Abstract—In recent years, the electrification of Canadian Remote Communities (RCs) has received significant attention, as their current electric energy systems are not only expensive, but are also highly polluting due to the prevalence of diesel generators. In addition, RCs’ inherent geographic characteristics impose a series of challenges that must be considered when planning their electricity supply. Thus, in this paper, an optimization model for the long-term planning of RC Microgrids (MGs) including Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs) is proposed, with the objective of reducing costs and emissions. The proposed model considers lithium-ion batteries and hydrogen systems as part of ESSs technologies. The model is used to investigate the feasibility of integrating RESs and ESSs in an MG in Sanikiluaq, an RC in the Nunavut territory in Northern Canada. The results show that wind resources along with solar and storage technologies can play a key role in satisfying RC electricity demand, while significantly reducing costs and Greenhouse Gas Emissions (GHG). In addition, insights on sustainable and affordable policies for RC MGs are provided.

Index Terms—Batteries, hydrogen systems, long-term planning, remote community microgrids, renewable energy sources.

NOMENCLATURE

Subscripts and Sets

$I$ Set of all generation and storage capacities $I = \{i\}$
$E$ Subset of existing diesel generators $E = \{e\} \in I$
$N$ Subset of new diesel generators $N = \{n\} \in I$
$\Pi$ Subset of RES and ESS $\Pi = \{p\} \in I$
$S$ Subset of solar panels $S = \{s\} \in \Pi$
$W$ Subset of wind turbines $W = \{w\} \in \Pi$
$B$ Subset of batteries $B = \{b\} \in \Pi$
$F$ Subset of fuel cells $F = \{f\} \in \Pi$
$\Xi$ Subset of electrolizers $\Xi = \{\xi\} \in \Pi$
$Q$ Subset of hydrogen tanks $Q = \{q\} \in \Pi$

$\eta$ Efficiency
$\lambda$ Total number of representative days in a month - 30
$A$ Total number of hours available in an average year for diesel generators [h]
$C$ Total number of cycles of charge and discharge of a battery
$D$ Cost of diesel [$/l]
$H$ Total amount of representative hours - 288 [h]
$M$ A very large number
$R$ Rated capacity of existing and new diesel generators [kW], RES [kW], or battery [kWh]
$T, \bar{T}$ Upper/lower limits for hydrogen tank [pu]
$\psi$ Minimum load operating level for existing and new diesel generators [pu]
$\rho$ Wind generation reserves coefficient [pu]
$\tau$ Solar cell temperature [°C]
$\tau_{stc}$ Solar cell temperature at standard test conditions [°C]
$\varphi$ Derating factor of solar panels [pu]
$c$ O&M cost [$/kWh]
$G$ Solar irradiance [kW/m²]
$G_{stc}$ Incident solar irradiance on solar panels at standard conditions [kW/m²]
$K$ Unit cost of new diesel generators [$/kW], RES [$/kW] or battery [$/kWh]
$l_C$ Hydrogen compressor load [pu]
$P_d$ Power demand [kW]
$S_h$ Wind speed
$t_{chg}$ Time duration a battery can charge continuously at a fixed power [h]
$t_{dchg}$ Time duration a battery can discharge continuously at a fixed power [h]
$V$ Higher Heating Value of hydrogen [kWh]

Parameters

$\alpha$ Temperature coefficient of power for solar panels [pu/°C]
$\beta$ Demand reserves coefficient [pu]
$\delta$ Depth-Of-Discharge (DOD) of a battery [pu]
$\eta^{Ch}$ Efficiency of battery charging [pu]
$\eta^{Dch}$ Efficiency of battery discharging [pu]
$\eta_{ef}$ Efficiency of fuel cell [pu]

Variables

$P$ Capacity addition of RESs [kW] or batteries [kWh]
$F$ Fuel consumption [litre]
$I$ Total installed capacity of RESs [kW] or batteries [kWh]
$N$ Number of types of RESs or batteries considered
$P$ Power generated or consumed by $i \in \{E,F,N,S,W\}$ or $i \in \{\Xi\}$ [kW], respectively
The deployment of clean Microgrids (MGs) has been recommended to satisfy RC electricity needs, as MGs have the potential to provide cheaper, cleaner and more flexible and reliable electricity using a wide variety of Distributed Energy Resources (DERs), including Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs) [4], [7], [8]. In addition, given the current state of development of hydrogen systems and considerable reduction in their capital costs, there is a potential for integration of electrolyzers and fuel cells in RC MGs [4], [7], [9], [10].

