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Optimizing an off-grid electrical system in Brochet, Manitoba, Canada

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ABSTRACT

Brochet is a remote, off-grid community located in Northern Manitoba, Canada. The existing diesel generating system is characterized by high economic and environmental cost. As the existing diesel generators are nearing their operational lifespan, this study uses the HOMER model to determine an optimum electricity system design at Brochet that has high electrical reliability, least cost, and low emissions. Two potential power generation options based on reduced sized diesel generator, and a wind–diesel hybrid system were evaluated and compared against the existing diesel-based electricity system at Brochet. The wind–diesel hybrid system performed best in all three (i.e. electrical, economics, and environmental) evaluation criteria. While maintaining high reliability, this hybrid system design resulted in 30% reduction in cost of electricity produced, and 18% reduction of carbon dioxide emissions when compared to the existing electricity system at Brochet. Thus, this study concludes that the wind–diesel hybrid system is the optimum electricity system design for Brochet and proposes this system to replace the existing system.

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1. Introduction

In September 2011, the United Nations (UN) General Assembly launched the Sustainable Energy for All initiative to make sustainable energy for all a reality by 2030 [1]. Sustainable energy is achieved when energy is readily and sustainably available at reasonable cost and can be utilized efficiently and effectively for all

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required tasks without causing negative societal impacts in the long run [2]. In the context of Canada, approximately 300 off-grid communities, including four communities (Brochet, Lac Brochet, Shamattawa, and Tadoule Lake) located in the northern Manitoba [3], are far away from achieving a sustainable energy system.

Aboriginal Affairs and Northern Development Canada (AANDC) defines off grid communities as "permanent or long – term (five years or more), have settlements of at least 10 permanent buildings and are neither connected to the provincial electricity grid nor to the piped natural gas network" [3]. As the off-grid communities span a vast geographical area, extension of the grid transmission lines is cost prohibitive due to the high construction and maintenance cost, low demand and small number of customers served [3,4]. Further, total dependence on long transmission lines also increases the energy insecurity of the community. If the grid fails and the transmission is disrupted, the survival of the whole community would be at risk.

In the majority of the off-grid communities (approximately 80%), diesel generators are the default source of electricity [3]. The micro-grid configuration usually involves one or two large diesel generators operating in duty/standby mode to meet the electricity load and a third generator is generally kept as a backup [5–7]. For remaining 20% of the off-grid communities, diesel generators play a crucial part in the electricity generation mix by either acting as back up electricity source or by complimenting and balancing load when electricity from other sources such as wind, photovoltaic, hydro, grid, and biomass are unavailable or insufficient to meet the demand [3]. Although, diesel generators have low capital cost and high electrical reliability, the cost of electricity produced in remote locations is extremely high due to expensive fuel prices, and high fuel transportation and storage costs [5,8]. Further, spillage and leakage during fuel transport and storage, and emissions of pollutants from transport and combustion of fossil fuel also result in high environmental cost [4,5]. In the case of Northern Canada, the diesel-based electricity system also faces increasing insecurity in its supply chain as fuel required for the generators is trucked in over the winter road [4,9]. The winter roads connecting the small communities to nearby regional hubs are open for a shorter period and have become less reliable due to changes in climatic conditions [9,10].

Many off-grid communities in Canada have incorporated locally available renewable energy resources such as hydro, wind, photovoltaics, and biomass in their electricity mix to not only reduce emissions of GHG gases but also to benefit from reduced cost of electricity, creation of jobs, diversity in electricity mix, reduced reliance on imported fossil fuel, and to achieve energy security and sustainable energy [8,11–17]. A hybrid energy system is composed of two different energy sources (renewable + renewable/non-renewable) operating in a stand alone or grid connected model [18]. Some examples of utility scale renewable hybrid energy systems in Canada are: Colville Lake and Fort Simpson in Northwest Territories, Xeni Gwet'in First Nation, Nemiah Valley in British Columbia (solar/diesel/battery hybrid), Ramea Island in New Foundland (wind/diesel/hydrogen hybrid), Bella Coola in British Columbia (hydro/hydrogen hybrid), Diavik Mine in Northwest Territories (wind/diesel/battery hybrid), Inuvik (LNG/diesel hybrid) [8,17]. As seen in the above example, there is no 'one-size-fits-all' hybrid system design and as the availability of renewable energy sources strongly depends on local weather and climatic conditions, it ultimately affects the hybrid system of choice [11,19].

