Renewable Energy Alternatives for Remote Communities in Northern Ontario, Canada

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***Abstract*—The paper investigates renewable energy alternatives to reduce diesel fuel dependency on electricity generation in Ontario´s remote northern communities; currently, these communities use diesel fuel as the sole energy source to produce electricity. The current operation is complex, involving several stakeholders, high operating costs, and a considerable CO_2 footprint. Several of these communities have electric load restrictions that limit further building construction and economic growth. This preliminary work discusses the barriers for Renewable Energy (RE) projects in northern Ontario communities by analyzing the current economic structure, the high capital costs, the available natural resources, and the installation and operation complexity. Also, a detailed analysis of six scenarios is presented; three scenarios consider a solar and/or wind-diesel system with a low RE penetration of 7% without any excess energy, whereas other three scenarios increase the RE penetration to 18%, requiring a dump load, an additional small diesel engine, or a battery storage system. The proposed systems reduce fuel consumption, operating costs and CO_2 emissions, considering the investment, operation and maintenance costs and constraints in remote regions.**

***Index Terms*—Microgrid, energy storage, hybrid power systems, remote community, diesel generators, solar energy, wind energy.**

I. Glossary

AANDC	Aboriginal Affairs and Northern Development Canada
CF	Capacity Factor
HAWT	Horizontal Axis Wind Turbine
HORCI	Hydro One Remote Communities Inc.
IRR	Internal Rate of Return
KLFN	Kasabonika Lake First Nation
LR	Load Restriction
O&M	Operation and Maintenance
PV	Photovoltaic
RE	Renewable Energy
RRRP	Rural or Remote Electricity Rate Protection
VAWT	Vertical Axis Wind Turbine
WT	Wind Turbine

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II. Introduction

Aboriginal Affairs and Northern Development Canada (AANDC) defines an off-grid community as "a permanent or long-term settlement that is not connected to the North American electric grid". In Canada, there are more than 175 off-grid communities that generate electricity using diesel-fuel generators as part of their energy mix [1]; 140 of these communities rely solely on diesel. Approximately 100,000 people live in these communities, where the average unsubsidized price for electricity is approximately $1.3/kWh, considering communities as far north as Nunavut. Ontario has a population of approximately 15,000 people distributed in more than 31 remote communities [2], where the electricity cost ranges from $0.4/kWh to $1.2/kWh. The operation and maintenance (O&M) of the electricity generation facilities involve logistical issues, generation constraints, carbon emissions, and strong dependency on fuel prices, apart from political and social issues, which contribute to the high operating costs of electricity generation in these remote locations. Fuel logistics are cumbersome and costly, since several of these communities can only be accessed by limited winter roads or year-round by air.

As electric demand increases, the installed generation capacity becomes a limiting factor that restricts electrical service growth and, hence, economic development [3]. The continuous rise of diesel-fuel price contributes significantly to the high direct operating cost and can be considered one of the main drivers to find technical and economic alternatives for electricity generation in remote locations. Diesel-fuel consumption has the inherent negative effect of CO_2 emissions during operation, as well as emissions incurred during fuel transportation and potential fuel leaks. Therefore, reducing diesel-fuel dependency is an important area for research and potential development in Canada's remote communities. In this context, recent efforts have been made to first apply energy efficiency measures in remote locations and then focus on testing the technical and economically viability of renewable energy (RE) integration [4]. While high-scale, on-grid RE projects have successfully been installed in Canada and, particularly, in the province of Ontario [5], off-grid RE projects have not been generally successful in Canadian remote northern communities [6]. Some of the barriers are the high capital and O&M costs, perceived technology maturity from the utilities point of view, high associated risks [7], and the absence of related incentive programs [5].

Previous projects have helped to understand the opportunities and difficulties of RE projects in remote communities in Canada, based on approximately three decades of RE project implementation throughout the country. In the 1980s, considerable research was done in Canada regarding wind turbines (WT) and their application in remote locations. Initial development focused on Vertical Axis Wind Turbines (VAWT), which were successfully installed in isolated meteorological stations in the Beaufort Sea and six other remote locations [8]. Further research resulted in the installation of a 4MW, 110-m VAWT prototype in the Gaspé Peninsula in Quebec [9]. In Ontario, two VAWT-diesel systems were tested in Toronto Island and in Sudbury [8]. Horizontal Axis Wind Turbines (HAWT) research started in the late 1980s which succeeded in deploying WTs to diesel-based microgrids in remote northern locations, such as the Atlantic Wind Test Site, P.E.I., Calvert Island, B.C., Cambridge Bay, Nunavut, and Fort Severn, Ont. The WTs' installed capacities for these test projects ranged from 2kW to 60kW [10].

In the 1990s, slightly larger HAWTs were installed in diesel-based microgrid remote communities, such as an 80kW WT project in Cambridge Bay, Nunavut, a 50kW WT project in Sachs Harbour, N.W.T., and a two 80kW WT project in Rankin Inlet, Nunavut. These projects had a mixture of planning, operation, and maintenance issues that limited their lifetime to only a few years; none of these projects are currently operational [11]. In addition, Photovoltaic (PV) systems have been installed in the Northwest Territories and Nunavut with positive outcomes (reliable operation and lower O&M costs); however, the installed capacity per project was limited to 5kW or less [12]-[14].

