Electrification of Canadian Northern Communities, using Low Emission Microgrids

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Abstract

Canadian northern territories contain nearly 40 percent of Canada's land mass and are sparsely populated. Planning an appropriate energy supply mix to satisfy electricity demand in these Remote Communities (RCs) is a challenging issue, due to extreme weather conditions, their consumption patterns, and availability of energy sources. In addition, due to their geographical location, they do not have access to the bulk power system and there is a prevalence of use of diesel for generating electricity. This increases the costs of electricity due to high fuel transportation and storage costs, and has detrimental environmental impacts due to Greenhouse Gas (GHG) emissions, soot, and fuel spills.

Due to the special RCs characteristics, Microgrids (MGs) are used to supply their electricity needs. MGs have enormous potential to provide access to cheaper, cleaner and more flexible and reliable electricity using a wide variety of Distributed Energy Resources (DERs), which include Renewable Energy Resources (RES) and Energy Storage Systems (ESS). Therefore, in this report, a long term planning model for the integration of RES and ESS, including hydrogen systems, is developed, applying it to study the feasibility of integrating RES into the MG of the RC of Sanikiluaq in Nunavut.

The goal of the presented MG planning model is to identify the optimal (most economic) size and mixture of generation resources, and the time of their deployment. It is based on estimated parameters such as electricity demand and RES availability, using historical data that reflects their variability. The planning of MGs is thus formulated through an optimization model, consisting of an objective function, a set of parameters, decision variables, and technical and economical constraints. The planning model presented in this report is based on previously proposed models for diesel-based MGs, and State of Charge (SOC) of hydrogen storage.

The model and the results presented here contribute to electrification and decarbonization of RCs, considering the fulfillment of the electricity needs of the community, using RES and ESS, including hydrogen systems, to reduce fuel consumption, and supports Canada's stated goals of net zero emissions by 2050. The planning model presented in

this report may be used by federal, provincial, territorial, municipal, and indigenous governments across Canada to study the integration of RES, ESS, and hydrogen systems in diesel-dependent RC MGs, providing information for, but not limited to, expansion capacity and investments, operation costs, and fuel consumption and its costs.

Abstrait

Les territoires nordiques canadiens contiennent près de 40 pourcent du territoire du Canada et sont peu peuplés. La planification d'un mélange énergétique approprié pour satisfaire la demande d'électricité dans ces communautés éloignées (CE) est une problème compliqué, en raison des conditions météorologiques extrêmes, de leurs modes de consommation et de la disponibilité des sources d'énergie. En plus, en raison de leur situation géographique, ils n'ont pas accès au système électrique de puissance et il existe une prévalence de l'utilisation du diesel pour produire de l'électricité. Cet augmente les coûts de l'électricité en raison des coûts élevés de transport et de stockage du carburant, et a des effets néfastes sur l'environnement en raison des émissions de Gaz à Effet de Serre (GES), de la suie et des déversements de carburant.

En raison des caractéristiques spéciales des CEs, les Microgrids (MGs) sont utilisés pour répondre à leurs besoins d'électricité. Les MGs ont un énorme potentiel pour fournir un accès à une électricité moins chère, plus propre, plus flexible et plus fiable en utilisant une grande variété de Ressources Énergétiques Distribuées (RED), qui comprennent les Ressources Énergétiques Renouvelables (RER) et les Systèmes de Stockage d'Énergie (SSE). Par conséquent, dans ce rapport, une modèle de planification à long terme pour l'intégration des RER et du SSE, y compris les systèmes à hydrogène, est développé, en l'appliquant pour étudier la faisabilité de l'intégration des RER dans la MG du CR de Sanikiluaq au Nunavut.

L'objectif du modèle de planification MG présenté est d'identifier la taille optimale (la plus économique) et le mélange des ressources de production, ainsi que le moment de leur déploiement. Il est basé sur des paramètres estimés tels que la demande d'électricité et la disponibilité des RER, en utilisant des données historiques qui reflètent leur variabilité. La planification des MG est ainsi formulée à travers un modèle d'optimisation, constitué d'une fonction objectif, d'un ensemble de paramètres, de variables de décision et de contraintes techniques et économiques. Le modèle de planification présenté dans ce rapport est basé sur des modèles précédemment proposés pour les MG en utilisant diesel et l'État de

Charge (EoC) du stockage d'hydrogène.

Le modèle et les résultats présentés ici contribuent à l'électrification et à la décarbonisation des CE, en tenant compte de la satisfaction des besoins en électricité de la communauté, en utilisant les RER et les SSE, y compris les systèmes à hydrogène, pour réduire la consommation de carburant, et soutient les objectifs déclarés du Canada d'émissions nettes nulles en 2050. Le modèle de planification présenté dans ce rapport peut-être utilisé par les gouvernements fédéral, provinciaux, territoriaux, municipaux et autochtones à travers le Canada pour étudier l'intégration des systèmes RER, SSE et hydrogène dans les MG CE dépendant du diesel, fournissant des informations pour, mais non limité à la capacité d'expansion et aux investissements, aux coûts d'exploitation, à la consommation de carburant et à ses coûts.

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Glossary of Acronyms

DER Distributed Energy Resource.

ESS Energy Storage Systems.

GHG Greenhouse Gas.

MG Microgrid.

MILP Mixed Integer Linear Programming.

NPC Net Present Cost.

RC Remote Community.

RES Renewable Energy Resources.

SOC State of Charge.

Nomenclature

Suscripts

e_D	Existing diesel generator type.
n_D	New diesel generator type.
n_S	Solar panel type.
n_B	Battery type.
n_W	Wind turbine type.
n_{HT}	Hydrogen tank type.
n_E	Electrolizer type.
n_{FC}	Fuel cell type.
h	Hour.
y	Year.

Parameters

α	Temperature coefficient of power for solar panels [$pu/°C$].
β	Generation reserve margin [pu].
η^{Ch}	Efficiency of battery charging [pu].
η^{Dch}	Efficiency of battery discharging [pu].
η_E	Efficiency of electrolizer [pu].
η_{Fc}	Efficiency of fuel cells [pu].
γ	Solar generation reserves coefficient [pu].
ρ	Wind generation reserves coefficient [pu].
d	Discount rate [pu].
HHV	Higher Heating Value of Hydrogen [kWh].
l_C	Hydrogen compressor load [p.u.].
Cap^{EDG}	Existing diesel capacity including stand-by mode units [kW].
$Dcost$	Diesel cost [$/L].
df	Derating factor of solar panels [pu].
DoD^B	Depth-of-discharge (DOD) of a battery [pu].
GH^{life}	Useful life of new diesel generator [h].
GH^{remain}	Remaining life of existing diesel generator [h].
GT^{STC}	Incident solar radiation on solar panels at standard conditions [kW/m^2].

Parameters

HOM^{EDG}	Hourly O&M costs of existing diesel generators [$/kWh].
HOM^{NDG}	Hourly O&M costs of new diesel generators [$/kWh].
HOM^{S}	Hourly O&M costs of solar[$/kWh].
HOM^{B}	Hourly O&M costs of battery [$/kWh].
HOM^{W}	Hourly O&M costs of wind turbine [$/kWh].
HOM^{HT}	Yearly O&M costs of hydrogen tank [$/y].
HOM^{E}	Yearly O&M costs of electrolizer [$/y].
HOM^{FC}	Hourly O&M costs of fuel cell [$/kWh].
HY	Hours in a year (model specific) [h].
M	A very large number.
ML^{EDG}	Minimum load operation of existing diesel generator [pu].
ML^{NDG}	Minimum load operation of new diesel generator [pu].
Ne_D	Number of existing diesel generators considered.
Nn_D	Number of types of new diesel generators considered.
Nn_S	Number of types of solar panels considered.
Nn_W	Number of types of wind turbines considered.
Nn_B	Number of types of batteries considered.
Nn_{HT}	Number of types of hydrogen tanks considered.
Nn_E	Number of types of electrolizers considered.
Nn_{FC}	Number of types of fuel cells considered.
PD	Power demand [kW].
PH	Proyect horizon [yr.].
SI	Solar insolation $[kW/m^2]$.
T^{Dch}	Time duration a battery can discharge continuously at a fixed power [h].
T^{OM}	% of hours/annum diesel generators are scheduled for maintenance [pu].
τ	Solar cell temperature in the current time step [° C].
τ^{STC}	Solar cell temperature under standard test conditions $[°C]$.
UC^{NDG}	Unit cost of new diesel generator [$/kW].
UC^{S}	Unit cost of solar panel set [$/kW].
UC^{W}	Unit cost of wind turbine [$/kW].
UC^{Bat}	Unit cost of new battery [$/kWh].
UC^{HT}	Unit cost of hydrogen tank [$/kg].
UC^{E}	Unit cost of electrolizer [$/kW].
UC^{FC}	Unit cost of fuel cells [$/kW].
$UCap^{B}$	Capacity of battery [kWh].
$UCap^{NDG}$	Capacity of new diesel generator unit [kW].
$UCap^{S}$	Capacity of solar panel [kW].
$UCap^{W}$	Capacity of wind [kW].
$UCap^{HT}$	Capacity of hydrogen tank [kg].
$UCap^{E}$	Capacity of electrolizer [kW].
$UCap^{FC}$	Capacity of fuel cells [kW].

