]
CC^{Sol}	NPV of solar PV capital cost [$]
CC^{Wnd}	NPV of wind capital cost [$]
FC^{Dsl}	NPV of total diesel fuel cost [$]
$Fcon^{ExDsl}$	Hourly fuel consumption rate of existing diesel generators [L/kWh]
$Fcon^{NewDsl}$	Hourly fuel consumption rate of new diesel generators [L/kWh]
NCA^{Bat}	New capacity addition of battery [kW]
NCA^{NewDsl}	New capacity addition of diesel [kW]
NCA^{Sol}	New capacity addition of solar PV [kW]
NCA^{Wnd}	New capacity addition of wind [kW]
OMC^{Bat}	NPV of battery O&M cost [$]
OMC^{Dsl}	NPV of total diesel O&M cost [$]
OMC^{Sol}	NPV of solar PV O&M cost [$]
OMC^{Wnd}	NPV of wind O&M cost [$]
Pb^{Ch}	Battery charging power [kW]
Pb^{Dch}	Battery discharging power [kW]
Pd^{ExDsl}	Power generated by existing diesel generator [kW]
Pd^{NewDsl}	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^{DslPur}	Binary variable to denote purchase of new diesel generator
$u^{ExDslOp}$	Binary variable to denote existing diesel generator ON/OFF state
$u^{NewDslOp}$	Binary variable to denote new diesel generator ON/OFF state
u^{SolPur}	Binary variable to denote purchase of solar PV
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. This study focuses on the 25 communities of Nunavut and 8 from the Inuvik region of the NWT.

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

All the communities considered in this study use only diesel for electricity generation, barring the community of Inuvik in the NWT, which has natural gas based generation as well; emission from these diesel electricity generation facilities are increasing the ill-effect of climate change in that region. Of particular concern is the emission of black carbon, which when deposited on snow and ice, darkens the surface and thereby enhances the absorption of solar radiation and consequently increases the melt rates [3]. 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 do 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 [4], is motivating the need for alternate sources of electricity generation. RE sources, mainly solar and wind, with or without energy storage using batteries, are of particular interest for these communities, since well-designed RE implementation plans have the potential for positive socio-economic-environmental effects. Building business cases for such plans is the ultimate objective of the studies carried out by WISE for the WWF.

A pre-feasibility study was undertaken to select the communities for detailed feasibility studies [5], 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 RE integration perspective. HOMER simulations were then performed to rank these pre-selected communities based on a certain set of ranking criteria, and the results were presented to the appropriate group of stakeholders for discussion and selection of the final 5 communities in Nunavut and 1 in NWT, shown in Figure 2, for detailed RE integration feasibility studies presented in this report.

1.1 Objectives

The primary objective of the present study is to displace diesel fuel by incorporating wind and solar plants and battery storage systems, so that local grids can be cleanly and securely operated,

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

as required by utility standards, at similar or even reduced costs than with the current diesel only systems. This can be accomplished by:

- Applying an existing feasibility study framework utilizing newly 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, diesel generators, and solar, wind, and temperature data to build a search space for the planning model.
- Presenting and analyzing long-term planning results and build 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 plan, where the optimization framework and the developed mathematical model are explained in detail; 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, along with important observations and analyses of the planning outcome. The techno-economic optimization results are presented as viable business cases for RE integration, 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 diesel only over the same time period. Section 4 provides the conclusions of the feasibility study, and recommends the RE plans that should be implemented in the various considered communities as possible pilot 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 [6], with a suitable modified optimization framework. The optimization framework in Figure 3, based on the approach proposed for northern communities in Ontario [7], is used here to build the planning model for the presented feasibility study.

A multi-time-step mathematical optimization model is developed here, incorporating various techno-economic considerations related to the integration of RE in diesel-driven communities, to determine the optimal plan for suitable RE deployment, with and without energy storage facilities. 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 operational technical restrictions, as well as the secure hourly operation of the community 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:

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

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

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

where $f(x)$ is the objective function; $h(x)$ and $g(x)$ are the sets of equality and inequality constraints, respectively; and x is the set of variables to be optimized. 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

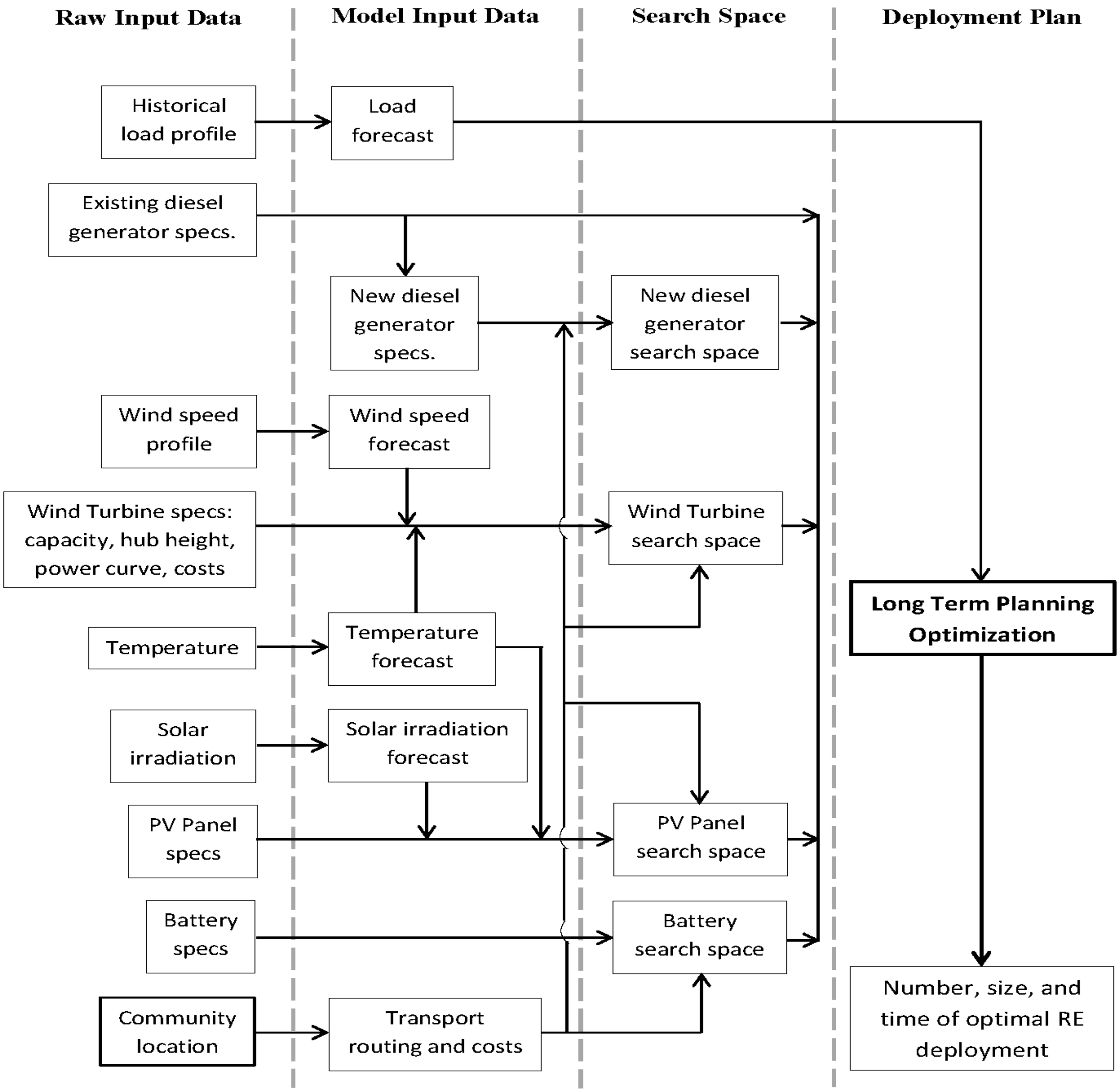


Figure 3: Optimization framework used for the feasibility studies.

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 equipment along with the purchase and operation of new diesel and RE equipment, as follows:

$$Z = \underbrace{CC^{Dsl} + FC^{Dsl} + OMC^{Dsl}}_{Diesel} + \underbrace{CC^{Sol} + OMC^{Sol}}_{Solar} + \underbrace{CC^{Wnd} + OMC^{Wnd}}_{Wind} + \underbrace{CC^{Bat} + OMC^{Bat}}_{Battery} \tag{4}$$

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.

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

$$CC^{NewDsl} = \sum_{y=1}^{PH} \frac{\sum_{n_D=1}^{Nd} UC_{n_D}^{NewDsl} \left(\sum_{h=1}^{HY} NCA_{n_D,y,h}^{NewDsl} \right)}{(1+d)^{y-1}} \tag{5a}$$

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

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

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

And the cost associated with the O&M of both existing and new diesel generators is given by:

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

where the factor 30 is associated with the time-step management of the project horizon as follows: The simulations for pre-feasibility studies in HOMER were based on $h = 1$ to 8760 per year, for the length of the project horizon, i.e., $y = 1$ to 25 years. However, this was found to be too time consuming for the proposed optimization model to arrive at a solution, as it took more than 50 hours in some cases to get an optimal solution. In view of this, the project horizon was reduced to $PH = 20$ years, and an hourly time-step for an average day of each month was used, which resulted in a total of $HY = 288$ hours in an average year. Hence, considering the averaging over a month, the factor of 30 was used, assuming 30 days in each month. The O&M costs of solar, wind and battery are given by the following expressions, respectively:

$$OMC^{Sol} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{n_S=1}^{Ns} HOM_{n_S}^{Sol}\, Cap_{n_S,y,h}^{Sol}}{(1+d)^{y-1}} \tag{7}$$

$$OMC^{Wnd} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{n_W=1}^{Nw} HOM_{n_W}^{Wnd}\, Cap_{n_W,y,h}^{Wnd}}{(1+d)^{y-1}} \tag{8}$$

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

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:

$$FC^{Dsl} = \sum_{y=1}^{PH} \frac{Dcost \sum_{h=1}^{HY} 30 \left(\sum_{e_D=1}^{Ned} Fcon_{e_D,y,h}^{ExDsl} + \sum_{n_D=1}^{Nd} Fcon_{n_D,y,h}^{NewDsl} \right)}{(1+d)^{y-1}} \tag{10}$$

where

$$Fcon_{e_D,y,h}^{ExDsl} = F_{e_D}\left(Pd_{e_D,y,h}^{ExDsl},\ u_{e_D,y,h}^{ExDslOp}\right) \tag{11a}$$

$$Fcon_{n_D,y,h}^{NewDsl} = F_{n_D}\left(Pd_{n_D,y,h}^{NewDsl},\ u_{n_D,y,h}^{NewDslOp}\right) \tag{11b}$$

denotes the fuel consumption of each existing and new diesel generator 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.

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:

$$\underbrace{\sum_{e_D=1}^{Ned} Pd_{e_D,y,h}^{ExDsl} + \sum_{n_D=1}^{Nd} Pd_{n_D,y,h}^{NewDsl}}_{Diesel} + \underbrace{\sum_{n_S=1}^{Ns} Ps_{n_S,y,h}^{Sol}}_{Solar} + \underbrace{\sum_{n_W=1}^{Nw} Pw_{n_W,y,h}^{Wnd}}_{Wind}$$
$$+ \underbrace{\sum_{n_B=1}^{Nb} \left(Pw_{n_B,y,h}^{Dch} - Pw_{n_B,y,h}^{Ch}\right)}_{Battery} = PD_{y,h} \tag{12}$$

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:

$$\underbrace{\sum_{e_D=1}^{Ned} Cap^{ExDsl}_{e_D,y}\, u^{ExDslOp}_{e_D,y,h} + \sum_{n_D=1}^{Nd} Cap^{NewDsl}_{n_D,y,h}}_{Diesel} + \underbrace{\sum_{n_B=1}^{Nb} SOC_{n_B,y,h}}_{Battery} \geq (1+\beta)PD_{y,h} + \underbrace{0.25\sum_{n_S=1}^{Ns} Ps^{Sol}_{n_S,y,h}}_{Solar} + \underbrace{0.5\sum_{n_W=1}^{Nw} Pw^{Wnd}_{n_W,y,h}}_{Wind} \tag{13}$$

Dynamic Addition of New Capacity

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

$$Cap^{NewDsl}_{n_D,y,h+1} = Cap^{NewDsl}_{n_D,y,h} + NCA^{NewDsl}_{n_D,y,h} \tag{14}$$

$$Cap^{Sol}_{n_S,y,h+1} = Cap^{Sol}_{n_S,y,h} + NCA^{Sol}_{n_S,y,h} \tag{15}$$

$$Cap^{Wnd}_{n_W,y,h+1} = Cap^{Wnd}_{n_W,y,h} + NCA^{Wnd}_{n_W,y,h} \tag{16}$$

$$Cap^{Bat}_{n_B,y,h+1} = Cap^{Bat}_{n_B,y,h} + NCA^{Bat}_{n_B,y,h} \tag{17}$$

and, to sequentialize the hour and year indices:

$$Cap^{NewDsl}_{n_D,y+1,1} = Cap^{NewDsl}_{n_D,y,HY} + NCA^{NewDsl}_{n_D,y,HY} \tag{18}$$

$$Cap^{Sol}_{n_S,y+1,1} = Cap^{Sol}_{n_S,y,HY} + NCA^{Sol}_{n_S,y,HY} \tag{19}$$

$$Cap^{Wnd}_{n_W,y+1,1} = Cap^{Wnd}_{n_W,y,HY} + NCA^{Wnd}_{n_W,y,HY} \tag{20}$$

$$Cap^{Bat}_{n_B,y+1,1} = Cap^{Bat}_{n_B,y,HY} + NCA^{Bat}_{n_B,y,HY} \tag{21}$$

where the new capacity additions are as follows:

$$NCA^{NewDsl}_{n_D,y,h} = Ucap^{NewDsl}_{n_D}\, u^{DslPur}_{n_D,y,h} \tag{22}$$

$$NCA^{Sol}_{n_S,y,h} = Ucap^{Sol}_{n_S}\, u^{SolPur}_{n_S,y,h} \tag{23}$$

$$NCA_{nRW,N,h}^{Wnd} = Ucap_{n_W}^{Wnd}\, u_{n_W,y,h}^{WndPur} \tag{24}$$

$$NCA_{nRB,N,h}^{Bat} = Ucap_{n_B}^{Bat}\, u_{n_B,y,h}^{BatPur} \tag{25}$$

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 to the requirements of the possible pilot projects, while considering for the gestation period of individual technologies; for diesel, the window is from the 3rd to the 10th year for a 20-yr project horizon.

