Renewable Energy Integration in Diesel-based Microgrids at the Canadian Arctic

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***Abstract*—The effect of climate change is significant in the arctic regions of the world, with the carbon footprint from diesel-only based electricity generation in remote arctic communities adding to the environmental degradation through greenhouse gas (GHG) emission, oil spills, and black carbon. Moreover, the dependency on diesel and its associated costs are an economic problem for these communities, particularly in the Canadian Arctic, where governments subsidize this fuel. Thus, this paper presents specific studies including new variable-speed generation (VSG) technologies that demonstrate the feasibility, impact, and benefits of introducing renewable energy (RE) together with VSGs in remote microgrids in the Canadian Arctic. More specifically, the paper describes a two-step procedure to select remote communities for detailed feasibility studies of deployment of RE sources, including a generation expansion planning (GEP) framework and optimization model for RE and new VSG integration applied to the selected communities, to minimize diesel dependency of isolated microgrids and maximize the incorporation of environmentally friendly generation technologies. The proposed approach is applied to communities in Nunavut and the North West Territories in the Canadian Arctic, based on actual data, to study the techno-economic feasibility of RE integration and develop business cases for diesel generation replacement with RE and VSG generation in these communities. The obtained optimal plans contain diesel-RE hybrid combinations that would yield substantial economic savings and reductions on GHG emissions, which are being used as the base for actual deployments in some of the studied communities.**

***Index Terms*—Canadian Arctic, diesel renewable energy hybrid, energy planning, feasibility study, generation expansion planning, GHG reduction, HOMER, optimal operation planning, pre-feasibility study, remote microgrids, renewable energy integration, variable speed generator.**

Abbreviations

AEA	Arctic Energy Alliance
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
GRM	Generation Reserve Margin
HOMER	Hybrid Optimization of Multiple Energy Resources
ISR	Inuvialuit Settlement Region
LCOE	Levelized Cost of Energy
MILP	Mixed Integer Linear Programming
NASA	National Aeronautics and Space Administration
NEAS	Nunavut Eastern Arctic Shipping
NPC	Net Present Cost
NPV	Net Present Value
NRCAN	Natural Resources Canada
NREL	National Renewable Energy Laboratory
NSSI	Nunavut Sealink and Supply Inc.
NTCL	Northern Transportation Company Limited
NTPC	Northwest Territories Power Corporation
NWT	Northwest Territories
O&M	Operation & Maintenance
QEC	Qulliq Energy Corporation
RE	Renewable Energy
SOC	State of Charge
SSE	Surface meteorology and Solar Energy
VSG	Variable speed generator
WISE	Waterloo Institute of Sustainable Energy
WWF	World Wildlife Fund

Sub-scripts

e_F	Existing diesel generators of different capacities and manufacturers
h	Hour
y	Year
n_B	New batteries from different manufacturers
n_G	New FSG or VSG 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^F	Existing diesel capacity including stand-by mode units [kW]
d	Discount rate [pu]

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$Dcost$	Diesel cost [$/L]
df	Derating factor of solar PV panels [pu]
DoD^B	Depth-of-discharge (DOD) of a battery [pu]
GH^L	Useful life of new diesel generator [h]
GH^R	Remaining life of existing diesel generator [h]
GT^{STC}	Incident solar radiation on the PV array at standard test conditions [kW/m^2]
HOM^B	Hourly Operation and Maintenance (O&M) costs of battery [$/kWh]
HOM^F	Hourly O&M costs of existing diesel generator [$/kWh]
HOM^{PB}	Hourly O&M costs of PowerBridge [$/kWh]
HOM^S	Hourly O&M costs of solar panel set [$/kWh]
HOM^G	Hourly O&M costs of new diesel generator [$/kWh]
HOM^W	Hourly O&M costs of wind turbine [$/kWh]
HY	Hours in a year (model specific) [h]
M	A very large number
ML^F	Minimum load operation of existing diesel generator [pu]
ML^G	Minimum load operation of new diesel generator [pu]
N_B	Number of batteries considered
N_F	Number of existing FSG considered
N_G	Number of new diesel generator considered
N_S	Number of solar panel sets considered
N_W	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^D	Time duration a battery can discharge continuously at a fixed power [h]
T^{OM}	Percentage of hours per annum scheduled for maintenance [%]
$Tcell$	Solar PV cell temperature at each time step [°C]
$Tcell^{STC}$	Solar PV cell temperature under Standard Test Conditions [°C]
UC^B	Unit cost of new batteries [$/kWh]
UC^G	Unit cost of new disel generator [$/kW]
UC^{PB}	Unit cost of new PowerBridge module [$]
UC^S	Unit cost of solar panel sets [$/kW]
UC^W	Unit cost of wind turbines [$/kW]
$Ucap^B$	Capacity of battery set [kWh]
$Ucap^G$	Capacity of new diesel generator unit [kW]
$Ucap^S$	Capacity of solar panel set [kW]
$Ucap^W$	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^C	Efficiency of battery charging [pu]
η^D	Efficiency of battery discharging [pu]

Variables

Cap^B	Aggregate capacity of battery [kWh]
Cap^G	Aggregate capacity of new diesel generators [kW]
Cap^S	Aggregate capacity of solar PV [kW]
Cap^W	Aggregate capacity of wind [kW]
$Capu$	Dummy variable to linearize a product [kW]
CC^B	Net present value (NPV) of battery capital cost [$]
CC^G	NPV of total capital costs of purchasing new VSG [$]
CC^{PB}	NPV of total capital costs of purchasing PowerBridge [$]
CC^S	NPV of solar PV capital cost [$]
CC^W	NPV of wind capital cost [$]
DL^{PB}	Dump load using PowerBridge [kW]
FC^F	NPV of total diesel fuel cost for existing FSGs [$]
FC^G	NPV of total diesel fuel cost for new FSG or VSGs [$]
$Fcon^F$	Hourly fuel consumption rate of existing diesel generators [L/kWh]
$Fcon^G$	Hourly fuel consumption rate of new diesel generators [L/kWh]
NCA^B	New capacity addition of battery [kW]
NCA^G	New capacity addition of diesel [kW]
NCA^S	New capacity addition of solar PV [kW]
NCA^W	New capacity addition of wind [kW]
OMC^B	NPV of battery O&M cost [$]
OMC^F	NPV of total diesel O&M cost for existing FSGs [$]
OMC^G	NPV of total diesel O&M cost for new diesel generators [$]
OMC^{PB}	NPV of total O&M cost for PowerBridge [$]
OMC^S	NPV of solar PV O&M cost [$]
OMC^W	NPV of wind O&M cost [$]
Pb^C	Battery charging power [kW]
Pb^D	Battery discharging power [kW]
Pd^F	Power generated by existing diesel generator [kW]
Pd^G	Power generated by new diesel generator [kW]
Ps^S	Power generated by solar PV [kW]
Pw^W	Power generated by wind [kW]
SOC	Battery state-of-charge [kWh]
u^{BP}	Binary variable to denote purchase of battery
u^C	Binary variable to denote ON/OFF state of battery charging
u^D	Binary variable to denote ON/OFF state of battery discharging
u^{FO}	Binary variable to denote existing diesel generator ON/OFF state
u^{GO}	Binary variable to denote new diesel generator ON/OFF state
u^{GP}	Binary variable to denote purchase of new diesel generator
u^{SP}	Binary variable to denote purchase of solar PV
u^{WP}	Binary variable to denote purchase of wind
x	Optimization variables

I. Introduction

TABLE I
REMOTE COMMUNITY PER-CAPITA GHG EMISSIONS FROM ELECTRICITY GENERATION

Location	**AB**	**BC**	**MB**	**NL**	**NT**	**NU**	**ON**	**QC**	**SK**	**YT**	**Canada**
Tonnes of CO2e	21.35	5.94	4.77	5.61	7.68	7.64	3.00	10.42	3.30	0.55	2.17

THE gradually diminishing ice cover of the arctic sea, caused by temperature increases due to climate change, is well documented; in fact, the arctic has been found to be warming at least twice as fast as the rest of the planet [1]. Furthermore, many arctic communities have only diesel-based electricity generation portfolios, with emission from diesel engines compunding the ill-effect of climate change in that region [2]. 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, thus increasing 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 that may result in extensive damage to the arctic environment.