Variables

Cap^{NDG}	Capacity addition of new diesel generators [kW].
Cap^{S}	Capacity addition of solar [kW].
Cap^{W}	Capacity addition of wind [kW].
Cap^{B}	Capacity addition of battery [kWh].
Cap^{HT}	Capacity addition of hydrogen tank [kg].
Cap^{E}	Capacity addition of electrolizer [kW].
Cap^{FC}	Capacity addition of fuel cells [kW].
CC^{NDG}	NPC of new diesel generators total capital cost [$].
CC^{S}	NPC of solar total capital cost [$].
CC^{W}	NPC of wind total capital cost [$].
CC^{B}	NPC of battery total capital cost [$].
CC^{HT}	NPC of hydrogen tanks total capital cost [$].
CC^{E}	NPC of electrolizers total capital cost [$].
CC^{FC}	NPC of fuel cells total capital cost [$].
FC^{EDG}	NPC of diesel fuel cost for existing diesel generators [$].
FC^{NDG}	NPC of diesel fuel cost for new diesel generators [$].
$Fcon^{EDG}$	Hourly fuel consumption rate of existing diesel generators [l/kWh].
$Fcon^{NDG}$	Hourly fuel consumption rate of new diesel generators [l/kWh].
I_{n_B}	Number of batteries of type n_B purchased.
I_{n_W}	Number of wind turbines of type n_W purchased.
I_{nHT}	Number of hydrogen tanks of type n_{HT} purchased.
I_{nE}	Number of electrolizers of type n_E purchased.
I_{nFC}	Number of fuel cells of type n_{FC} purchased.
$NCap^{NDG}$	Net capacity addition of diesel [kW].
$NCap^{S}$	Net capacity addition of solar [kW].
$NCap^{W}$	Net capacity addition of wind [kW].
$NCap^{B}$	Net capacity addition of batteries [kW].
$NCap^{HT}$	Net capacity addition of hydrogen tanks [kg].
$NCap^{E}$	Net capacity addition of electrolizers [kW].
$NCap^{FC}$	Net capacity addition of fuel cells [kW].
OMC^{EDG}	NPC of total diesel O&M cost for existing diesel generators [$].
OMC^{NDG}	NPC of total diesel O&M cost for new diesel generators [$].
OMC^{S}	NPC of solar O&M cost [$].
OMC^{W}	NPC of wind O&M cost [$].
OMC^{B}	NPC of battery O&M cost [$].
OMC^{HT}	NPC of hydrogen tank O&M cost [$].
OMC^{E}	NPC of electrolizer O&M cost [$].
OMC^{FC}	NPC of fuel cell O&M cost [$].
Pb^{Ch}	Battery charging power [kW].
Pb^{Dch}	Battery discharging power [kW].
Pd^{EDG}	Power generated by existing diesel generators [kW].
Pd^{NDG}	Power generated by new diesel generators [kW].

Ps	Power generated by solar [kW].
Pw	Power generated by wind [kW].
Pf	Power generated by fuel cells [kW].
Pe	Power consumed by electrolizer [kW].
SOC	Battery state-of-charge [kWh].
SOC^{HT}	Hydrogen tank state-of-charge [kgh].
$u^p_{n_D}$	Binary variable for the purchase of diesel generator type n_D.
u^{Ch}	ON/OFF state of battery charging.
u^{Dch}	ON/OFF state of battery discharging.
u^{EDG}	Binary variable for existing diesel generator ON/OFF state.
u^{NDG}	Binary variable for new diesel generator ON/OFF state.

Chapter 1

Introduction

1.1 Electricity in Canada's Remote Communities (RCs)

Canadian northern territories (Nunavut, Northwest Territories, and Yukon) contain nearly 40 percent of Canada's land mass, and are sparsely populated. Among 114,000 people, who live in northern territories, many reside in the territorial capitals of Iqaluit, Yellowknife, and Whitehorse. The largest of the 13 provinces and territories in Canada is Nunavut, with a total landmass of 1,936,113 km^2, distributed along 25 fully differentiated communities [1].

Planning an appropriate energy supply mix to satisfy electricity demand in RCs is a challenging issue due to their geographical location, extreme weather conditions, their consumption patterns, and availability of energy sources. In addition, many RCs are only reachable by seasonal roads, sea, or air, and since the supply of fuel to their locations is limited, there is a need for storing fuel to continuously satisfy their energy demand. Moreover, because RCs are spread across Canada without access to the bulk power system, they cannot benefit from the economy of scale or low cost of generation. Therefore, high Operation and Maintenance (O&M) costs along with high transportation and fuel storage costs need to be added to the total cost of electricity. Currently, these communities heavily rely on diesel generation and fluctuations in oil price can negatively impact the cost of electricity generation.

In this report, the community Sanikiluaq in Nunavut shown in Figure 1.1 is studied, which is the only permanent settlement of the Archipelago, as other parts of the region serve for camp or temporary residence. Nearly 800 people reside there, and the community serves as the center of administration, trade, and communal life. Therefore, in addition to the residential electricity needs, a variety of institutional electricity demand should be satisfied. Thus, the center for administrative services is the hamlet office, which includes the Departments of Finance, Recreation, Economic Development, Community Lands, Justice, and Alcohol and Drug control. Over 200 students attend the Nuiyak School and daycare, which has about 25 employees, and there is a branch of the Nunavut Arctic College that offers adult education. Healthcare is offered to the residents of this community at the local clinic, and dentists, doctors and other specialists also visit the hamlet on a regular basis.

Figure 1.1: Sanikiluaq's geographical location (source: Google Earth).

The Qulliq Energy Corporation (QEC) is the sole power utility that oversees the generation and distribution of electricity in Nunavut, by supplying electricity to approximately

14,400 customers, requiring electricity to heat, light, and power their homes. Nunavut's energy system is different from traditional systems in Canada, since it is formed by isolated and not connected local Microgrids (MGs). Therefore, each community generates and distributes its own electricity in an independent/islanded fashion. The fuel for diesel generators is purchased and shipped in bulk during the short summer seasons and stored in tank facilities in each community for the longer cold seasons.

1.2 Electric Generation Planning for RC MGs

Due to special needs and limitations of RCs, deploying MGs is recommended to supply their energy needs. MGs have enormous potential to provide access to cheaper, cleaner and more flexible and reliable electricity [2]. Using a wide variety of DERs, which include Renewable Energy Resources (RES) and Energy Storage Systems (ESS), MGs can provide a range of services such as lighting, entertainment, refrigeration, and productive commercial use, and can enhance the reliability of the electric grid [3]. To plan for the deployment and/or expansion of MGs, electric generation planning models are used, which provide economic and environmental viable solutions to plan the future of the energy supply mixture to satisfy electricity demand. Such planning models enable a flexible and economic operation in the short, medium, and long term for electricity users, utility designers, and system operators. However, energy planning for RC MGs is more challenging due to the community location and a combination of legal, political, financial, social, geographical, and environmental restrictions [1].

The goal of the planning of MGs is to identify the optimal (most economic) size and mixture of the generation resources, and the time of their deployment [4]. Planning models use estimation of parameters such as electricity demand and RES availability, using historical data, while directly or indirectly considering their uncertainty. Generally speaking, the planning of MGs is formulated through an optimization model, involving an objective function, a set of parameters, decision variables, and technical, economical, and/or environmental constraints.

Chapter 2

MG Planning Model

2.1 Model Description

The planning model presented in this report is based on the model presented in [5] and [6] for RC MGs, and the model for the State of Charge (SOC) of hydrogen storage in [7]. The proposed mathematical model contains binary variables associated with the hourly on/off status of diesel generators, the charging and discharging status of batteries and hydrogen storage systems, and purchase of new diesel generators. The variables prescribing the number of investments in RES are integer variables. In addition, the model contains continuous variables to represent the generation power output and SOC of batteries and hydrogen storage systems. Therefore, the optimization model can be classified as a Mixed Integer Linear Programming (MILP) problem, and a general representation of the problem is as follows:

$$\begin{aligned} \min_{x} \quad & f(x) \\ \text{s.t.} \quad & g(x) \leq u \\ & h(x) = v \end{aligned} \tag{1}$$

where f is the objective function, g and h represent the inequality and equality constraints respectively, u and v are constants parameters, and x represents the decision variables.

2.1.1 Objective Function

The model objective function represents the summation of the Net Present Cost (NPC) of the overall discounted costs of the MG, which includes investments in RES, ESS (batteries and hydrogen storage systems), and new diesel generators; NPC of their O&M; and NPC of the fuel costs for the diesel generators. Thus, the proposed planning model minimizes the following objective function for a planning horizon, subject to the constraints explained next:

$$\begin{aligned} Z = \;& CC^{NDG} + FC^{NDG} + FC^{EDG} \\ & + CC^{S} + CC^{W} + CC^{B} + CC^{E} + CC^{FC} + CC^{HT} \\ & + OMC^{EDG} + OMC^{NDG} + OMC^{S} + OMC^{W} + OMC^{B} \\ & + OMC^{HT} + OMC^{FC} + OMC^{E} \end{aligned} \tag{2}$$

where all terms, here and for all other equations, are defined in the Nomenclature Section at the beginning of the report.