In the 2000s, several projects have continued to identify and solve some of the issues regarding RE remote deployment. Thus, a PV-Diesel mini-grid was installed in the Nemiah Valley, B.C. [15]; the system consists of a 27.36kW PV and two diesel engines (30-95kW) which have successfully reduced the fuel cost by 25%, but no reference to the project investment cost is mentioned. In Atlantic Canada, the wind-diesel system installed in the reasonably accessible Ramea Island has been a successful example of a system with 10%-13% wind penetration (6× 65kW wind turbines) [16]; the system is now being tested with hydrogen storage and further wind power (162kW electrolizer, 5×62.5kW hydrogen engines, 300kW wind turbines) to increase the RE penetration level with a capital investment of $9.7M [17], [18]. The government of Saskatchewan has recently announced funding for a wind-storage demonstration project considering an 800kW wind turbine and a 1,000kWh lithium-ion battery bank for a community close to the province capital [19]. Hydro One has also installed three 10kW WTs at the Kasabonika Lake First Nation (KLFN) community as an initial step to understand the deployment of RE technologies in Ontario's remote communities [20], and an additional 30kW Wenvor WT and wind measurement equipment is being currently deployed.

TABLE I
ELECTRIC ENERGY SUPPLY STATUS FOR ONTARIO REMOTE COMMUNITIES [2]-[6]-[26]-[27].

Community	# People	Fuel (lt/year) × 10^6	Energy Output (GWh/ year)	CO_2 Emissions × 10^3	Loading levels[a] (2010)
Hydro One Operated Communities					
Bearskin Lake	499	0.76	2.73	2.2	50-60%
Deer Lake	800	0.80	3.8	2.3	N/A
Fort Severn	449	0.79	2.65	2.3	75%
Gull Bay	452	0.32	1.09	0.9	70-75%
Kasabonika L.	862	1.01	3.63	2.9	90%
Kingfisher Lake	313	0.58	1.90	1.7	82%
Kitchenuhm…	883	1.51	5.55	4.3	78%
Landsdowne H.	300	0.62	2.06	1.8	N/A
N. CaribouLake	702	1.17	4.22	3.3	77%
Sachigo Lake	460	0.82	2.86	2.4	65%
Sandy Lake	2,111	2.95	10.77	8.5	70%
Wapekeka	341	0.68	2.13	1.9	75%
Webequie	622	0.77	2.74	2.2	75%[b]
Others	800	1.22	4.20	3.3	-
Subtotal	9,594	14.01	50.33	40.0	
Community-based Operated Communities					
Eabametoong	1,140	1.73	6.17	4.98	-
Kee-Way-Win	320	0.66	2.36	1.91	-
Muskrat Dam L.	255	0.39	1.38	1.11	-
Neskantaga F.N.	265	0.53	1.90	1.53	-
North Spirit Lake	255	0.49	1.74	1.41	-
Peawanuck	139	0.34	1.23	0.99	-
Pikangikum	2,443	3.71	13.22	10.66	-
Wawakapewin	47	0.06	0.22	0.18	-
Weenusk	225	0.34	1.22	0.98	-
Wunnumin	490	0.59	2.09	1.69	-
Subtotal	5,579	8.86	31.54	25.43	
Total	15,173	22.87	81.87	65.43	

[a] Percentage of installed capacity.
[b] On-going projects to increase installed capacity.

Going forward, there is considerable interest in continuing the efforts to deploy RE in remote locations. In North West Territories, detailed pre-feasibility assessments have been done for Tuktoyaktuk, as well as projects to measure the wind resource in six remote communities and correlate the results to the on-site airport wind data [21], [22]. In the Yukon, there is an on-going effort to model the wind resource in rough terrains [23].

Alaska has been leading the wind-diesel development in remote northern communities. By 2009, Alaska had a total wind installed capacity of 13MW distributed in 21 wind projects. The average wind installation cost for the systems is estimated at $10,200/kW, with diverse RE penetration levels [24]. However, the full impact of such projects performance and economics is not yet fully understood, and has yet to reach a mature and commercial level [25].

This paper contributes to the effort of promoting RE in remote northern communities by taking the current electricity cost model to:

- Analyze wind and solar capacity factors in 22 northern Ontario communities.
- A tailored wind, solar, and battery installation costs in a remote community, which can be scaled to other isolated

communities.

- Present optimal and economically feasible scenarios for low and medium RE penetration scenarios at an actual community (KLFN).

The rest of the paper is organized as follows: Section III summarizes the electricity demand for Ontario's northern communities, electricity supply organizational structure and associated costs. Section IV analyzes the RE potential in northern Ontario communities, highlighting the most viable RE alternatives. Section V focuses on the KLFN community, analyzing the potential costs of RE alternatives and discussing six possible RE integration scenarios at different RE penetration levels. Finally, Section VI concludes the paper by highlighting the most feasible alternatives and future related work for the promotion of RE in northern Ontario.

III. Northern Ontario Remote Microgrids

Ontario has more than 31 remote communities where off-grid diesel-based microgrids supply electricity to the population; 21 of them are operated by the provincial utility, Hydro One, and 10+ communities are operated by community-based utilities [2], [6], [26], [27]. Table I shows a summary of the energy status of the communities where electricity generation, fuel consumption, and CO_2 emission data were available at the time of this study.