Diesel Generation Limits

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

$$Pd_{n_D,y,h}^{NewDsl} \leq Cap_{n_D,y,h}^{NewDsl}\, u_{n_D,y,h}^{NewDslOp} \tag{26}$$

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 [8], based on the following product of two variables:

$$q = x_1 x_2 \tag{27}$$

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 $x_1 x_2$, as follows:

$$q \leq x_1^{\text{Max}} x_2 \tag{28a}$$

$$q \leq x_1 \tag{28b}$$

$$q \geq x_1 - x_1^{\text{Max}}(1 - x_2) \tag{28c}$$

$$q \geq 0 \tag{28d}$$

To implement this method in the planning model, the positive continuous variable is defined as $x_1 = Cap_{n_D,y,h}^{NewDsl}$, with the upper limit assumed to be $x_1^{Max} = 5(Ucap_{n_D}^{NewDsl})$, while the binary variable is defined as $x_2 = u_{n_D,y,h}^{NewDslOp}$. Thus, a new positive continuous variable is defined as

$Capu_{n_D,y,h} = q$, and the following set of equations linearize and replace (26) in the model:

$$Pd^{NewDsl}_{n_D,y,h} \leq Capu_{n_D,N,h} \tag{29}$$

$$Capu_{n_D,y,h} \leq 5\left(Ucap^{NewDsl}_{n_D}\right)\, u^{NewDslOp}_{n_D,y,h} \tag{30}$$

$$Capu_{n_D,y,h} \leq Cap^{NewDsl}_{n_D,y,h} \tag{31}$$

$$Capu_{n_D,y,h} \geq Cap^{NewDsl}_{n_D,y,h} - 5\left(UCap^{NewDsl}_{n_D}\right)\left(1 - u^{NewDslOp}_{n_D,y,h}\right) \tag{32}$$

$$Capu_{n_D,y,h} \geq 0 \tag{33}$$

For existing diesel generators, the maximum power generation constraint is as follows:

$$Pd^{ExDsl}_{e_D,y,h} \leq Cap^{ExDsl}_{e_D,y}\, u^{ExDslOp}_{e_D,y,h} \tag{34}$$

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:

$$Pd^{NewDsl}_{n_D,y,h} \geq ML^{NewDsl}_{n_D}\, Capu_{n_D,y,h} \tag{35}$$

$$Pd^{ExDsl}_{e_D,y,h} \geq ML^{ExDsl}_{e_D}\, Cap^{ExDsl}_{e_D,y}\, u^{ExDslOp}_{e_D,N,h} \tag{36}$$

Diesel Generator Life

The useful life of new diesel generators and the remaining life of existing diesel generators, in hours, are incorporated in the model by the following two expressions, respectively:

$$\sum_{y=1}^{PH}\sum_{h=1}^{HY} 30\, u^{NewDslOp}_{n_D,y,h} \leq GH^{life}_{n_D} \tag{37}$$

$$\sum_{y=1}^{PH}\sum_{h=1}^{HY} 30\, u^{ExDslOp}_{e_D,y,h} \leq GH^{remain}_{e_D} \tag{38}$$

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:

$$\sum_{h=1}^{HY} u^{ExDslOp}_{e_D,y,h} \leq 288(1 - T^{OM}) \tag{39}$$

$$\sum_{h=1}^{HY} u^{NewDslOp}_{n_D,y,h} \leq 288(1 - T^{OM}) \tag{40}$$

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. Thus this equality constraint is expressed as follows:

$$Pw^{Wnd}_{n_W,y,h} = W_{n_W}\left(Cap^{Wnd}_{n_W,y,h},\ WS_{h}\right) \tag{41}$$

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:

$$Ps^{Sol}_{n_S,y,h} = Cap^{Sol}_{n_S,y,h}\, df^{Sol} \left(\frac{SI_h}{GT^{stc}}\right)[1 + \alpha\,(Tcell_h - Tcell^{stc})] \tag{42}$$

Dynamic Variation of 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:

$$SOC_{n_B,y,h+1} - SOC_{n_B,y,h} = \eta^{Ch}\, Pb^{Ch}_{n_B,y,h} - \frac{\eta^{Dch}}{Pb^{Dch}_{n_B,y,h}} + 0.8\, NCA^{Bat}_{n_B,y,h} \tag{43}$$

$$SOC_{n_B,y+1,`1'} - SOC_{n_B,y,`HY'} = \eta^{Ch}\, Pb^{Ch}_{n_B,y,`HY'} - \frac{\eta^{Dch}}{Pb^{Dch}_{n_B,y,`HY'}} + 0.8\, NCA^{Bat}_{n_B,y,`HY'} \tag{44}$$

Battery SOC Limits

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:

$$SOC_{n_B,y,h} \leq Cap^{Bat}_{n_B,y,h} \tag{45}$$

$$SOC_{n_B,y,h} \geq DoD^{Bat}\, Cap^{Bat}_{n_B,y,h} \tag{46}$$

Battery Charging/Discharging Limits

The maximum discharging capacity of a battery is constrained by the power value 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:

$$Pb^{Dch}_{n_B,y,h} \leq \left(\frac{1 - DoD^{Bat}}{T^{Dch}}\right) Cap^{Bat}_{n_B,y,h} \tag{47}$$

$$Pb^{Ch}_{n_B,y,h} \leq \left(\frac{1 - DoD^{Bat}}{T^{Dch}}\right) Cap^{Bat}_{n_B,y,h} \tag{48}$$

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):

$$Pb^{Dch}_{n_B,y,h} \geq u^{Dch}_{n_B,y,h} \tag{49}$$

$$Pb^{Ch}_{n_B,y,h} \leq u^{Ch}_{n_B,y,h} \tag{50}$$

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.

The battery life is computed as follows:

$$\sum_{y=1}^{PH}\sum_{h=1}^{HY}\left(P_{n_B,y,h}^{Dch}+P_{n_B,y,h}^{Ch}\right)\leq 3000\sum_{y=1}^{PH}\sum_{h=1}^{HY}NCA_{n_B,y,h}^{Bat} \tag{51}$$

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

Battery Charging/Discharging Complementarity

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

$$Pb_{n_B,y,h}^{Ch}\,Pb_{n_B,y,h}^{Dch}=0 \tag{52}$$

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 [9]:

$$x_1 \leq M\,q_1 \tag{53a}$$

$$x_2 \leq M\,q_2 \tag{53b}$$

$$q_1+q_2\leq 1 \tag{53c}$$

Hence, (52) is replaced by:

$$Pb_{n_B,y,h}^{Dch}\leq u_{n_B,N,h}^{Dch}M \tag{54}$$

$$Pb_{n_B,y,h}^{Ch}\leq u_{n_B,y,h}^{Ch}M \tag{55}$$

$$u_{n_B,y,h}^{Ch}+u_{n_B,y,h}^{Dch}\leq 1 \tag{56}$$

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, 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:

$$\sum_{n_S=1}^{Ns}\sum_{h=1}^{HY} Ps^{Sol}_{n_S,y,h} \geq 0.01 \sum_{h=1}^{HY} load_{y,h} \tag{57}$$

$$\sum_{n_W=1}^{Nw}\sum_{h=1}^{HY} Pw^{Wnd}_{nw,y,h} \geq 0.01 \sum_{h=1}^{HY} load_{y,h} \tag{58}$$

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

$$\sum_{n_B=1}^{Nb}\sum_{y=1}^{PH}\sum_{h=1}^{HY} u^{BatPur}_{n_B,y,h} \geq 1 \tag{59}$$

2.1.3 Final Model

The resulting MILP optimization model is comprised of equations (4) to (25), (29) to (51), and (54) to (56), with equations (57) to (59) being optional, as required. This model was solved in the GAMS environment [10], using the CPLEX solver [11], 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. Most of the data being used here was utilized in the pre-feasibility studies; thus, the input data presented in this section replicates some of the dataset used in the pre-feasibility study. However, some new data is used to remove some significant assumptions made in the pre-feasibility studies, such as different wind turbine sizes and power curves and different fuel curves for various diesel generators. 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.

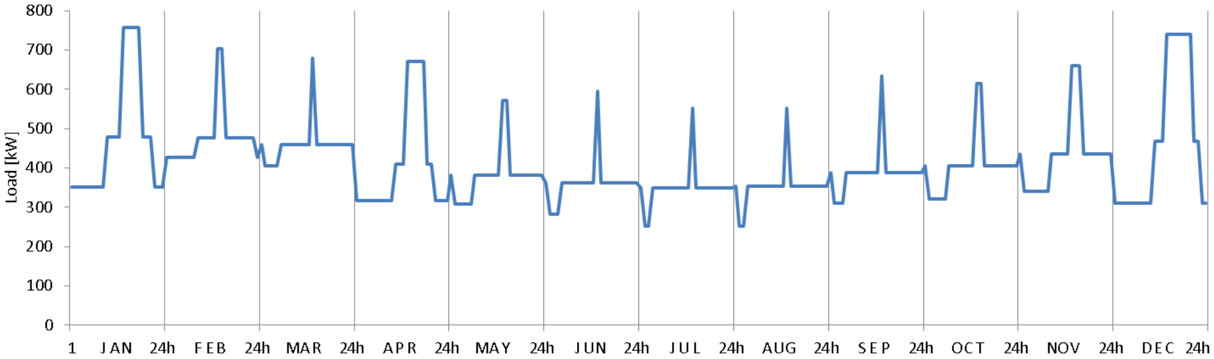


Figure 4: Daily average hourly load profile per month for Sanikiluaq, NU.

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 [12], and Northwest Territories Power Corporation (NTPC) for the community of Sachs Harbour of NWT [13]. 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 the per-minute load data for the year of 2012 of 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) [14], were gathered and processed to obtain the required hourly profiles of

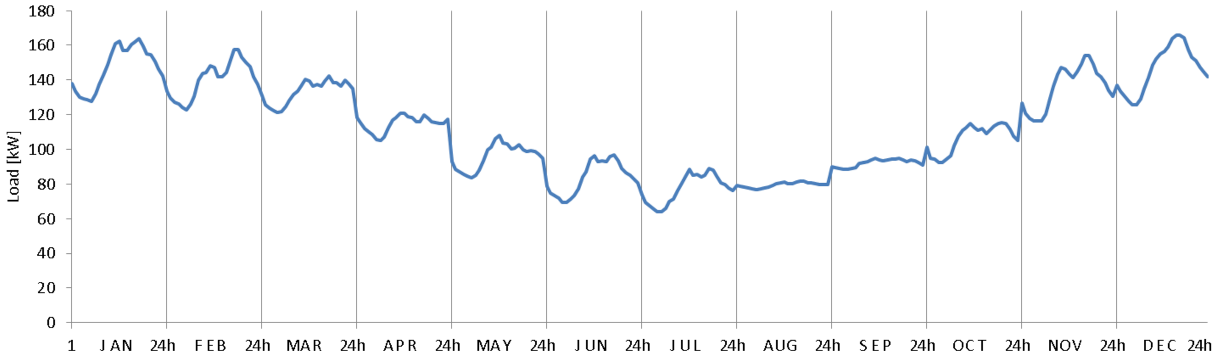


Figure 5: Daily average hourly load profile per month for Sachs Harbour, NWT.

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 Diesel Generators

A complete list of all existing diesel generators in the 6 communities in consideration is presented in Table 1, along with their manufacturers, capacities, and model numbers. This information was used to find the data-sheets of these generators, in order to obtain their fuel consumption curves, and thereby replace the assumption of the linear fuel consumption curves made during the pre-feasibility studies. 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 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.

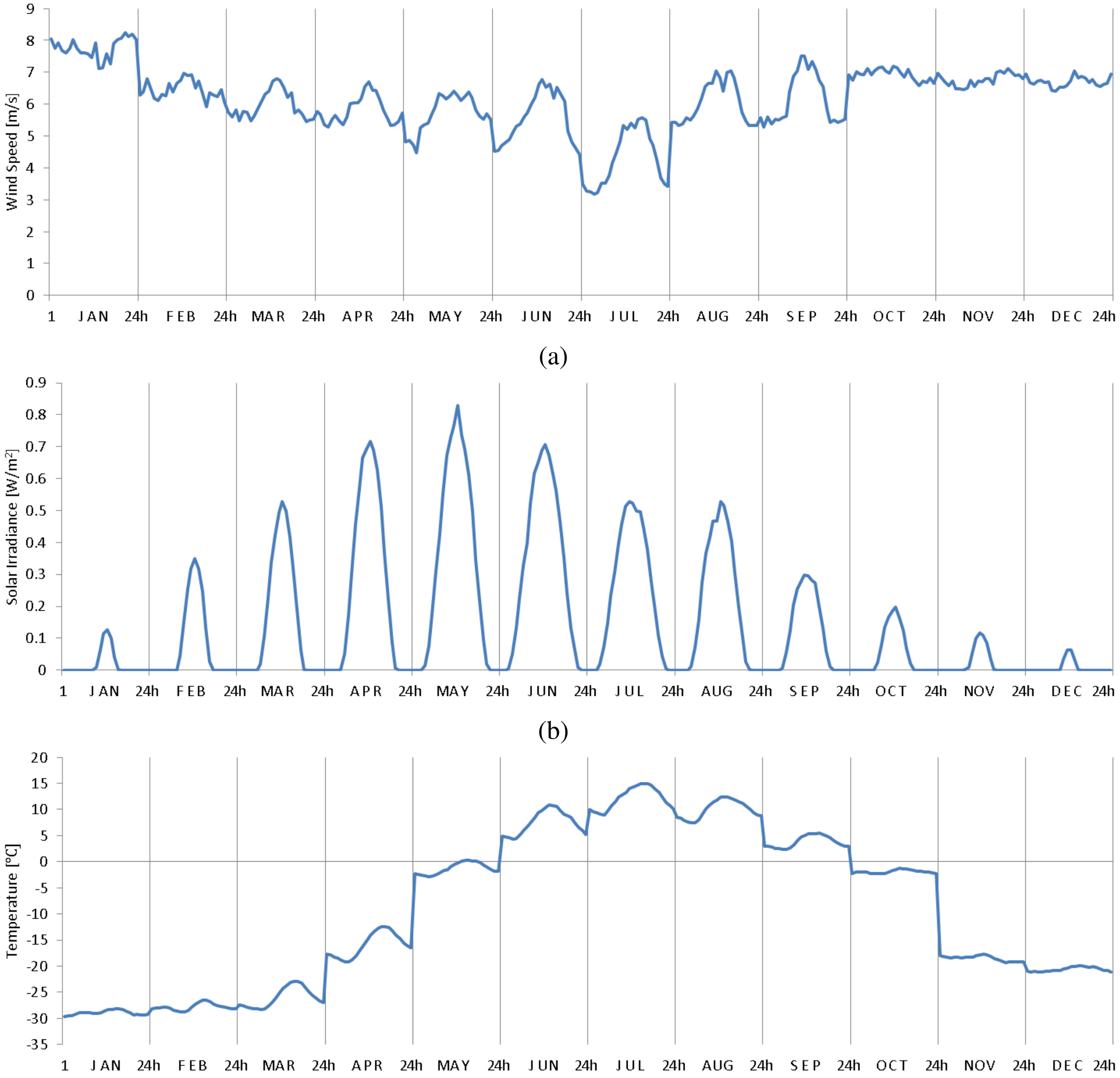
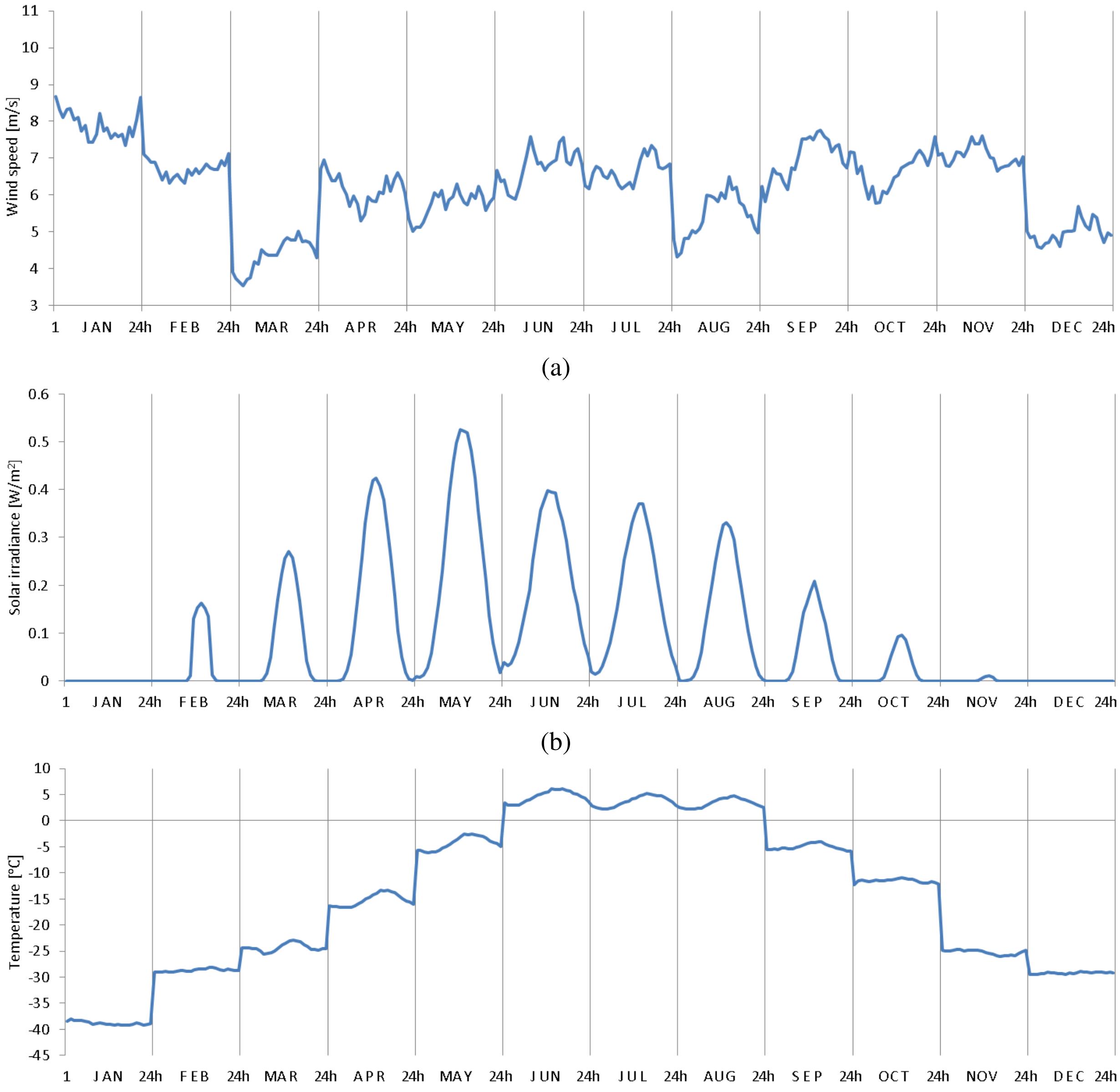


Figure 6: Daily average hourly profiles per month of (a) wind speed at 21m hub height, (b) solar insolation, and (c) temperature for the community of Sanikiluaq, NU.