The Arctic communities of Canada includes all communities of Nunavut (NU) and some communities of the Northwest (NWT) and Yukon Territories (YT), since the provinces of Alberta (AB), British Columbia (BC), Manitoba (MB), Newfoundland and Labrador (NL), Ontario (ON), and Saskatchewan (SK) do not have arctic communities. The overall emissions of GHGs from all these communities combined are small in comparison to the rest of Canada (704 Mt CO2e per year), i.e., less than 0.3% in tonnes of CO2e per year [4]. On the other hand, their per capita GHG emission vary largely depending on the type of fuel used for electricity generation, transportation and industrial demand; thus, for Nunavut it is 3% below the Canadian average (19.4 tonnes CO2e per capita), whereas for NWT, it is 86% over, while for the Yukon, it is 39% lower.

The capacity of electricity generation in Canada is about 145 GW [5], yielding 11.16% of the total GHG emissions or 2.17 tonnes of CO2e emission per capita [4]. For remote communities, the generation capacity for non-arctic remote communities is 237 MW, and 217 MW for artic communities, which yields the GHG emissions per capita depicted in Table I for 7 out of 10 provinces and all 3 territories (the provinces of Nova Scotia and Prince Edward Island do not have any remote off-grid communities), based on the community-wise fuel consumption dataset in [6], emission factors to transform liters of diesel or m3 of natural gas into tonnes of CO2e from [7], and the population data from [8], where it is shown that the population of all the remote communities combined is about 200,000, which is less than 0.6% of the countrys population of about 35 million, with arctic communities being less than 0.3%; the data for BC is extracted from [9].

The Canadian Arctic, also called “Far North”, is a part of Northern Canada, i.e., “The North”, where The North politically refers to the territories of Yukon, NWT, and Nunavut. The Far North is subdivided into the Eastern Arctic, comprising Nunavut, Nunavik (part of Quebec), and Nunatsiavut (part of Newfoundland and Labrador), and the Western Arctic, i.e., the northernmost portion of NWT and a small part of Yukon. The latter, called the Inuvialuit Settlement Region (ISR), consists of 6 communities, and, along with Fort McPherson and Tsiigehtchic in NWT, form the Inuvik Region. The geographical region selected for studies presented here comprises all 25 communities in the territory of Nunavut and 8 from the Inuvik region of NWT.

All communities in Nunavut are solely dependent on diesel for electricity generation, and similarly for the ISR communities, with the exception of Inuvik where there are some natural gas based generators. There is no territorial power grid in this regions, and for the territory of Nunavut, in particular, there are no inter-community road access. The remoteness of these communities, along with the inaccessibility of land-based transportation, increases the risk for oil spills since fuel has to be transported by sea-barges and then stored locally in storage tanks, which results in high costs of transporting diesel to all these remote communities. In addition, the age of diesel generators in operation at a majority of these communities, particularly in Nunavut [10], is more than 35 years, and thus require replacement in the next few years. All these facts are the main motivation to search for alternative sources of electricity generation that are environmentally friendly as well as cost-effective. Thus, non-polluting energy sources, such as solar and wind, should be considered for deployment in these communities, which could yield positive economic and environmental results, as demonstrated in this paper. Of a total of 33 communities in consideration here, the first stage of the paper describes the selection of 6 communities for detailed feasibility analyses, and the second stage presents a feasibility study for RE integration, with and without VSG technologies, in 5 communities of Nunavut and 1 from NWT, to build business cases for optimal RE-integration plans in these communities.

Feasibility studies, which are customary prior to design, installation and operation of hybrid-RE systems, have been reported in the literature [11], [12], and in some cases [13]–[16], the studies used the well known commercial software Hybrid Optimization of Multiple Energy Resources (HOMER) [17]. Various solution methods have been used to optimally plan diesel-RE hybrid systems [18], [19], but the effectiveness of HOMER-based analysis for pre-feasibility studies is evident from the review presented in [20]; the versatility of this software to analyze diesel only, RE only, diesel-RE hybrid, and grid-connected microgrids is also discussed in [21]. Furthermore, HOMER has been used to simulate wind-diesel systems [22], demonstrate the need for energy storage to improve the economics of wind-diesel systems [23], and design a PV-diesel-battery system in [24], and a

PV-wind-diesel-battery hybrid system in [25]. In [26], it is shown that diesel-RE hybrid systems can be economically feasible in remote off-grid communities of Northern Ontario, Canada, where the transportation and storing of diesel is costly. Therefore, building on available work in diesel-RE hybrid simulations using HOMER, the first stage of the current paper, based on [27], discusses methodologies to utilize high level datasets and HOMER results to select 6 communities for further in-depth RE integration feasibility studies. Then, given the limitations of this software, more detailed feasibility studies are carried out using a planning approach based on a novel optimization framework and models initially proposed in [28], [29].

Traditional planning methodologies used for diesel-based isolated microgrids need significant changes in the GEP models to properly integrate less polluting RE sources, in response to environmental concerns and associated governmental policies on emission reductions. Modifications and improvements to the traditional GEP models and various associated solution methodologies have been presented in, for example, [30] and [31], and including RE technologies in, for example, [32]. The costs associated with RE equipment have been a concern, but in recent years these prices have significantly decreased, particularly for solar, to such an extent that it is now an economically viable option for solar-hybrid systems in some locations, with solar capacity deployment depending on the quality of resources available in the geographical area under consideration [33], [34]. For systems with both solar and wind deployment, it has been shown that off-grid applications, especially in remote areas, can be economically viable due to the high cost of transportation and storing of diesel [32], [35].

RE sources are intermittent in nature and thus a backup power source is required to ensure reliable power supply. Hence, energy storage technologies are needed as an alternative to diesel-based backup generators [36], [37]; thus, specifically, battery-based backup schemes have been proposed [38], [39]. Therefore, diesel-RE hybrid systems must be planned considering the integration of battery technologies [35], [38], [40]. The components of diesel-RE hybrid systems have been modeled for various design and simulation studies [41], [42], particularly optimum economic designs focused on minimizing the Net Present Cost (NPC) or the Levelized Cost of Energy (LCOE), using linear programming [43], genetic algorithms [44], and iterative optimization methods [45]. Detailed optimization models of diesel-RE hybrid systems are presented for day-ahead operational planning in [40], and long-term operational planning in [32]. Thus, based on the available work on diesel-RE optimal planning and models for remote, isolated microgrid, the second stage of this paper, based on [28] and [29], presents an hourly operational planning model combined with long-term capacity expansion planning techniques to determine the optimal RE integration plan for the 6 community microgrids in the Canadian Arctic identified in the previous stage.

