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Hydrogen and Gas Generation for Renewable Energy Integration in Canadian Remote Community Microgrids: Is it feasible?

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1 Introduction

Approximately 1.1 billion or 14% of the global population do not have access to electricity, due to the challenges associated with energy supply. Around 84% of those without electricity access reside in rural areas, with more than 95% of them being in sub-Saharan Africa and developing parts of Asia. In Canada, about 72% of off-grid aboriginal and non-aboriginal communities use fossil fuel (oil: 71%, natural gas: 0.8%) as their main source of electricity generation, and only 4.7% of these communities rely on renewable energy sources. In addition, 17.9% of the communities fulfill their energy demand through interconnections with other communities, as they don't have enough resources to support their own needs. The remaining 5.6% of these communities are reported to rely on unknown sources of electricity (see Arriaga et al. 2014).

Satisfying electricity demand in Remote Communities (RC) is a challenging issue due to their geographical location, extreme weather conditions, their consumption patterns, and availability of energy sources. In Canada, RC are only reachable by seasonal roads, sea or air, the supply of fuel to their location is limited, and therefore there is need for storing fuel to supply energy when needed. Moreover, since remote communities 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. In addition, fluctuations in oil price can negatively impact the cost of electricity generation in these communities.

This paper is focused on microgrid (MG) planning for Canadian remote communities using different mixture of Renewable Energy Sources (RES) and non-RES in order to address the concerns regarding the availability and affordability of electricity supply in RC. The outcomes of this paper rely on the studies performed by the Waterloo Institute for Sustainable Energy (WISE) and University of Waterloo for the World Wildlife (WWF) Canada (see Das and Cañizares 2019).

The feasibility of implementing solar PV, wind generators, natural gas generators, hydrogen systems, and flow batteries in the community of Sanikiluaq by considering their economical and environmental viability is discussed here. The presented studies focus on analyzing whether that combination of renewable energy resources along with storage capacities, including hydrogen, is economically and environmentally advantageous compared to the current diesel generators. The analysis is based on evaluating the Levelized Cost of Electricity (LCOE), as well as the number of operating hours for diesel generators and their impact of the operating costs, fuel consumption, and emissions, while considering hydrogen storage and natural gas generation, to determine whether the introduction of renewable resources ensures cost savings, while satisfying demand in the long-term.

The rest of the paper is organized as follow: Section 2 describes the main characteristics of Canadian Arctic Communities and the nature of their electricity demand. Section 3 outlines the planning models utilized for the presented studies, and Section 4 discusses their implementation for the Sanikiluaq community and associated results. Finally, in Section 5, the main conclusions of this paper are presented.

2 Electricity in Canadian Arctic Communities

Canadian northern territories, Nunavut, Northwest Territories, and Yukon, which are nearly 40 percent of Canada's land mass are massive and 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, illustrated in Figure 1, with a total landmass of 1,936,113 km^2, distributed along 25 fully differentiated communities. The presented study focuses on

Sanikiluaq, which is located in the southernmost part of Nunavut, about 150 kilometers off the west coast of Nunavik, Quebec.