(a)

(b)

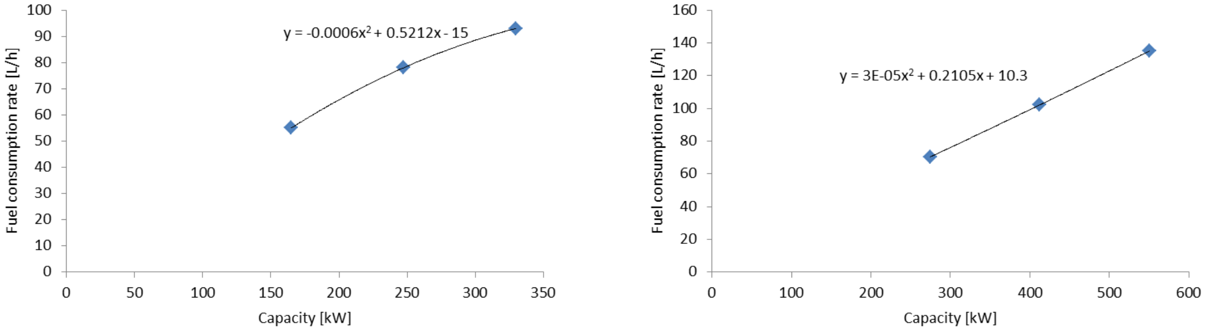
(c)

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	**Model**	**Community**	**Capacity** kW	**Model**
Arviat	550	Cat.[a] D3508B	Rankin Inlet	850	Cat. D3516
	800	Cat. D3512B		1,450	EMD 8V710
	800			1,650	Cat. D3606
	960	Cat. D3516B		2,150	EMD 12V710
Baker Lake	550	Cat. D3508B	Sanikiluaq	330	DD Series 60
	920	Cat. D3512BHD		330	
	1,150	Cat. D3516BHD		330	
Iqaluit	330	DD[b] Series 60		330	
	2,000	Wrt. [c] 12V200		500[d]	Cat. D3508B
	2300	EMD 20V645		540	DD Series 2000
	4,300[d]	Wrt. 12V32		550	Cat. D3508B
	5,250	Wrt. 12V32	Sachs Harbour	175	Cat. D3406
	5,250	Wrt. 12V32		300	Cat. D3412
				320[d]	DD Series 60

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



(a) (b)

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** kW	**Year of Project Horizon**																			
		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			●			●			●			●			●			●		

2.2.4 General Considerations

Data assumed constant for all communities are the following:

- The simulation time steps of the multi-time step model are 1 hour for an average of 24 h × 12 months = 288 h/year for a 20-year horizon.
- Discount rate of d = 8%.
- System operation criteria:
  - Economic minimization.
  - Operation strategy of load following.
  - Operating reserves of 50% of wind and 25% of solar power generated at every time step [15], [16].
- Generation reserve margin for system adequacy limit of β=10%.
- Minimum loading of a diesel generator is ML = 40% of the rated capacity for the existing units, and ML = 50% for the new ones purchased.
- Minimum percent of time per year a diesel generator must be off-line for maintenance is T^{OM} = 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} = 98%.
- Charging and discharging efficiencies of a battery are assumed to be η^{Ch} = η^{Dch} = 95%.
- Depth-of-Discharge of a battery is assumed to be DoD = 20%.
- Number of hours a battery can discharge continuously at peak power is aasumed 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 [17]. 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 the Government of Nunavut. 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.

2.2.5 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. These search spaces remove some of the assumptions made during pre-feasibility studies regarding replacement diesel generators, solar PV panelset capacity, and wind turbine capacity and power curves.

Diesel

New diesel generators are all assumed to be bought from Caterpillar, as nearly half of the existing portfolio has been supplied by this company. Thus, the new diesel generator search space, based on the existing capacities, is shown in Table 3, and their fuel curves in Appendix A.4.

Table 3: New diesel generator search space.

n_D	**Arviat**	**Baker Lake**	**Iqaluit**	**Rankin Inlet**	**Sanikiluaq**	**Sachs Harbour**
1	520	520	320	800	320	175
2	800	800	2,000	1,000	520	320
3	1,000	1,000	4,000	1,500	-	-
4	-	1,500	-	2,000	-	-

Solar

The search space for solar PV comprises 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 $\alpha = -0.41\%/°C$, and that for First Solar panels is $\alpha = -0.29\%/°C$, while the unit panelset capacities are $Ucap$ = 9.6 kW and 10 kW, respectively.

Table 4: 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	-	-	-

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 can be made for the Arctic. 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 4, and the wind power curves are presented in the Appendix A.5.

Battery

Li-ion batteries are considered in the presented studies as energy storage systems instead of the lead-acid batteries used in the pre-feasibility stage, as its operating characteristics and O&M handling and costs are better. This once costly battery's capital cost has decreased considerably

Table 5: Community-wise capital costs of RE equipment and diesel generators.

Community	**Wind**		**Solar**		**Battery**	**Diesel**	
	low	high	low	high		low	high
	\$/kW	\$/kW	\$/kW	\$/kW	\$/kWh	\$/kW	\$/kW
Arviat	8,715	9,076	5,424	5,507	1,594	719	726
Baker Lake	9,295	10,971	5,439	5,574	1,627	721	863
Iqaluit	8,076	10,235	5,142	5,277	1,577	737	1,136
Rankin Inlet	8,612	9,459	5,254	5,391	1,572	721	999
Sanikiluaq	7,943	8,614	5,082	5,211	1,504	727	738
Sachs Harbour	10,183	11,537	5,540	5,644	1,548	778	794

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 this project, and only Canadian Solar has been selected as the supplier, as it is more cost-effective over similar batteries from Tesla, and company personnel claim that these 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, and, as already mentioned, assumed a charging and discharging efficiencies of $\eta^{Ch} = \eta^{Dch} = 98\%$, $DoD = 20\%$, with $T^{Dch} = 4$ h of continuous peak power discharge capability.

Capital and O&M costs of Diesel and RE equipment

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 [18], 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 [19].

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 [7]), respectively. The final capital costs of RE equipment and diesel generators, varying with destination community, are shown in Table 5. 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. The per kW cost

Table 6: 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	**Equipment + Transport + Installation Cost**	**Overhead**				**Final Costs**
		Proj. Mgt.	Spare	Contingency	Logistics	
Sanikiluaq	5,714.69	342.88	571.47	857.20	457.18	7,943.42
Baker Lake	6,499.76	519.98	649.98	974.96	649.98	9,294.66

Table 7: Range of the O&M costs of diesel and RE equipment (all values in $/kWh) [18].

Community	**Wind**		**Solar**		**Battery**	**Diesel Generator**		
						Existing		New
	low	high	low	high		low	high	
Arviat	0.0398	0.0414	0.0155	0.0157	0.0073	0.0225	0.0256	0.0198
Baker Lake	0.0531	0.0626	0.0186	0.0191	0.0093	0.0257	0.0291	0.0225
Iqaluit	0.0231	0.0292	0.0088	0.0090	0.0036	0.0171	0.0194	0.0150
Rankin Inlet	0.0295	0.0324	0.0120	0.0123	0.0054	0.0197	0.0223	0.0173
Sanikiluaq	0.0363	0.0393	0.0145	0.0149	0.0069	0.0218	0.0248	0.0191
Sachs Harbour	0.0581	0.0659	0.0190	0.0193	0.0088	0.0260	0.0295	0.0228

of diesel generators varies similarly to the wind costs, except for the high values for Baker Lake, Iqaluit, and Rankin Inlet, which correspond to the generator that has the lowest capacity above 1,000 kW. In Table 6, 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 people are based, and the resulting O&M costs are depicted in Table 7.

3 Feasibility Analysis

The feasibility study is based on seven case studies as follows:

1. NoRE: BAU case involving 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 presented next.

3.1 Community-wise Results

Of the 5 communities in Nunavut, the largest load of more than 9 MW is for Iqaluit, the capital city, and the smallest is about 700 kW for the community of Sanikiluaq. The search spaces are different depending on the load, resulting in simulation times that are nearly 50 times more for Iqaluit than that for Sanikiluaq. On the other hand, the community of Sachs Harbour in NWT is quite small, with a peak load of around 200 kW; thus, this community has the smallest overall search space, resulting in average simulation times of less than 1 hour.

3.1.1 Arviat, NU

This is a mid-size community, with the second southernmost location of all communities in Nunavut, and thus has a reasonable solar insolation profile along with medium quality wind profiles. The results for this community, shown in Figures 9, 10, and 11, indicate that S and SB are not cost effective solutions for this community, since in both cases constraints for minimum solar and battery must be enforced, thereby generating higher NPCs than BAU for the project. The cases of SW and WB show that the inclusion of solar and battery, respectively, with wind

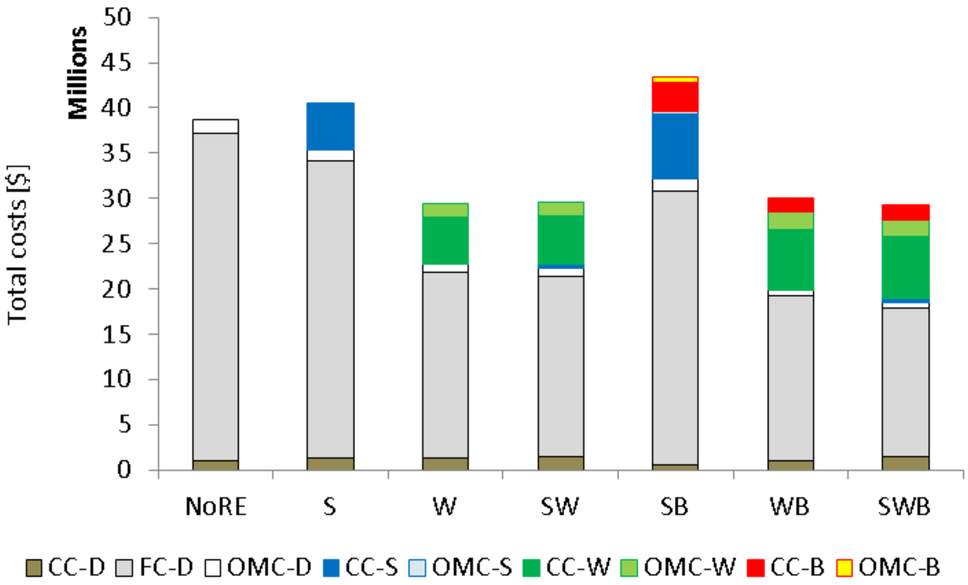


Figure 9: NPC components for Arviat, NU.

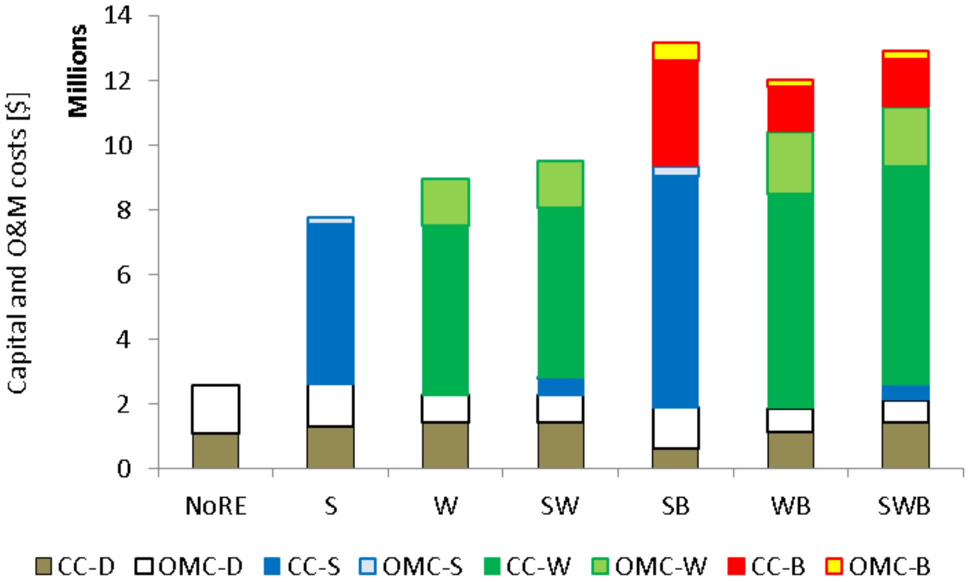


Figure 10: Net present value (NPV) of capital and O&M costs for Arviat, NU.

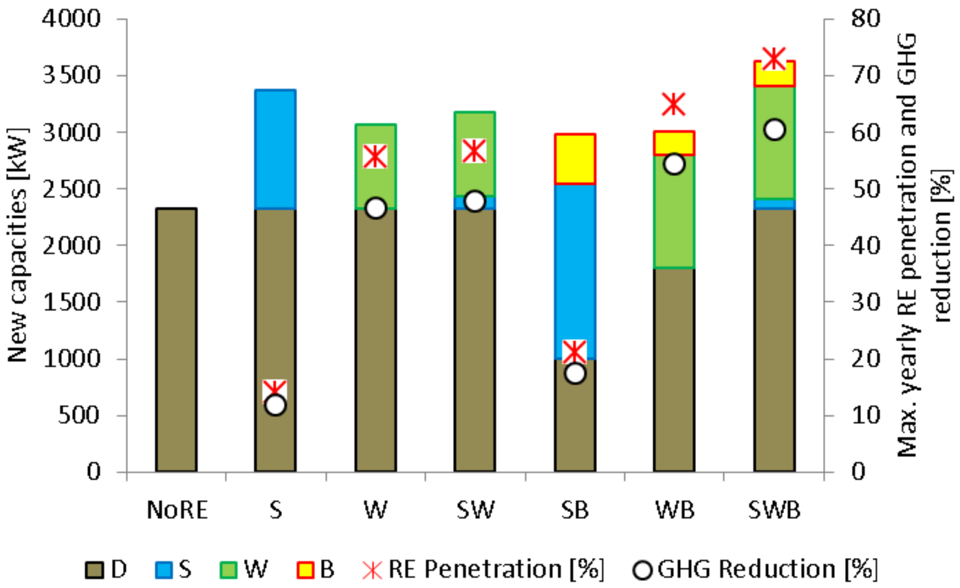


Figure 11: New capacity additions and percentages of annual maximum RE penetration and GHG reduction for Arviat, NU.

increases the NPC, resulting in a slight reduction in diesel consumption. SWB is the best case scenario for this community, with annual maximum and average RE penetrations of 72.96% and 66.49%, 60.4% reduction in emission, and savings of $9.32 million over 20 years, which is approximately 24% of BAU costs.