The authors of [1]–[3], [8], [11]–[14] propose models and techniques to design and plan MGs for RCs using RESs and ESSs, while highlighting their benefits and advantages. In all these references, planning approaches for small RCs with consideration of the communities electrification needs are proposed, with wind and/or solar generation being considered in the planning horizon. Most of them propose a multi-year planning optimization approach to examine the economic and environmental impacts of RES integration in Canadian RC MGs, demonstrating that RES integration with ESS and an appropriate diesel capacity can result in significant cost savings. However, none of these publications consider hydrogen storage systems as part of the ESS technologies.

This paper proposes a long term planning model for RC MGs with RESs and ESSs, including hydrogen systems. The proposed mathematical model investigates the feasibility of integrating such technologies in the planning of an MG in Sanikiluaq, an RC in Nunavut, which is part of the Canadian northern territories. The paper is based on [15], which is a non-reviewed technical report, with limited reach and validation. The proposed model includes a wide variety of renewable and nonrenewable generation resources and ESSs, such as hydrogen systems and lithium-ion batteries, which makes it stand out from other approaches available in the literature. In addition, due to its linear characteristics, possible solutions can be evaluated in a fast, reliable, and inexpensive way to support energy planners in studying various planning alternatives. Finally, appropriate operating reserves are included to accommodate uncertainties associated with demand, solar, and wind generation.

In order to assess the impact of different technologies, several planning scenarios with various combinations of resources are considered. The results of the long term planning for each scenario are compared in terms of economic, environmental, and other technical indices. The analysis includes an evaluation of the impact of RESs and ESSs in Canadian RCs, while quantifying the potential benefits of their implementation to support Canada’s decarbonization goals.

The rest of the paper is organized as follow: In Section II, the optimization model proposed for the long term planning of RC MGs is explained. In Section III, all the required data to apply the model in the community of Sanikiluaq are provided. Section IV presents and discusses the results of the long term planning model for the Sanikiluaq MG. Finally, the main conclusions of the presented work are highlighted in Section V.

I. INTRODUCTION

Remote Communities’ (RCs) unique features such as distant location, extreme weather conditions, energy consumption patterns, limited availability of energy sources, and absence of connection to the bulk power system have made supplying their electricity needs a challenging problem. Currently, the main source of electricity in RCs is diesel generators, and therefore, due to their significant Operations and Maintenance (O&M), transportation, and fuel costs, delivering electricity to them has become economically and environmentally expensive [1]–[6].

The deployment of clean Microgrids (MGs) has been recommended to satisfy RC electricity needs, as MGs have the potential to provide cheaper, cleaner and more flexible and reliable electricity using a wide variety of Distributed Energy Resources (DERs), including Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs) [4], [7], [8]. In addition, given the current state of development of hydrogen systems and considerable reduction in their capital costs, there is a potential for integration of electrolyzers and fuel cells in RC MGs [4], [7], [9], [10].

The authors of [1]–[3], [8], [11]–[14] propose models and techniques to design and plan MGs for RCs using RESs and ESSs, while highlighting their benefits and advantages. In all these references, planning approaches for small RCs with consideration of the communities electrification needs are proposed, with wind and/or solar generation being considered in the planning horizon. Most of them propose a multi-year planning optimization approach to examine the economic and environmental impacts of RES integration in Canadian RC MGs, demonstrating that RES integration with ESS and an appropriate diesel capacity can result in significant cost savings. However, none of these publications consider hydrogen storage systems as part of the ESS technologies.

This paper proposes a long term planning model for RC MGs with RESs and ESSs, including hydrogen systems. The proposed mathematical model investigates the feasibility of integrating such technologies in the planning of an MG in Sanikiluaq, an RC in Nunavut, which is part of the Canadian northern territories. The paper is based on [15], which is a non-reviewed technical report, with limited reach and validation. The proposed model includes a wide variety of renewable and nonrenewable generation resources and ESSs, such as hydrogen systems and lithium-ion batteries, which makes it stand out from other approaches available in the literature. In addition, due to its linear characteristics, possible solutions can be evaluated in a fast, reliable, and inexpensive way to support energy planners in studying various planning alternatives. Finally, appropriate operating reserves are included to accommodate uncertainties associated with demand, solar, and wind generation.

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II. MODEL DESCRIPTION

The proposed planning model is formulated using an optimization framework to plan the energy resources in RCs using diesel, wind, and solar generators, in combination with battery and hydrogen ESSs. In addition to planning constraints restricting the type and amount of generation in different years, the model contains operational constraints with binary variables associated with the hourly on/off status of diesel generators, and the charging and discharging status of batteries and hydrogen storage systems. Integer variables are used to prescribe the quantities of different technologies for economic evaluation, while the variables representing the generation in kW, State-of-Charge (SOC) of batteries in kWh, and hydrogen storage systems in kg are continuous. The model can therefore be characterized as a Mixed Integer Linear Programming (MILP) problem as described in detail next.