VSG technology is essentially the decoupling of the generator speed, i.e., the frequency of the generators power output, from the power systems frequency. This is achieved by means of power electronic converters that decouple the generator from the grid, which allows the generators prime-mover to run at optimal speeds for the power output, i.e., the efficiency of the required mechanical power being fed to the electrical generator is near or at its optimal value for the prime mover. For the case of the prime-mover being a diesel engine, this translates into savings in diesel fuel, as the engine operates at its optimal fuel consumption efficiency to produce the mechanical torque and corresponding power demanded by the power system. The VSG technology developed by Innovus Power is stated to have unique fuel consumption characteristics and the ability to run at very low loading conditions of around 10% of its rated capacity; it can also provide through its “PowerBridge” fast start-up capability and a dump load to facilitate RE integration [46]. Hence, in the feasibility studies presented, Innovus’ VSGs are considered for the 6 selected arctic communities studied, to analyze the impact of this VSG’s unique characteristics in the deployment of RE and diesel consumption for these communities. This is accomplished by incorporating in the optimization model used in the feasibility study a representation of the VSG, considering its unique fuel consumption and low loadability properties, as well as its PowerBridge.

The main objectives and contributions of this work can thus be summarized as follows:

- Present a relevant methodology to pre-select communities based on high level data ranging from RE resource profiles to community size, location, and associated costs of transportation.
- Design a new set of ranking criteria, such as project investment cost versus savings and replacement of diesel generators at minimum costs, and apply HOMER to rank the communities, identifying 6 communities suitable for detailed feasibility studies to be used to build business cases for RE deployment.
- Develop a novel optimal planning framework and models suitable for the communities under study, incorporating VSGs in the optimization model, to analyse its impact in designing an optimal RE integration plan for remote communities.
- Apply the new proposed approach to 6 communities in the Canadian Arctic, based on actual collected data, to develop expansion plans for optimal integration of RE into their diesel-based microgrids, with and without VSGs.
- Evaluate and quantify for the first time the possible benefits of optimal RE integration into the communities under study, with and without VSGs, to identify the locations with the most significant potential for RE integration, and build business cases for actual deployment.

The rest of this paper is organized as follows: Section II presents an empirical pre-selection methodology and associated results to select the communities for HOMER-based analysis and ranking. Section III describes the details of the pre-feasibility studies, including the ranking criteria, HOMER simulations and results, and the final ranking of communities for further feasibility studies. Section IV presents the details of the proposed RE integration model, including new VSG technologies. Section V describes the feasibility studies for the considered communities in the territories of Nunavut and NWT, Canada, with and without VSGs, and presents a suitable business case for each community to make recommendations for pilot projects. Finally, Section VI highlights the main conclusions and contributions of the work presented.

II. Community Pre-Selection

The studies for integrating RE in the communities of Nunavut and the Inuvik region of NWT were initiated by performing a pre-selection of the 33 communities in these regions based on certain criteria. The objective of the pre-selection process described next was to reduce the number of communities to a manageable list, where HOMER-based simulations of RE integration can be performed to rank these pre-selected communities as per the considered criteria, for more detailed feasibility studies.

A. Basic Input Data

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

- *Geographical Location*: The latitude and longitude was used to determine solar insolation, wind, and temperature profiles, when metered data were not available.
- *Air-cargo and Sea-lift Rates*: These rates, coupled with data on flight connections and air-distances, helped to identify the cheapest route to transport goods and personnel to/from communities, using the preferred/required modes of transport, as applicable (e.g. converters can be transported by air, whereas wind turbine blades and hubs require sea-lift). Air cargo rates were obtained from [47]–[51]. The rates for sea-lift to/from the communities of Nunavut were available in [52] and [53] for Nunavut, and [54] for ISR.
- *Community Size*: Existing population (as of 2013) and its annual growth data, available in [55]–[57], helped to determine the size of the community.
- *Electricity Rates*: The rates paid by the customers in these two regions were divided into 2 groups: governmental and non-governmental, and domestic and commercial. Nunavut's electricity rates were provided by Qulliq Energy Corporation (QEC) [58], and for the Inuvik region, it was provided by the Northwest Territories Power Corporation (NTPC) [59].
- *Energy Demand and GHG Emissions*: This data, in the pre-selection stage, was obtained from Nunavut Energy for Nunavut [60], and from the Arctic Energy Alliance (AEA) for the communities in ISR [61].
- *Solar PV and Wind Potential*: High level data for solar PV potential, on an annual energy generation capability per installed capacity (kWh/kW) basis, was obtained from photovoltaic and solar resource maps of Natural Resources Canada (NRCAN) [62]. Similarly, data on wind potential, i.e., annual average wind speed and wind energy, was obtained from the Wind Atlas Canada [63].

B. Methodology

The first task was to gather all the information from various sources and compile them for comparative analysis. The next step was to define attributes for different ranges of a given parameter, in order to perform a qualitative comparison. For example, it was found that the wind speed data varies from 3.44 m/s to 7.71 m/s; hence, the ranges were divided in four categories, low (L), medium low (ML), medium high (MH), and high (H), as follows:

$$L < 4 \text{ m/s} \leq ML \leq 5 \text{ m/s} \leq MH \leq 6 \text{ m/s} \leq H$$

This process of assigning attributes was confined to a certain set of input parameters, which were deemed to be important in the selection process; the parameters and their respective ranges for defining attributes are shown in Table II. Observe that the values for air and sea cargo rates are considered in the opposite order than the rest to define their corresponding attributes. All these attributes were cumulatively considered attaching weights to them, where the weights depend on the importance of the parameter in consideration (e.g., wind or solar characteristics have higher importance than community size). The cumulative attributes were finally sorted in descending order to determine the rank of the communities.

The overall ranking for all the communities in Nunavut is shown in Fig. 1, along with the parameters considered for the pre-selection process, and the region the ranked community belongs to. A similar ranking procedure was followed to select the 4 communities from the Inuvik region of NWT, as shown in Fig. 2. The first four parameters were given twice the weight than the other parameters, because these have a large impact on possible RE deployment. Observe that none of the communities of the Kitikmeot region, which includes Cambridge Bay, feature in the top 15 rank; on the other hand, all the communities in the Kivalliq region rank in the top 10. This regional disparity can be largely attributed to the vicinity of the Kivalliq region to the main sea connection points, as RE equipment would require sea-lift transport. Hence, to improve the ranking a regional selection of the communities of Nunavut was carried out, based on the results of Fig. 1, to properly consider the merits of possible RE deployment in all regions. Thus, for each region, approximately 50% of the communities were selected for further study, stopping when there were some significant differences in some of the criteria illustrated in Fig. 1 for the region; for example, for the Kivalliq region, the community of Baker Lake has better solar potential and similar electricity rates than Repulse Bay.

III. Pre-Feasibility Study

The pre-feasibility study determined the suitability of the communities for RE integration, and defined the final rankings of the communities for in-depth feasibility studies, based on more detailed ranking criteria for the group of communities selected in the pre-selection stage. To determine the least-cost RE deployable option with and without battery storage systems, HOMER was used as the main tool to simulate the RE integrated operation of the remote micro-grids for generation planning in these communities [17].

TABLE II
PARAMETERS AND RANGES FOR COMMUNITY PRE-SELECTION

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

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

Fig. 1. Overall ranking of all 25 communities in Nunavut for pre-feasibility studies.