2.1.2 Model Constraints

a. NPC of Capital and O&M Costs

In this model, the capacity additions Cap of diesel generators, RES, and ESS are considered annually. Therefore, the NPC of the capital cost CC for each generator and storage unit is defined as a function of the unit cost UC and the yearly capacity additions Cap, as follow:

$$CC^{NDG} = \sum_{y=1}^{PH} \frac{\sum_{n_D=1}^{Nn_D} UC^{NDG} Cap_{n_D,y}^{NDG}}{(1+d)^{y-1}} \tag{3}$$

$$CC^S = \sum_{y=1}^{PH} \frac{\sum_{n_S=1}^{Nn_S} UC^S Cap^S_{n_S,y}}{(1+d)^{y-1}} \tag{4}$$

$$CC^W = \sum_{y=1}^{PH} \frac{\sum_{n_W=1}^{Nn_w} UC^W Cap^W_{n_W,y}}{(1+d)^{y-1}} \tag{5}$$

$$CC^B = \sum_{y=1}^{PH} \frac{\sum_{n_B=1}^{Nn_B} UC^B Cap^B_{n_B,y}}{(1+d)^{y-1}} \tag{6}$$

$$CC^{HT} = \sum_{y=1}^{PH} \frac{\sum_{n_{HT}=1}^{Nn_{HT}} UC^{HT} Cap^{HT}_{n_{HT},y}}{(1+d)^{y-1}} \tag{7}$$

$$CC^E = \sum_{y=1}^{PH} \frac{\sum_{n_E=1}^{Nn_E} UC^E Cap^E_{n_E,y}}{(1+d)^{y-1}} \tag{8}$$

$$CC^{FC} = \sum_{y=1}^{PH} \frac{\sum_{n_{FC}=1}^{Nn_{FC}} UC^{FC} Cap^{FC}_{n_{FC},y}}{(1+d)^{y-1}} \tag{9}$$

The next expressions define the NPC of the operation and maintenance costs OMC, which is a function of hourly/yearly O&M cost HOM and available capacity $NCap$ or power generated Pd, Pf, by each generator and fuel cells respectively, at each time period. To simplify the model, only one representative day of each month is considered, and therefore 288 (24 hour x 12 days) hours are used for simulating the operations of the MG ($HY = 288$). The total cost of the operation for representative days is multiplied by a factor of 30, to approximately extend the calculations to the whole year. As shown in the following equations, the total cost of generation for each type of generator is considered over all the years of the planning horizon PH:

$$OMC^{EDG} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{e_D=1}^{Ne_D} HOM_{e_D}^{EDG} Pd_{e_D,y,h}^{EDG}}{(1+d)^{y-1}} \tag{10}$$

$$OMC^{NDG} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{n_D=1}^{Nn_D} HOM_{n_D}^{NDG} Pd_{n_D,y,h}^{NDG}}{(1+d)^{y-1}} \tag{11}$$

$$OMC^{S} = \sum_{y=1}^{PH} \frac{30 \times 288 \sum_{n_S=1}^{Nn_S} HOM_{n_S}^{S} NCap_{n_S,y}^{S}}{(1+d)^{y-1}} \tag{12}$$

$$OMC^{W} = \sum_{y=1}^{PH} \frac{30 \times 288 \sum_{n_W=1}^{Nn_W} HOM_{n_W}^{W} NCap_{n_W,y}^{W}}{(1+d)^{y-1}} \tag{13}$$

$$OMC^{B} = \sum_{y=1}^{PH} \frac{30 \times 288 \sum_{n_B=1}^{Nn_B} HOM_{n_B}^{B} NCap_{nB,y}^{B}}{(1+d)^{y-1}} \tag{14}$$

$$OMC^{HT} = \sum_{y=1}^{PH} \frac{\sum_{n_{HT}=1}^{Nn_{HT}} HOM_{n_{HT}}^{HT} NCap_{n_{HT},y}^{HT}}{(1+d)^{y-1}} \tag{15}$$

$$OMC^{E} = \sum_{y=1}^{PH} \frac{\sum_{n_E=1}^{Nn_E} HOM_{n_{El}}^{E} NCap_{n_E,y}^{E}}{(1+d)^{y-1}} \tag{16}$$

$$OMC^{FC} = \sum_{y=1}^{PH} \frac{30 \sum_{h=1}^{HY} \sum_{n_{FC}=1}^{Nn_{FC}} HOM_{n_{FC}}^{FC} Pf_{n_{FC},y,h}}{(1+d)^{y-1}} \tag{17}$$

Finally, the NPC of the fuel cost FC for the existing diesel generators EDG and new diesel generators NDG is defined as a function of the cost of diesel $Dcost$ and the fuel consumption $Fcon$, as follows:

$$FC^{EDG} = \sum_{y=1}^{PH} \frac{30 \times Dcost \sum_{h=1}^{HY} \sum_{e_D=1}^{Ne_D} Fcon_{e_D,y,h}^{EDG}}{(1+d)^{y-1}} \tag{18}$$

$$FC^{NDG} = \sum_{y=1}^{PH} \frac{30 \times Dcost \sum_{h=1}^{HY} \sum_{n_D=1}^{Nn_D} Fcon_{n_D,y,h}^{NDG}}{(1+d)^{y-1}} \tag{19}$$

where $Fcon_{n_D,y,h}^{NDG}$ and $Fcon_{e_D,y,h}^{EDG}$ are computed using the fuel curves available in [5, 6], which are nonlinear and, therefore, piecewise linearization is used for their representation.

b. Commissioning of New Generation

In addition to the aforementioned constraints, the following equality constraints facilitate the dynamic addition of the new diesel generation, RES and ESS capacity to the generation portfolio, by updating the net capacity additions $NCap$ for each type of generation at a specific year, considering the amount of the capacity additions Cap at that year:

$$NCap_{n_D,y+1}^{NDG} = Cap_{n_D,y}^{NDG} + NCap_{n_D,y}^{NDG} \qquad \forall n_D, y \tag{20}$$

$$NCap_{n_S,y}^{S} = Cap_{n_S,y}^{S} + NCap_{n_S,y-1}^{S} \qquad \forall n_S, y \tag{21}$$

$$NCap_{n_W,y}^{W} = Cap_{n_W,y}^{W} + NCap_{n_W,y-1}^{W} \qquad \forall n_W, y \tag{22}$$

$$NCap_{n_B,y}^{B} = Cap_{n_B,y}^{B} + NCap_{n_B,y-1}^{B} \qquad \forall n_B, y \tag{23}$$

$$NCap_{n_{HT},y}^{HT} = Cap_{n_{HT},y}^{HT} + NCap_{n_{HT},y-1}^{HT} \qquad \forall n_{HT}, y \tag{24}$$

$$NCap_{n_E,y}^{E} = Cap_{n_E,y}^{E} + NCap_{n_E,y-1}^{E} \qquad \forall n_E, y \tag{25}$$

$$NCap_{n_{FC},y}^{FC} = Cap_{n_{FC},y}^{FC} + NCap_{n_{FC},y-1}^{FC} \qquad \forall n_{FC}, y \tag{26}$$

where the capacity additions Cap for each type of generation at each year, is defined by the number of RES and ESS I and new diesel generator defined by the binary variable

u^p at each year, and their respective individual rated capacity $UCap$, as follows:

$$Cap^{NDG}_{n_D,y} = u^p_{n_D,y} UCap^{NDG}_{n_D} \qquad \forall n_D, y \tag{27}$$

$$Cap^{W}_{n_W,y} = I_{n_W,y} UCap^{W}_{n_W} \qquad \forall n_W, y \tag{28}$$

$$Cap^{B}_{n_B,y} = I_{n_B,y} UCap^{B}_{n_B} \qquad \forall n_B, y \tag{29}$$

$$Cap^{HT}_{n_{HT},y} = I_{n_{HT},y} UCap^{HT}_{n_{HT}} \qquad \forall n_{HT}, y \tag{30}$$

$$Cap^{E}_{n_{El},y} = I_{n_E,y} UCap^{E}_{n_E} \qquad \forall n_E, y \tag{31}$$

$$Cap^{FC}_{n_{FC},y} = I_{n_{FC},y} UCap^{FC}_{n_{FC}} \qquad \forall n_{FC}, y \tag{32}$$

The capacity addition of solar is a continuous variable, as the installation of solar panels is more versatile and power fractions can be accommodated in practice.

c. Supply-Demand Balance

The supply of electrical energy needs to match the energy demand at every time step during the planning horizon. Thus, the summation of the power generated by diesel generators Pd, solar panels Ps, wind turbines Pw, fuel cells Pf, and battery storage discharge Pb^{DCh} has to be equal to the summation of the consumers demand PD, the battery storage charge Pb^{Ch}, and the power consumed by the electrolizer Pe, as follow:

$$\begin{aligned}\sum_{e_D=1}^{Ne_D} Pd^{EDG}_{e_D,y,h} + \sum_{n_D=1}^{Nn_D} Pd^{NDG}_{n_D,y,h} + \sum_{n_S=1}^{Nn_S} Ps_{n_S,y,h} + \sum_{n_W=1}^{Nn_W} Pw_{n_W,y,h} + \sum_{n_B=1}^{Nn_B} Pb^{Dch}_{n_B,y,h} \\ + \sum_{n_{FC}=1}^{Nn_{FC}} Pf_{n_{FC},y,h} = PD_{y,h} + \sum_{n_B=1}^{Nn_B} Pb^{Ch}_{n_B,y,h} + \sum_{n_E=1}^{Nn_E} Pe_{n_E,y,h} \qquad \forall h, y\end{aligned} \tag{33}$$

d. Operating Reserves

In order to accommodate uncertainties regarding demand, solar, and wind generation, the amount of capacity generation from diesel generation, i.e., Cap^{EDG} and $NCap^{NDG}$, fuel cells $NCap^{FC}$, and batteries storage SOC has to be greater than the consumers demand PD by a given factor β, and solar and wind by given factors γ and ρ, as follows:

$$\sum_{e_D=1}^{Ne_D} Cap_{e_D}^{EDG} + \sum_{n_D=1}^{Nn_D} NCap_{n_D,y}^{Nn_D} + \sum_{n_B=1}^{Nn_B} SOC_{n_B,y,h} + \sum_{n_{FC}=1}^{Nn_{FC}} NCap_{n_{FC},y}^{FC} \geq (1+\beta)PD_{y,h}+ \\ \gamma \sum_{n_S=1}^{Nn_S} Ps_{n_S,y,h} + \rho \sum_{n_W=1}^{Nn_W} Pw_{n_W,y,h} \qquad \forall h, y \tag{34}$$

where, typically, $\beta = 0.1$, $\gamma = 0.25$, and $\rho = 0.5$ as in [5, 6].