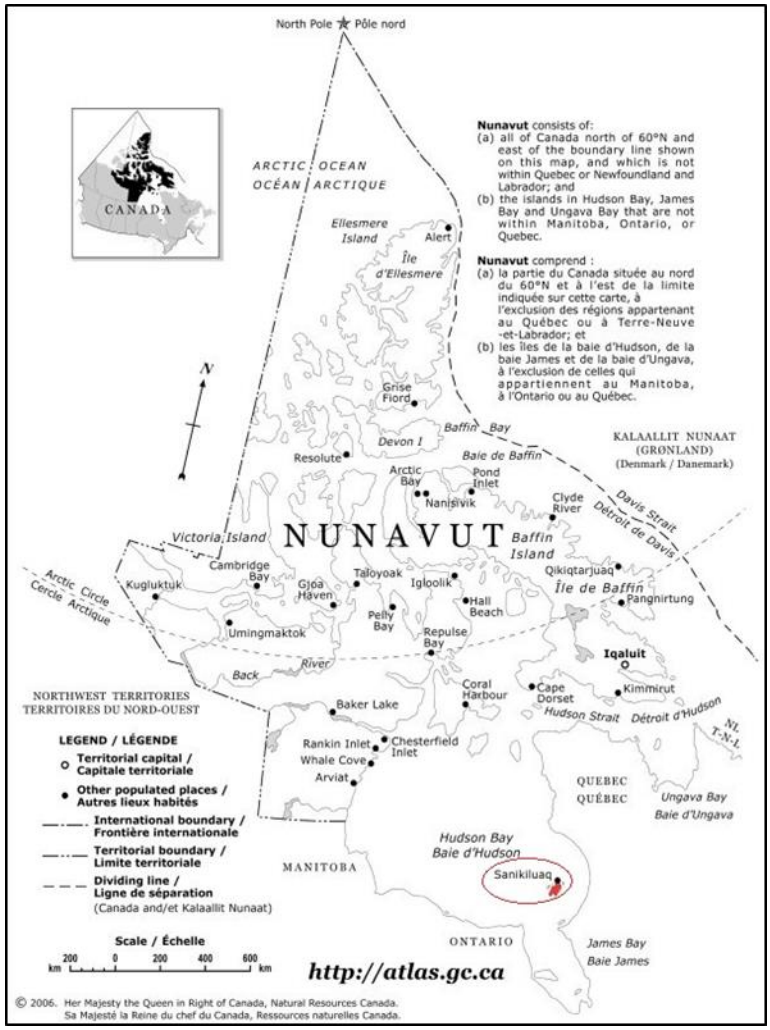


Figure 1: Nunavut (https://atlas.gc.ca).

Sanikiluaq is the only permanent settlement of the archipelago, as other parts of the islands serve for camp or temporary residence. Thus, nearly 800 people reside in this community, which is also the center of administration, trade, and communal life. Therefore, in addition to the residential electricity load, there enough capacity is needed to support a variety of institutional electricity demand. The center for administrative services is the hamlet office, which includes the Departments for 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.

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 MGs. Therefore, each community generates and distributes its own electricity in an independent/islanded fashion. The main source of electricity for each

community is diesel generators, with the fuel being purchased and shipped in bulk during the short summer seasons and stored in tank facilities in each community for the longer cold seasons.

3 Microgrid Planning for Remote Communities

3.1 Framework

Electric generation planning models provide economic, environmental, and viable solutions to plan the future of the energy supply mixture to satisfy the required demand. Such planning models enable a flexible and economic operation in the short, medium, and long term for electricity users, utilities, and system operators. However, energy planning for MGs in remote communities is more challenging due to the sparsity of the communities and a combination of legal, political, financial, social, geographical, and environmental restrictions. Traditionally, the planning of MGs is studied from a systematic and operational point of view, where their topology and optimal point of connection are decisive factors in choosing the most suitable combination of resources. The planning problem is formulated through an optimization problem, in which the size, type, and location of the available resources are optimally determined. In this paper, the optimization model from the well-known Hybrid Optimization Model for Multiple Energy Resources (HOMER) toolbox is used to plan the MG of a remote community, based on the following framework:

1. Data gathering: Collected and analyzed data pertained to demand and supply requirements, general technical specifications of new equipment, and regulatory and environmental requirements. Due to the nature of Canadian RC, special attention has to be paid to other additional parameters such as cost of transportation of fuel and equipment through ice-roads.
2. MG model: A MG model was implemented using the provided schematic fashion in HOMER. In the proposed model, the components of the MG model for the community of interest, and their specific parameters (technical and economical) were determined.
3. Optimization model and results: After running the model and determining the features particular to the community of interest, the results obtained from the economic optimizer in HOMER were analyzed for optimal and feasible solutions.