COMMUNITIES	OVERALL RANK	WIND SPEED	SOLAR ENERGY	Tr. COST SEA	Tr. COST AIR	COMM. SIZE	ENERGY DEMAND	GHG EMISSION	ELECTR. RATE
Inuvik	1	ML	ML	L	ML	H	H	MH	ML
Sachs Harbour	2	MH	ML	L	ML	L	H	H	H
Ulukhaktok	3	H	ML	L	ML	L	H	ML	MH
Tuktoyaktuk	4	MH	ML	L	ML	MH	ML	ML	MH
Paulatuk	5	MH	ML	L	ML	L	ML	ML	H
Tsiigehtchic	6	ML	ML	MH	ML	L	H	ML	H
Fort McPherson	7	L	ML	MH	ML	MH	L	ML	H
Aklavik	8	MH	ML	ML	ML	ML	ML	ML	ML

Fig. 2. Overall ranking of all 8 communities in ISR for pre-feasibility studies.

A. Procedure

Certain operational constraints and various input requirements were considered to simulate realistic scenarios, as per the following procedure:

1) The base case for any community was the "No RE" case, considering the present scenario, which provided the basis for comparison purposes based on the chosen ranking criteria (e.g., system cost and emission reductions).
2) The next study incorporated RE with no storage availability.
3) Further studies were carried out increasing storage/battery capacities, until the following criteria was met:
   a) Replacement of required new diesel generators by RE.
   b) System costs when introducing RE with batteries was more than the base-case system costs, i.e., system

savings becoming negative.

4) RE and battery capacities were increased to determine the costs of a diesel free operation, if possible.

Communities were ranked to enable the selection of the 6 communities for feasibility studies based on the following criteria:

1) Replacement of new required diesel generators, considering emergency and stand-by generators.
2) Maximum savings on system costs, which include fuel, diesel capital, and operations and maintenance (O&M) costs of both diesel and RE equipment.
3) System savings equal to RE installation costs.
4) Maximum reduction in CO_2 emissions.
5) Maximum RE penetration in percentage of the total energy.
6) Diesel-free operation.

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

The first ranking criterion revealed a problem faced by the ageing generator fleet of Nunavut, which is not the case of generating stations in ISR; thus, this criterion was applied to rank the communities of Nunavut only. In addition to the age of generators, it was learned from discussions with personnel of QEC [58], that they intend to equip all the communities with appropriate stand-by and emergency generators; it was also reported that not every community has sufficient number of generators with remaining operating life to fulfill these roles. This prompted the allocation of such generators wherever they did not exist for this role, thereby reducing the number of available generators to supply demand, and thus, requiring the purchase of new generators. The simulation then tried to find a feasible condition where all the regular energy demand could be supplied by the existing available diesel generators, i.e., those not on stand-by or emergency mode, and the addition of adequate capacity of RE wind and solar resources, along with sufficient capacity of battery storage. This RE capacity replaced required new diesel generators, and the battery provided operating reserves traditionally provided by diesel generators.

The second ranking criterion was applied to all the communities of the two regions in consideration. Since almost all of the energy generated in these communities is from diesel generators (barring a couple of natural gas generators in Inuvik), the cost of diesel itself, along with the transportation of it, is a concern; hence, the incorporation of RE in the supply mix would reduce the diesel requirement and the associated system costs. The presented study found the maximum system cost reduction point for each community, and then ranked them based on descending percentage points of savings achieved.

In the third ranking criterion, a condition was sought where the RE installation cost would be nearly equal to the system cost reduction. This condition allowed the reallocation of money saved in system O&M to the installation cost of RE equipment. The next two ranking criteria are well established, and self-explanatory; these two were considered in order to fulfill the ultimate goal of emission reduction and to develop business cases for substantial RE deployment. Finally, the last ranking criterion was considered to assess the possibility and cost requirement of diesel-free operation.

A final ranking of 13 communities in Nunavut and 4 in the Inuvik region was obtained considering the rankings provided by all the criteria described earlier, as applicable. Five communities were picked from Nunavut, and 1 from the Inuvik region for the next study stage, i.e., detailed feasibility studies.

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

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

- Capacity shortage was not allowed.
- Spinning reserves of 10% of the load at the current time step were considered, as per usual utility operating policies in the studied communities.
- To account for the variability of the energy generated by renewable sources, additional spinning reserves were used [64], [65], which are HOMER default values:
  - 25% of solar energy generation at any given time step.
  - 50% of wind energy generation at any given time step.
- For reliability, an additional operating reserve of 10% of the peak load was considered.

B. Input Data

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

- The simulation time step was 60 minutes, except for Paulatuk, Tuktoyaktuk, and Ulukhaktok, which had 1 minute step size, based on the available demand data provided by QEC and NTPC.
- System economics:
  - Discount rate = 8%, and inflation rate = 2%.
  - Project life = 25 years.
- System operation criteria as per HOMER:
  - Economic minimization.
  - Operation strategy of load following.
  - Allow system with multiple generators.
  - Allow generators to operate simultaneously, as per QEC and NTPC operating procedures.
  - Allow system with generator capacities less than peak load.
  - Allow diesel-off operation.

The following assumptions, apart from the one related to operational constraints, were made to perform the pre-feasibility study:

- The same linear relationship of fuel consumption rate with respect to rated capacity for all existing generators was used.
- PV panel sets of 100 kW for all communities in Nunavut and the community of Inuvik, and 50 kW for the remaining 3 communities of ISR.
- Useful life of solar, wind, converter, and battery of 25, 30, 15, and approximately 15 years, depending on energy use, respectively.
- Useful life of diesel generators from 72,000 hours to 160,000 hours, depending on the manufacturer, for the community of Nunavut; for the communities in ISR, 100,000 hours generator life, with half of it being already consumed, as NTPC was not able to provide this information for all the communities, with the exception of Sachs Harbour for the feasibility studies.

Load data was made available by QEC and NTPC. Data corresponding to all communities of Nunavut and the community of Inuvik included the maximum and minimum monthly values along with the monthly total energy generation; this was then synthesized to represent an hourly load profile for these communities. For the remaining three communities in NWT, load data was available in higher granularity, i.e., in minutes, and therefore the time-step of simulation for these communities was also kept in minutes. A 10% hourly variation in the synthesized input load profile was implemented by HOMER, resulting in nearly 40% increase in peak load over 25 years (amounting to 1.41% annual increase); however, in the simulation, only the maximum annual load profile for all years was considered, since the HOMER version 3.4 used did not allow year to year increase as an input.

The hourly solar insolation profile was derived from Canadian Weather Energy and Engineering Datasets (CWEEDS) [66], and from HOMER's National Aeronautics and Space Administration's (NASA) Surface meteorology and Solar Energy (SSE) database [67]. The hourly wind profile was calculated using data obtained from the database of Environment and Climate Change, Canada [68], for most communities, and HOMER's NASA SSE dataset, for the 3 communities where the data was not available. Temperature profiles of all the communities were available in HOMER's NASA SSE database to implement the effect of temperature on solar cell and wind turbine output.

All the communities considered in this study generate electricity using diesel generators only, except Inuvik, which has a couple of natural gas based generators as well; the size of these generators varies from 165 kW to 5 MW, and age varies from less than a year old to more than 40 years old. Solar PV panel sets of 100 kW capacity were considered as the unit-size for PV plants for all the communities, using technical data of panels manufactured by Canadian Solar [69]; the panel tilt was assumed to be equal to the latitude of the location where it would be installed. Wind turbine sizes were considered to be 100 kW at 30 m hub height, for all communities except Iqaluit and Inuvik, where 1.5 MW at 80 m hub height and 500 kW at 50 m hub height turbines were used, respectively, due to the large loads at these communities. Only lead acid batteries were considered at this stage, as these are the cheapest available.