In 2008, the communities' electricity demand per capita (5,395kWh/year/person) was 70% lower than Canada´s national average (17,061kWh/year/person); similarly, the CO_2 emissions were 73% lower than the national average [28]. The lower electricity demand is in part a consequence of the cap set by the limited installed capacity. Currently, some of these communities are about to reach their limit [29], due to the increasing demand and lack of capital funds for expansions [3]. If the peak demand reaches 75% of the generation capacity, the community falls into a Load Restriction (LR) status [29]; as the name suggests, this requires the community to hold off any building construction or economic growth projects that would increase the electrical load. The load levels with reference to installed capacity were solely available for Hydro One operated communities, where six of them have already reached the 75% limit and are thus in LR. Nearly half of these communities are already considering new alternatives or expansion projects to maintain a reliable source of electricity without drastic restrictions; some of them are mostly considering diesel generators to increase their electrical capacity. Hence, it is important to examine RE alternatives that can partially overcome the current electrical restrictions, reduce carbon emissions and O&M costs.

A. *Electricity Model Structure and Cost*

1) *Electricity Generation Stakeholders*

The electricity cost model for the remote communities in Ontario involves four stakeholders: the provincial government, the utility (mostly Hydro One), the local fuel supplier, and the customers. The government of Ontario, through the Ontario Energy Board, sets regulations for

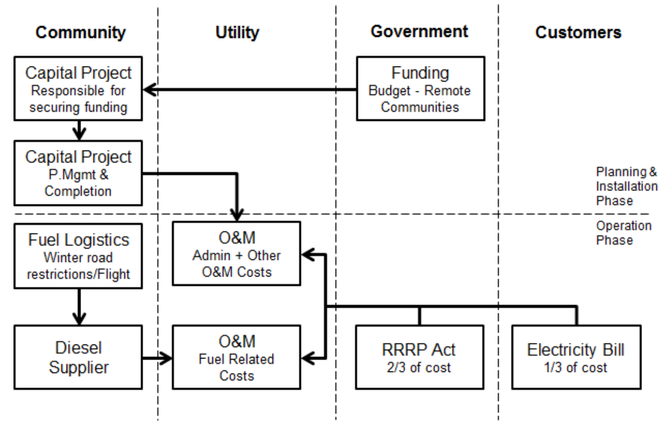

Fig. 1. Stakeholders´cash flow from electric generation activities.

supplying service to these communities, which includes the baseline for the electrical subsidy under the Rural or Remote Electricity Rate Protection (RRRP) [30]; province wide, utilities charge 0.13 cts/kWh as the RRRP subsidy [31]. Hydro One Remote Communities Inc. (HORCI) is a non-for-profit Crown Corporation that has the government mandate of supplying electricity to remote communities, and it is responsible for the O&M of the diesel generators. Most HORCI purchases the diesel fuel from the community, which represents an income for the community. Customers that do not receive direct or indirect funding at these communities pay a subsidized electricity price approximately equal to what Ontario's on-grid customers pay [26]. Figure 1 summarizes the stakeholders' participation in the electricity generation activities, showing that capital projects are typically the responsibility of the community, with the required funds coming from the federal government.

The O&M, from the utility point of view, is a zero-sum process. In 2008, HORCI estimated an annual expense of \$45.2M, of which \$15.1M was recovered through customers, and the remaining \$30.1M was paid from the RRRP budget [32]. In the current business model, the utility and the community have low or non-existent incentives to reduce operating expenses.

2) *Current Operation and Maintenance Costs*

For HORCI operated communities, the electricity cost can be estimated using Table I and the utility's annual budget forecast. Thus, the total electricity demand for all HORCI operated communities is estimated at 57 GWh/year, which is 15% larger than the 2004 values. Since HORCI's 2008 annual expense was \$45M, an estimated O&M average electricity cost of \$0.80/kWh can be obtained; however, the community's remoteness influences the electricity cost significantly. The O&M cost can be estimated using the total fuel consumption, HORCI's expenses, current fuel prices [33], and assuming a linear relationship between latitude and diesel-fuel price. For example, Gull Bay is 183km from Thunder Bay with all-year road access; hence, considering the current diesel retail pump price at Thunder Bay, the O&M electricity costs can be estimated to be \$0.4/kWh. In contrast, Fort Severn is 850km north of Thunder Bay with limited accessibility due to its remote location, resulting in an estimated O&M electricity cost of $1.2/kWh.

In Ontario, diesel fuel prices continue to rise considerably, directly increasing the electricity cost for northern communities. In 2011, the annual average cost of diesel fuel for Northern Ontario was $1.24/litre [33], i.e., 24% higher than the 2010 average and 74% higher than that in 2001. With the current fuel price trend, the average cost of electricity in these remote communities could increase to $1.12/kWh (40% increase) in the next 10 years. Hence, for example, Gull Bay's and Fort Severn's electricity costs could conservatively rise to $0.56/kWh and $1.68/kWh, respectively, in a 10 year period.

B. CO_2 Emissions and Environmental Issues

CO_2 emissions are an inherent disadvantage of supplying electricity using diesel generators. The electrical generation in the 21 Hydro One-operated communities accounts for 40,000 tons of CO_2 equivalent emission annually [27]. This value is equivalent to the annual emissions of approximately 8,000 passenger vehicles.