e. Diesel Generator Limits

The power generated by diesel generators Pd, at every hour during the planning horizon, has to be less than or equal to the rated capacity of existing generators Cap and new generators $NCap$, and greater than the minimum load operating level ML, which is a factor of the rated capacity, as follows[1]:

$$Pd_{n_D,y,h}^{NDG} \leq NCap_{n_D,y}^{NDG} u_{n_D,y,h}^{NDG} \qquad \forall n_D, h, y \tag{35}$$

$$Pd_{e_D,y,h}^{EDG} \leq Cap_{e_D}^{EDG} u_{e_D,y,h}^{EDG} \qquad \forall e_D, h, y \tag{36}$$

$$Pd_{n_D,y,h}^{NDG} \geq ML_{n_D}^{NDG} NCap_{n_D,y}^{NDG} u_{n_D,y,h}^{NDG} \qquad \forall n_D, h, y \tag{37}$$

$$Pd_{e_D,y,h}^{EDG} \geq ML_{e_D}^{EDG} Cap_{e_D}^{EDG} u_{e_D,y,h}^{EDG} \qquad \forall e_D, h, y \tag{38}$$

f. Diesel Generator Service Life

These inequality constraints take into account the useful life of the new diesel generators and the remaining life of the existing diesel generators in hours GH, by computing their

[1] Equations (35) and (37) are not linear, and thus are linearized using the techniques described in Appendix 1.

total amount of operating states during the planning horizon as follows:

$$\sum_{y=1}^{PH}\sum_{h=1}^{HY} 30u^{EDG}_{e_D,y,h} \leq GH^{remain}_{e_D} \qquad \forall e_D \tag{39}$$

$$\sum_{y=1}^{PH}\sum_{h=1}^{HY} 30u^{NDG}_{n_D,y,h} \leq GH^{life}_{n_D} \qquad \forall n_D \tag{40}$$

g. Diesel Generator Availability

This set of constraints are used to reflect the maintenance of diesel generators during the planning horizon. Thus, a percentage of the total number of the hours available T^{OM} in an average year is assigned for this purpose, as follows:

$$\sum_{h=1}^{HY} u^{EDG}_{e_D,y,h} \leq 288(1 - T^{OM}) \qquad \forall e_D \tag{41}$$

$$\sum_{h=1}^{HY} u^{NDG}_{n_D,y,h} \leq 288(1 - T^{OM}) \qquad \forall n_D \tag{42}$$

h. Solar Power Generation

The solar power generation output is computed as a direct function of the incident radiation SI, the cell temperature τ, and the derating factor df, 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:

$$Ps_{n_s,y,h} = NCap^S_{n_S,y} df \left(\frac{SI_h}{GT^{STC}}\right)\left[1 + \alpha(\tau - \tau^{STC})\right] \qquad \forall n_S, y, h \tag{43}$$

i. Wind Power Generation

The wind power is computed as a function of the hourly wind speed as follows:

$$Pw_{n_W,y,h} = W_{n_W}(NCap^W_{n_W,y}, WS_h) \qquad \forall n_W, y, h \tag{44}$$

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

j. Battery SOC and Limits

The following equality constraints compute the SOC of the batteries as a function of the power of charge Pb^{Ch} and discharge Pb^{DCh} for every hour of operation, considering the charging η^{Ch} and discharging η^{Dch} efficiency rates:

$$SOC_{n_B,y,h+1} - SOC_{n_B,y,h} = \eta^{Ch} Pb^{Ch}_{n_B,y,h} - \frac{Pb^{Dch}_{n_B,y,h}}{\eta^{Dch}} \qquad \forall n_B, y, h \tag{45}$$

$$SOC_{n_B,y+1,h} - SOC_{n_B,y,h} = \eta^{Ch} Pb^{Ch}_{n_B,y,HY} - \frac{Pb^{Dch}_{n_B,y,HY}}{\eta^{Dch}} \qquad \forall n_B, y, h \tag{46}$$

These are subject to the following inequality constraints reflecting SOC limits:

$$SOC_{n_B,y,h} \leq NCap^B_{n_B,y} \qquad \forall n_B, y, h \tag{47}$$

$$SOC_{n_By,h} \geq DoD^B NCap^B_{n_B,y} \qquad \forall n_B, y, h \tag{48}$$

The following inequality constraints reflect the maximum charging and discharging limits respectively, and are functions of the depth of discharge DoD, the capacity of the battery $NCap$, and the continuous time duration of charging T^{Ch} and discharging T^{DCh}:

$$Pb^{Dch}_{n_B,y,h} \leq \left(\frac{1 - DoD^B}{T^{Dch}}\right) NCap^B_{n_B,y} \qquad \forall n_B, y, h \tag{49}$$

$$Pb^{Ch}_{n_B,y,h} \leq \left(\frac{1 - DoD^B}{T^{Ch}}\right) NCap^B_{n_B,y} \qquad \forall n_B, y, h \tag{50}$$

And the following constraints guarantee minimum charging/discharging powers at a given hour:

$$Pb^{Dch}_{n_B,y,h} \geq u^{Dch}_{n_B,y,h} \qquad \forall n_B, y, h \qquad (51)$$

$$Pb^{Ch}_{n_B,y,h} \geq u^{Ch}_{n_B,y,h} \qquad \forall n_B, y, h \qquad (52)$$

The following constraint assures that the charging and discharging do not occur at the same time[2]:

$$Pb^{Dch}_{n_B,y,h} Pb^{Ch}_{n_B,y,h} = 0 \qquad \forall n_B, y, h \qquad (53)$$

Finally, the following constraint defines the life length of each battery considering a total of 3000 cycles of charge and discharge:

$$\sum_{y=1}^{PH} \sum_{h=1}^{HY} (Pb^{Ch}_{n_B,y,h} + Pb^{Dch}_{n_B,y,h}) \leq 3000 \sum_{y=1}^{PH} \sum_{h=1}^{HY} Cap^{B}_{n_B,y} \qquad \forall n_B \qquad (54)$$

k. Hydrogen System

The hydrogen system is composed of an electrolizer, consuming electricity Pe for generating the hydrogen that is stored at high pressure in tanks, which is used later by the fuel cells to generate electricity Pf. A schematic representation of this process is presented in Figure 2.1. The state of the charge of the hydrogen tank in kilograms SOC^{HT} is a function of the power generated by the fuel cells and the power consumed by the electrolizer, which are transformed into hydrogen consumption, as follow:

$$SOC^{HT}_{n_{HT},y,h+1} = SOC^{HT}_{n_{HT},y,h} + \frac{1}{1+l_C} \frac{Pe_{n_E,y,h}\eta_E}{HHV} - \frac{Pf_{n_{FC},y,h}}{HHV \eta_{FC}} \qquad \forall n_{HT}, y, h \qquad (55)$$

$$SOC^{HT}_{n_{HT},y+1,h} = SOC^{HT}_{n_{HT},y,HY} + \frac{1}{1+l_C} \frac{Pe_{n_E,y,h}\eta_E}{HHV} - \frac{Pf_{n_{FC},y,h}}{HHV \eta_{FC}} \qquad \forall n_{HT}, y, h \qquad (56)$$

$$SOC^{HT}_{n_{HT},y,h} \leq 0.95 NCap^{HT}_{n_{HT},y} \qquad \forall n_{HT}, y, h \qquad (57)$$

[2]Equation (53) is not linear and is hence linearized using the technique described in Appendix 2.

$$SOC^{HT}_{n_{HT},y,h} \geq 0.15 NCap^{HT}_{n_{HT},y} \qquad \forall n_{HT}, y, h \quad (58)$$

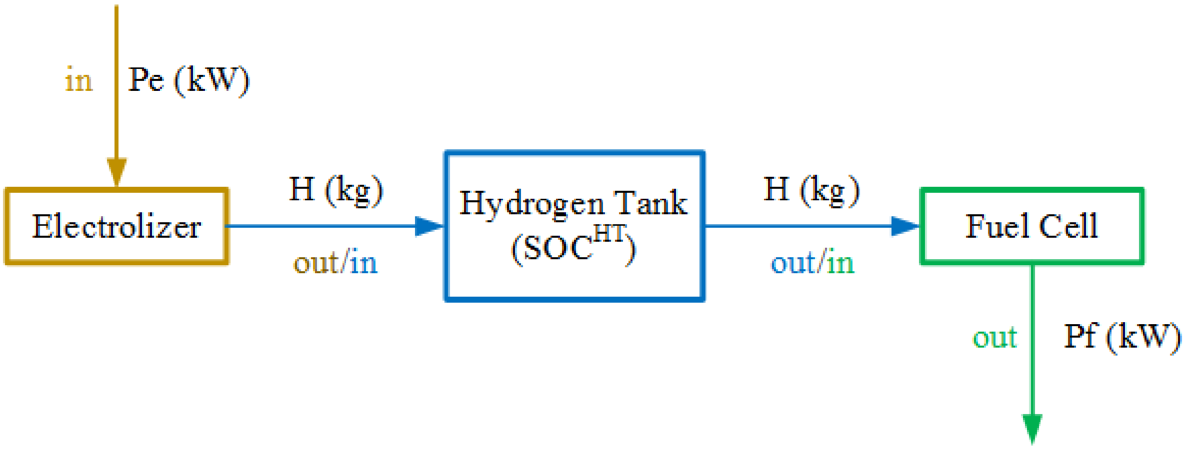


Figure 2.1: Schematic representation of hydrogen system.