3.1.2 Baker Lake, NU

This community is not situated near the shore and thus has a higher transportation costs with respect to other Nunavut communities in consideration. Simulation results for this community are presented in Figures 12, 13, and 14. Observe that both S and SB not cost-effective for this community either. The best case solution is the WB system, with the SWB case containing a minimum amount of solar (as per the 1% energy constraint) and increasing the NPC by nearly $3 million. The WB best case reduces new diesel generator purchases to the lowest of all the scenarios for this community, with both annual maximum and average RE penetrations being the

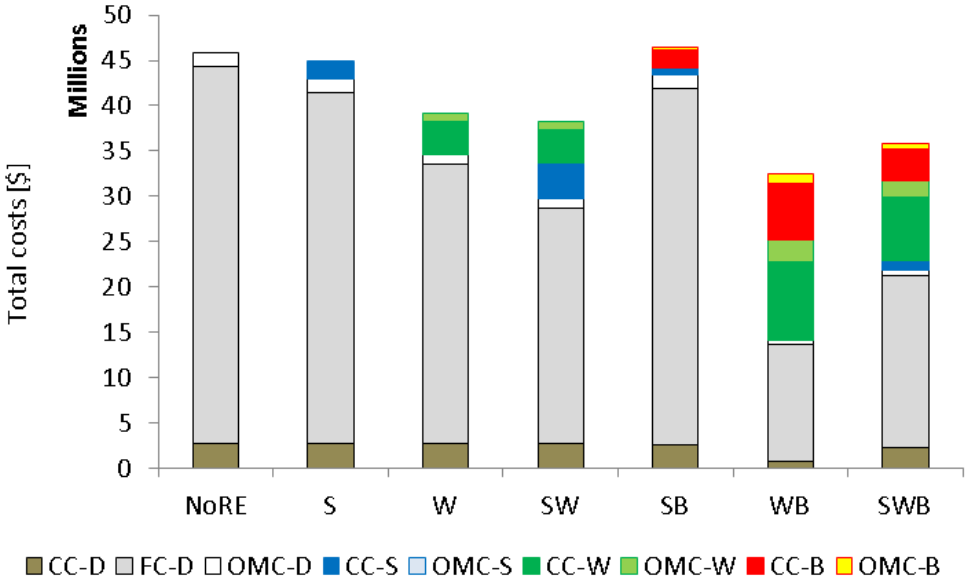


Figure 12: NPC components for Baker Lake, NU.

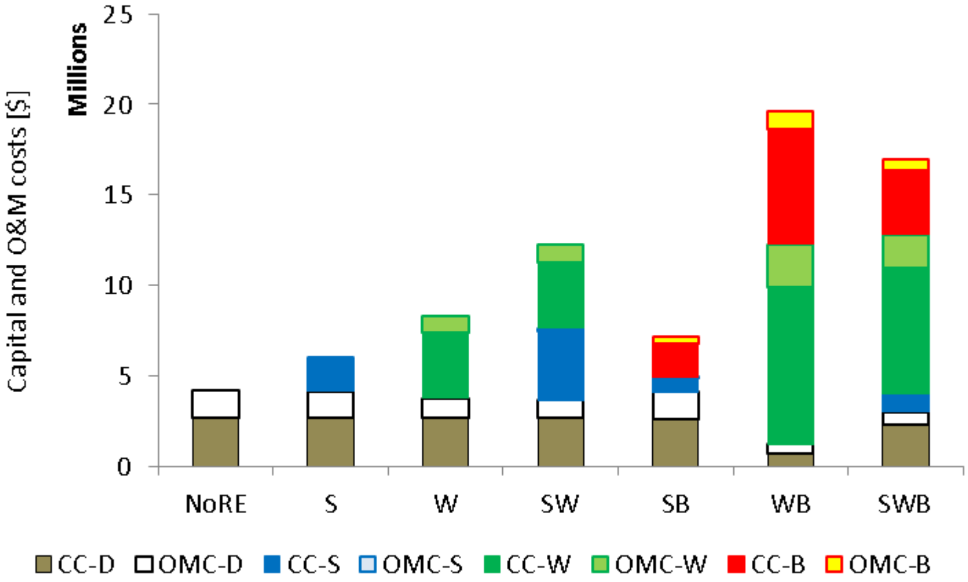


Figure 13: NPV of capital and O&M costs for Baker Lake, NU.

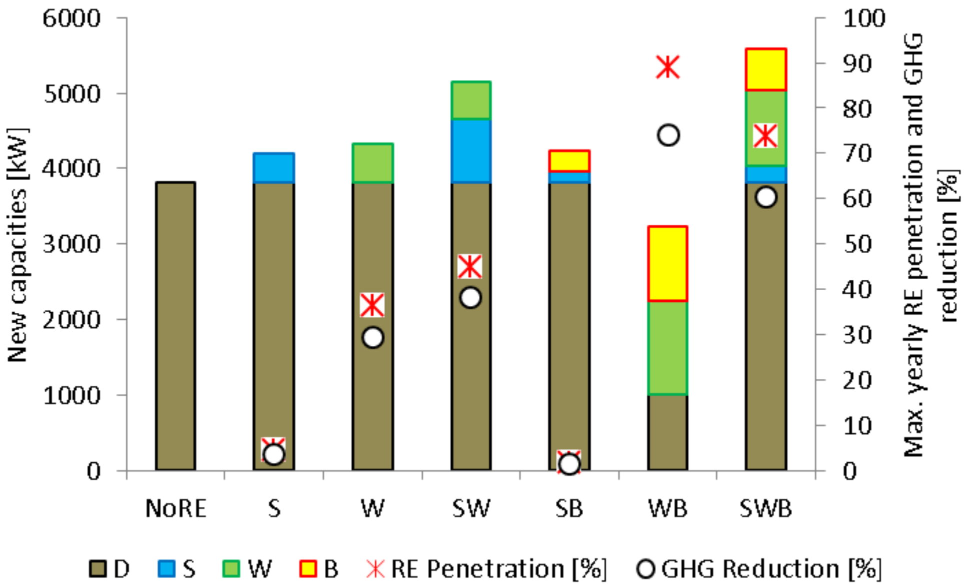


Figure 14: New capacity additions and percentages of annual maximum RE penetration and GHG reduction for Baker Lake, NU.

highest among all communities considered at 89.03% and 81.59%, respectively, a GHG reduction of 74.12%, and total savings of $13.4 million over 20 years (approximately 29% of the BAU costs).

3.1.3 Iqaluit, NU

Being the largest community in the territory of Nunavut, Iqaluit has the highest peak load of over 9 MW; hence, the search space is also the largest of all the communities considered, which consequently results in the longest simulation runtime of 55 hours (for the SWB scenario). The results for all the case studies are presented in Figures 15, 16, and 17. Observe that the NPCs of W and the SWB cases are very close to each other, with the latter being less by $1 million only. The SWB option reduces the diesel consumption by 14% of the W case, and hence nearly doubles both reduction in GHG emission to 26.2%, with the annual maximum and average RE penetrations of 31% and 28.82%, respectively. The savings for the best case is $29.7 million over

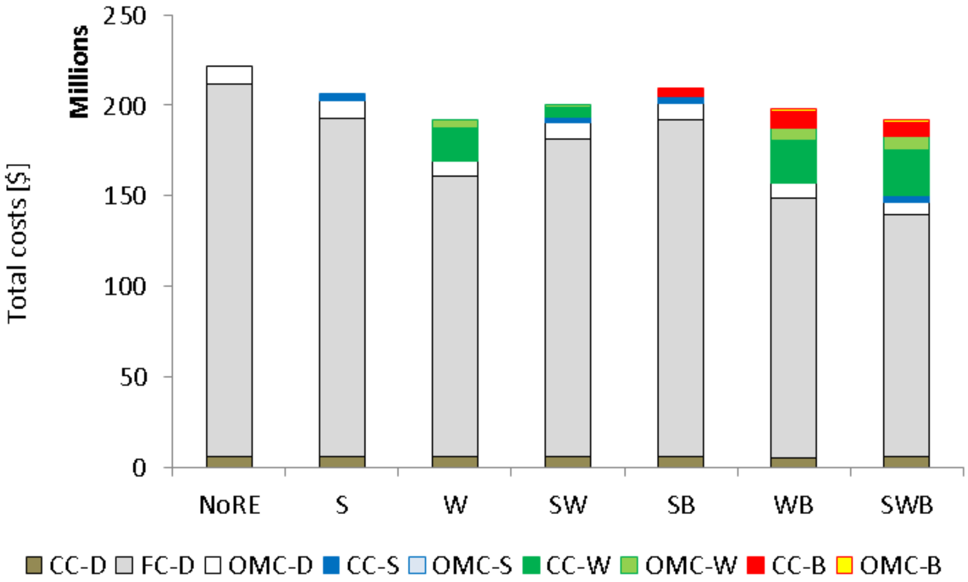


Figure 15: NPC components for Iqaluit, NU.

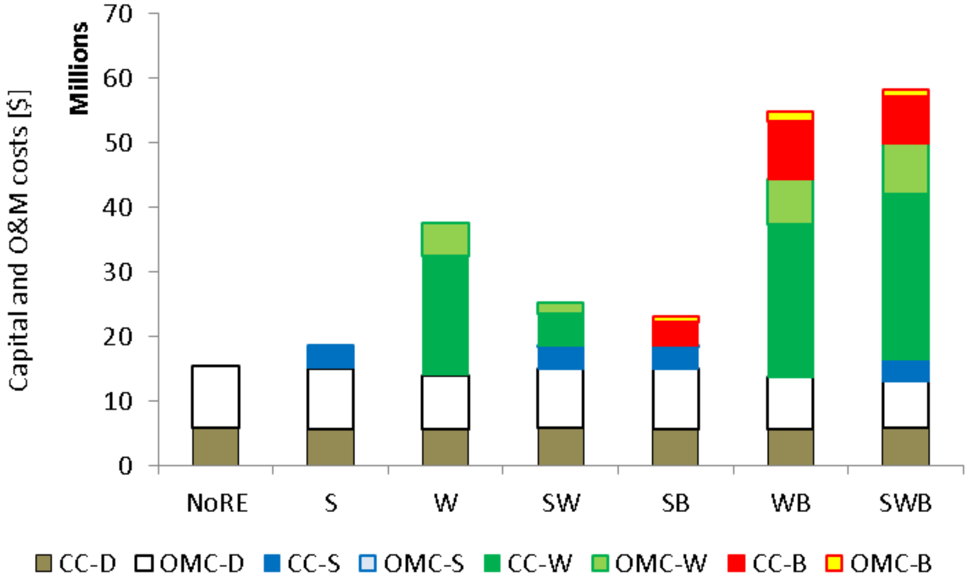


Figure 16: NPV of capital and O&M costs for Iqaluit, NU.

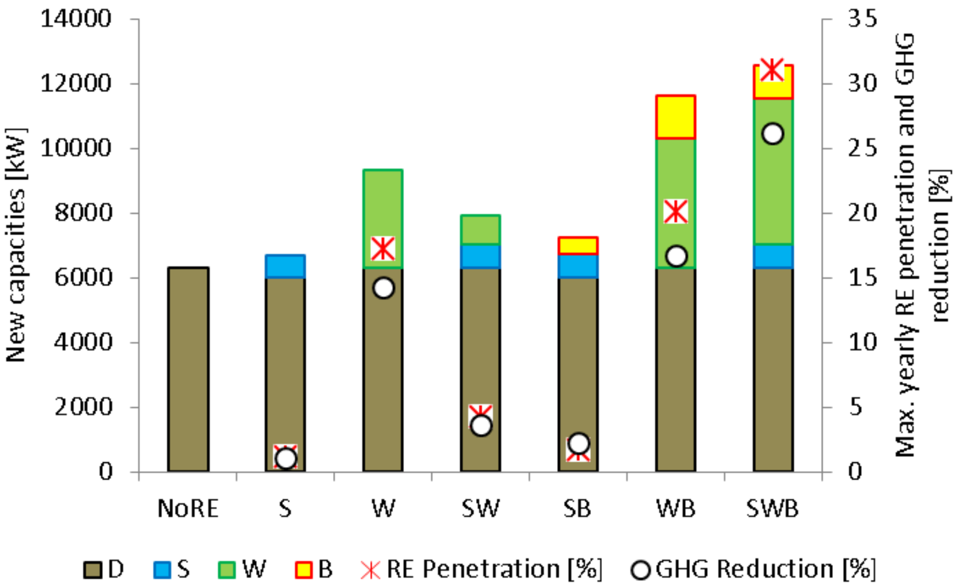


Figure 17: New capacity additions and percentages of annual maximum RE penetration and GHG reduction for Iqaluit, NU.

20 years, which is the highest among all the communities considered given its size. Note that the NPCs of all the RE cases are less than the BAU costs, thereby justifying all combinations of RE integration.

3.1.4 Rankin Inlet, NU

The results, presented in Figures 18, 19, and 20, show that a minimum of \$3 million can be saved by incorporating only solar in this community's generation portfolio, with the addition of a wind or battery increasing the savings. The NPCs of W, SW, WB, and SWB indicate that wind is the best solution, with WB being the most cost effective option, generating almost \$27 million of savings over a 20 year period (approximately 27% of BAU costs), while yielding around 60% of annual maximum RE penetration (annual average of 53.32%) and 48% of GHG reduction. Note that the integration of RE in this community's generation portfolio is economically feasible with any combination of solar, wind, and battery, as it is evident from the NPCs of the various

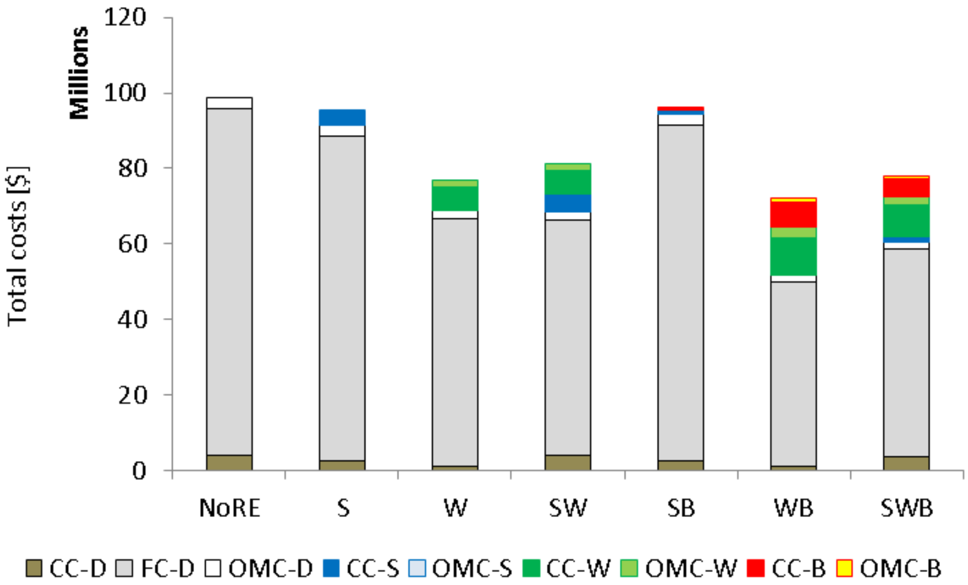


Figure 18: NPC components for Rankin Inlet, NU.

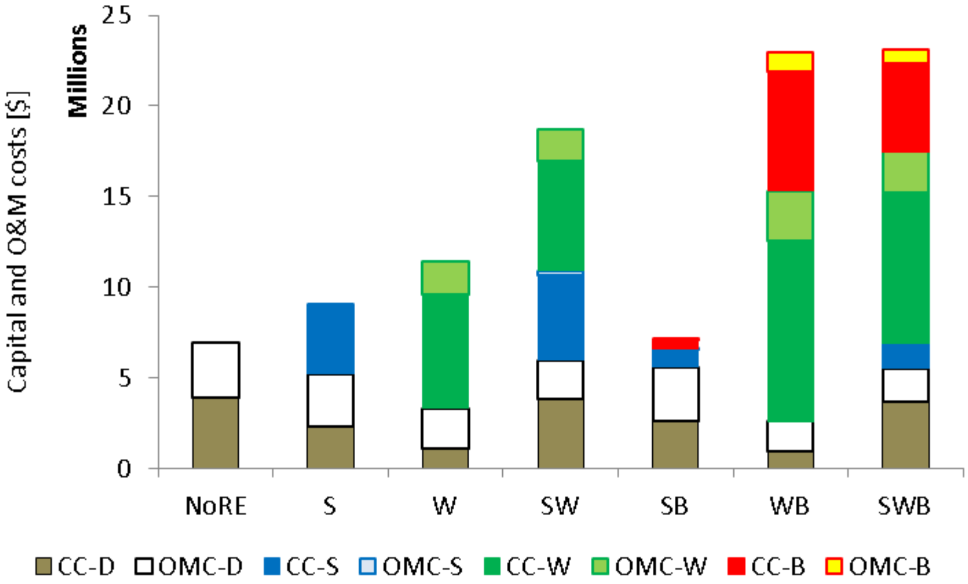


Figure 19: NPV of capital and O&M costs for Rankin Inlet, NU.