Fuel transportation and storage is also considered an environmental hazard. Potential leaks and spills during transportation and storage could be reduced if less fuel is required for electricity generation when RE technologies are added to the electricity generation mix.

C. RE-based Microgrid Operational Issues

Installation of RE equipment in northern remote locations has inherent technical operational challenges that are related to equipment and/or RE-penetration levels. For equipment, its performance and reliability depend on various issues, such as, for diesel generators low-load conditions, lower efficiency, and premature wear. Diesel generators in northern remote locations are usually oversized due to the large difference between average and peak load, and as a result, generators usually run at partial load resulting in lower efficiency rates; most remote northern communities have installed different rated generator capacities to partially overcome low-load issues [10], [16]. Furthermore, the generator's efficiency is likely to be further reduced when RE equipment is integrated into the microgrid due to the negative load that RE generation implies. RE integration would likely keep diesel generators running longer at partial load conditions, which will result in carbon build up in cylinder heads and pistons, that can be potentially overcome by succeeding periods of full-load runtime [34], [35]. In addition, integration of an intermittent RE source would result in heavy, pulsating loads that can potentially cause surface fatigue and eventually cracks in the engine bearings [35].

As RE-penetration levels increase the requirement for further and more advanced equipment also increases to ensure the stable operation of RE-diesel-microgrids. An Energy Management System would be required to efficiently control the different energy sources [16], [36]. Also, quick diesel engine governors are required to compensate for wind fluctuations to avoid affecting grid frequency [22]. Synchronous condenser(s) might be required to maintain voltage stability in the system; this could be accomplished using one of the existing generators at no load [10], [22]. There is also the need for dump loads to handle excess RE, and thus avoid frequency stability problems [10]. Finally, high RE-penetration levels, diesel plants could potentially be turned off for certain time period; hence, in cold climates a diesel plant heating system is needed to assure that the engines can start-up again quickly [10].

IV. Mathematical Model

On-site wind and solar information is scarce in remote communities; hence, these resources are estimated here using existing mesoscale resources. For this study, 22 remote communities were identified in the province of Ontario; 13 operated by HORCI and 9 operated by community owned utilities. In addition, the mathematical generation model used in this work for the different system scenarios are those available in the distributed generation optimization package used, i.e. HOMER [37], where only a simple power balance equation is assumed, with no representation of the grid. A detailed description of these models can be found in [37], [38]. The model inputs are the community load demand, the estimated energy resources, and the RE equipment described in this work. Then, the software optimizes the dispatch strategy that will yield the minimum project cost for each configuration. Finally, the optimal solution for each scenario is found by computing the Internal Rate of Return (IRR) for all configurations in the search space and selecting the configuration with the highest IRR. The next sections describe in detail the modeling of the wind and solar resources, and the dispatch strategies of diesel generators and batteries that are directly relevant to the remote microgrids considered in this paper.

A. Wind and Solar Resources

On-site 10-min average data for at least a year is required to properly assess the wind profile in any given location and determine the optimal on-site location for WT(s) [39]. However, the authors are not aware of available raw wind data for any of the considered remote communities. The installation of proper measuring equipment at different heights is desirable, and should be considered as an essential part of any future northern wind project; indeed, this is the case for the 30kW Wind Turbine (WT) being installed at KLFN. Detailed wind data is of special interest for small wind projects, as the local terrain can considerably change the wind regime [40]. Since no detailed data is available, average wind speed information obtained from the Canadian National Wind Atlas is used here [41].

On-site solar data is similarly not available for the communities considered; however, a solar irradiation estimate can be obtained from [42]. Due to similar latitudes of the sites, the solar resource is fairly constant across the province, with solar irradiation in the communities varying from 3.12 to 3.49 kWh/m^2/day. Hence, a solar project in one community could be considered a reference to be replicated in other communities with comparable expected energy output. Yet, on-site solar measurement equipment should be considered as part of a deployment project to reduce solar resource uncertainty, and determine the optimal on-site location of PV panels.

The wind resource varies considerably based on the location, while the solar resource stays fairly constant for the studied northern communities. An objective high-level comparison of the suitable approaches for individual communities can be performed by comparing capacity factors (CF) for both technologies at each site.

The wind CF calculation depends on the selected WT; the power curve of an Endurance E-3120 50 kW wind turbine is used here due to its low cut-in speed of 3.5 m/s, and rated power at 9.5 m/s [43]. The wind CF formula used in this study is:

$$CF_{WT_i} = \frac{\sum_{j=1}^{ws_{cut\_off}} \left(\left(WD\left(ws_{i,j}, A_i, k_i\right) - WD\left(ws_{i,j-1}, A_i, k_i\right) \right) PC\left(ws_j\right) \right)}{\frac{(1-df)}{P_{WT}}} \quad (1)$$

where WD is the Weibull distribution value at a specific wind speed (ws); A and k are the scale and shape factors, respectively, for community i; PC is the power curve value at ws_i; df is the WT de-rating factor (df = 10%); P_{WT} is the nominal WT power (P_{WT} = 50kW); and ws_{cut_off} is the WT cut-off wind speed. On the other hand, the solar CF is calculated considering the monthly irradiation at each site as follows:

$$CF_{PV_i} = \frac{\sum_{n=1}^{12} G_{i_n} \cdot PR}{8760} \quad (2)$$

where G_i represents the monthly solar irradiation for community i, and PR is the performance ratio for a PV array (0.85) [44].