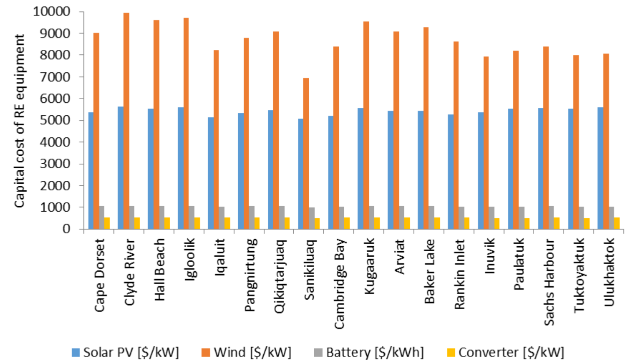

Fig. 3. Capital cost, including transportation and installation, of RE equipment at studied communities.

The costs of transporting and installing both RE and diesel generation equipment were considered in computing the capital costs, retrieving basic equipment costs from Lazard's Levelized Cost of Energy (LCOE) Analysis [70]. Figure 3 presents the final capital costs for RE equipment.

C. Results

In this section, the final results for the base case and the 6 different ranking criteria stated in Section III-A are presented and discussed. It is worth mentioning here that the existing diesel and natural gas based generators were modeled with zero capital costs, as these costs would not be incurred during the time-line of the project. The omission of this capital cost from the simulations resulted in a lower than expected value of LCOE, and thus these values are not presented here.

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

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

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

The results corresponding to the first 5 ranking criterion, based on HOMER simulations, were used to obtain the final ranking (details can be found in [27]; the sixth ranking criterion was not used to determine the final ranking of the communities due to the high installation costs). The comprehensive results from HOMER simulations, for the top 5 and 3 communities of Nunavut and the Inuvik region, respectively, are presented in Figures 4 and 5. For the last position, the communities of Kugaaruk, Hall Beach, and Arviat could be selected; however, QEC recommended selecting Arviat as the fifth community. For the ISR communities, only Sachs

Communities	Overall Ranking	Maximum Annual RE Penetration [%]	CO_2 Reduction over 25-yr. [%]	Total Sys. Savings over 25-yr. [M$]	Fuel Use Reduction over 25-yr. [M L]	Total RE Investment Required [M$]
Sanikiluaq	1	52.10	53.06	12.56	13.54	10.29
Iqaluit	2	41.50	42.29	87.40	164.04	95.81
Rankin Inlet	3	40.60	40.50	24.91	49.99	41.74
Baker Lake	4	40.30	39.50	4.13	23.82	26.50
Arviat	5	34.60	34.25	9.98	21.08	15.06

Fig. 4. Final ranking of top 5 communities of Nunavut.

Communities	Overall Ranking	Maximum Annual RE Penetration [%]	CO_2 Reduction over 25-yr. [%]	Total Sys. Savings over 25-yr. [M$]	Fuel Use Reduction over 25-yr. [M L]	Total RE Investment Required [M$]
Sachs Harbour	1	26.30	28.50	2.10	2.85	2.56
Paulatuk	2	6.20	9.06	0.40	1.06	0.82
Ulukhaktok	3	1.90	3.50	0.12	0.57	0.59

Fig. 5. Final ranking of top 3 communities of ISR.

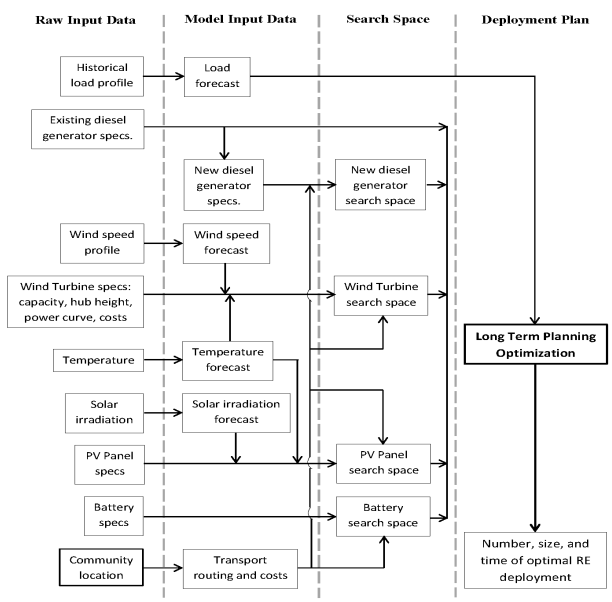

Fig. 6. Optimization framework used in the presented feasibility studies [28].

Harbour was considered for the feasibility studies, as requested by NTPC.

IV. RE Integration Planning Framework and Model

The long-term planning approach for integration of RE described in this report is based on a GEP approach [71], with the suitable modified optimization framework depicted in Fig. 6, based on the approach proposed for northern communities in Ontario [72]. This approach was used to build the planning model for the feasibility study, considering either FSGs or VSGs as 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 both FSGs and VSGs as new 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 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 microgrids.

A. Mathematical Model

Mathematical optimization is a technique to determine the best outcome (such as maximum profit or least cost) based on the following generic mathematical model, satisfying a list of constraints represented by linear/non-linear relationships:

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

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

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

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 Mixed Integer Linear Programming (MILP) problem. Thus, the mathematical model for the present microgrid planning problem is an MILP problem, since all constraints are linear and 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.

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 FSG or VSG and RE equipment, as follows:

$$\begin{aligned} Z = & \underbrace{FC^F + OMC^F}_{\text{Existing FSG}} + \underbrace{CC^S + OMC^S}_{\text{Solar}} \\ & + \underbrace{CC^W + OMC^W}_{\text{Wind}} + \underbrace{CC^B + OMC^B}_{\text{Battery}} \\ & + \underbrace{CC^G + FC^G + OMC^G}_{\text{New FSG/VSG}} \end{aligned} \tag{4}$$

where the various parts of the equation represent the total costs of the different types of equipment considered, with the notation used in this equation and all others in this document being defined in the Nomenclature section at the beginning of the paper. As it is common practice in remote communities in Canada, diesel generators are assumed here to be owned and installed by the corresponding utility of the territory, whereas RE technologies may or may not be paid by this entity. Furthermore, only the total cost of installing new generation capacity is accounted for, considering the capital costs of existing diesel generators as sunk costs and neglecting their salvage values, thus lumping together new and existing generation for planning purposes.

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

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

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

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

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

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

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

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

where the factor 30 is associated with the time-step management of the project horizon based on the following procedure to reduce the computational burden, and thus allow obtaining results in the available timeline: The project horizon is reduced to $PH = 20$ years from 25 years in the pre-feasibility studies, 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; this is done to reduce the size of the optimization problem so that the computational burden is reasonable. 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:

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

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

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

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:

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

$$FC^G = \sum_{y=1}^{PH} \frac{Dcost \sum_{h=1}^{HY} 30 \left(\sum_{n_G=1}^{N_G} Fcon_{n_G,y,h}^G \right)}{(1+d)^{y-1}} \tag{12}$$

where

$$Fcon_{e_F,y,h}^F = F_{e_F} \left(Pd_{e_F,y,h}^F, \; u_{e_F,y,h}^{FO} \right) \tag{13a}$$

$$Fcon_{n_G,y,h}^G = F^G \left(Pd_{n_G,y,h}^G, \; u_{n_G,y,h}^{GO} \right) \tag{13b}$$

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 for FSGs; and 100%, 50%, and 10% for VSGs.