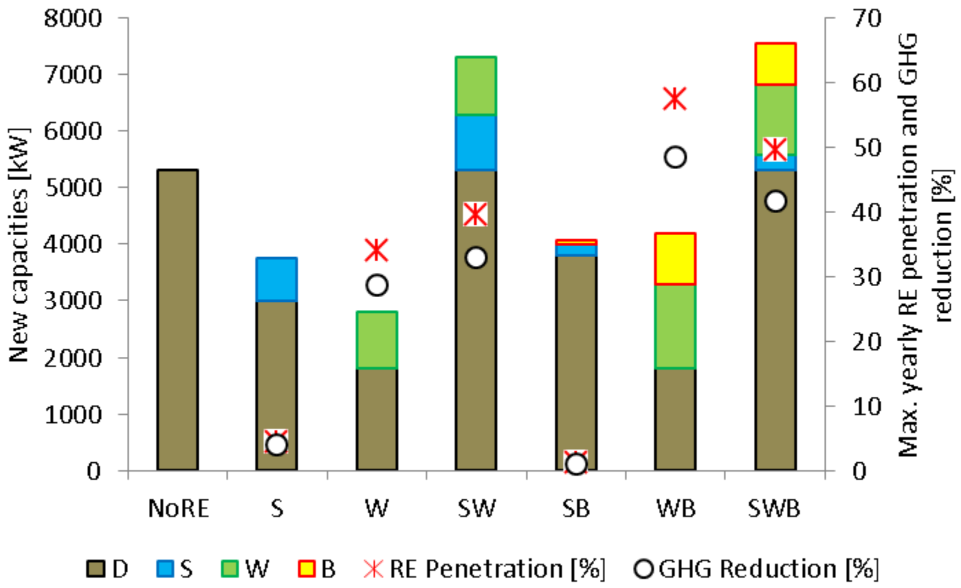


Figure 20: New capacity additions and percentages of annual maximum RE penetration and GHG reduction for Rankin Inlet, NU.

case studies.

3.1.5 Sanikiluaq, NU

As the southernmost community in the territory of Nunavut, this community has reasonable solar insolation that is comparable to the southern regions of the country. It is situated on a small island and thus has the best average wind speed among the communities under consideration. With the location being quite close to the mainland across Hudson's Bay, this community also enjoys the cheapest transportation costs of all. The results obtained are shown in Figures 21, 22, and 23. The optimal NPCs for all RE cases are less than the BAU NPC by a minimum of $1.5 million (approximately 5.5 % of BAU costs), thus justifying RE deployment in all cases. Observe that, ignoring the SB case, the NPCs gradually reduce as RE equipment is added to the system, which can be attributed to this community's RE resource profile. For the SB case, the cost of battery increases the NPC with respect to the S case, and thus it can be safely assumed that

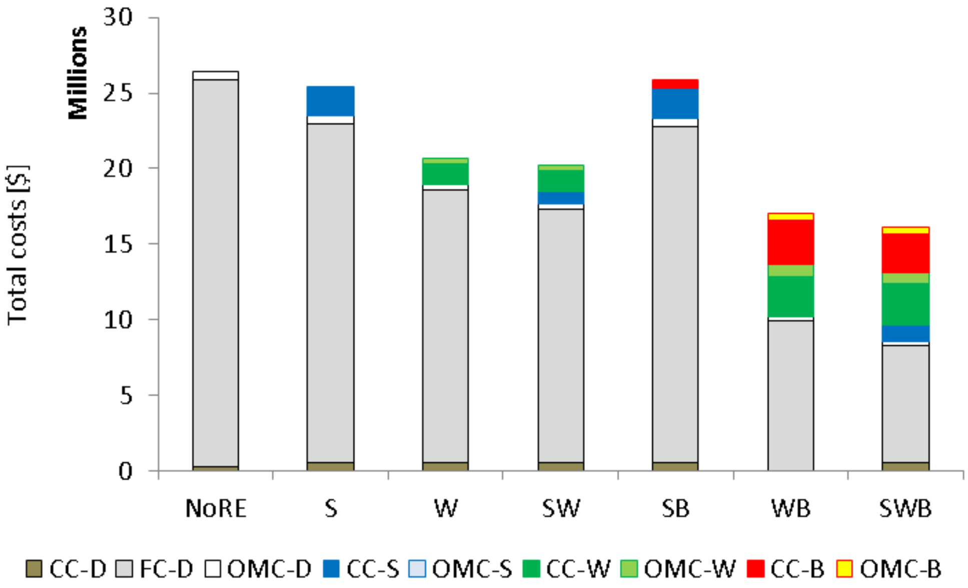


Figure 21: NPC components for Sanikiluaq, NU.

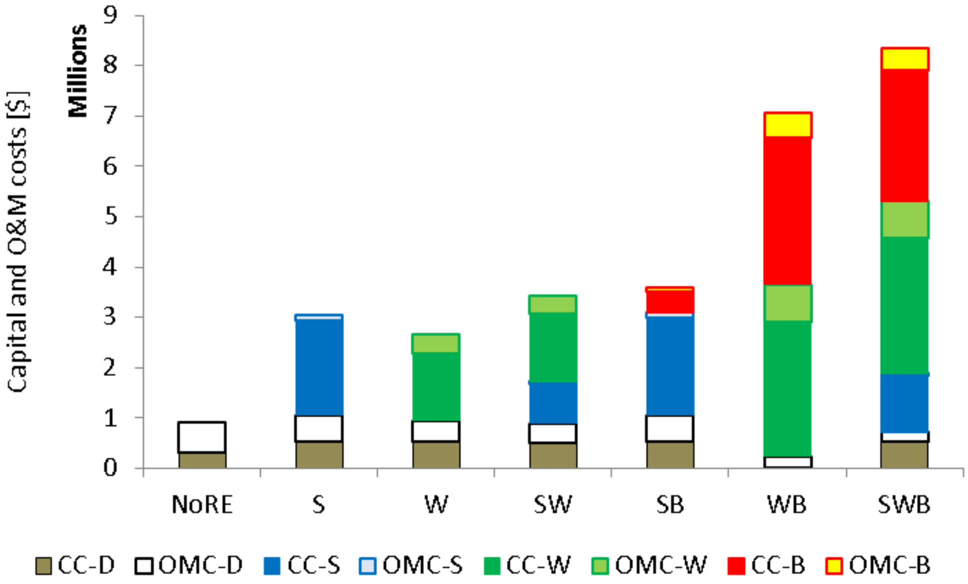


Figure 22: NPV of capital and O&M costs for Sanikiluaq, NU.

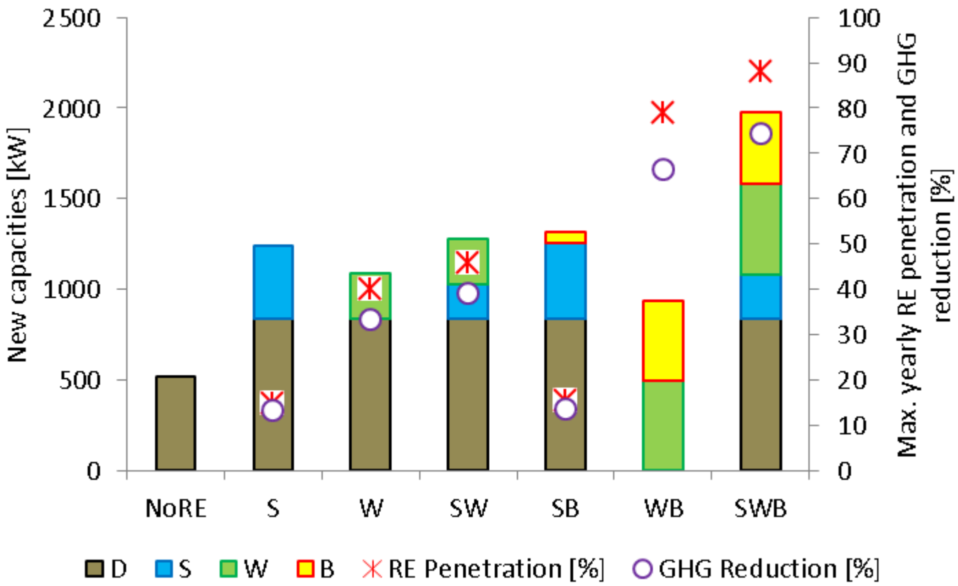


Figure 23: New capacity additions and percentages of annual maximum RE penetration and GHG reduction for Sanikiluaq, NU.

future reductions in battery energy storage costs will greatly enhance the cost-effectiveness of SB in Sanikiluaq. Note that there is no new diesel generator addition in the WB case, indicating that adequate energy storage can replace these generators. The best case occurs for the SWB model and results in maximum GHG reduction of about 69.5%, with close to the highest annual maximum and average RE penetrations for all communities of 87.92% and 81.48% (89.03% and 81.59% for Baker Lake), respectively, and total savings of about $10 million over 20 years (39% of BAU costs), which is the maximum in terms of percentage of BAU costs. Furthermore, it is evident from Figure 21 that for all RE options there is a business case with respect to BAU.

3.1.6 Sachs Harbour, NWT

This community from the Beaufort delta region is the smallest of all communities considered in the feasibility study, with a peak load of around 200 kW. The results of the simulations are shown in Figures 24, 25, and 26. Note that the inclusion of battery to any combination of solar

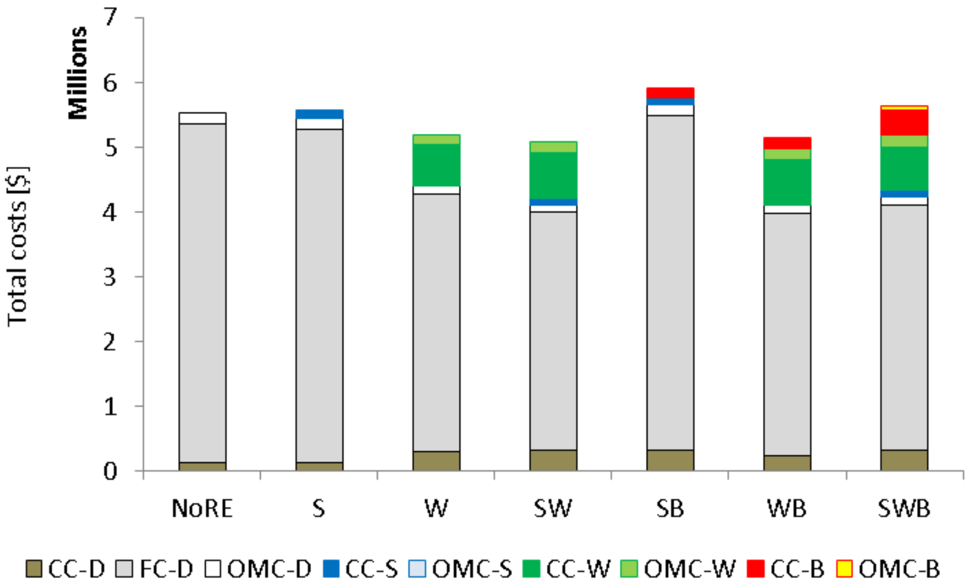


Figure 24: NPC components for Sachs Harbour, NWT.

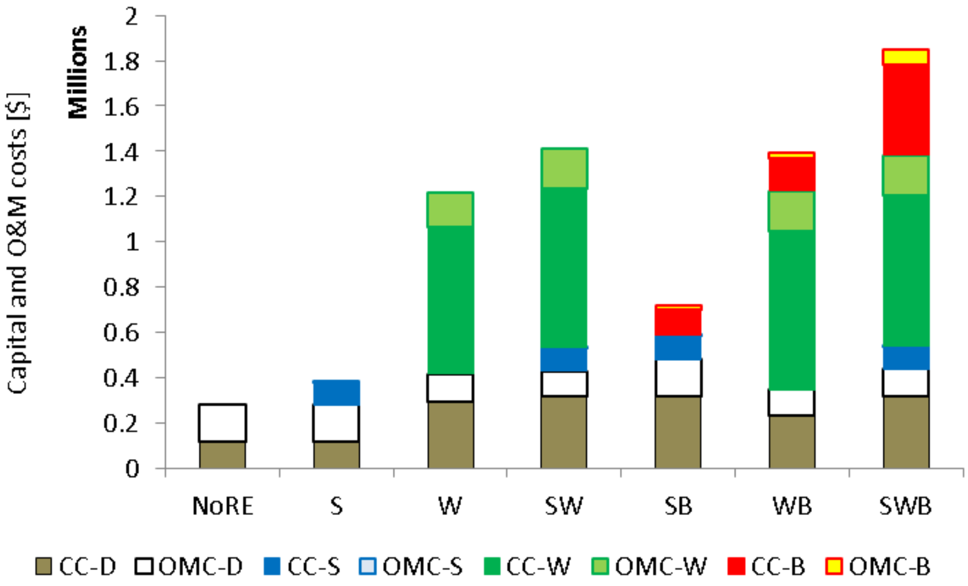


Figure 25: NPV of capital and O&M costs for Sachs Harbour, NWT.

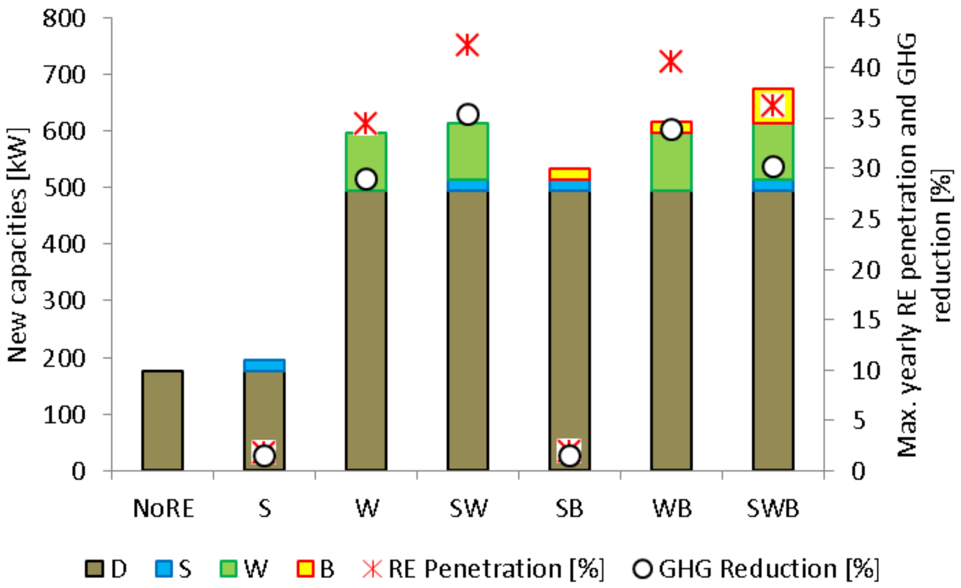


Figure 26: New capacity additions and percentages of annual maximum RE penetration and GHG reduction for Sachs Harbour, NWT.

and wind integration increases the NPC; this can be attributed to the low value of the peak load, which leads to low annual consumption of diesel, and the high cost of batteries. The best case scenario for this community is the SW model, which results in annual maximum and average RE penetrations of 42% and 38.99%, respectively, with 35% reduction in GHG emissions, and savings of $0.5 million over 20 years.

As per the advice of GNWT and NTPC colleagues, an EWT250 wind turbine was also considered; however, this proved to be economically infeasible, given that its capacity exceeds the peak load, and the costs of batteries do not justify economically the excess capacity. Furthermore, the estimated per kW costs of solar and wind for Sachs Harbour, were considered to be lower than the values expected by NTPC & GNWT colleagues. In view of this, a cost-variation analyses of solar and wind capital costs were carried out, in order to determine the break-even value of these costs, i.e., when the optimal solution no longer results in a viable business case with respect to the BAU NPC. Thus, observe in Figure 24 that the per kW cost estimated for solar PV is high enough in the S case resulting in higher costs than the BAU option; hence, the

Table 8: Best case scenarios of feasibility study simulations for each community.

	NUNAVUT					**NWT**
	Arviat	**Baker Lake**	**Iqaluit**	**Rankin Inlet**	**Sanikiluaq**	**Sachs Harbour**
Best case scenario	SWB	WB	SWB	WB	SWB	SW
Annual max. RE penetration [%]	72.96	89.03	31.01	57.48	87.92	42.15
GHG reduction [%]	60.40	74.12	26.17	48.35	74.24	35.41
NPV of savings [M$]	9.32	13.39	29.70	26.83	10.32	0.44
Savings (w.r.t. BAU) [%]	24.10	29.18	13.41	27.15	39.03	7.97
NPV of RE installation cost [M$]	8.69	15.05	35.94	16.52	6.39	0.80
NPV of savings in diesel cost [M$]	19.63	28.83	72.61	42.88	17.75	1.57
Diesel-cost savings w.r.t. BAU [%]	54.43	69.16	35.23	46.66	69.48	29.95
NPV of RE O&M costs [M$]	2.11	3.36	9.29	3.85	1.23	0.18

break-even value for solar PV capital cost is even lower than the $5,540/kW considered in the studies. Wind capital cost variations for the W option resulted in a break-even value of capital cost between $12,220/kW and $12,729/kW (i.e., a 20% and 25% increase in originally estimated costs. For the SW option, where both solar and wind capital costs were increased simultaneously at the same rate, break-even percentage point of 55% above estimated costs was obtained, i.e., $8,587/kW for solar and $15,784/kW for wind.