3.2 HOMER Overview

The HOMER Micropower Optimization Model is a computer software developed by the U.S. National Renewable Laboratory (NREL) to assist in the optimal design of grid-connected and off-grid MGs. Thus, its fundamental capability is simulating the long-term operation of MGs. HOMER models and simulates possible alternatives and combinations of the energy system equipment such as photovoltaic modules, wind turbines, small hydro, biomass power, microturbines, fuel cells, batteries, and hydrogen storage. The Total Net Present Cost (NPC) is used to represent the life-cycle cost of the system, which includes all costs and revenues, with future cash flows discounted to present.

There are two optimization algorithms in HOMER: the “original search grid,” which simulates all the feasible system configurations defined by the search space, and the “derivative-free” algorithm, which looks for the system with the least cost. During the lifetime of the project, at every time step, HOMER computes the supply-demand balance considering system reserves, calculates the power flows to and from each component of the system, and the operation of Energy Storage System (ESS). This facilitates the determination of the technical feasibility and life-cycle costs of the system.

In addition, by simulating all the feasible configurations defined by the search space, the system that satisfies the technical constraints (adequacy of the system, RES penetration, and allowable capacity shortage) at the lowest life-cycle cost can be selected. The program provides feasible and optimal solutions,

consisting of the number and size of the required components, associated costs, and other aspects of the operation of the system such as the number of operational hours per year, fuel consumption, and energy output. Another relevant feature of HOMER is its sensitivity analysis capability, as it facilitates uncertainty analysis for some input parameters. Creating a planning model in HOMER follows a schematic fashion. The general procedure in Figure 2 illustrates the steps for creating a model in HOMER.

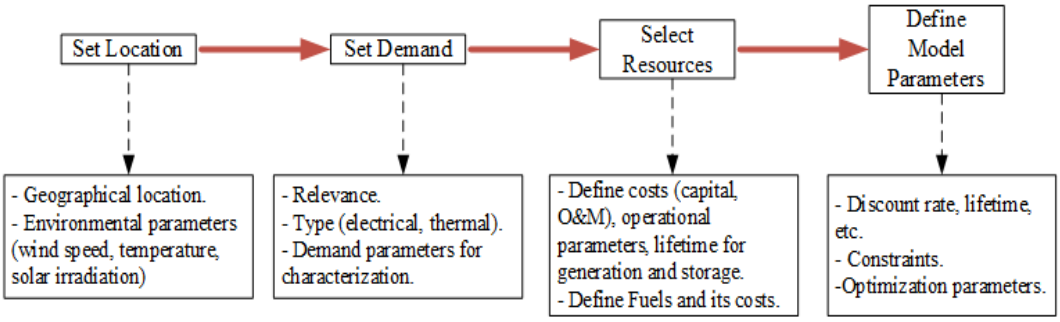


Figure 2: Recommended steps for modelling in HOMER.

4 Case Study

4.1 Base Case

Data related to the Sanikiluaq community was used to plan the proposed MG. Figure 3 illustrates the existing MG in Sanikiluaq, which was used as the base-case. The electricity demand of this community is satisfied through 6 diesel generators (3 main and 3 backup generators). The diesel generators' minimum load was assumed to be 40% of the nominal capacity, and the diesel price was assumed to be 2.391 ($/L) for all years (see Das and Cañizares 2019). The most relevant characteristics of the main generators, such as capacity, replacement value, O&M cost, and their lifetime are presented in Table 1.