2) 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:

$$\underbrace{\sum_{e_F=1}^{N_F} Pd_{e_F,y,h}^F}_{\text{Existing FSG}} + \underbrace{\sum_{n_S=1}^{N_S} Ps_{n_S,y,h}^S}_{\text{Solar}} + \underbrace{\sum_{n_W=1}^{N_W} Pw_{n_W,y,h}^W}_{\text{Wind}} + \underbrace{\sum_{n_G=1}^{N_G} Pd_{n_G,y,h}^G}_{\text{New FSG/VSG}}$$
$$+ \underbrace{\sum_{n_B=1}^{N_B} \left(Pb_{n_B,y,h}^D - Pb_{n_B,y,h}^C \right)}_{\text{Battery}} = PD_{y,h} \quad \forall y, h \tag{14}$$

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, to guarantee that enough dispatchable generation is available to supply the required variable load while considering the stochastic nature of wind and solar generation:

$$\underbrace{\sum_{e_F=1}^{N_F} Cap_{e_F,y}^F}_{\text{Existing FSG}} + \underbrace{\sum_{n_B=1}^{N_B} SOC_{n_B,y,h}}_{\text{Battery}} + \underbrace{\sum_{n_G=1}^{N_G} Cap_{n_G,y,h}^G}_{\text{New FSG/VSG}} \geq (1+\beta) PD_{y,h}$$
$$+ \gamma \underbrace{\sum_{n_S=1}^{N_S} Ps_{n_S,y,h}^S}_{\text{Solar}} + \rho \underbrace{\sum_{n_W=1}^{N_W} Pw_{n_W,y,h}^W}_{\text{Wind}} \quad \forall y, h \tag{15}$$

3) Dynamic Addition of New Capacity: The commissioning of new FSGs or VSGs and RE capacity at a specified hour in the planning horizon is dynamically added to the generation portfolio using the following expressions, for diesel generation, solar, wind, and battery, respectively:

$$Cap^G_{n_G,y,h+1} = Cap^G_{n_G,y,h} + NCA^G_{n_G,y,h} \quad \forall n_G, y, h \tag{16}$$
$$Cap^S_{n_S,y,h+1} = Cap^S_{n_S,y,h} + NCA^S_{n_S,y,h} \quad \forall n_S, y, h \tag{17}$$
$$Cap^W_{n_W,y,h+1} = Cap^W_{n_W,y,h} + NCA^W_{n_W,y,h} \quad \forall n_W, y, h \tag{18}$$
$$Cap^B_{n_B,y,h+1} = Cap^B_{n_B,y,h} + NCA^B_{n_B,y,h} \quad \forall n_B, y, h \tag{19}$$

and, to sequentialize the hour and year indices:

$$Cap^G_{n_G,y+1,1} = Cap^G_{n_G,y,HY} + NCA^G_{n_G,y,HY} \quad \forall n_G, y, h \tag{20}$$
$$Cap^S_{n_S,y+1,1} = Cap^S_{n_S,y,HY} + NCA^S_{n_S,y,HY} \quad \forall n_S, y, h \tag{21}$$
$$Cap^W_{n_W,y+1,1} = Cap^W_{n_W,y,HY} + NCA^W_{n_W,y,HY} \quad \forall n_W, y, h \tag{22}$$
$$Cap^B_{n_B,y+1,1} = Cap^B_{n_B,y,HY} + NCA^B_{n_B,y,HY} \quad \forall n_B, y, h \tag{23}$$

where the new capacity additions are as follows:

$$NCA^G_{n_G,y,h} = Ucap^G_{n_G} \ u^{GP}_{n_G,y,h} \quad \forall n_G, y, h \tag{24}$$
$$NCA^S_{n_S,y,h} = Ucap^S_{n_S} \ u^{SP}_{n_S,y,h} \quad \forall n_S, y, h \tag{25}$$
$$NCA^W_{n_W,N,h} = Ucap^W_{n_W} \ u^{WP}_{n_W,y,h} \quad \forall n_W, y, h \tag{26}$$
$$NCA^B_{n_B,N,h} = Ucap^B_{n_B} \ u^{BP}_{n_B,y,h} \quad \forall n_B, y, h \tag{27}$$

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

4) Diesel Generation Limits: The maximum power generation for new diesel generators is limited by the rated capacity of the diesel generator:

$$Pd^G_{n_G,y,h} \leq Cap^G_{n_G,y,h} \ u^{GO}_{n_G,y,h} \quad \forall n_G, y, h \tag{28}$$

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 [73], resulting in a new positive continuous variable being defined as $Capu_{n_G,y,h}$, and the following set of equations that linearize and replace (28) in the model:

$$Pd^G_{n_G,y,h} \leq Capu_{n_G,N,h} \quad \forall n_G, y, h \tag{29}$$
$$Capu_{n_G,y,h} \leq 5 \ Ucap^G_{n_G} \ u^{GO}_{n_G,y,h} \quad \forall n_G, y, h \tag{30}$$
$$Capu_{n_G,y,h} \leq Cap^G_{n_G,y,h} \quad \forall n_G, y, h \tag{31}$$
$$Capu_{n_G,y,h} \geq Cap^G_{n_G,y,h} - 5 \ UCap^G_{n_G} \left(1 - u^{GO}_{n_G,y,h}\right) \quad \forall n_G, y, h \tag{32}$$
$$Capu_{n_G,y,h} \geq 0 \quad \forall n_G, y, h \tag{33}$$

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

$$Pd^F_{e_F,y,h} \leq Cap^F_{e_F,y} \ u^{FO}_{e_F,y,h} \quad \forall e_F, y, h \tag{34}$$

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

$$Pd^G_{n_G,y,h} \geq ML^G \ Capu_{n_G,y,h} \quad \forall n_G, y, h \tag{35}$$

$$Pd^F_{e_F,y,h} \geq ML^F_{e_F} \ Cap^F_{e_F,y} \ u^{FO}_{e_F,N,h} \quad \forall e_F, y, h \tag{36}$$

5) 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.

6) Diesel Generator Life: The useful life of new diesel generators and the remaining life of existing FSGs, in hours, are incorporated in the model using the following two expressions, respectively:

$$\sum_{y=1}^{PH} \sum_{h=1}^{HY} 30 \ u^{FO}_{e_F,y,h} \leq GH^R_{e_F} \quad \forall e_F \tag{37}$$
$$\sum_{y=1}^{PH} \sum_{h=1}^{HY} 30 \ u^{GO}_{n_G,y,h} \leq GH^L_{n_G} \quad \forall n_G \tag{38}$$

7) 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:

$$\sum_{h=1}^{HY} u^{FO}_{e_F,y,h} \leq 288(1 - T^{OM}) \quad \forall e_F, y \tag{39}$$
$$\sum_{h=1}^{HY} u^{GO}_{n_G,y,h} \leq 288(1 - T^{OM}) \quad \forall n_G, y \tag{40}$$

8) PowerBridge Model: The PowerBridge component is integrated with the VSG for studies where existing FSGs are wholly replaced with VSGs after 2 years and only VSGs are considered for new diesel generation, in which case its capital cost is modeled as follows:

$$CC^{PB} = \sum_{y=1}^{PH} \frac{\sum_{n_G=1}^{N_G} UC^{PB} \left(\sum_{h=1}^{HY} u^{GP}_{n_G,y,h} \right)}{(1+d)^{y-1}} \tag{41}$$