3.2 Observations and Analysis

The best case scenarios of each community in consideration are shown in Table 8. Observe that, for the communities of Nunavut, RE integration in Iqaluit is the least justifiable in comparison with others; this is due to the fact that, even though the savings are the highest in terms of dollars, it has the highest capital costs and lowest percentages of GHG reductions and annual maximum RE penetration. The results for Baker Lake and Sanikiluaq stand out as the best 2 communities for RE integration pilot projects, as they are the top 2 ranked in annual maximum RE penetrations, GHG reductions, and total and diesel cost savings percentages with respect to BAU costs. The third ranked is Arviat in terms of higher GHG reduction and RE penetration percentages; however, the total savings for Rankin Inlet are nearly 3 times as high than those at Arviat.

4 Conclusions and Recommendations

The simulation results indicate that:

- The deployment of RE-diesel hybrid systems in any community will always economically reduce the consumption of diesel.
- The addition of battery energy storage system will reduce fuel use, but it is an overall more expensive solution for some communities.
- In general wind is the preferable RE option, and in some cases the introduction of solar increases the project NPC with reduction in RE penetration; however, in the communities of Arviat, Iqaluit, and Sanikiluaq, the diesel-solar-wind-battery option was the most cost-effective.
- Substantial reduction in greenhouse gas (GHG) emissions, ranging from 26% to 74%, can be obtained, with higher than expected annual average penetrations of RE from 28% to 81.6%, and a range of savings of \$0.5 million to \$29.7 million over a 20-year period.
- Based on the results obtained, pilot projects should be pursued for Baker Lake and Sanikiluaq, and if possible, also Arviat or Rankin Inlet.

A APPENDIX

A.1 Load Profiles for the rest of the Communities

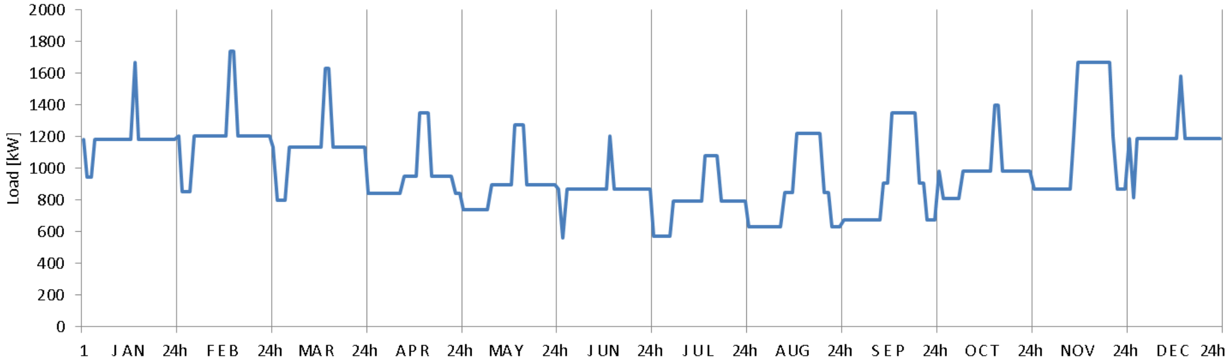


Figure 27: Daily average hourly load profile per month for Arviat, NU.

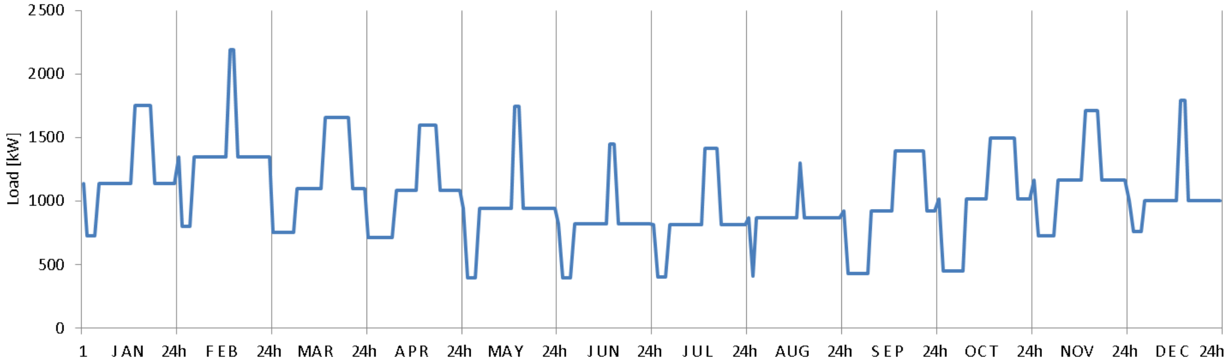


Figure 28: Daily average hourly load profile per month for Baker Lake, NU.

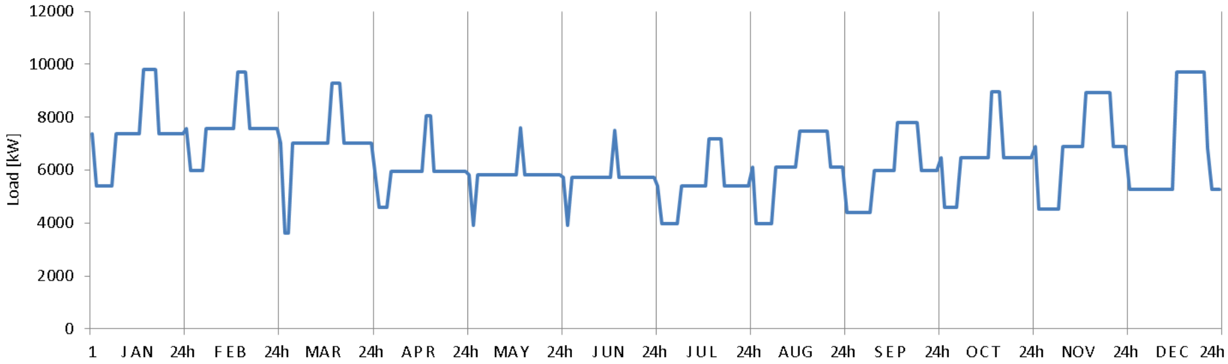


Figure 29: Daily average hourly load profile per month for Iqaluit, NU.

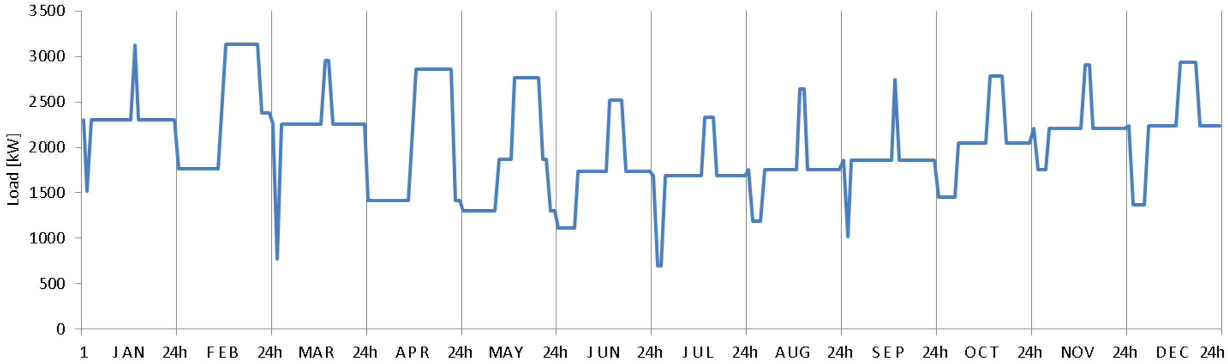
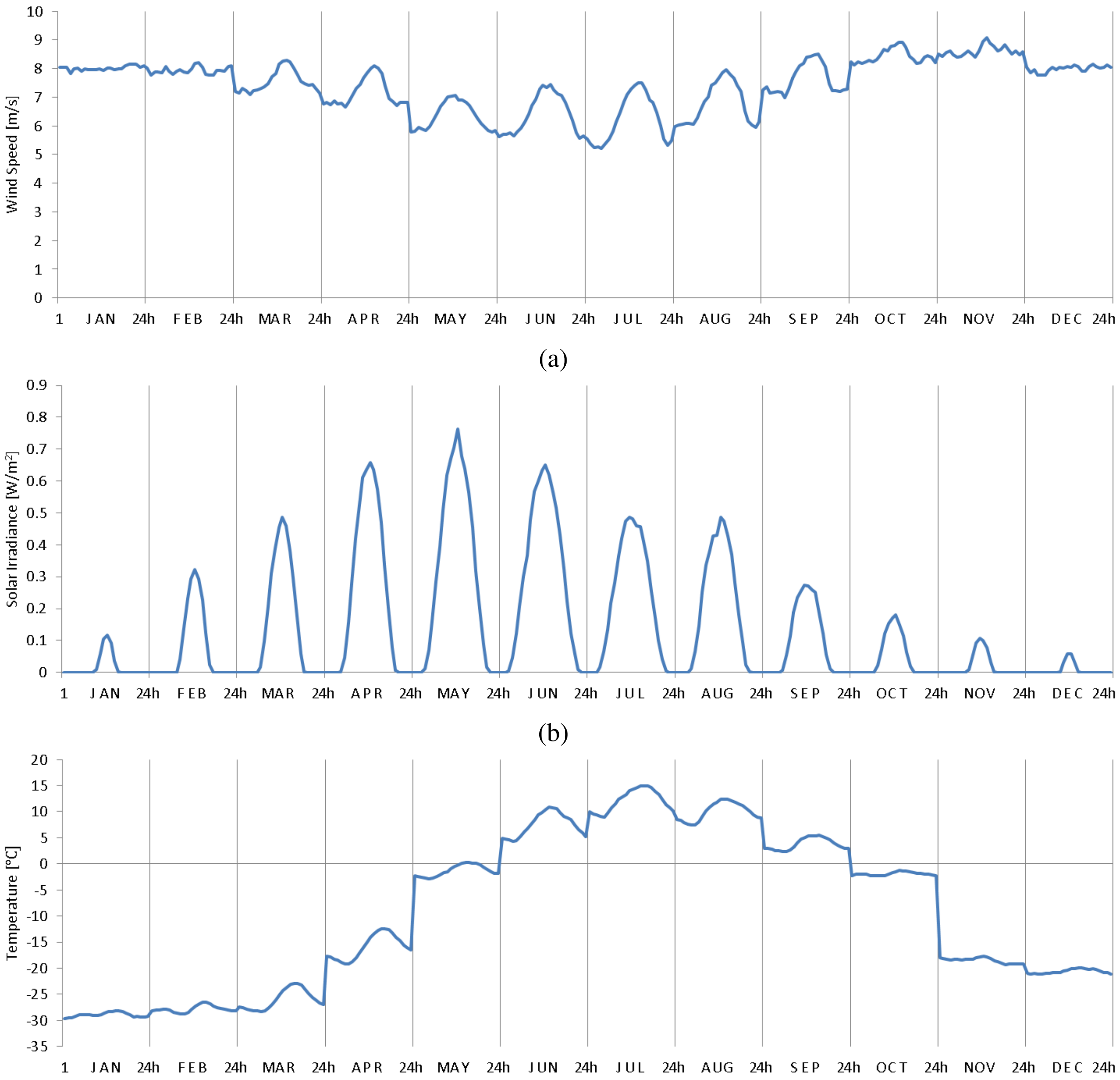


Figure 30: Daily average hourly load profile per month for Rankin Inlet, NU.

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

RE resource profiles include daily averaged hourly profiles of wind speed at a certain hub height, solar insolation on a horizontal surface, and temperature.

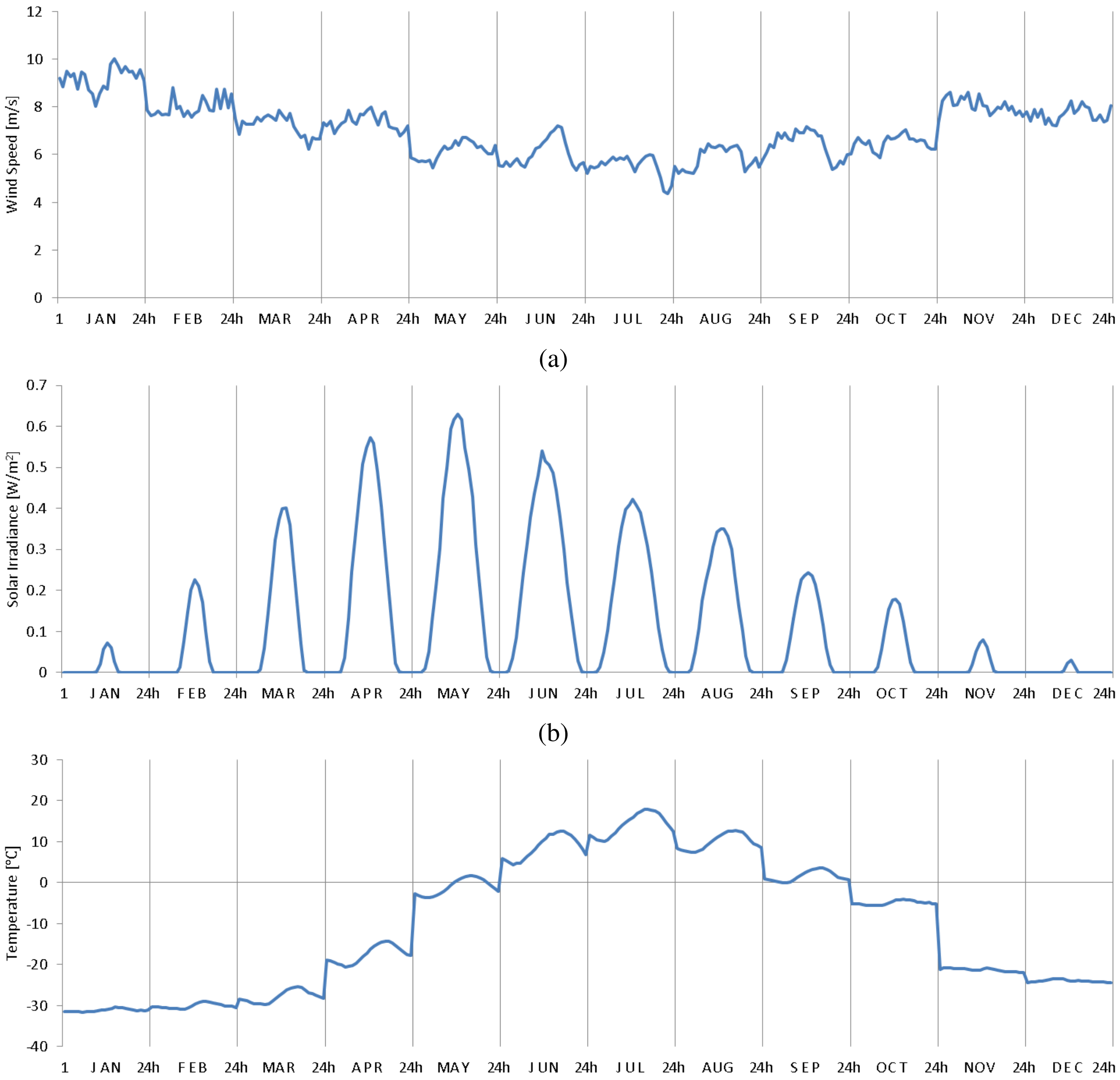


(a)

(b)

(c)

Figure 31: 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.