In addition, the power generated by the fuel cells Pf and the power consumed by the electrolizers Pe need to be less than their net capacity $NCap$, as follows:

$$Pe_{n_E,y,h} \leq NCap^{E}_{n_E,y} \qquad \forall n_{El}, y, h \quad (59)$$

$$Pf_{n_{FC},y,h} \leq NCap^{FC}_{n_{FC},y} \qquad \forall n_{FC}, y, h \quad (60)$$

Chapter 3

Case Study for MG Planning

3.1 Data Sources

The formulation of the mathematical model for the long term planning of MGs is presented in detailed in Chapter 2. The various parameters needed to apply the presented optimization model and their sources are provided in the following sections.

3.2 Model Inputs

a. Electricity Demand

The hourly load for the Sanikiluaq community was obtained from the authors of [5] and [6]. This data can be used to calculate the hourly averages for a year with 288 representative hours, as explained in Section 2.1.2-a. The load is primarily residential and the corresponding demand profile is depicted in Figure 3.1 [5, 6].

b. Solar Panels and Solar Radiation Data

Sets of 9.6 kW solar panels are assumed to be connected through an inverter to the MG. The solar cell temperature τ and monthly Solar Irradiation SI and their averages,

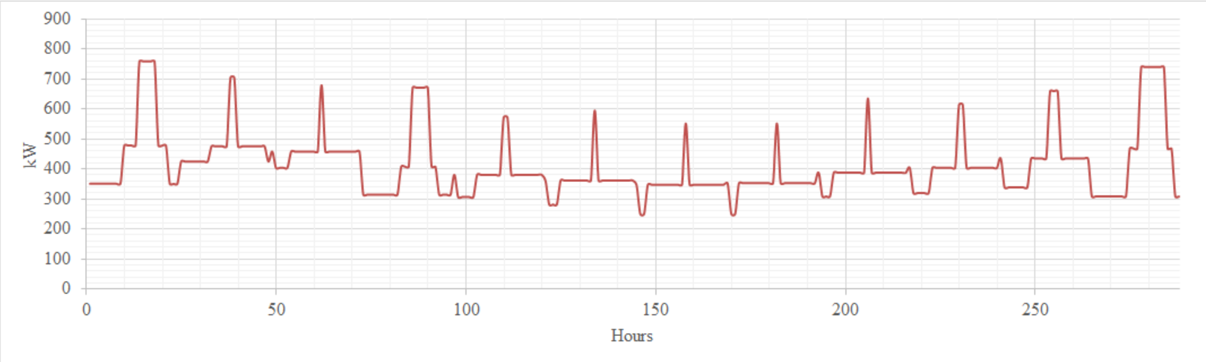


Figure 3.1: Sanikiluaq yearly average load profile [6].

depicted in Figure 3.2, were obtained from [5, 6]. The operational parameters and costs associated with the panels are shown in Table 3.1, and were extracted from [5, 6].

Cost (\$/kW)	O&M (\$/kWh)	α (p.u./°C)	GT^{STC}	df	Lifetime
5,082	0.0145	-0.041	1 kW/m^2	98%	20 years

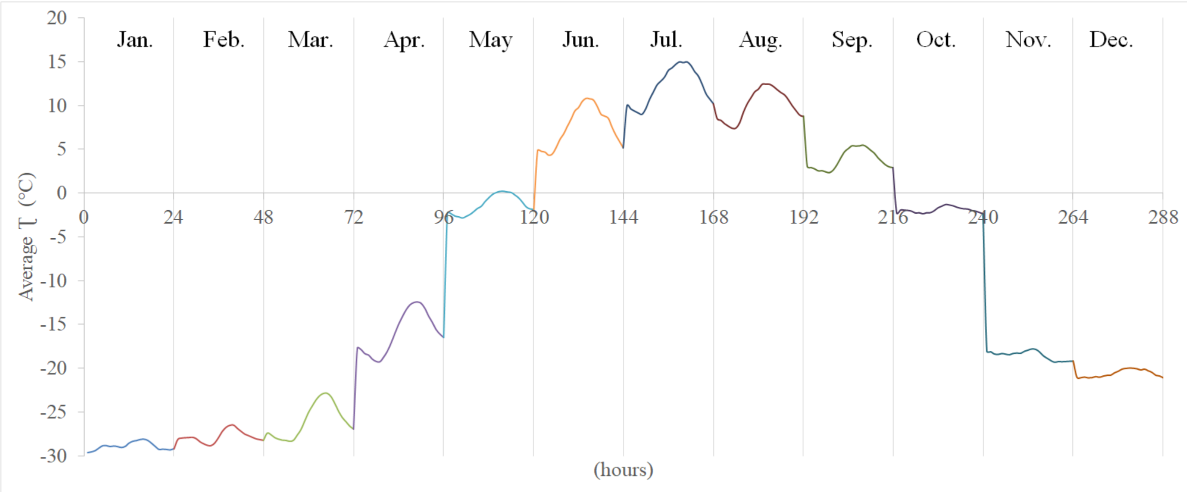
Table 3.1: Parameters and costs for solar panels at Sanikiluaq.

c. Existing Diesel Generators

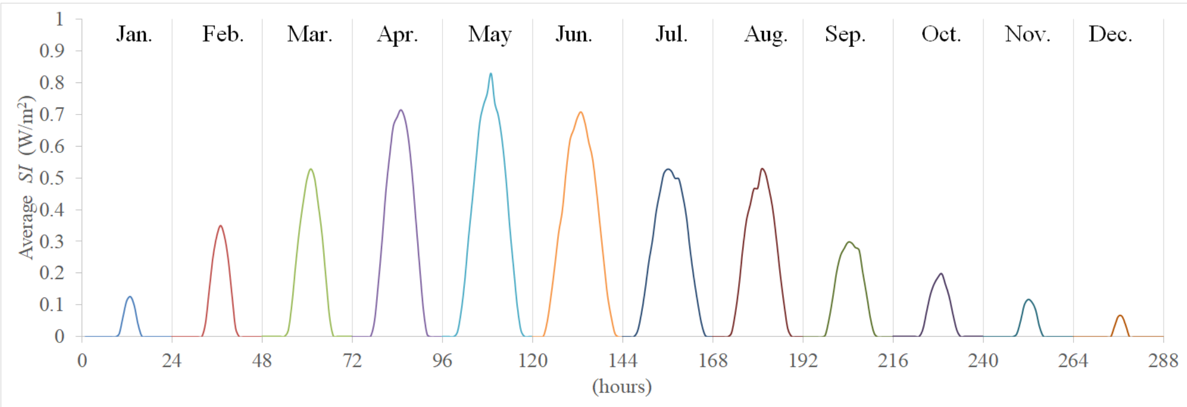
The main characteristics of the existing diesel generators are presented in Table 3.2. It was assumed that the minimum load of these generators is 40% of their nominal power. In addition, the stand-by mode of the existing diesel generators has been considered for the supply-demand balance at every time step according to Table 3.3. All generators, including those in stand-by mode, are assumed to act as reserves for the MG. The information related to the existing generators was obtained from [5, 6].

d. 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 3.4. It was assumed that the minimum load of these generators is also 40% of their nominal power, as per their operating characteristic. This information was extracted from [5, 6].



a)



b)

Figure 3.2: Sanikiluaq's monthly average (a) temperatures τ and (b) solar irradiation SI [6].

Gen.	Capacity (kW)	O&M ($/kWh)	Lifetime (h)	a $(l/h/kW^2)$	b $(l/h/kW)$	c (l/h)
1	330	0.0218	35,339	-0.0006	0.5212	-15
2	330	0.0218	21,600	-0.0006	0.5212	-15
3	330	0.0218	14,400	-0.0006	0.5212	-15
4	330	0.0218	7,200	-0.0006	0.5212	-15
5	500	0.0218	64,696	0.00003	0.2105	10.3
6	540	0.0218	68,820	0.00003	0.2144	10.3
7	550	0.0218	100,000	0.00003	0.2105	10.3

Table 3.2: Main generators' characteristics at Sanikiluaq.

Year of Project Horizon																				
Gen.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1		*		*		*		*		*		*		*		*		*		*
2		*		*		*		*		*		*		*		*		*		*
3	*		*		*		*		*		*		*		*		*		*	
4	*		*		*		*		*		*		*		*		*		*	
5	*		*		*		*		*		*		*		*		*		*	
6	*		*		*		*		*		*		*		*		*		*	
7		*		*		*		*		*		*		*		*		*		*

Table 3.3: Existing diesel generators in stand-by mode (*).

Gen.	Capacity (kW)	O&M ($/kWh)	Lifetime (h)	Cost ($/$kW$)	a ($l/h/kW^2$)	b ($l/h/kW$)	c (l/h)
1	320	0.0191	100,000	727	-0.0002	0.3287	3
2	520	0.0191	100,000	727	-0.00003	0.2227	10.3

Table 3.4: New diesel generator parameters and costs.

e. Wind Turbines and Wind Data

Wind generators with 250 kW of nominal capacity were considered, as in [5, 6]. Monthly average wind speeds were obtained from [5, 6], and their average is depicted in Figure 3.3. The economical and technical input parameters for the model are presented in Table 3.5, and were obtained from [5, 6]. The turbine curve $W(\cdot)$ was assumed linear between the cut-in and nominal speed, based on the actual power curves provided in [6].

Cost ($/kW)	O&M ($/kWh)	Cut-in Speed	Nominal Speed	Cut-out speed	Lifetime
7,943	0.0363	2.5 m/s	7.5 m/s	25 m/s	20 years

Table 3.5: Parameters and costs of wind generators.