Figure 2 shows that the wind CF is higher for all analyzed communities due to the previously mentioned characteristics of the wind turbine (low cut-in speed and rated power at a low wind speed). Hence, even for communities with annual average wind speeds of as low as 4.5 m/s, the wind resource will have a higher energy output than solar. However, as it is further discuss in the next section, solar technologies in remote northern locations should still be considered an alternative due to its installation simplicity, and lower capital and O&M costs, which are important issues to consider during the decision making process.

B. Diesel and Battery Dispatch Strategy

The current dispatch strategy for the considered microgrids with multiple diesel generators is simple, reliable, and robust since these are run only one diesel generator at a time, with the exception of a few minutes of overlap. For example, the engine switching strategy for a three-diesel engine microgrid can be defined as:

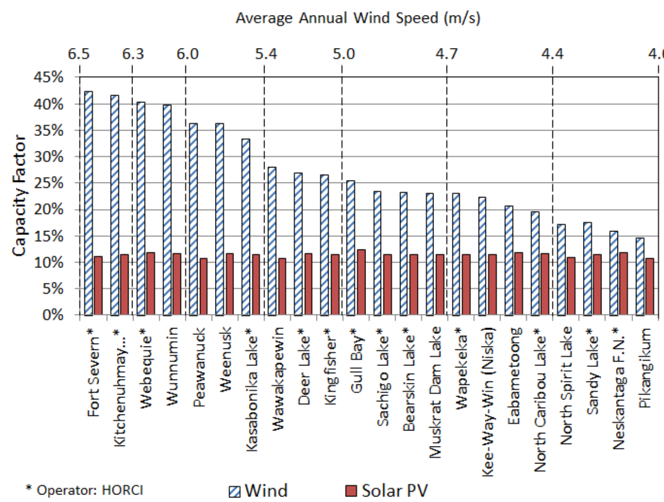

Fig. 2. Wind and solar capacity factors for Ontario's remote communities.

$$UC_{Gen} = \begin{cases} [1\ 0\ 0]\ if\ \left(\alpha_{LL} P_{Gen_1} < P_D < \alpha_{UL} P_{Gen_1}\right) \& \left(UC_{Gen_2} = 1\right) \\ [0\ 1\ 0]\ if\ \left(\alpha_{LL} P_{Gen_2} < P_D < \alpha_{UL} P_{Gen_2}\right) \& \left(UC_{Gen_3} = 1\right) \\ [0\ 1\ 0]\ if\ \left(\beta_{LL} P_{Gen_2} < P_D < \beta_{UL} P_{Gen_2}\right) \& \left(UC_{Gen_1} = 1\right) \\ [0\ 0\ 1]\ if\ \left(\beta_{LL} P_{Gen_3} < P_D < \beta_{UL} P_{Gen_3}\right) \& \left(UC_{Gen_2} = 1\right) \end{cases} \quad (3)$$

where UC_{Gen_i} is the unit commitment binary variable for the diesel generator i; P_D is the load demand; P_{Gen_i} is the rated power for the diesel generator i, with P_{Gen_1}<P_{Gen_2}<P_{Gen_3}; α_{LL} and α_{UL} are the reduced partial-load ratios' lower and upper limits, respectively; and β_{LL} and β_{UL} are the increased partial-load ratios' lower and upper limits, respectively. If a low RE penetration scheme is implemented, the dispatch strategy will not probably be affected, since the RE contribution will only be seen by the system as a negative load.

As the RE-penetration level increases, the requirement for energy storage can be seen as a feasible alternative that needs to be managed simultaneously with the diesel engines. The critical load for cycle charging (L_C) corresponds to the load value where the cost of energy generation with the diesel engine is equal to the cost of supplying the load with the battery bank, and can be defined as [38]:

$$L_C = \frac{F_0 C_f}{C_{bw} + C_f F_i \left(\frac{1}{\eta_{RT}} - 1 \right)} \quad (4)$$

where F_0 is the diesel engine fuel consumption at no load (lt/hr), C_f is the diesel fuel cost ($/lt), C_{bw} is the cost of battery wear ($/kWh), F_i is the incremental fuel consumption rate (lt/kWh), and η_{RT} is the roundtrip storage efficiency. If P_D<L_C, the RE and/or diesel generators will supply the load and charge the battery bank in which the objective is to maximize the IRR.

V. RE Alternatives for KLFN

A. The Community

KLFN, with a population of 914 people, and located at 53°N

49' and 88°W 40', is a remote northern community approximately 500km north of Thunder Bay. The community can be accessed all-year by plane or via winter roads, subjected to weight restrictions depending on ice-thickness conditions, which in recent years have frequently resulted in reduced loads of 18 ton from the original 36 ton. In 2006, the total KLFN energy requirement was 13.7GWh/year: 26% electricity, 36% wood, 18% heating fuel oil, 2% diesel (transportation), and 18% gasoline [45]. An estimated 66% of the total energy is used for space and water heating.

From the electricity perspective, KLFN has currently three installed diesel generator units, rated at 400kW, 600kW, and 1MW to supply the electric loads of the community. In 2007, the total electricity demand was 12MWh/day (4.4GWh/year), with a power peak of 850kW [46]. The diesel generator plant consumes an estimated 1.2M litres/year, equivalent to 3,600 ton equivalent CO_2/year.