In the equations that follow, all generators and storage capacities are part of the set \( I = \{ i \} \), while existing diesel generators, new diesel generators, and RES and ESS form the sub-sets \( E = \{ e \} \), \( N = \{ n \} \), and \( \Pi = \{ p \} \), respectively. The subset \( \Pi \) includes subsets of solar panels \( S = \{ s \} \), wind turbines \( W = \{ w \} \), batteries \( B = \{ b \} \), fuel cells \( F = \{ f \} \), electrolyzers \( E = \{ \xi \} \), and hydrogen tanks \( Q = \{ q \} \). Finally, \( y \) is the index used for years, and the index \( h \) is used for representative hours.

A. Objective Function

The following objective function represents the summation of the Net Present Cost (NPC) of the capital, fuel, and O&M costs of the generators in the MG:

\[
Z = \sum_{i, y \in \{ N, \Pi \}} K_{i,y} \hat{P}_{i,y} + \sum_{i, y, h \in \{ E, N \}} \lambda D F_{h, y, i} + \sum_{i, y, h \in \{ E, F, N \}} \lambda C_{i} P_{i, y, h} + \sum_{i, y \in \Pi - F} H C_{i} T_{i, y}
\]

where \( K_{i,y} \) is the NPC of the capital cost of a generation unit \( i \), installed in year \( y \); \( \hat{P}_{i,y} \) is the amount of installed capacity
of \( i \) in year \( y \); \( D \) is the cost of diesel fuel; \( F_{i,y,h} \) is the hourly diesel fuel consumption; \( c_i \) is the hourly O&M cost; \( P_{i,y,h} \) is the generated power from generator \( i \), in year \( y \) and hour \( h \); and \( I_{i,y} \) is the total installed capacity of generator \( i \) in year \( y \). Note that the total capital cost in the first term of (1) is defined over generators \( I \) and \( N \), and the fuel cost is considered only for \( N \) and \( E \). Factors \( \lambda = 30 \) and \( H = 288 \) were used to carry out the calculations over the whole year, where \( H \) is the total number of representative hours in a year, i.e., 24 (average hours/month) \( \times \) 12 (months) = 288 hours, representing a 24-hours day for each of the 12 months, and \( \lambda \) indicates the representative number of days in a month. The units of each parameter and variable are discussed in Section III.

B. Constraints

1) Installed Capacity: The total installed capacity \( I_{i,y} \) for \( i \in \{ N, I \} \) each year \( y \) is calculated by updating the total installed capacity of the previous year \( I_{i,y-1} \), as follows:

\[
I_{i,y} = \hat{P}_{i,y} + I_{i,y-1} \quad \forall i \in \{ N, I \}, y
\]

where the capacity additions \( \hat{P}_{i,y} \) for \( i \in \{ N, I - S \} \) at each year \( y \) is defined by the product of the number of generators added each year \( N_{i,y} \) and their respective individual rated capacity \( R_i \), as follows:

\[
\hat{P}_{i,y} = N_{i,y}R_i \quad \forall i \in \{ N, I - S \}, y
\]

Note that \( N_{i,y} \) is an integer variable for \( i \in I - S \), and is a binary variable for \( i \in N \), since only one diesel generator of predefined capacities can be added to the generation portfolio each year. Finally, the capacity additions of solar \( \hat{P}_{s,y} \) is a continuous variable, as the installation of solar panels is more versatile, since power fractions can be accommodated in practice.

2) Supply-Demand Balance: The summation of the power generated by existing and new diesel generators \( P_{e,y,h} \) and \( P_{n,y,h} \), solar panels \( P_{s,y,h} \), wind turbines \( P_{w,y,h} \), fuel cells \( P_{f,y,h} \), and battery storage discharge \( P_{b,y,h} \) should satisfy the total consumers’ demand \( P_{d,y,h} \), the battery storage charge \( P_{b,y,h} \), and the power consumed by the electrolyzer \( P_{e,y,h} \), at each hour \( h \) and year \( y \), as follows:

\[
\sum_{i \in \{ E,F,N,S,W \}} P_{i,y,h} + \sum_B P_{b,y,h} + P_{d,y,h} + \sum_B P_{b,y,h} + \sum_{i \in \Xi} P_{\xi,y,h} \quad \forall h, y
\]