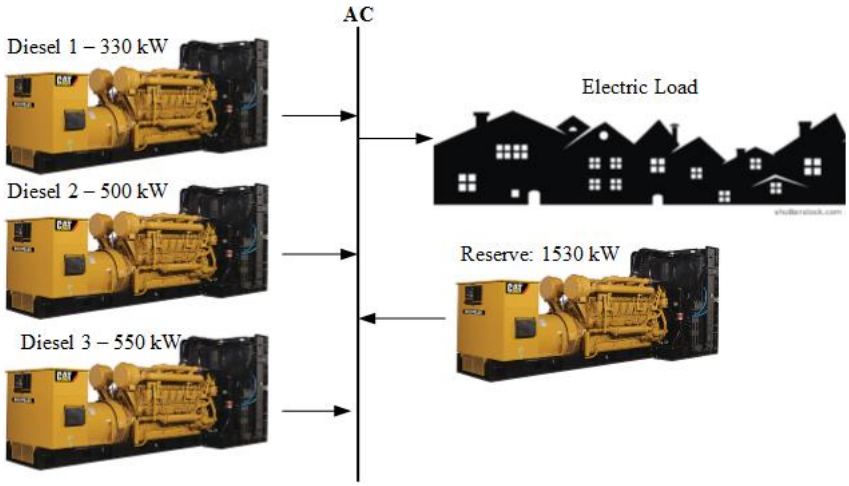


Figure 3: HOMER model for Sanikiluaq's Base Case.

Table 1: Main generators' characteristics at Sanikiluaq.

Generator	Capacity (kW)	Replacement value ($)	O&M ($/h)	Lifetime (h)
Diesel 1	330	239,910	7.19	35,339
Diesel 2	500	396,000	10.90	64,696
Diesel 3	550	398,520	11.19	100,000

The hourly load profile for Sanikiluaq community was calculated by averaging the hourly load over a year and was modeled in HOMER as a primary load, which means that the demand must be met at all times. The load is mainly residential, and the peak occurs between 14:00 and 19:00, as depicted in Figure 4. The main characteristics of the demand are presented in Table 2.

Table 2: Sanikiluaq demand parameters.

Metric	**Value**
Average (kWh/day)	9,921.40
Average (kW)	413.39
Peak (kW)	1,072.0
Load Factor	0.39

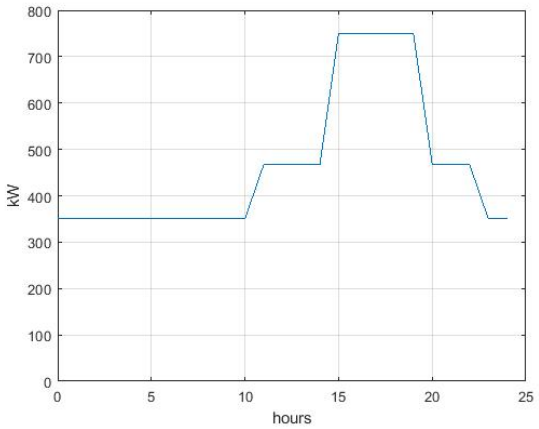


Figure 4: Sanikiluaq daily load profile.

In the following sections, various combinations of renewable and storage capacities are studied and compared with the base-case.

4.2 Hydrogen and Gas Generation Integration

In this section, the integration of hydrogen and gas generation along with RES for Sanikiluaq community is presented, based on the MG architecture depicted in Figure 5. Proposed HOMER MG model with hydrogen and natural gas generation. The main purpose of these studies is to investigate the suitability of hydrogen and gas generation in comparison to conventional diesel generators. In addition to the optimal results, guaranteeing the least cost scenario, other feasible solutions are presented to illustrate the impact of total replacement of diesel generators (Feasible 1) and higher integration of renewables (Feasible 2). Two case studies were considered with different types of storage capacities for the simulations. The main characteristics of the considered equipment for the planning of Sanikiluaq's MG are presented next.