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, as per [5, 6]. The economical and technical parameters for the implemented battery model are presented in Table 3.6, and were extracted from [5, 6].

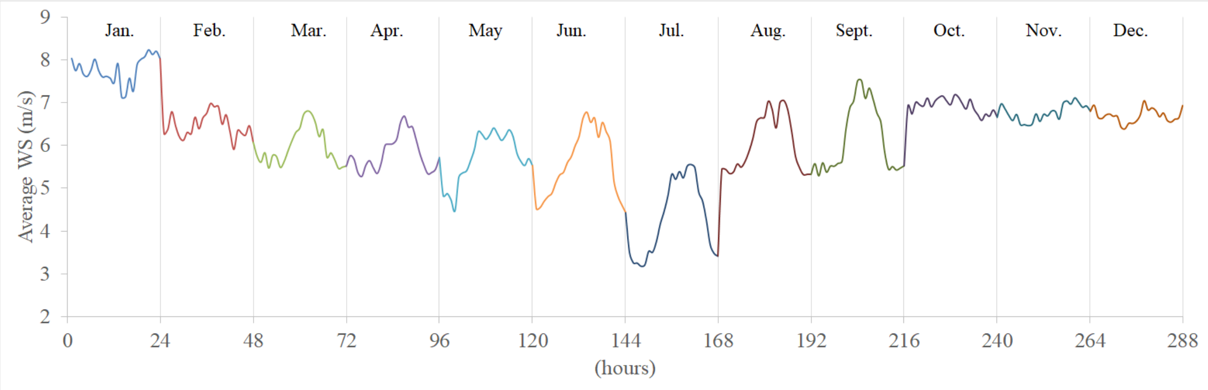


Figure 3.3: Average wind speed WS at 21m hub height [6].

Cost (\$/kWh)	O&M (\$/kWh)	SOC_0	DoD	η_{Ch}	η_{DCh}
1,504	0.0069	50%	20%	95%	95%

Table 3.6: Parameters and costs of batteries.

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 Tables 3.7, 3.8, and 3.9. This information was obtained from [1, 7].

Capacity (kW)	Cost (\$/u)	O&M (\$/h)	η_{FC}	Lifetime (h)
250	168,581	2	60%	50,000

Table 3.7: Parameters and costs of fuel cells.

Capacity (kW)	Cost (\$/u)	O&M (\$/y)	η_E	Lifetime (y)
330	1,279,000	194	70%	15

Table 3.8: Parameters and costs of electrolizer.

Capacity (kg)	Cost (\$/u)	O&M (\$/h)	HHV	l_C	Lifetime (y)
200	249,745	12,400	39.4 kWh	0.02 p.u.	25

Table 3.9: Parameters and costs of the hydrogen tank.

3.3 Scenarios and Assumptions

3.3.1 Scenarios

Five cases have been defined for testing the long term planning model presented in Chapter 2. The main characteristics of these scenarios, are the following, considering all possible combinations of DERs:

- Base Case: This case does not consider the inclusion of DERs, thus corresponding to business as usual, and serves as the base case to compare all other scenarios in terms of costs, use of diesel, and GHG reductions.
- First planning scenario 1A (D+S+W+B+H) and 1B (D+W+B+H) : In this planning scenario, all DERs, i.e., Hydrogen (H), Batteries (B), Wind (W), Diesel (D), and Solar (S) are considered.
- Second planning scenario 2A (D+S+W+H) and 2B (D+W+H): This planning scenario consists of all DERs but batteries are not considered.
- Third planning scenario 3A (D+S+W+B) and 3B (D+W+B): This planning scenario consists of all DERs but hydrogen. Since hydrogen systems are not considered, electrolizers, fuel cells, and hydrogen tanks are not included in the studies.
- Fourth planning scenario 4A (S+W+B+H) and 4B (W+B+H) : This case consist of only RES and ESS. Diesel generation is considered but exclusively for reserves, to represent a MG supplied primarily by renewable power.

3.3.2 Assumptions and Simulation Criteria

The optimization problem was solved using GAMS [8], with CPLEX being used to solve the MILP problem in Chapter 2. The following are the assumed values for the remaining model parameters [5, 6]:

- The discount rate is 8%.
- 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 grow of 1.0%/year.
- Ramping up/down constraints are not considered, since all diesel generators are able to turn on and off in fractions of 1 hour.
- Temperature at standard test conditions for solar cells $\tau^{STC} = 25°\text{C}$.
- The number of hours a battery can discharge continuously T^{DCh} and T^{Ch} is 4 hours.
- The cost of diesel is fixed at 2.391 $/l [5, 6].
- For the cases where hydrogen is included in the MG, one full system is included in the first year, leaving the algorithm to decide on additional capacity. Thus, at least one electrolizer needs to be replaced at year 16, according to their useful lifetime, assuming a nil salvage value.
- To control de inclusion of certain RES and ESS, 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.
- Addition of new capacity is allowed in predefined windows; thus, RES additions are allowed in the first 5 years only, and for new diesel generators the window is from the 3^{rd} to 10^{th} year, as per [5, 6].

3.4 Information delivered by the model

The planning model presented in this report may be used by federal, provincial, territorial, municipal, and indigenous governments across Canada to establish carbon free policies using RES and ESS in diesel-dependent RC MGs. The model offers the following information, which can be used in policy design and policy analysis:

- Expansion capacity and investments (Tables 4.1 and 4.2): The model offers annual additions for each technology, considering the NPC of the expenditures. Therefore, it could assist in deciding when and which mix of technologies to invest in.
- Fuel consumption and associated costs: One of the main objectives of the model is minimizing cost including NPC of the fuel consumed during the planning horizon by adjusting the cost of fuel ($) and the consumption ($l$), as they are outputs of the model. This information has been used to deduce possible emissions and Greenhouse Gas (GHG) emissions reductions (Table 4.1).
- Total investment and operation costs for RC MGs (objective function): This is one of the outputs of the model, and includes all the investment and operation costs during the planning horizon. For an optimal solution of the optimization problem, this is the lowest possible cost.
- Individualized operation costs: The model offers the NPC of the O&M costs of all the generation technologies operating in the RC MG (Table 4.1), which is an essential input for any asset management process.

3.5 Modelling Gap

From a planning perspective, the model presented in this report intends to help RCs recognize and quantify the potential benefits of implementing MGs through the use of RES and ESS, promoting their adoption for RC MGs decarbonization [9]. The particular gap that this model addresses is the inclusion of hydrogen systems as part of the ESS technologies considered in the planning process, which allows for more integration of RES in RC MGs, at reasonable costs.

3.6 Accessibility and Transparency of the Model and Data

The complete mathematical formulation of the proposed planning model with detailed explanations of the corresponding equations have been presented in the Second Chapter of this report, including the linearization techniques used for new diesel generator limits and battery charging/discharging, which are presented in Appendices 1 and 2. The references used for defining the parameters of the model have been disclosed and cited accordingly, and are based on realistic values obtained from the Saniqiluak community and other references, which were used to model the planning of the MG. The codes can also be made accessible upon request.

3.7 Usability for Policy Design

The planning of electric systems is an strategic process to identify users and stakeholder needs and limitations, to define policies to satisfy those needs and facilitate the decision-making process for the benefiting of all stakeholders. In this context, the suggested RC MG planning framework presented here can be used for designing policies aligned with energy sustainability and affordability targets for RCs in Canada. The suggested model facilitates the possibility of considering environmental, economical, and community factors [10].

Chapter 4

Results and Discussion

4.1 Planning Results

The results from the simulations performed in GAMS are presented in Tables 4.1 and 4.2. In addition, the amount of supply from each type of generation versus demand during the first 10 years of the MG operation is presented for every planning scenario in Figures 4.1 to 4.8. The demand includes the power for charging the batteries and the power consumed by the electrolizers, when applicable. From these tables and figures, the following can be observed:

- Base Case: For this case, the MG operates only with diesel generators, as previously indicated. During the planning horizon, no additional diesel generation is needed and there are enough resources to be considered for reserves. The NPC of the total costs of the MG, including operation and maintenance and fuel costs is 25.76 M$.

- First planning scenario 1A and 1B: For case 1A (D+S+W+B+H), there is a reduction of 29.3% on total costs, 88.8 % on O&M and fuel costs, and of 85.83% on GHG relative to the Base Case. For case 1B (D+W+B+H) there is a reduction of 33.6% on total costs, 93.4% on O&M and fuel costs, and of 86.1% in GHG relative to the Base Case.

Case		Capacity Additions							
		Diesel (kW)	Solar (kW)	Wind (kW)	Batteries (kWh/kW)	Fuel Cells (kW)	Hydrogen Tank (kg)	Electrolizer (kW)	GHG Red. (%)
Only Diesel									
1A	D+S+W+B+H	0	264	750	800/160	250	200	990	85.8%
2A	D+S+W+H	0	92	1000		250	400	1320	93.2%
3A	D+S+W+B	0	431	500	1800/360				64.3%
4A	**S+W+B+H**	0	577	1000	1000/200	500	200	660	**100.0%**
1B	D+W+B+H	320		1000	200/20	250	400	1320	86.1%
2B	D+W+H	0		1000		250	400	1320	93.5%
3B	D+W+B	840		500	1900/380				51.9%
4B	**W+B+H**	0		1250	3900/780	500	200	660	**100.0%**

Table 4.1: Total Capacity additions during the planning horizon.