This component is included in the objective function whenever the 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:

$$Z = \underbrace{FC^F + OMC^F}_{\text{Existing FSG}} + \underbrace{CC^S + OMC^S}_{\text{Solar}} + \underbrace{CC^W + OMC^W}_{\text{Wind}} + \underbrace{CC^{PB} + OMC^{PB}}_{\text{PowerBridge}} + \underbrace{CC^G + FC^G + OMC^G}_{\text{New VSGs}} \tag{42}$$

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

$$OMC^{PB} = \sum_{y=1}^{PH} \frac{\sum_{h=1}^{HY} 30 \left(\sum_{n_G=1}^{N_G} HOM^{PB} \ Cap^G_{n_G,y,h} \right)}{(1+d)^{y-1}} \tag{43}$$

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:

$$\underbrace{\sum_{e_F=1}^{N_F} Pd^F_{e_F,y,h}}_{\text{Existing FSG}} + \underbrace{\sum_{n_S=1}^{N_S} Ps^S_{n_S,y,h}}_{\text{Solar}} + \underbrace{\sum_{n_W=1}^{N_W} Pw^W_{n_W,y,h}}_{\text{Wind}}$$
$$+ \underbrace{\sum_{n_G=1}^{N_G} Pd^G_{n_G,y,h}}_{\text{[New VSG}} = PD_{y,h} + \underbrace{\sum_{n_G=1}^{N_G} DL^{PB}_{n_G,y,h}}_{\text{PowerBridge}} \quad \forall y,h \tag{44a}$$
$$DL^{PB}_{n_G,y,h} \leq Cap^G_{n_G,y,h} \quad \forall n_G, y, h \tag{44b}$$

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

$$\underbrace{\sum_{e_F=1}^{N_F} Cap^F_{e_F,y} u^{FO}_{e_F,y,h}}_{\text{Existing FSG}} + \underbrace{\sum_{n_G=1}^{N_G} Cap^G_{n_G,y,h}}_{\text{New VSG}}$$
$$\geq (1+\beta)PD_{y,h} + \gamma \underbrace{\sum_{n_S=1}^{N_S} Ps^S_{n_S,y,h}}_{\text{Solar}} + \rho \underbrace{\sum_{n_W=1}^{N_W} Pw^W_{n_W,y,h}}_{\text{Wind}} \quad \forall y,h \tag{45}$$

9) 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 represented as follows:

$$Pw^W_{n_W,y,h} = W_{n_W}\left(Cap^W_{n_W,y,h},\ WS_h\right) \quad \forall n_W, y, h \tag{46}$$

10) 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:

$$Ps^S_{n_S,y,h} = Cap^S_{n_S,y,h}\ df^S\ \left(\frac{SI_h}{GT^{STC}}\right)$$
$$\times\left[1+\alpha\left(Tcell_h - Tcell^{STC}\right)\right] \quad \forall n_S, y, h \tag{47}$$

11) Battery SOC and life: 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:

$$SOC_{n_B,y,h+1} - SOC_{n_B,y,h}$$
$$= \eta^C\ Pb^C_{n_B,y,h} - \frac{Pb^D_{n_B,y,h}}{\eta^D} + 0.8\ NCA^B_{n_B,y,h} \quad \forall n_B, y, h \tag{48}$$
$$SOC_{n_B,y+1,1} - SOC_{n_B,y,HY} = \eta^C\ Pb^C_{n_B,y,HY}$$
$$- \frac{Pb^D_{n_B,y,HY}}{\eta^D} + 0.8\ NCA^B_{n_B,y,HY} \quad \forall n_B, y, h \tag{49}$$

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:

$$SOC_{n_B,y,h} \leq Cap^B_{n_B,y,h} \quad \forall n_B, y, h \tag{50}$$
$$SOC_{n_B,y,h} \geq DoD^B\ Cap^B_{n_B,y,h} \quad \forall n_B, y, h \tag{51}$$

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 as the discharging rates, thus yielding the following maximum charging and discharging limits:

$$Pb^D_{n_B,y,h} \leq \left(\frac{1-DoD^B}{T^D}\right)\ Cap^B_{n_B,y,h} \quad \forall n_B, y, h \tag{52}$$
$$Pb^C_{n_B,y,h} \leq \left(\frac{1-DoD^B}{T^D}\right)\ Cap^B_{n_B,y,h} \quad \forall n_B, y, h \tag{53}$$

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):

$$Pb^D_{n_B,y,h} \geq u^D_{n_B,y,h} \quad \forall n_B, y, h \tag{54}$$
$$Pb^C_{n_B,y,h} \geq u^C_{n_B,y,h} \quad \forall n_B, y, h \tag{55}$$

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 constraint is imposed:

$$Pb^C_{n_B,y,h}\ Pb^D_{n_B,y,h} = 0 \quad \forall n_B, y, h \tag{56}$$

This is a non-linear equation, since it is a product of two continuous variables, which is linearized as follows [74]:

$$Pb^D_{n_B,y,h} \leq u^D_{n_B,N,h} M \quad \forall n_B, y, h \tag{57}$$
$$Pb^C_{n_B,y,h} \leq u^C_{n_B,y,h} M \quad \forall n_B, y, h \tag{58}$$
$$u^C_{n_B,y,h} + u^D_{n_B,y,h} \leq 1 \quad \forall n_B, y, h \tag{59}$$

Finally, the battery life is computed as follows:

$$\sum_{y=1}^{PH}\sum_{h=1}^{HY}\left(Pb^D_{n_B,y,h} + Pb^C_{n_B,y,h}\right) \leq 3000 \sum_{y=1}^{PH}\sum_{h=1}^{HY} NCA^B_{n_B,y,h} \quad \forall n_B \tag{60}$$

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

12) 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:

$$\sum_{n_S=1}^{N_S}\sum_{h=1}^{HY} Ps^S_{n_S,y,h} \geq 0.01 \sum_{h=1}^{HY} PD_{y,h} \quad \forall y, h \tag{61}$$

$$\sum_{n_W=1}^{N_W}\sum_{h=1}^{HY} Pw^{W}_{n_W,y,h} \geq 0.01 \sum_{h=1}^{HY} PD_{y,h} \quad \forall y,h \tag{62}$$

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

$$\sum_{n_B=1}^{N_B}\sum_{y=1}^{PH}\sum_{h=1}^{HY} u^{BP}_{n_B,y,h} \geq 1 \tag{63}$$

13) Final Model: The resulting MILP optimization model when PowerBridge is not considered, i.e., for the studies where FSGs are only replaced by VSGs at their end-of-life, is comprised of equations (4) to (27), (29) to (40), (46) to (55), and (57) to (60), with equations (61) to (63) 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 (42), (44a), and (45), respectively, with (43) and (44b) added, and all the battery related equations, i.e., (5d), (10), (19), (23), (27), (48) to (55), and (57) to (60), removed from the model. The model was solved in the GAMS environment [75], using the CPLEX solver [76], on an Intel(R) Xeon(R) CPU L7555, 1.87 GHz 4-processor server.

B. Input Data

Various sets of input data were required for the simulations for the 6 studied communities (5 in Nunavut and 1 in ISR), some of which were constant for all communities and some were specific for the community in consideration. The details of the important input data used for the studies presented here are discussed next.

1) Load Profiles: Load data was made available by the respective territorial utilities, i.e., QEC for the 5 communities of Nunavut [58], and NTPC for the ISR community of Sachs Harbour in NWT [59]. 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 IV-A1, the load and RE data was averaged per day over a month, so that simulations could be carried out in a timely fashion.