3) Operating Reserves: To accommodate the uncertainties associated with demand, solar, and wind generation, the rated capacity of existing diesel generators \( R_e \), and total installed capacity of new diesel generators \( I_{n,y} \) and fuel cells \( I_{f,y} \), plus batteries storage power capacity per hour \( SOC_{b,y,h} \) have to be greater than the hourly consumers demand \( P_{d,y,h} \) by a given factor \( \beta \), and solar and wind generation by given factors \( \gamma \) and \( \rho \), respectively, for every hour during the planning horizon, as follows:

\[
\begin{align*}
\sum_{i \in \{ E,F,N \}} R_e + \sum_B I_{i,y} + \sum B SOC_{b,y,h} & \geq (1 + \beta)P_{d,y,h} + \gamma \sum S P_{s,y,h} + \rho \sum W P_{w,y,h} \quad \forall h, y
\end{align*}
\]

4) Diesel Generator Limits: At every hour during the planning horizon, the power generated by diesel generators \( P_{i,y,h} \) for \( i \in \{ E, N \} \) has to be less than or equal to the rated capacity of existing generators \( R_e \) and the total installed capacity of new diesel generators \( I_{n,y} \), and should also be greater than the minimum load operating level \( \psi_i \) for \( i \in \{ E, N \} \), which is a factor of the rated capacity, as follows:

\[
\begin{align*}
P_{n,y,h} & \leq I_{n,y}u_{n,y,h} \quad \forall n, h, y \quad (6) \\
P_{e,y,h} & \leq R_eu_{e,y,h} \quad \forall e, h, y \quad (7) \\
P_{n,y,h} & \geq \psi_{n}I_{n,y}u_{n,y,h} \quad \forall n, h, y \quad (8) \\
P_{e,y,h} & \geq \psi_{e}R_{e}u_{e,y,h} \quad \forall e, h, y \quad (9)
\end{align*}
\]

where \( u_{i,y,h} \) for \( i \in \{ E, N \} \) is a binary variable indicating the operating on/off state of each generator. Equations (6) and (8) are nonlinear, and thus a common linearization technique is applied, as per [16].

5) Diesel Generator Service Life: The useful life of new diesel generators and the remaining life of existing diesel generators \( \theta_i \) for \( i \in \{ E, N \} \), in hours, is taken into account by computing their total amount of operating states \( u_{i,y,h} \) for \( i \in \{ E, N \} \) during the planning horizon as follows:

\[
\sum_{h,y} \lambda u_{i,y,h} \leq \theta_i \quad \forall i \in \{ E, N \} \quad (10)
\]

Note that the factor \( \lambda = 30 \) is used to represent the life of the generators over a year. Therefore, their use is optimized and they get retired when reaching their limits.

6) Diesel Generator Availability: This constraint is used to reflect the maintenance of existing and new generators during the planning horizon. Thus, a percentage of the total number of the hours available \( A \) in an average year is assigned for this purpose, as follows:

\[
\sum_h u_{i,y,h} \leq AH(1 - A) \quad \forall i \in \{ E, N \}, y
\]

7) Solar Power Generation: The solar power generation output is computed as a direct function of the hourly incident irradiance \( G_h \), hourly cell temperature \( \tau_h \), and derating factor \( \varphi \), which is a scaling factor to account for effects of dust, wire loses, and other deviations of the solar output from its ideal value, as follows:

\[
P_{s,y,h} = \varphi IS_{s,y} \left( \frac{G_h}{G_{stc}} \right) [1 + \alpha(\tau_h - \tau_{stc})] \quad \forall s, y, h
\]

where \( stc \) stands for standard test conditions.
8) Wind Power Generation: The wind power is computed as a function of the hourly wind speed $S_h$ as follows:

$$P_{w,y,h} = W(I_{w,y}, S_h) \quad \forall w, y, h \quad (13)$$

where the power generated by every wind turbine is computed using its turbine power curve $W(\cdot)$ and the wind speed $S_h$ at every time-step [17].