The KLFN community is the sole supplier of diesel fuel for the operation of the diesel generator plant operated by HORCI; hence, this operation represents an important source of income for the community. The preferential diesel-fuel price is $1.8/litre [47], and the O&M cost is estimated at $3.7M/year ($1.9M fuel, $1M direct O&M, and $0.7M indirect/administration costs). Therefore, considering an annual electric demand of 4.4GWh/year, the annual O&M cost can be estimated to be $0.84/kWh.

Besides the high electricity cost, KLFN has further electricity related issues that affect its economic and social development. Thus, KLFN has reached 90% of its electrical capacity and it is currently under LRs. The community has already purchased, with federal funds, a 1.2 MW diesel generator but has no further capital funds for the next five years for its installation [3]. Hence, energy alternatives to partially alleviate the current LR situation are a priority for KLFN.

B. RE Equipment Characteristics and Costs

Off-grid RE projects are more sensitive to cost variations than on-grid projects due to the unique nature of most projects, which results on less standardize design processes and special deployment conditions. The cost analysis, presented next, for the installation of RE equipment (wind, solar, and battery bank) at KLFN results in a 2 – 2.5 times price increase compared to a similar on-grid installation. Here, the installation costs are classified in equipment, installation, project management, crane operation (if applicable) and contingency.

The wind energy conversion system used for this study is the Endurance E-3120 50 kW considered in the previous section. The wind turbine (WT) installation cost per kW varies significantly with the rated nominal power. As a reference, the IEA reports an average installed cost of $1,960/kW for 2MW WT in Canada [48]; however, for the 50 kW small wind turbine considered, the cost for the turbine itself is approximately $7,289/kW [49]. The WT installation and project management cost are estimated considering the

TABLE II
ESTIMATED INSTALLATION COSTS OF RE EQUIPMENT AT KLFN

Capital Expense	Small Wind Turbine		Solar Photovoltaic		Battery Bank	
	($/kW)	%	($/kW)	%	($/kWh)	%
Equipment	7,289	54	3,700	44	348	54
Installation	1,709	13	1,840	22	48	7
P.Mgmt.	605	5	600	7	-	0[a]
Logistics	639	5	653	8	134	21
Crane Op.	640	5	-	0	-	0
Spare parts	900	7	554	7	40	6
Contingency	1,632	12	1,019	12	80	12
Total	13,414	100	8,365	100	650	100
	($/kW/year)	%	($/kW/year)	%	($/kWh/year)	%
O&M Cost[b]	335	2.5	42	0.5	13	2.0

[a] P.mgmt. cost assumed to be included in the PV and/or wind project.
[b] Percentage of capital expense.

IEA cost breakdown presented in [48], where 76% is the WT cost, 18% installation, and 6% are project management costs. Hence, if the WT projects were located in an easily accessible site, the total installation cost would be approximately $9,600/kW. However, due to the site remoteness, additional costs need to be considered such as remote equipment transportation, remote crane operation, site available spare parts, and contingency. The remote transportation cost estimate, from Dryden to KLFN, is based on an equipment quote provided by KLFN in which the cost is approximately $4.65/kg ($639/kW). The remote crane operation is based on a quote from a company based in Dryden, ON, considering $1,600/day and 10 days for the installation process ($640/kW). Spare parts are considered to be 10% of the equipment and installation cost ($900/kW). Finally, the contingency cost is estimated to be 15%, due to the uncertainty level of the operation ($1,632/kW). Hence, the total turnkey cost estimate for a WT installation at KLFN is $13,414/kW.

Photovoltaic (PV) panels have a lower installation cost per kW when compared to small wind turbines. As a reference, the estimated equipment cost is $3,700/kW; which accounts for the panels, converter, and connection equipment [50], and considering the current trend of price decrease of PV panels [51]. The installation cost is calculated using the KLFN service rates set at $50/hr certified electrician and $37.5/hr electrician in-training ($1,840/kW). The estimated project management cost was estimated to be equal to the WT installation ($600/kW). Remote transportation costs are estimated at $3.50/kg, which is 75% of the wind turbine rate due to the PV panels modularity ($653/kW). Spare parts ($554/kW) and contingency (1,019/kW) are estimated similarly as for the WT installation. As a result, the expected turnkey cost estimate for a PV installation at KLFN is $8,365/kW.

The battery used in this study is the Rolls/Surrette (4KSS21P), 4V, 1,104Ah, and 4.42kWh [52]. The battery equipment cost is estimated from a RE seller at $157/kWh for the battery, and $190/kWh for the bi-directional inverter, building requirements, and connections. The installation cost is estimated using the same KLFN service rates for two people and a rental truck ($48/kWh). The project management costs are waived since this would be included in the PV or WT installation. The transportation costs are calculated at $3.50/kg; the same as the PV installation ($134/kWh). Spare parts ($40/kWh) and contingency (80/kWh) are estimated similarly as for the WT installation. As a result, the expected turnkey cost estimate for a battery installation at KLFN is $650/kWh.

Table II summarizes the costs of the wind, solar, and battery bank systems per installed capacity. The table can be used as a reference for this and future similar remote sites. As previously mentioned, the cost is site-dependent; hence, a factor can be added to account for the transportation and installation cost change based on its remoteness and service rates. Of the two RE technologies, solar PV has a lowest overall cost and no need for crane transportation, which, as discussed in the next section, may compensate for its lower CF, under certain conditions.