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 CWEEDS dataset [66], were gathered and processed to obtain the required hourly profiles of daily averages per month. The stochastic nature of these data is captured in these profiles, which are treated as fixed values in the proposed deterministic optimization model, similarly to HOMER.

3) Existing FSGs: All existing FSGs in the 6 communities, along with their capacities, remaining life, manufacturers, and model numbers were considered as per [28]. This information was used to find the data-sheets of these generators in order to obtain their fuel consumption curves.

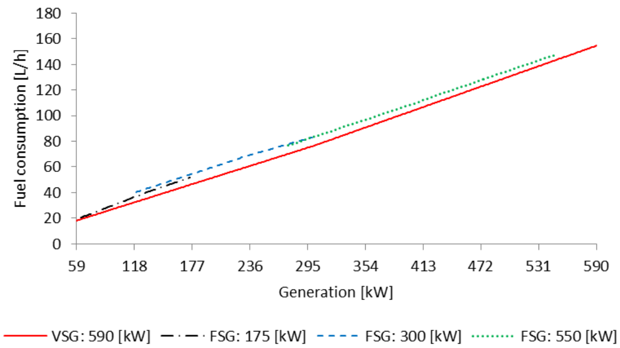

Fig. 7. Comparison of fuel consumption and loadability of VSG versus similar capacity FSGs.

It is preferable to have some generators of a community in a stand-by mode, but, as previously mentioned, 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 in the case of the pre-feasibility studies, and 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.

4) New VSGs: The 590 kW VSGs from Innovus Power have unique characteristics of low loadability and fuel consumption, as shown in Fig. 7, where the fuel curves are compared with three other FSGs. This unique characteristic is enhanced by adding the PowerBridge, which is designed as an energy buffer and stabilizing load system, and is used to manage excess RE generation. Another aspect of the PowerBridge is the capability to allow turning off the engine and stabilize other running FSGs by using ultra-capacitors. However, this was not modeled in this study, since ramping constraints, start up and shut down costs, and minimum uptime and downtime constraints do not need to be modeled here, since the time interval used in the studies was 1 h, as mentioned in Section III-A; in this time scale, any generator can start up and shut down instantaneously, which is what the PowerBridge allows.

5) General Considerations: The data assumed constant for all communities were the following:

- The simulation time steps of the multi-time step model were 1 hour 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 [64], [65].
- Generation reserve margin for system adequacy of $\beta = 0.1$ (10%).
- Minimum loading of a diesel generator was $ML = 0.4$ (40%) of the rated capacity for FSGs, and $ML = 0.1$ (10%) for the VSGs.

TABLE III
NEW DIESEL GENERATOR SEARCH SPACE IN [KW]

Communities	n_G			
	1	2	3	4
Arviat	520	800	1,000	-
Baker lake	520	800	1,000	1,500
Iqaluit	320	2,000	4,000	-
Rankin Inlet	800	1,000	1,500	2,000
Sanikiluaq	320	520	-	-
Sachs Harbour	175	320	-	-

- Minimum percent of time per year a diesel generator must be off-line for maintenance was T^{OM} = 0.1 (10%).
- Useful life of diesel generators was considered to be in the range of GH^{life} = 72,000 to 100,000 h.
- Temperature at Standard Test Conditions (STC) for PV cell was $Tcell^{STC}$ = 25°C.
- The solar radiation incident on the PV cell at STC was GT^{STC} = 1 kW/m^2.
- Derating factor of solar PV cell was assumed to be df^{sol} = 0.98 (98%).
- Charging and discharging efficiencies of a battery were assumed to be $\eta^{Ch} = \eta^{Dch}$ = 0.95 (95%).
- Depth-of-Discharge of a battery was assumed to be DoD = 0.2 (20%).
- Number of hours a battery can discharge continuously at peak power was 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 [60]. 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, which is higher than the subsidized rate at the fuel-pump level (1.01 $/L to 1.72 $/L, with Iqaluit having 1.3 $/L), since the point of view of the presented studies is from the main payee, i.e., territorial governments. The rest of the dataset input is presented next.

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.

The new FSG search space is shown in Table III, based on the existing capacities, whereas new VSGs were all considered to be 590 kW from Innovus Power.

The search space for solar PV was 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 $\alpha = -0.0041 pu/$°C, and that for First Solar panels is $\alpha = -0.0029 pu/$°C, while the unit panelset capacities are $Ucap$ = 9.6 kW and 10 kW, respectively.

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 included 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, resulting in the search space for each community illustrated in Table IV.

Li-ion batteries were considered in the presented studies as energy storage systems, as their operating characteristics and O&M handling and costs can be considered adequate. Furthermore, this once costly battery's capital cost has decreased considerably in the last few years, and is forecasted to reduce further with the announcement of Tesla's Gigafactory project. Only Canadian Solar was selected as the supplier, as it is more cost-effective than similar batteries from Tesla, and the company claims 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.

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 [70], 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 [77]. 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 added $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 [72]), respectively. The final capital costs of RE equipment and diesel generators, varying with destination community, are shown in Table V. 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 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. These costs vary based on the fact that required tools, 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, resulting in the O&M costs depicted in Table VI. 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.

V. FEASIBILITY STUDIES

The feasibility studies performed were based on seven case studies as follows [28]:

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.

TABLE IV
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	-	-	-

TABLE V
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 VI
RANGE OF THE O&M COSTS OF DIESEL AND RE EQUIPMENT IN $/KWH [70]

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

TABLE VII
FEASIBILITY STUDY RESULTS FOR THE NORE (BAU) CASE [28]

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

Fig. 8. Optimal solutions obtained for RE integration without VSGs [28].

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 VII for the BAU case, and in Fig. 8 for the optimal RE integration case without VSGs.

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 from the 3rd year of the project horizon (VSG-2yr), with standby and emergency generation being provided by existing FSGs. Simulations for the VSG studies for all communities were executed only for the optimal RE mix obtained from the study, and the results of these simulations are presented in Fig. 9. Observe that, 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 strategy, which includes the PowerBridge, 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 of GHG emissions for all communities, except Baker Lake, while completely removing the requirement of battery storage. The different outcome for the community of Baker Lake can be attributed to various causes, such as transportation costs, demand levels, and RE resource profiles.

The LCOE in Fig. 9 is computed using the depreciated costs of existing FSGs 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.

VI. Conclusions

This paper first presented and discussed the details of a pre-feasibility study to choose the best suitable communities in Nunavut and ISR regions in the Canadian Arctic for in-depth feasibility studies, to determine the final RE equipment to be optimally deployed in some of these communities. The result of the pre-feasibility study indicates that substantial reduction in CO_2 emission can be achieved at a relatively low initial investment cost.

In the feasibility stage, a novel GEP-based RE integration framework and model for diesel-RE hybrid systems was proposed to determine the optimal plan for incorporating RE to achieve maximum savings in diesel use, along with the reduction in GHGs, for the selected Canadian Arctic communities. The simulation results indicate that the deployment of VSGs in RE-diesel hybrid systems in any of the studied communities may reduce the consumption of diesel, and that, with the introduction of VSGs with PowerBridge, there is no need for batteries; furthermore, adding VSGs in the generation portfolios for the communities studied may result in substantial reductions in GHG emissions. The application of the proposed framework and model to several communities in Nunavut and NWT, based on available real data, resulted in compelling business cases for RE integration in some of the studied communities.

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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.

Fig. 9. Comparison of community-wise optimal RE integration plan and operational savings obtained for two VSG deployment strategies.

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