9) Battery SOC and Limits: The following constraints compute the SOC of the batteries as a function of the batteries’ charge $P_{b,y,h}^{ch}$ and discharge $P_{b,y,h}^{dch}$ for every hour of operation $h$, considering the charging $\eta^{ch}$ and discharging $\eta^{dch}$ efficiency rates:

$$SOC_{b,y,h+1} - SOC_{b,y,h} = \eta^{ch} P_{b,y,h}^{ch} - \frac{P_{b,y,h}^{dch}}{\eta^{dch}} \quad \forall b, y, h \quad (14)$$

$$SOC_{b,y+1,h} - SOC_{b,y,h} = \eta^{dch} P_{b,y,h}^{dch} - \frac{P_{b,y,h}^{ch}}{\eta^{ch}} \quad \forall b, y, h \quad (15)$$

The SOC of batteries is subject to the following constraints reflecting the minimum and maximum capacity of the batteries:

$$SOC_{b,y,h} \leq I_{b,y} \quad \forall b, y, h \quad (16)$$

$$SOC_{b,y,h} \geq \delta I_{b,y} \quad \forall b, y, h \quad (17)$$

where $\delta$ is a factor to indicate depth of discharge of the batteries. The following constraints reflect the maximum charging and discharging limits respectively, and are functions of the depth of discharge $\delta$, the total installed battery capacity $I_{b,y}$, and the continuous time duration of charging $t^{ch}$ and discharging $t^{dch}$, which are battery parameters chosen to keep reasonable equipment costs, while having adequate energy resources in a day:

$$P_{b,y,h}^{dch} \leq \left( \frac{1 - \delta}{t^{dch}} \right) I_{b,y} \quad \forall b, y, h \quad (18)$$

$$P_{b,y,h}^{ch} \leq \left( \frac{1 - \delta}{t^{ch}} \right) I_{b,y} \quad \forall b, y, h \quad (19)$$

Furthermore, the following constraints guarantee minimum charging/discharging power at a given hour:

$$P_{b,y,h}^{dch} \geq u_{b,y,h}^{dch} \eta^{dch} \quad \forall b, y, h \quad (20)$$

$$P_{b,y,h}^{ch} \geq u_{b,y,h}^{ch} \eta^{ch} \quad \forall b, y, h \quad (21)$$

where $u_{b,y,h}^{dch}$ and $u_{b,y,h}^{ch}$ are binary variables indicating the battery operating states.

In order to prevent charging and discharging occurring at the same time, the following equation is used:

$$P_{b,y,h}^{dch} P_{b,y,h}^{ch} = 0 \quad \forall b, y, h \quad (22)$$

which is not linear and is therefore substituted by the following set of equations:

$$P_{b,y,h}^{dch} \leq u_{b,y,h}^{dch} M \quad \forall b, y, h \quad (23)$$

$$P_{b,y,h}^{ch} \leq u_{b,y,h}^{ch} M \quad \forall b, y, h \quad (24)$$

10) Hydrogen System: The hydrogen system is composed of an electrolizer, consuming electricity $P_{\xi,y,h}$ for generating the hydrogen that is stored at high pressure in tanks, which is used later by the fuel cells to generate electricity $P_{f,y,h}$. A schematic representation of this process is presented in Fig. 1. For this system, the SOC of the hydrogen tank for every hour of operation $h$, $SOC_{q,y,h}$, is a function of the power generated by the fuel cells $P_{f,y,h}$ and the power consumed by the electrolizer $P_{\xi,y,h}$, which can be transformed into hydrogen consumption as follows [9].

$$SOC_{q,y,h+1} - SOC_{q,y,h} = \frac{1}{1 + l_C} \frac{P_{\xi,y,h} \eta_{\xi}}{V} - \frac{P_{f,y,h}}{V \eta_f} \quad \forall q, y, h \quad (27)$$

$$SOC_{q,y+1,h} - SOC_{q,y,h} = \frac{1}{1 + l_C} \frac{P_{\xi,y,h} \eta_{\xi}}{V} - \frac{P_{f,y,h}}{V \eta_f} \quad \forall q, y, h \quad (28)$$

where, for every year $y$, the hourly SOC limits of the hydrogen tank are as follows:

$$SOC_{q,y,h} \leq \overline{\theta} I_{q,y} \quad \forall q, y, h \quad (29)$$

$$SOC_{q,y,h} \geq \underline{\theta} I_{q,y} \quad \forall q, y, h \quad (30)$$

and $V$ is the Higher Heating Value of Hydrogen in kWh; $l_C$ is the hydrogen compressor load in pu; $I_{q,y}$ is the net capacity of the hydrogen tank in kg; $\eta_f$ and $\eta_{\xi}$ are the efficiency of fuel cells and electrolizers, respectively; and $\overline{\theta}$ and $\underline{\theta}$ are per unit constants defining the maximum and minimum hydrogen tank limits. In addition, the power generated by the fuel cells $P_{f,y,h}$ and the power consumed by the electrolizers $P_{\xi,y,h}$ need to be less than their total installed capacity $I_{q,y}$ for $i \in \{ F, \Xi \}$, as follows:

$$P_{i,y,h} \leq I_{q,y} \quad \forall i \in \{ F, \Xi \}, y, h \quad (31)$$
III. CASE STUDY

The proposed model in Section II is used to investigate the feasibility of integrating RESs and ESSs in the planning of an MG in Sanikiluaq, an RC in Nunavut, which is part of the Canadian northern territories [17]. The various parameters needed to apply the presented optimization model and their sources are provided next.