Case		Net Present Costs				
		Fuel Cost (M$)	O&M Diesel Gen. (M$)	Investment (M$)	RES and ESS O&M (M$)	Total Cost (M$)
Only Diesel		24.87	0.89			25.76
1A	D+S+W+B+H	3.06	0.11	11.54	3.49	18.19
2A	D+S+W+H	1.77	0.06	11.94	3.55	17.32
3A	D+S+W+B	9.12	0.32	8.52	3.19	21.15
4A	**S+W+B+H**	0.00	0.00	16.57	4.62	21.19
1B	D+W+B+H	1.64	0.06	11.87	3.54	17.11
2B	D+W+H	1.76	0.06	11.53	3.43	16.78
3B	D+W+B	11.97	0.40	6.55	2.71	21.63
4B	**W+B+H**	0.00	0.0	19.20	6.60	25.80

Table 4.2: Associated Costs.

- Second planning scenario 2A and 2B: For case 2A (D+S+W+H), there is a reduction of 32.7% on total costs, 92.9% on O&M and fuel costs, and of 93.2% on GHG relative to the Base Base. For case 2B (D+W+H), there is a reduction of 34.8% on total costs, 96.8% on O&M and fuel costs, and of 93.5% on GHG relative to the Base Base. Since these cases do not consider the inclusion of batteries, the fuel cells provide the energy that is not been served by RES or diesel generators, as seen in Figures 4.3 and 4.4.

- Third planning scenario 3A and 3B: For case 3A (D+S+W+B), there is a reduction of 17.9% on total costs, 63.4% on O&M and fuel costs, and of 64.3% on GHG relative to the Base Base. For case 3B (D+W+B), there is a reduction of 16% on total costs, 52% on O&M and fuel costs, and of 51.9 on % GHG relative to the base case. In this planning scenario, due to to the absence of fuel cells, the power that is not being supplied by RES or diesel generators is being served by the batteries, as seen in Figures 4.5 and 4.6.

- Fourth planning scenario 4A and 4B: In this case, the diesel generators are used only for emergency, thus reflecting in 100% GHG reduction in normal operation. As depicted in Tables 4.1 and 4.2, 4A (S+W+B+H) reduces the total costs by up to 18%, and 4B (W+B+H) increases the total costs by only 0.2%.

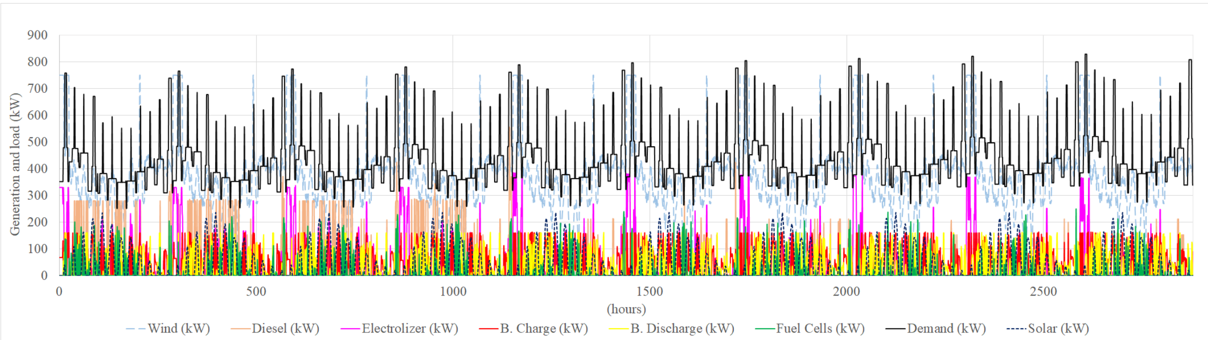


Figure 4.1: Case 1A operation for first 10 years.

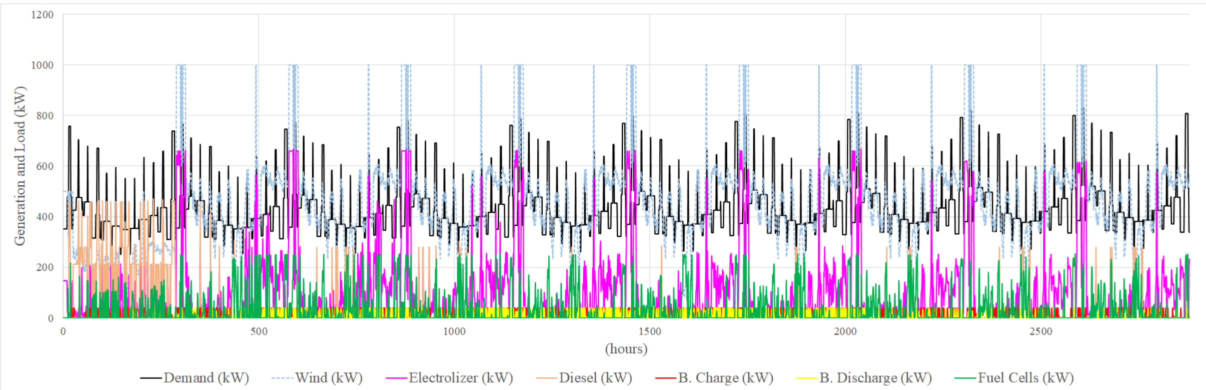


Figure 4.2: Case 1B operation for first 10 years.

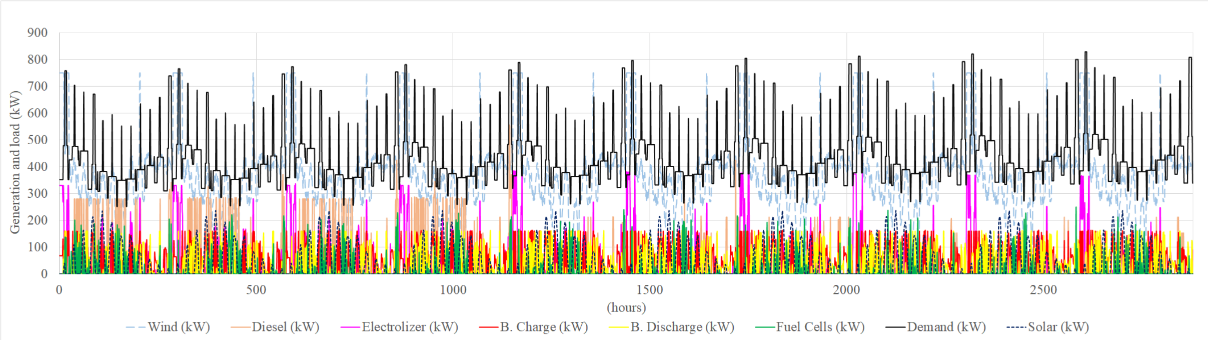


Figure 4.3: Case 2A operation for first 10 years.

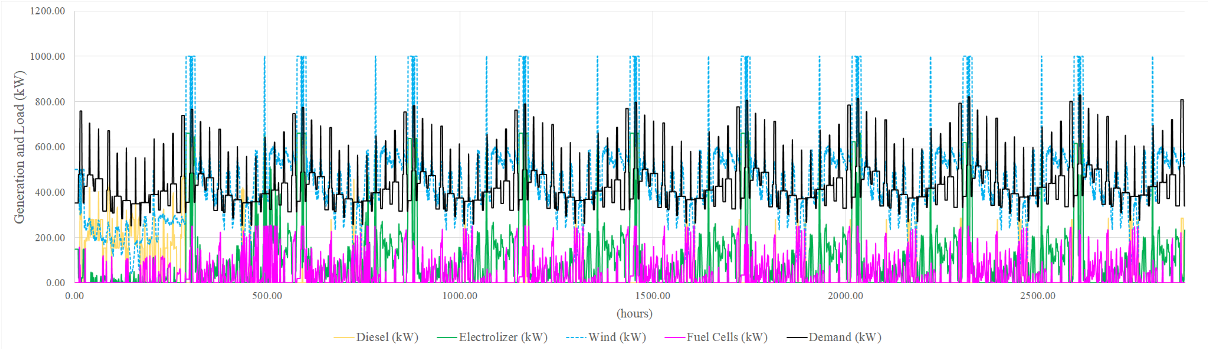


Figure 4.4: Case 2B operation for first 10 years.

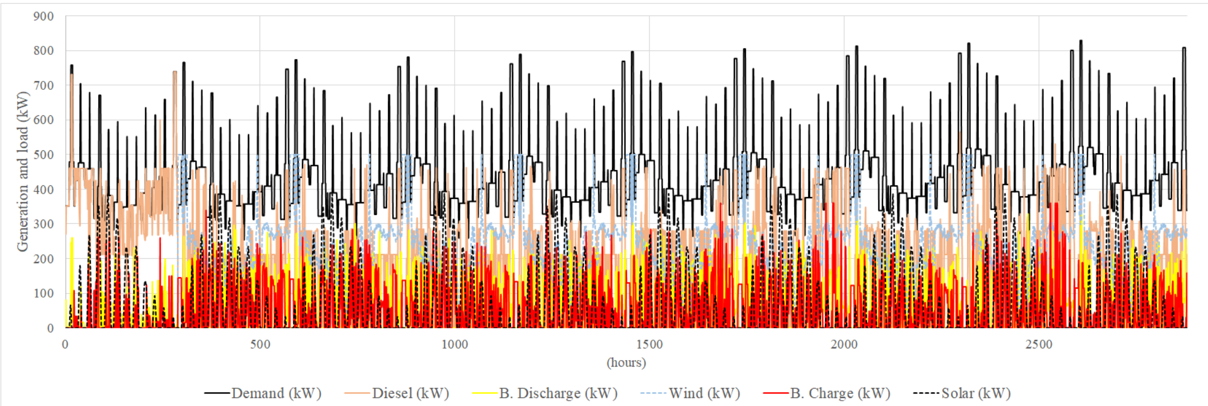


Figure 4.5: Case 3A operation for first 10 years.