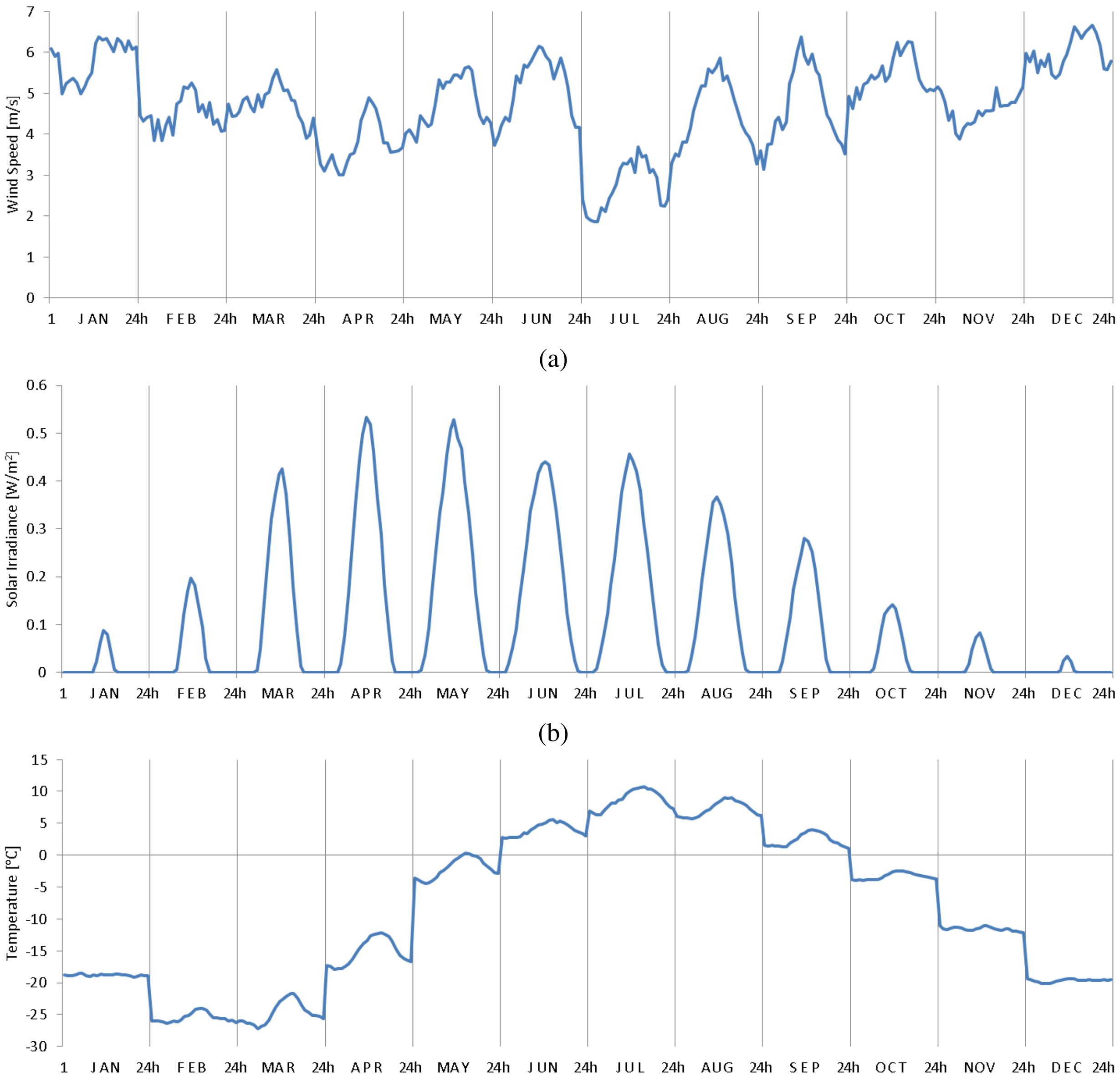


(a)

(b)

(c)

Figure 32: 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.

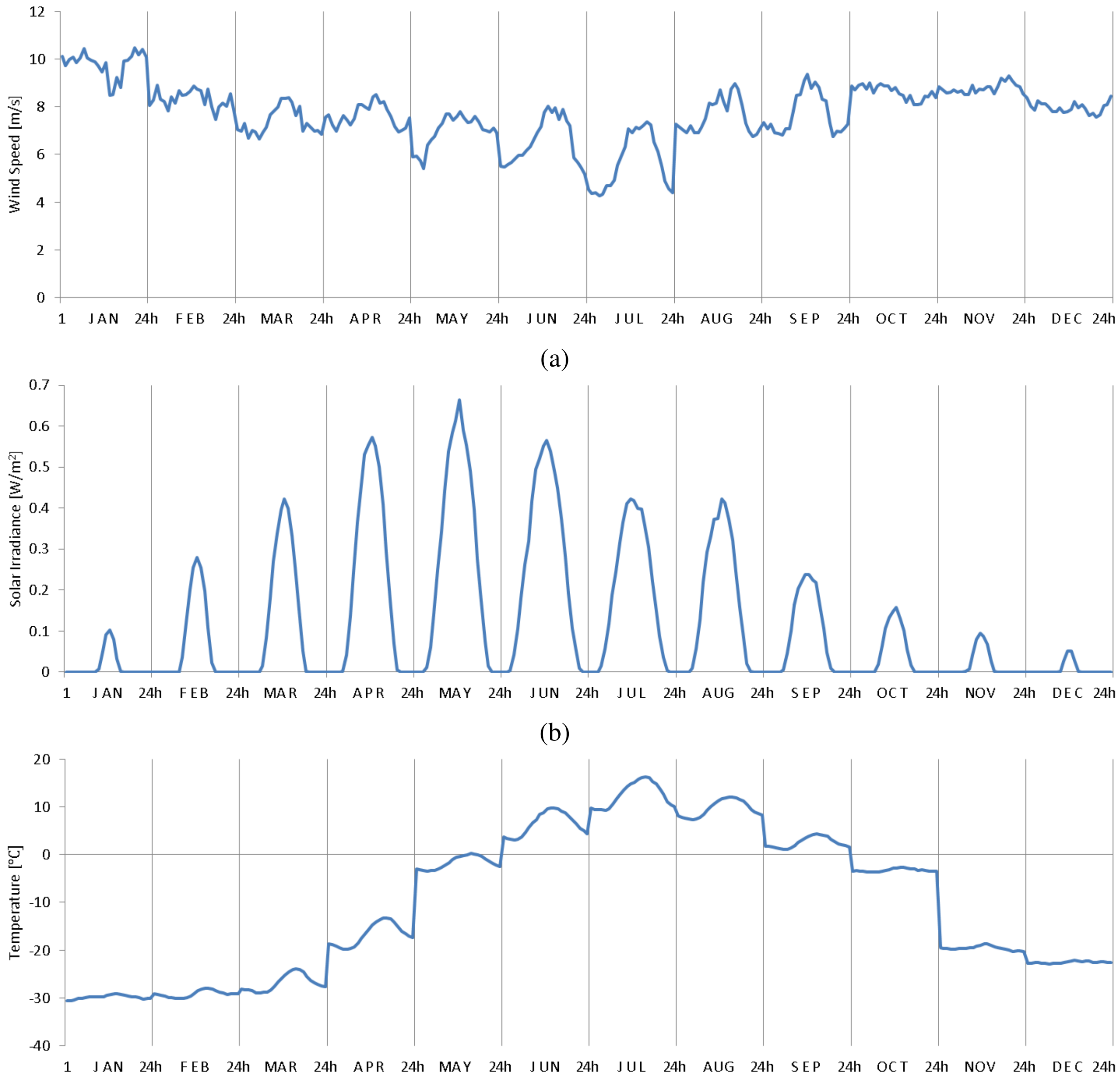


(a)

(b)

(c)

Figure 33: 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.



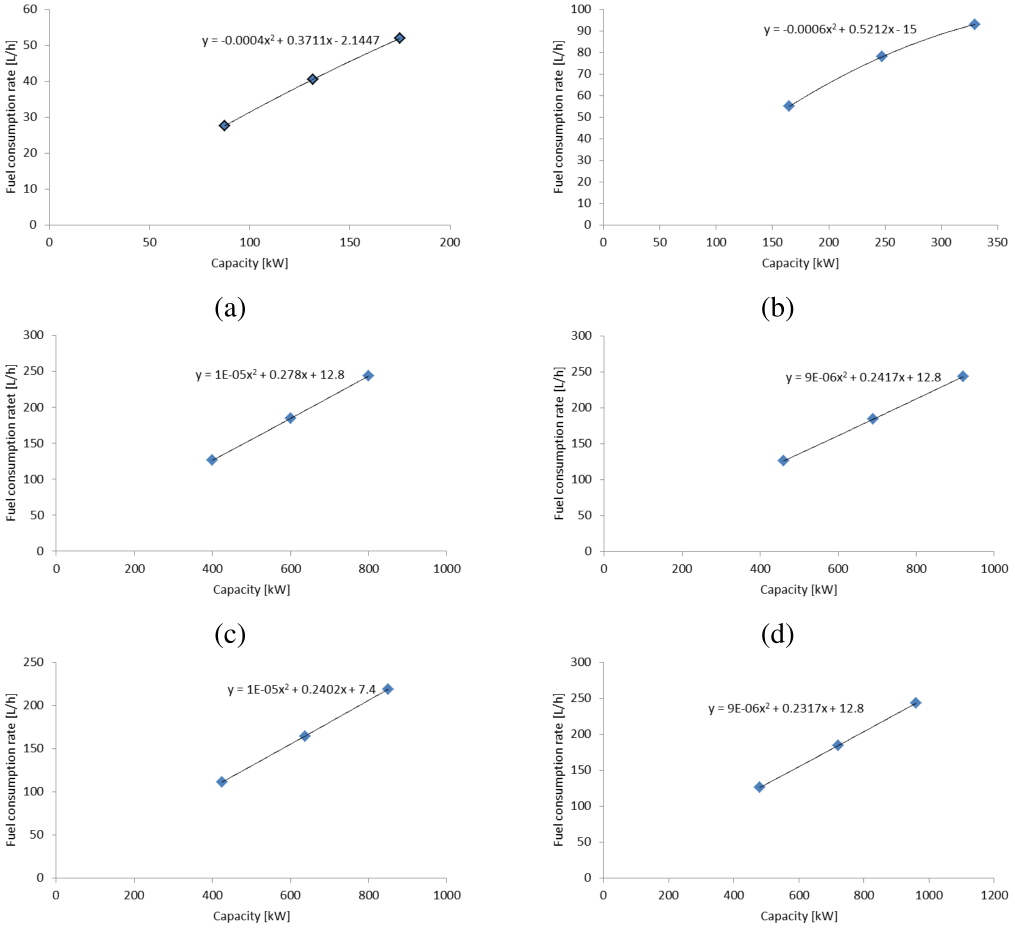
(a)

(b)

(c)

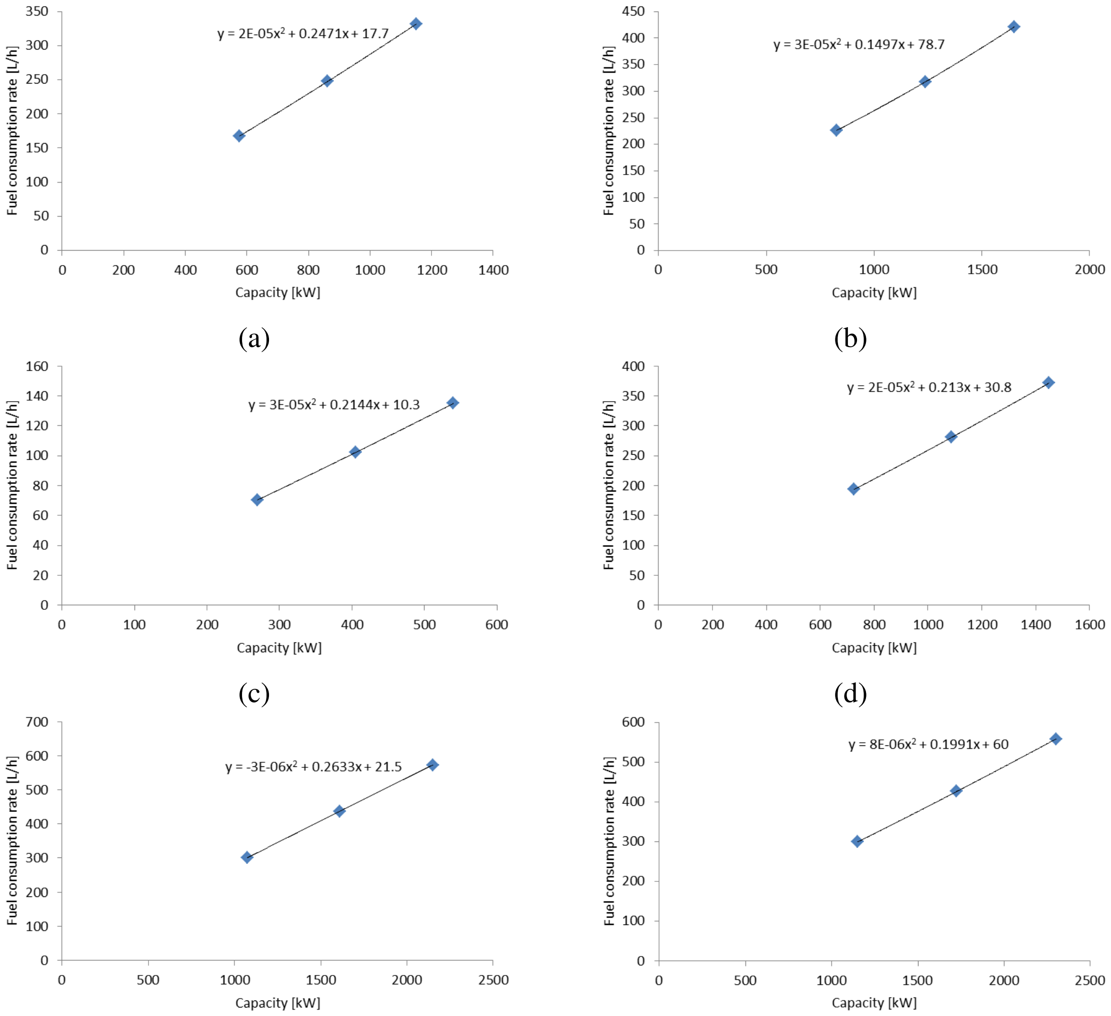
Figure 34: Daily average hourly profiles per month of (a) wind speed at 50m hub height, (b) solar insolation, and (c) temperature for the community of Rankin Inlet, NU.

A.3 Fuel Curves of Existing Diesel Generators



(a) (b) (c) (d) (e) (f)

Figure 35: 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 [20].

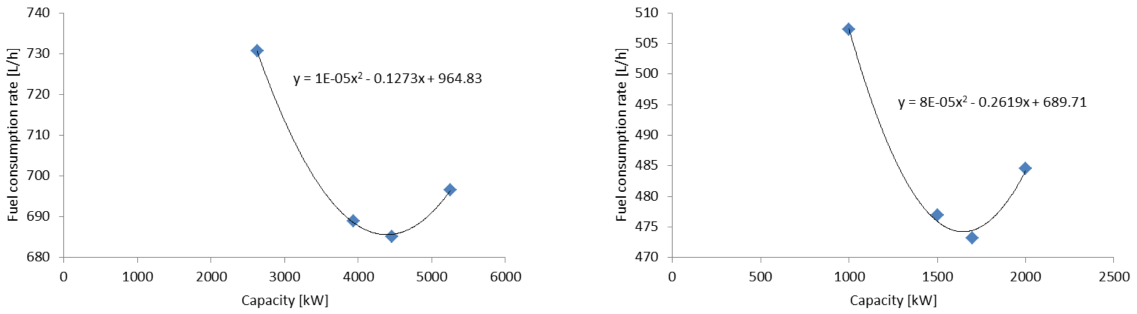


(a) (b)

(c) (d)

(e) (f)

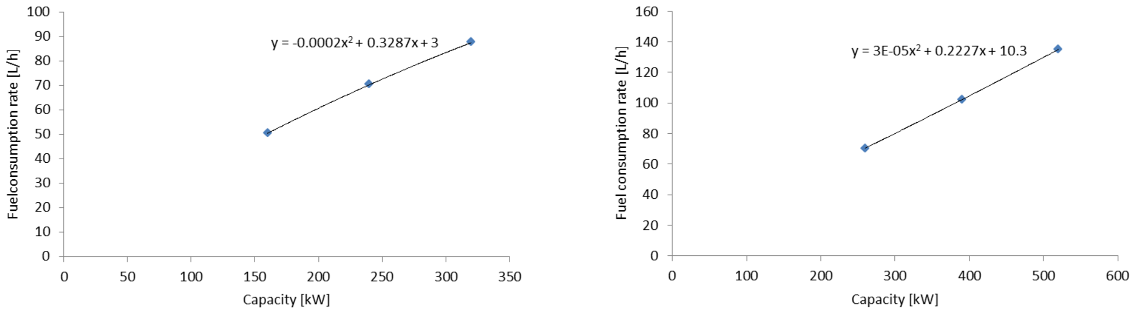
Figure 36: Fuel consumption curves for (a) Cat. D3516BHD 1150 kW, (b) Cat. D3606 1650 kW, (c) DD2000 540 kW, (d) EMD 8V710 1450 kW, (e) EMD 12V710 2150 kW, and (f) EMD 20V645 2300 kW diesel generators [20], [21].