A. Electricity Demand

The hourly load for the Sanikiluaq community was extracted from [1] and [17]. This data can be used to calculate the hourly averages for a year with 288 representative hours, as explained in Section II-A. The load is primarily residential and the corresponding demand profile is depicted in Fig. 2.

B. Existing Diesel Generators

The main characteristics of the existing diesel generators are presented in Table I. It is assumed that the minimum load of these generators is 40% of their nominal power, i.e., $\psi_n = 0.4$, as per [1] and [17].

C. New Diesel Generators

It is assumed that diesel generators may be aggregated in the generation portfolio for load supply and as reserves. Therefore, two types of diesel generators were considered, with their main characteristics being presented in Table II. It was assumed that the minimum load of these generators is also 40% of their nominal power, i.e., $\psi_n = 0.4$, as per [1] and [17].

D. Solar Panels and Irradiance

The sets of 9.6 kW solar panels were assumed to be connected through an inverter to the MG. The solar cell temperature $\tau$ and monthly solar irradiance $G$, with their averages, are illustrated in Fig. 3. The operational parameters and costs associated with the panels are shown in Table III.

E. Wind Turbines and Speed

Wind generators with 250 kW of nominal capacity were considered with monthly average wind speeds, as shown in Fig. 4. The economical and technical parameters for the model are presented in Table IV. The turbine curve $\dot{W}(\cdot)$ was assumed linear between the cut-in and nominal speed, based on the actual power curves provided in [17], as follows:

F. Batteries

The battery modules in the MG planning model are Li-ion batteries with 100 kWh and 20 kW peak power of charge/discharge, i.e., $t^{ch} = t^{dch} = 4h$ for $\delta = 0.2$, as per [1] and [17]. The economical and technical parameters for the implemented battery model are presented in Table V.

G. Hydrogen System

To model a hydrogen system, the fuel cells, an electrolyzer, and a hydrogen tank need to be considered. The costs and main characteristics of these elements are presented in Table VI.

H. Scenarios

Five scenarios are defined to apply the long term planning model presented in Section II. Note that in order to highlight the contributions of solar generators, each scenario includes one case with solar and one case without solar generators. The cases with solar generation are labeled with A, and the ones without solar are labeled with B. Thus, the main characteristics
of these scenarios, considering all possible combinations of DERs, are as follows:

- Business-As-Usual (BAU) (Base Case): In this case, the only source of generation considered is diesel generation. Other DERs are not included here, in order to compare all other scenarios in terms of costs, use of diesel, and GHG reductions.
- 1A (I) and 1B (I − S): These scenarios include all DERs, i.e., diesel (E, N), solar (S), wind (W), batteries (B), and hydrogen (F, Q, Ξ).
- 2A (I − B) and 2B (I − {B, S}): All DERs except batteries are considered in this scenario.
- 3A (I − {F, Q, Ξ}) and 3B (I − {F, S, Q, Ξ}): All DERs except hydrogen storage systems are considered in this scenario.
- 4A (II) and 4B (II − S): In this scenario, only RESs and ESSs are considered. Diesel generation is considered but exclusively for reserves, to represent a MG supplied primarily by renewable generation.

### I. Assumptions and Simulation Criteria

The MILP model, described in Section II, was solved using GAMS [18], with the CPLEX solver. The following are the assumed values for the remaining model parameters [1], [15], [17]:

- The discount rate is 8%.
- The planning horizon is 20 years.
- Operation reserves for system adequacy: 50% for wind ($\rho = 0.5$), 25% for solar ($\gamma = 0.25$), and 10% for load ($\beta = 0.1$).
- Load growth is 1.0%/year.
- It is assumed that the cost of the technology will not be changing throughout the planning horizon, as the balance of the cost associated with the transportation of the equipment and their capital cost may cancel each other for R.C.
- Ramping up/down constraints are not considered, since all diesel generators are able to turn on and off in fractions of an hour.
- The cost of diesel is fixed at 2.391 $/l.
- $A = 0.1$ for all diesel generators.
- $C = 3000$ cycles of charge and discharge for the batteries.
- To control the inclusion of certain RESs and ESSs, as per the considered scenarios, there must be at least one battery module, 1% of the annual energy supplied by solar, and/or one hydrogen system module, otherwise the model does not include them due to the cost minimization approach.
- The investment in RESs is allowed only in the first 5 years to accommodate possible pilot projects, and new
TABLE VI
HYDROGEN SYSTEM PARAMETERS [10], [15]