C. Renewable Energy Scenarios

The wind and solar CFs at KLFN are estimated to be 33% and 12%, respectively. The wind CF could likely be lower due to the lack of on-site wind data; regardless, the WT can be considered to have a significant energy output advantage over the solar resource. In contrast, the solar technology has a lower installation and O&M costs than can potentially compensate for the investment. Thus, the following six scenarios analyze the deployment of both technologies at KLFN: the first set of scenarios (wind, solar, and wind & solar technologies) considers 7% to 9% RE penetration levels that do not require any advance control systems, whereas the second set increases the RE penetration to 18%, requiring additional energy management considerations. Furthermore, the latter set of scenarios is analyzed considering first only the WT equipment, then WTs with a battery storage system, and finally WTs with an additional 250kW diesel engine. These scenarios are studied using the above estimated costs, and simulated using HOMER, following the above described dispatch strategy [37]. The objective of the simulation is to find for each scenario the optimal equipment configuration that maximizes the IRR of the RE-based systems while maintaining the RE penetration level required. The additional project parameters used are: a discount rate of 8%, a project lifetime of 15 years, and an electric load of 12 MWh/day. The objective of both scenarios is to analyze the expected installation, O&M costs, and financial feasibility of RE systems considering the remoteness of KLFN.

1) Low Penetration Wind-Diesel System

The objective of the first set of scenarios is to obtain the optimal equipment configuration that maximizes the IRR considering a low-RE-penetration system in which the diesel engines are in continuous operation, and at a given instant, the RE contribution would be no higher than 50% of the total load. Scenario A considers wind energy, Scenario B analyzes solar energy, and Scenario C studies a wind & solar hybrid system. The RE components aim to reduce the diesel

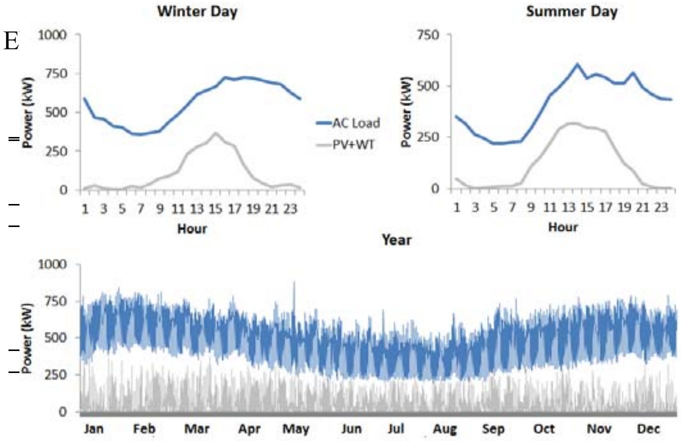

Fig. 3. Annual/Daily power load and RE contribution – Low Penetration

Wind Energy	M$	-	1.34	-	0.67	3.35	3.35	3.35
Storage	M$	-	-	-	-	-	-	0.18
Diesel Engine	M$	-	-	-	-	-	0.75	-
Total	M$	-	1.34	2.09	2.34	3.35	4.10	3.53
Annual O&M Costs								
O&M Cost	M$	3.68	3.55	3.48	3.46	3.38	3.35	3.35
Reduction[a]	M$	-	0.13	0.20	0.22	0.31	0.34	0.33
Financial Indicators								
NPV	M$	-	-0.11	-0.19	-0.20	-0.44	-0.87	-0.79
IRR	%	-	6.5%	6.3%	6.4%	5.6%	4.0%	3.7%

[a]Compared to Baseline

Scenario A considers a WT rating search space from 0 to 250kW of WT installed capacity, considering the operation of only one diesel engine at a time. The resulting RE system with the lowest O&M costs for the given constraints consists of two 50kW WTs (100kW). The annual RE contribution can be estimated at 7%, with a capital cost of M$1.34, and savings of M$0.13/year, which results in an expected IRR of 6.5%.

Scenario B considers a PV rating search space from 0 to 500kW$_p$ of PV installed capacity, considering the operation of only one diesel engine at a time. The resulting RE system with the lowest O&M costs for the given constraints consists of 250kW$_p$ of solar PV. The annual RE contribution can be estimated at 7%, with a capital cost of M$2.09, and savings of M$0.20/year, which results in an expected IRR of 6.3%. Notice that the RE penetration and IRR are similar for Scenario A and B; however, the initial investment is 56% higher for the PV installation, since it requires more installed capacity to deliver the same RE penetration level.