(a) (b)

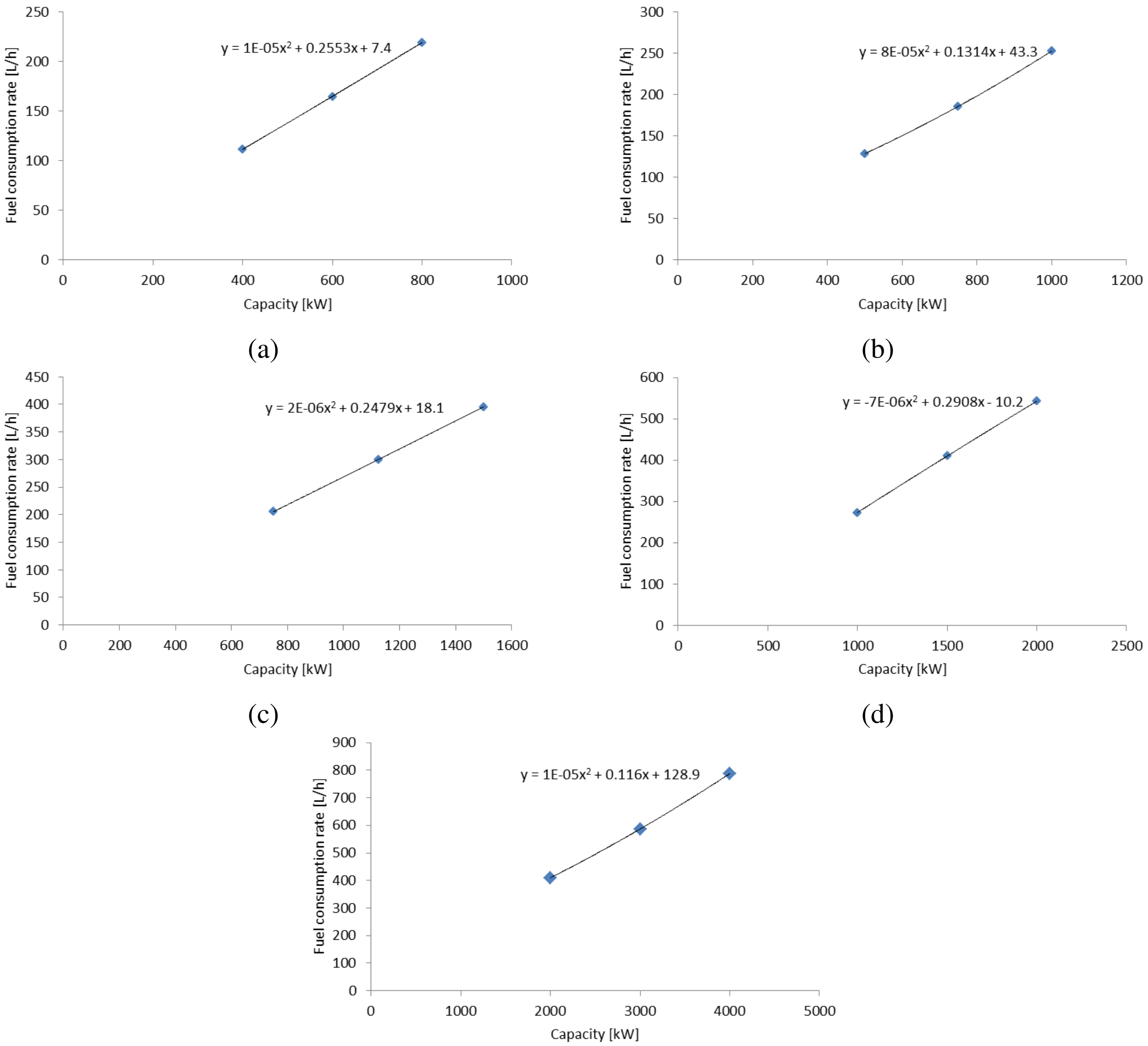
Figure 37: Fuel consumption curves for Wartsilla (a) 12V32 5250 kW, and (b) 12V200 2000 kW diesel generators [22].

A.4 Fuel Curves of New Diesel Generators



(a) (b)

Figure 38: Fuel consumption curves for Caterpillar (a) C13 320 kW, and (b) C18 520 kW diesel generators [23].



(a)

(b)

(c)

(d)

(e)

Figure 39: Fuel consumption curves for Caterpillar (a) C27 800 kW, (b) C32 1000 kW, (c) D3512C 1500 kW, (d) D3516C 2000 kW, and (e) C175-20 4000 kW diesel generators [23].

A.5 Power Curves of Wind Turbines

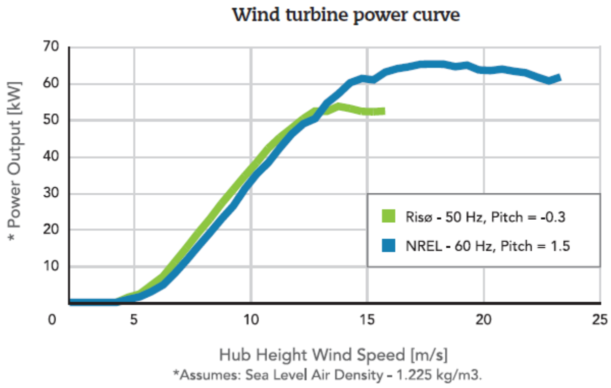
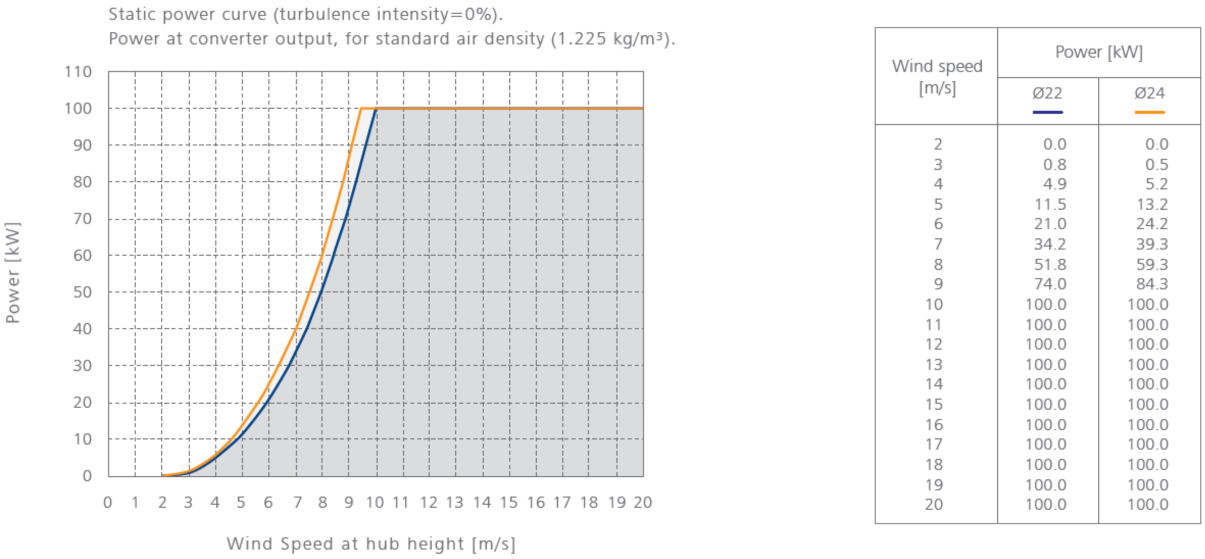
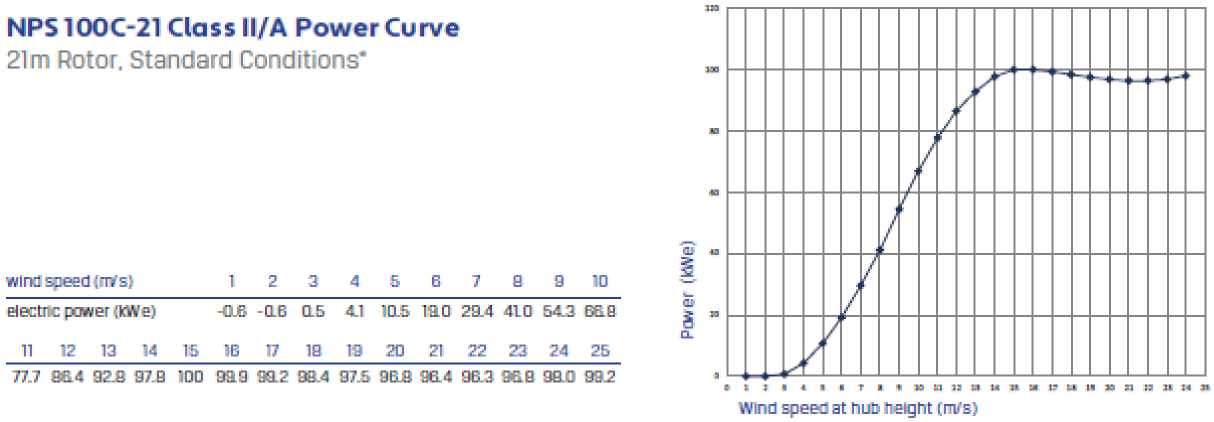


Figure 40: Wind power curve for 50 kW Entegrity EW50 turbine [24].



Wind speed [m/s]	Power [kW]	
	Ø22	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 41: Wind power curve for 100 kW Norvento nED100 turbine [25].



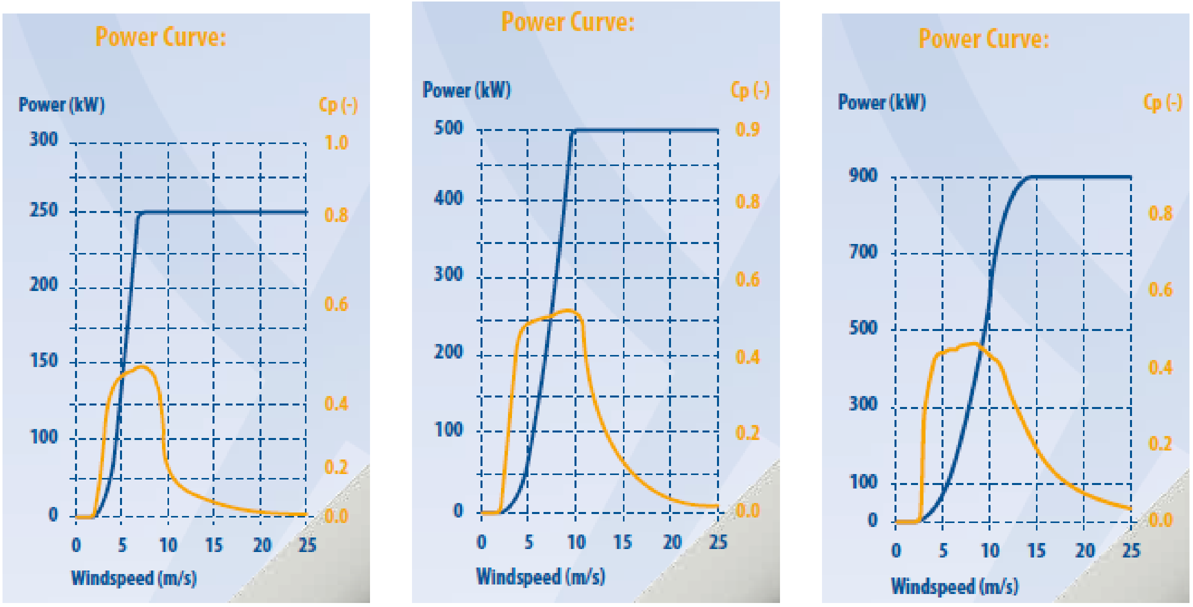
NPS 100C-21 Class II/A Power Curve

21m Rotor, Standard Conditions*

wind speed (m/s)	1	2	3	4	5	6	7	8	9	10
electric power (kWe)	-0.6	-0.6	0.5	4.1	10.5	19.0	29.4	41.0	54.3	66.8

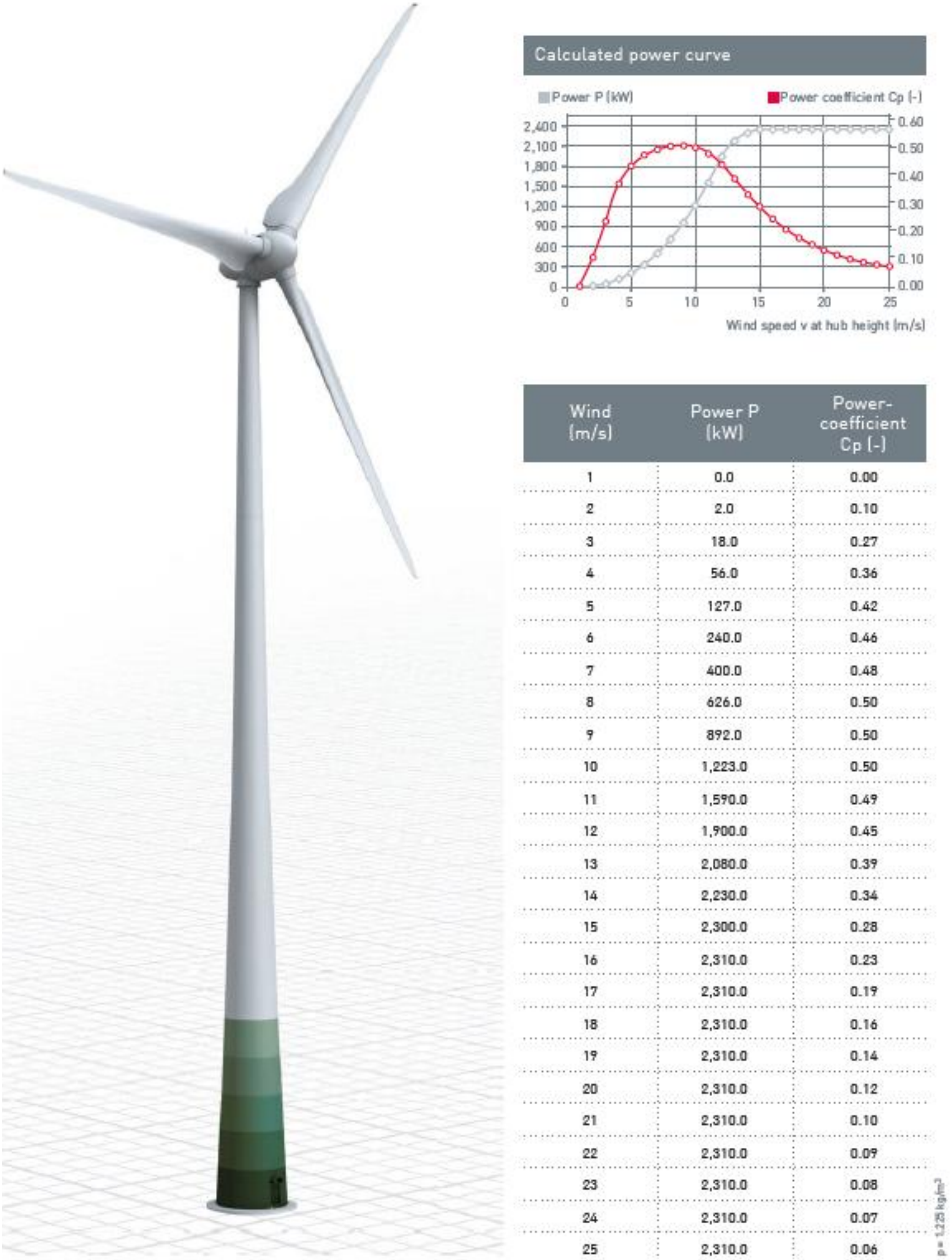
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
77.7	86.4	92.8	97.8	100	99.9	99.2	98.4	97.5	96.8	96.4	96.3	96.8	98.0	99.2

Figure 42: Wind power curve for 100 kW Northern Power Systems NPS100 turbine [26].



(a) (b) (c)

Figure 43: 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

Figure 44: Wind power curve for 2300 kW Enercon En-70 E4 turbine [28].

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