| Parameter   | Fuel Cells | Electrolizer | Hydrogen Tank |
|-------------|------------|--------------|---------------|
| Capacity    | 250 kW     | 330 kW       | 200 kg        |
| Cost        | 168,581 $/u| 1,279,000 $/u| 249,745 $/u   |
| O&M         | 2 $/h      | 194 $/y      | 12,400 $/y    |
| Efficiency  | $\eta_{FC} = 60\%$ | $\eta_{E} = 70\%$ |           |
| Lifetime    | 50,000 h   | 15 y         | 25 y          |
| System      | $V = 39.4$ kWh, $I_C = 0.02$ pu | | |
| Constants   | $\vartheta = 0.95$ pu, $\varphi = 0.15$ pu | | |

diesel generators are being added from the 3rd to 10th year [10].

- For the cases where hydrogen is included in the MG, one full system is included in the first year, leaving the algorithm to decide for additional capacities in the future years. Thus, at least one electrolizer needs to be replaced at year 16, according to their useful lifetime, assuming a zero salvage value.

IV. RESULTS

The results of the simulations are shown and discussed in this section. The energy mix resulting from running each scenario can be observed in Fig. 5, which illustrates the following:

- Scenarios 1B and 3B, in which solar generation is not considered, recommend investment in diesel generation. Note that larger diesel generation capacities are recommended in Scenario 3B, in which the only source of storage is batteries. Wind generators do not replace solar generation as they have larger capacity, which is not needed to satisfy demand.
- In all scenarios, storage capacities of either fuel cells or batteries are used. For example, in the scenarios with only fuel cells (2A and 2B), the energy that has not been served by RESs or diesel generators is served by hydrogen storage systems. Also, in Scenarios 3A and 3B, batteries are used, as these are the only available storage capacity.
- In Scenarios 1A and 1B, in which the model can choose between investment in hydrogen or batteries, it recommends a portion of both systems.
- In Scenarios 4A and 4B, in which diesel generators are not allowed, more investment in storage capacities is recommended to account for the associated uncertainties in the system.

In Figs. 6 and 7 the comparisons among costs and GHG reductions for different scenarios are illustrated. Thus, Fig. 6 depicts different types of costs associated with each scenario, and Fig. 7 illustrates the reductions of total cost, O&M costs, and GHG reductions in relation to BAU. As observed in Fig. 7, the total O&M costs decrease from 41% (3B) to 82% (4A), and the total costs decrease from 16% (3B) to 34% (1B), with respect to BAU. Similarly, the cost of fuel is reduced from 52% (3B) to 100% (4A&4B), with respect to BAU. The most expensive scenario is (4B), in which all renewable resources except solar are recommended, surpassing the total cost of BAU by only 0.16%, while reducing GHG emissions by 100%. It can be also observed that the cases with only hydrogen storage systems (2A&2B) are less expensive than the cases with only batteries as the storage capacity (3A&3B).

Figs. 8 and 9 present the hourly operation of the MG generators and storage systems versus demand, according to Eq. (5), during the 10th year of its operation for scenarios 1A and 4A, which are chosen as they differ on their type of generation. Note that Scenario 1A allows all DERs including diesel, while Scenario 4A allows only ESSs and RESs. As shown, both batteries and hydrogen systems in combination with other DERs are incorporated in the generation mix of the MG to satisfy the hourly demand. In addition, observe that the hydrogen systems can considerably increase the total demand of the MG because of the presence of electrolizers, but the costs can still be reasonable with very low or zero
It is demonstrated here, based on the proposed MILP planning model, that the integration of RES and ESS in the RC MGs' generation portfolio enhances electric grid flexibility, and promotes decarbonization goals. Thus, as shown in the simulation results, the inclusion of such technologies significantly reduces the use of fossil fuels, resulting in lower emissions (between 51.9% and 100%) for the RC MG studied. It also not only helps lowering other costs of the energy system, such as fuel storage and its transportation to RCs, but also reduces the uncertainties associated with diesel fuel prices. Thus, these results clearly show that wind resources along with solar and storage technologies (batteries and fuel cells) can play a key role in satisfying the electricity demand of RCs, while significantly reducing costs and GHG emissions.