Scenario C combines both RE technologies considering the previous rating search spaces for WT and PV to analyze a hybrid system. The minimum O&M cost system consists of one WT (50kW) and 200 kW$_p$ of solar PV. The annual RE contribution can be estimated at 9%, with a capital cost of M$2.34, and savings of M$0.22/year, which results in an expected IRR of 6.4%. Scenario C has the highest RE

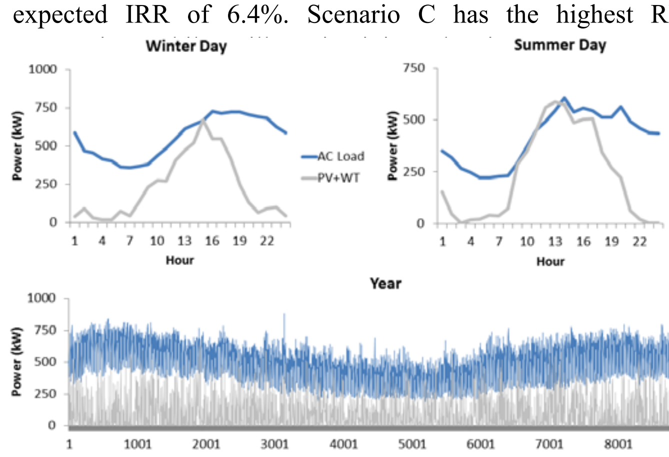

Fig. 4. Annual/Daily power load and RE contribution – Medium Penetration

2) Medium Penetration Wind-Diesel Systems

The objective of the second set of scenarios is to obtain the optimal equipment configuration that maximizes the IRR considering a medium-RE-penetration system where wind energy contributes to a higher extent to the energy mix. This system would require a more advanced control system to deal with the RE uncertainty and a dispatch strategy for the WT-Diesel operation [24]. This section presents three configuration setups to deal with the higher penetration wind energy installation. Scenario D considers a dump load solution that handles the wind excess energy. Storage alternatives are analyzed to minimize the use of the dump load. Thus, Scenario E considers the installation of a small diesel engine to supply the smaller energy gap between the load and the generated wind energy; this small diesel engine serves the purpose of operating at higher efficiencies under high RE penetration levels and low load conditions. Scenario F considers the addition of a battery bank to manage the excess energy. The RE sizing criteria is based on maintaining an average and instantaneous RE penetration of less than 20% and approximately 100%, respectively [24], as shown in Fig. 4.

For Scenario D, the WT rating search space is from 0 to 500kW of installed capacity, considering the operation of only one diesel engine at a time. The resulting RE system with the lowest O&M costs for the given constraints is the installation of five 50kW WTs (250kW). The annual RE contribution is estimated at 18%, with a capital cost of M$3.35 and savings of M$0.31/year, which results in an expected IRR of 5.6%, which is lower than the low penetration case (7%). Hence, the following Scenarios E and F were considered to analyze if the extra capacity and storage can be used to improve the financial output of the project.

Scenario E sets the WT capacity at 250kW and considers a small diesel engine in the 50–300 kW range, so as to avoid running higher capacity engines at a low efficiency, thus increasing dispatch flexibility for periods with low load. The diesel engine installation cost is calculated following the same methodology as the RE equipment, resulting in an installation cost of $2,400/kW. The simulation yields an optimal size of the new diesel engine of 250kW, considering a total capital expense (WT + diesel engine) of M$4.10 and savings of M$0.34/year, which results in an IRR of 4.0%, which is lower still lower than the low-RE-penetration Scenarios and Scenario D.

Scenario F keeps the WT capacity at 250kW and considers a battery bank in the 27–137 kWh range of usable nominal capacity, which represents 50% of installed capacity. The minimum O&M cost is attained with a battery bank of 54.8kWh nominal capacity (27 kWh usable capacity). The expected capital cost is M$3.53, with savings of M$0.33/year, which results in an expected IRR of 3.7%, which is the lowest value of all presented scenarios.

D. Discussion

The results from the analysis of the baseline, low-RE-penetration and medium-RE-penetration scenarios are summarized in Table III. The first section of the table presents the main characteristics of the systems considered, including the RE installed capacity selected and considering the three-diesel-generator system as the baseline. The second section in the table presents the estimated annual fuel consumption savings and expected CO_2 emission reductions. The third section summarizes the capital and O&M costs. Observe that the IRR of the low-RE-penetration scenarios are higher than the medium level scenarios, which is a result of the excess energy that does not further reduce operation cost (Scenario D), and the high installation costs of batteries and the small diesel engine that reduce operation cost but not enough to justify the additional investment (Scenario E and F).

VI. CONCLUSIONS

This paper discussed the current electric energy issues in remote communities considering the available RE technologies for such locations. A customized RE cost reference was also presented to evaluate RE projects in remote locations with limited access. It was shown that the RE installation cost can be as high as 2.5 times of an equivalent on-grid system. Six case studies were presented, analyzing the economic wind and solar feasibility of three low-RE-penetration scenarios (7%– 9%) and three medium-RE-penetration scenarios (18%). The wind and solar low-RE-penetration alternatives result in similar return on investment (6%). The wind has the main advantage of reaching higher RE penetration levels with a lower capital investment, while the solar installation requires approximately a 50% higher investment, but due to the low O&M costs, the expected financial results are comparable. The wind medium-RE-penetration scenarios presented have a lower return on investment due to diesel-engines operating at lower efficiencies and wind excess energy that do not further reduce operation cost. The addition of a battery bank or a small diesel engine partially alleviates these issues; however, the extra capital investment does not show a positive economic effect.

The high installation costs of the RE technologies in remote communities are still one of the major barriers to the commercial development of such projects. However, even with the current overall costs, remote RE projects are close to breaking-even under certain conditions, and as diesel fuel costs rise, the potential to reduce the O&M costs as well as the related CO_2 emissions may make these projects economically feasible in the medium-term. More efficient alternatives to deal with the excess energy, as well as understanding the incentives, revenue structure, and social impacts of such projects in remote communities need to be considered.

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