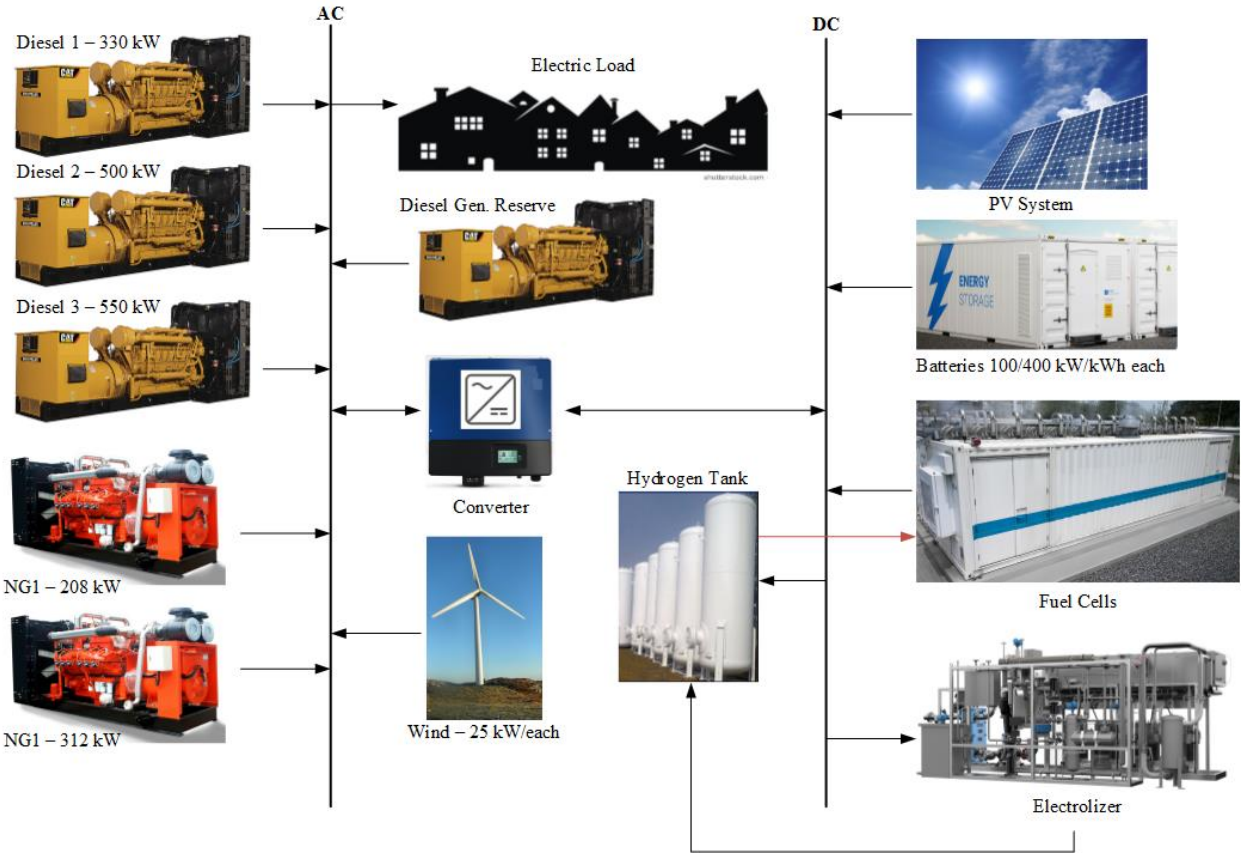


Figure 5. Proposed HOMER MG model with hydrogen and natural gas generation.

4.2.1 PV System

In order to study the integration of solar panels into the MG of study, sets of 0.39 kW photovoltaic (PV) panels connected to the dc side of the MG were considered. HOMER computes the output power of each PV panel as a direct function of the incident radiation, the cell temperature, and the derating factor, which is a scaling factor to account for effects of dust, wire loses, and any other aspect that would deviate the output of the PV array from its ideal value. The monthly average temperature and monthly average Global Horizontal Irradiance (GHI) data shown in Figure 6 were obtained from NASA's database at https://power.larc.nasa.gov. The operational parameters and costs associated with the panels are shown in Table 3.

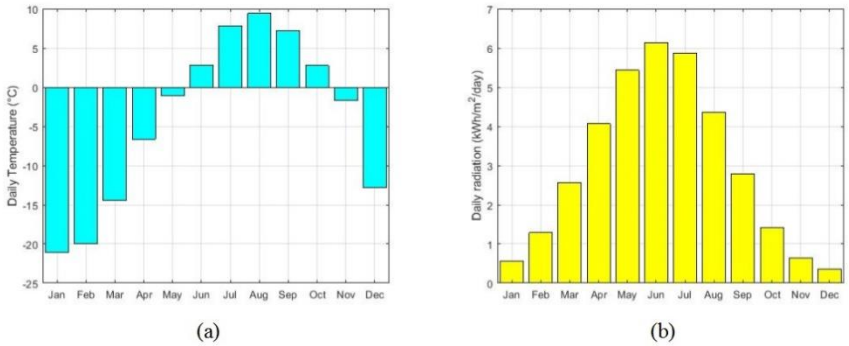


Figure 6. Sanikiluaq's (a) monthly average temperature and (b) monthly average solar GHI.