V. CONCLUSIONS

It is demonstrated here, based on the proposed MILP planning model, that the integration of RES and ESS in the RC MGs' generation portfolio enhances electric grid flexibility, and promotes decarbonization goals. Thus, as shown in the simulation results, the inclusion of such technologies significantly reduces the use of fossil fuels, resulting in lower emissions (between 51.9% and 100%) for the RC MG studied. It also not only helps lowering other costs of the energy system, such as fuel storage and its transportation to RCs, but also reduces the uncertainties associated with diesel fuel prices. Thus, these results clearly show that wind resources along with solar and storage technologies (batteries and fuel cells) can play a key role in satisfying the electricity demand of RCs, while significantly reducing costs and GHG emissions. The model proposed in this paper encourages a structural and economical change, and supports Canada in meeting zero emission targets by introducing RESs and ESSs in RCs, while demonstrating the operational and economic feasibility of such systems.

REFERENCES

[1] C. Canizares and I. Das, “Feasibility studies of variable speed generators for Canadian Arctic Communities,” WISE, Technical Report, 2017.
[2] M. Arriaga, C. A. Canizares, and M. Kazerani, “Renewable Energy Alternatives for Remote Communities in Northern Ontario, Canada,” IEEE Transactions on Sustainable Energy, vol. 4, no. 3, pp. 661–670, 2013.
[3] M. Arriaga, C. A. Canizares, and M. Kazerani, “Long-term renewable energy planning model for remote communities,” IEEE Transactions on Sustainable Energy, vol. 7, no. 1, pp. 221–231, 2016.
[4] A. Maitra, L. Rogers, and R. Handa, “Program on Technology Innovation: Microgrid Implementations: Literature Review,” Electric Power Research Institute, Palo Alto, California, USA, Technical Report, Jan. 2016.
[5] M. Arriaga, E. Nasr, and H. Rutherford, “Renewable Energy Microgrids in Northern Remote Communities,” IEEE Potentials, vol. 36, no. 5, pp. 22–29, 2017.
[6] A. Dane and L. Doris, “Alaska Strategic Energy Plan and Planning Handbook,” U.S. Department of Energy, Office of Indian Energy, Technical Report, 2013.
[7] M. Farrokhabadi, C. Canizares, J. W. Simpson-Porco, and et al., “Microgrid Stability Definitions, Analysis, and Examples,” IEEE Transactions on Power Systems, pp. 13–29, Apr. 2019.
[8] T. V. Chambers, “Generation planning for small rural remote communities with the inclusion of PV and wind resources,” Ph.D. dissertation, University of Manchester, Manchester, England, UK, 2007.
[9] Oливares, Daniel, “An Energy Management System for Isolated Microgrids Considering Uncertainty,” Ph.D. dissertation, University of Waterloo, Waterloo, Canada, 2014.
[10] Energy Efficiency Markets, LLC, “Fuel Cell Microgrids: The Path to Lower Cost, Higher Reliability, and Cleaner Energy,” Technical Report, 2017.
[11] S. Mizani and A. Yazdani, “Design and Operation of a Remote Microgrid,” in 45th Annual Conference of IEEE Industrial Electronics, 2009, pp. 4299–4304.
[12] D. Akinneyele, L. latomiwa, D. E. Ighravwe, M. O. Babatunde, C. Monyei, and D. Aikhule, “Optimal planning and electricity sharing strategy of hybrid energy system for remote communities in Nigeria,” Scientific African, vol. 10, 2020.
[13] E. Karimi and M. Kazerani, “Impact of renewable energy deployment in Canada’s remote communities on diesel generation carbon footprint reduction,” in 2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE), 2017, pp. 1–5.
[14] C. Abbey and G. Joos, “A Stochastic Optimization Approach to Rating of Energy Storage Systems in Wind-Diesel Isolated Grids,” IEEE Transactions on Power Systems, vol. 24, no. 1, pp. 418–426, 2009.
[15] E. Vera, C. Canizares, and M. Pirmia, “Electrification of Canadian Northern Communities, using Low Emission Microgrids.” Energy Modelling Initiative, Technical Report, 2021.
[16] J. Bisschop, *AIMMS Optimization Modeling: Integer Linear Programming Tricks*. AIMMS B.V., Aug. 2021.

[17] I. Das and C. A. Cañizares, “Renewable Energy Integration in Diesel-Based Microgrids at the Canadian Arctic,” *Proceedings of the IEEE*, vol. 107, no. 9, pp. 1838–1856, 2019.

[18] GAMS Development Corp. Gams documentation center. [Online]. Available: https://www.gams.com/latest/docs/