4.2 Model Contribution to Electrification and Decarbonization

Through this study, and as demonstrated by the results presented in the previous sections, the feasibility of deployment of clean technologies to promote decarbonization pathways

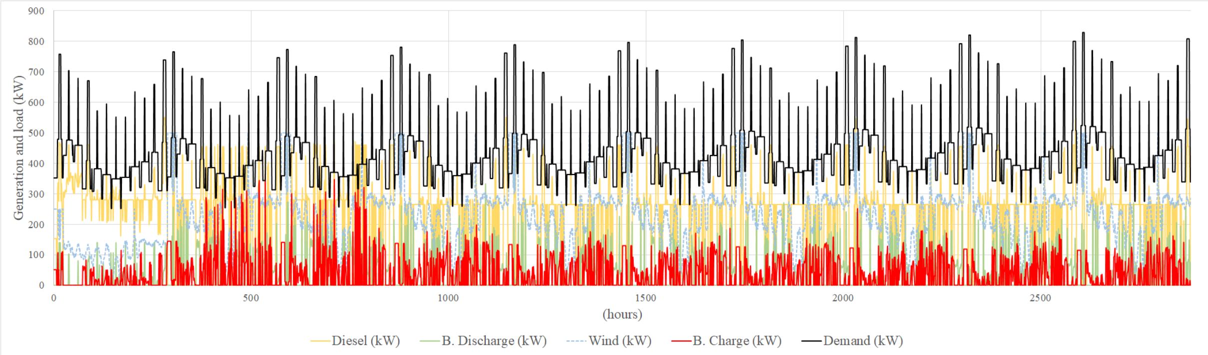


Figure 4.6: Case 3B operation for first 10 years.

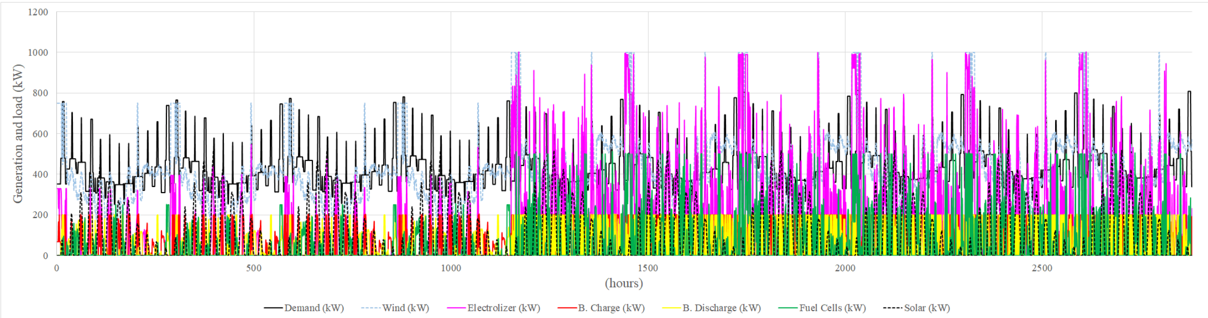


Figure 4.7: Case 4A operation for first 10 years.

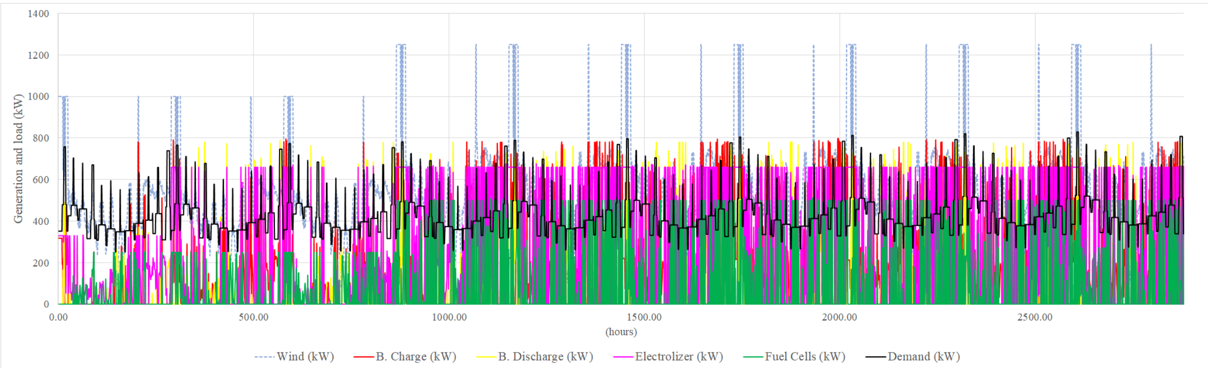


Figure 4.8: Case 4B operation for first 10 years.

in Canadian RCs has been demonstrated. Using the proposed planning model, different types of clean generation technologies in the MG of the community of Sanikiluaq have been examined. The results clearly show that wind resources along with solar and storage technologies (batteries and fuel cells) can play a key role in satisfying a RC electricity demand, while significantly reducing costs and GHG emissions, which could be utilized for long term operation of RC MGs. Therefore, the proposed model contributes to RCs electrification and decarbonization pathways by:

- Guaranteeing the fulfillment of the electricity needs of the inhabitants of the RCs; since the model includes operational details, the obtained optimal solutions guarantee that the generation will meet the demand at all times, with consideration of adequate level of reserves.
- Advocating decarbonized electrification; since one of the main objectives of the planning model presented in this report is the use of RES and ESS. As shown in the simulations results, the inclusion of this type of technologies may significantly reduce the use of fossil fuels, which reduces emissions (between 51.9% and 100%). In addition, by reducing their use, a reduction in fuel storage and transportation will also take place.
- Reducing uncertainty related to the prices of fossil fuels; since the developed model guarantees the integration of RES and ESS, thus reducing diesel consumption, which would facilitate buying diesel at lower prices.
- Promoting a structural change in the Canadian economy; since the planning model promotes introducing RES and ESS in RCs, which would help make these Canadian communities become less dependent on fossil fuel, while impacting the costs of the required RES and ESS technologies through increasing demand for them [11].
- Enhancing electric grid flexibility; since the planning model would promote flexibility in generation supply.
- Supporting Canada in meeting zero emissions target; since the planning model presented in this report promotes the integration of RES and ESS in RC MGs, resulting in significant reduction in GHG emissions, which is a key part of Canada's transition to zero emissions [12].

4.3 Integration in a National Modeling Platform

The presented model should be useful for experts, researchers, investors, and policy-makers in the context of modeling platform, to determine requirements for financing, construction, management, and real time operation of RC MGs. Such platform could allow creating products, services, and strategies that help mitigate and solve energy-related public problems for RCs.

4.4 Future Work

The presented work could be enhanced as follows:

- Apply the model to address the needs of RCs in Canada.
- Consider more sophisticated methods to incorporate uncertainties in the proposed model.

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APPENDICES

Appendix 1

Recall Equations 35 and 37:

$$Pd^{NDG}_{n_D,y,h} \leq NCap^{NDG}_{n_D,y} u^{NDG}_{n_D,y,h} \qquad \forall n_D, h, y \qquad (35)$$

$$Pd^{NDG}_{n_D,y,h} \geq ML^{NDG}_{n_D} NCap^{NDG}_{n_D,y} u^{NDG}_{n_D,y,h} \qquad \forall n_D, h, y \qquad (37)$$

The right hand side of Equation 35 is no linear since it is the product of a continuous and a binary variable. A linearization technique is applied, and a dummy variable *Capu* is utilized for this purpose [16, 6]. Equation 35 is substituted by the following set of equations:

$$Pd^{NDG}_{n_D,y,h} \leq Capu_{n_D,y,h} \qquad \forall n_d, y, h \qquad (61)$$

$$Capu_{n_D,y,h} \leq 5 \cdot UCap^{NDG}_{n_D} u^{NDG}_{n_D,y,h} \qquad \forall n_d, y, h \qquad (62)$$

$$Capu_{n_D,y,h} \leq NCap^{NDG}_{n_D,y} \qquad \forall n_d, y, h \qquad (63)$$

$$Capu_{n_D,y,h} \geq NCap^{NDG}_{n_D,y} - 5 \cdot UCap^{NDG}_{n_D}(1 - u^{NDG}_{n_D,y,h}) \qquad \forall n_d, y, h \qquad (64)$$

$$Capu_{n_D,y,h} \geq 0 \qquad \forall n_d, y, h \qquad (65)$$

Finally, Equation 37 is replaced by:

$$Pd^{NDG}_{n_D,y,h} \geq ML^{NDG}_{n_D} Capu_{n_D,y,h} \qquad \forall n_d, y, h \qquad (66)$$

Appendix 2

Recall Equation 53, which is non-linear since it is the product of two continuous variables:

$$Pb^{Dch}_{n_B,y,h} Pb^{Ch}_{n_B,y,h} = 0 \qquad \forall n_B, y, h \qquad (53)$$

A linearization technique is applied and Equation 53 is substituted by the following set of equations:

$$Pb^{DCh}_{n_B,y,h} \leq u^{DCh}_{n_B,y,h} M \qquad \forall n_B, y, h \qquad (67)$$

$$Pb^{Ch}_{n_B,y,h} \leq u^{Ch}_{n_B,y,h} M \qquad \forall n_B, y, h \qquad (68)$$

$$u^{DCh}_{n_B,y,h} + u^{Ch}_{n_B,y,h} \leq 1 \qquad \forall n_B, y, h \qquad (69)$$

where M is a very large number.