Table 3: Parameters and costs for solar PV panels at Sanikiluaq.

Cost ($/kW)	O&M ($/y)	Efficiency	Derating Factor	Operation Temperature	Lifetime
7,009.93	140.90	13%	85%	47.8°C	20 years

4.2.2 Converter

A generic solid-state converter was considered for the MG with a capital cost of $750, $22.50 O&M annual costs, 96% efficiency, and 10 years lifetime.

4.2.3 Wind Generator

The wind generators considered for this study have 25 kW of nominal capacity, and connected at the ac side of the MG. A wind turbine is modeled in HOMER as a device that converts kinetic energy of the wind into electricity according to a specific power curve, assuming a standard air density of 1.225 kg/m^3; thus, monthly average wind speed data was obtained from NASA's database. The economical and technical input parameters for the model in HOMER are presented in Table 4.

Table 4: Parameters and costs of wind generators.

Cost ($/u)	O&M ($/y)	Hub Height	Cut-in Speed	Cut-out Speed	Lifetime
178,069	5,342	23 m	2.75 m/s	20 m/s	20 years

4.2.4 Flow Batteries

A battery is modeled in HOMER as a storage device with a fixed round-trip energy efficiency that limits the rate of charge and discharge, the depth of discharge (DoD), and its lifetime. The batteries used in the MG model were all-iron flow batteries with 50 and 100 kW peak power, which can deliver up to 400 kWh. This type of storage offers cost-effective, safe, and environmentally friendly solutions due to the abundance of iron and its none-toxic nature. The parameters for the implemented flow battery model in HOMER are presented in Tables 5 and 6.

Table 5. Parameters and costs of 50 kW flow batteries.

Cost ($/u)	O&M ($/y)	SOC_o	SOC_{min}	Nominal Voltage	Nominal Current	Roundtrip Efficiency	Lifetime
370,936	7,418	50%	15%	500 V	120 A	78%	25 years

Table 6. Parameters and costs of 100 kW flow batteries.

Cost ($/u)	O&M ($/y)	SOC_o	SOC_{min}	Nominal Voltage	Nominal Current	Roundtrip Efficiency	Lifetime
372,873	7,457	50%	15%	500	240	78%	25 years

4.2.5 Natural Gas Generator

In this study, two types of natural gas generators (NG) were considered at the ac side of the MG, which were integrated in the planning problem to analyze the impact of this type of generation in remote communities. The price of the natural gas was assumed to be fixed at 0.3 $/m3 for all years. The economical and operational input parameters for the models in HOMER are presented in Table 7.

Table 7. Parameters and costs of NG generators.

Capacity	Cost ($/u)	O&M ($/h)	Minimum Load Ratio	Lifetime
208 kW	299,444	8.73	25%	40,000 h
312 kW	299,444	12.14	25%	40,000 h

4.2.6 Hydrogen System

Fuel cells are continuously operating batteries, which generate electricity from a fuel, such as hydrogen and an oxidant, such as air. To model a hydrogen system, an electrolyzer and a hydrogen tank need to be implemented, with the electrolyzer generating hydrogen through water electrolysis, which involves the consumption of electricity, while the tank storages this hydrogen at high pressure to be used later by the fuel cell. The costs and main characteristics of these elements are presented in Tables 8, 9, and 10.

Table 8. Parameters and costs of fuel cells.

Capacity	Cost ($/u)	O&M ($/h)	Lifetime
250 kW	168,581	2	50,000 h

Table 9. Parameters and costs of electrolyzer.

Capacity	Cost ($/u)	O&M ($/year)	Efficiency	Lifetime
330 kW	1,279,222	194	80%	15 years

Table 10. Parameters and costs of the hydrogen tank.

Capacity	Cost ($/u)	O&M ($/year)	Initial tank level	Lifetime
200 kg	249,745	12,400	10%	25 years

4.3 Results

In this section, the optimal and some feasible simulation results are compared with the Base Case, which contains only diesel generators. The obtained results show different combinations of renewables, storage, gas and fuel cells, for two case-studies, considering different storage capacities. The following is the criteria used to perform the study:

- The load was assumed to grow at 1.41%/year.
- The optimization module was used to obtain the optimal and feasible results by assuming 10% error from the predicted values of the model, such as demand and solar irradiation.
- An additional cost of $2.35 million with of 5%/year growth was added to the variable and capital cost of investment, since HOMER does not consider overhead costs such as salaries, travels, operations, office expenditures, etc., based on the overhead costs for Sanikiluaq from Qullik Energy Corporation's 2013-2014 annual report.
- The discount rate considered for the calculation of the LCOE was 8%.
- The overhead cost information for each community was allocated based on their unique usage in relation to the total consumption.
- The existing diesel generators were considered to last for two more years, and thus their book value at the end of the third year was considered.
- The minimum penetration of RES was considered to be 25% of the total generation.
- Generation reserves were assumed to be 10% for the load, 25% for solar PV generation, and 50% for wind generation.

- The project lifetime was 25 years.

4.3.1 Base Case

The optimal solution of the Base Case indicates the need for 241 kW of extra generator requirement in order to satisfy the N-1 security criterion. The resulting optimized system for the Base Case is shown in **Error! Reference source not found.** (see Das and Cañizares 2019).

Table 11: Base Case

Annual Energy Demand	**Peak Load**	**Diesel Generation**			**New Generator Requirements (kW)**
		Capacity	Engine Life	Remaining	N -1 Contingency
kWh	**kW**	**kW (Yr.)**	**h**	**h**	**HOMER**
9,921.47 kwh/day 3,631,373.00 kwh/year	1,072	330 500 550	100,000 100,000 100,000	35,990 69,696 100,000	241

4.3.2 Case 1

In this case, an optimal and two feasible solutions for the inclusion of fuel cells, hydrogen tank, electrolyzer, and natural gas generation were analyzed. The capacity of the flow battery was considered to be 50 kW/400 kWh. Table 12 presents the results obtained from HOMER for this case compared to the Base Case.

Table 12: Case 1 results for hydrogen and gas generation integration, with 50 kW/400 kWh flow batteries.

	Base Cse	**Optimal**	**Feasible 1**	**Feasible 2**
Gen. Cap. Removed	0	500 kW	1,380 kW	1,380 kW
Initial Capital	0	3.93 M$	9.55 M$	35.3 M$
NPV of O&M	28.35 M$	6.63 M$	5.32 M$	11.51 M$
Savings*	-	17.19 M$	13.48 M$	- 18.46 M$
Battery	-	1 unit	6 units	41 units
Solar PV	-	-	2.39 kW	513 kW
Wind	-	7 units	26 units	76 units
Diesel Generators	1380 kW	880 kW	-	-
Natural Gas Generators	-	704 kW	704 kW	-
Fuel Cells	-	500 kW	750 kW	500 kW
Electrolyzer	-	330 kW	330 kW	330 kW
Hydrogen Tank	-	100 kg	100 kg	200 kg
Converter	-	50.9 kW	324 kW	1433 kW
RE Penetration	-	25.5%	67.3%	100%
Emissions	2.42 tons/y	1.37 tons/y	0.58 tons/y	0 tons/y
LCOE	1.54 $/kWh	1.14 $/kWh	1.23 $/kWh	1.92 $/kWh

*With respect to the Base Case

Observe in Table 12 that in the optimal solution for Case 1 the solar generation does not appear as part of the generation portfolio, due to the low solar irradiation in this part of Canada. In addition, the mix of wind, flow batteries, diesel, fuel cells, and natural gas generators allows for the removal of 500 kW of diesel generation, which reduces emissions by over 43%. There is also a significant reduction of $17.2 million in

the expenses related to investments and O&M. Thus, the LCOE of the optimal configuration is about 26% less than that for the Base Case.

The cheapest configuration of energy sources, which does not include diesel generation is shown in Feasible 1. In this case, hydrogen and natural gas generators are integrated in the MG along with solar, wind, and batteries. This mix of resources allows the removal of all diesel generation, thus reducing emissions by 76%, due to the emissions from gas generation. However, there is a reduction in the savings, which are lower than the ones for the optimal solution, as it is a more expensive solution. The LCOE for this option is about 8% higher than the optimal solution.

The Feasible 2 solution corresponds to the highest feasible penetration of RES, with the total removal of diesel and natural gas generators. Such mix of generation makes it possible to remove all diesel generation, which brings the emissions down to 0, as there is no gas generation. However, this is an expensive solution with negative savings, i.e., higher costs than the Base Case, and results in a 68% LCOE increase with respect to the optimal solution.

4.3.3 Case 2

In this case, the flow battery capacity was increased to 100 kW/400 kWh. The results of the optimization model along with two feasible solutions are shown in Table 13.

Table 13: Case 2 results for hydrogen and gas generation integration, with 100 kW/400 kWh flow batteries.

	BASE	Optimal	Feasible 1	Feasible 2
Gen. Cap. Removed	0	500 kW	1380 kW	1380 kW
Initial Capital	0	3.95 M$	6.67 M$	35.4 M$
NPV of O&M	28.35 M$	6.27 M$	5.02 M$	11.52 M$
Savings*	-	18.13 M$	16.66 M$	- 18.57 M$
Battery	-	1 unit	3 units	41 units
Solar PV	-	-	0.255 kW	513 kW
Wind	-	7 units	17 units	76 units
Diesel Generators	1380 kW	880 kW	-	-
Natural Gas Generators	-	704 kW	704 kW	-
Fuel Cells	-	500 kW	500 kW	500 kW
Electrolyzer	-	330 kW	330 kW	330 kW
Hydrogen Tank	-	100 kg	100 kg	200 kg
Converter	-	86.9 kW	336 kW	1433 kW
RE Penetration	-	25.5%	53.5%	100%
Emissions	2.42 tons/y	1.36 tons/y	0.83 tons/y	0 tons/y
LCOE	1.54 $/kWh	1.14 $/kWh	1.17 $/kWh	1.92 $/kWh

*With respect to the Base Case

Comparing the results obtained from the two studied cases:

- Both optimal solutions are similar in terms of the investment necessary to install new DERs. However, in the Case 2, the O&M costs are lower, and therefore the savings are higher (5.46% higher than in Case 1).
- When comparing the Feasible 1 solution for both case studies, the savings in Case 2 are higher. This is reflected in a reduced investment in RES, increased emissions, and lower LCOE.
- The mix of generation in Feasible 1 for Case 2 could be potentially easier to implement and operate since there are less generation units, and therefore less physical space would be needed for its deployment.

- The Feasible 2 (zero emission) solution for both cases requires additional investment and operating funds of around 18.5 M$.
- From the results and analysis presented, it can be concluded that the best option for this community is the implementation of the Feasible 1 solution of Case 2, given the reduction in costs and emission with respect to the base case, and the broader energy mix with hydrogen and natural gas generation.

5 Conclusions

In this paper, several combinations of energy sources, including RES, flow batteries, hydrogen, and natural gas generation, for an MG in the remote community of Sanikiluaq in the Canadian Arctic were studied. HOMER was used to find the optimal mixture of energy sources and estimated cost parameters considering the limitations and characteristics of Canadian Arctic Communities. The obtained results demonstrate that a significant reduction and even elimination of diesel generation is possible for Canadian Arctic communities, with substantial RES penetration, large savings and smaller LCOEs, as well as a broad energy mix that includes flow batteries and wind, solar PV, hydrogen and natural gas generation.

6 For Further Reading

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