The aim of this paper is to determine an optimum electricity system design for the off-grid community of Brochet. In this study 'optimum' is determined by high electric reliability, least cost, and low environmental impact. In the first step the existing system is benchmarked to establish reference points to measure performance. Next, two hypothetical electricity system designs were investigated based on: (1) reduced sized diesel generators, and (2) a mix of wind and diesel generators. As the existing generators installed in Brochet are near the end of their operational life span and are expected to be replaced soon in 2015–2016, there is an opportunity to reduce diesel generators and/or include renewables. The first hypothetical scenario will provide a realistic option to replace the existing electricity system at Brochet with appropriately sized diesel generators that closely match the load profile and achieve energy efficiency on the producer's end. The second hypothetical scenario takes a staged approach to integrate locally available wind resource with the diesel generators. Finally, a sensitivity analysis of wind speed and fossil fuel will be performed on the wind–diesel hybrid system.

1.1. Site background

Brochet is located at 57°52′47″N 101°40′16″W and is approximately 125 km NW of Lynn Lake. Brochet is composed of two communities: Barren Lands First Nation (BLFN) under federal jurisdiction and the adjacent Non-FN community under provincial jurisdiction (Fig. 1). As seen in Fig. 1 below, the diesel generating station and the fuel farm, consisting of 40 storage tanks with 50,000 l capacity per tank, are both situated on the non-FN side of the community [7]. However, the electricity produced is transmitted and distributed to both communities via a single micro-grid configuration. Thus, from an electricity perspective, both

Fig. 1. Map of Brochet in Northern Manitoba, Canada. Source: Google Earth, 2013 and NRCAN, 2013.

communities are treated as a single unit. The total population of Brochet is 537 and all the 126 residential units and 19 non-residential facilities in both communities have connection to the diesel generated electricity [20]. Residential sector consumes bulk of the total electricity produced (approximately 80%) [20].

The diesel generating station at Brochet has an installed capacity of 2.63 MW consisting of two Caterpillar 3512B diesel generator sets (from here after referred to as gen set), each rated 1015 kW at 1200 rpm, and one Caterpillar 3508B gen set, rated 600 kW at 1200 rpm [4]. During normal operations, only one 1015 kW gen set is used while the other 1015 kW gen set is constantly kept on stand-by [4]. The 600 kW unit is mainly used during overhaul of the larger 1015 kW gen sets and serves as a backup to provide critical load to the community [4].

Canada's constitution grants the provinces an exclusive authority over electricity generation [21]. In Manitoba, Manitoba Hydro is the sole provider of electricity and undertakes all functions of generation, transmission, distribution, wholesale, and retail of electricity supply and service [22]. It was set up as a Crown corporation of the Manitoba Government and the electricity rate is fixed by Manitoba Public Utilities Board [22]. As a measure to increase efficiency at the users end, the diesel-generated electricity is restricted by Manitoba Hydro to 60 Amps in all the four off-grid communities [4]. This prohibits the use of electricity for space heating purposes [4], requiring, either fuel oil and/or wooden furnaces to meet heating demand [23].

The existing electricity system in the diesel zone has high economic cost to both customers and utility provider. The tariff rates for various consumer groups for 2014/15 are given in Table 1. According to Manitoba Hydro, the total cost to provide service in these communities was $1.069/kWh [24]. For 2011/12, the total variable cost was estimated at 58.49¢/kWh, and fuel cost alone represents approximately 62% of this cost [23]. The full monetary cost of electricity includes high variable cost, the capital cost of the generating station and fuel farms, as well the soil remediation cost of accidental fuel spillage [4].

Capital expenditure at the diesel generating stations is contributed by the federal and provincial governments and Manitoba Hydro, whereas the majority (approximately 77%) of the total variable cost is recovered from the current electricity tariff rate applicable to the off-grid communities approved by the Manitoba Public Utilities Board [23]. The remaining portion of the total variable cost is cross subsidized by the grid-connected customers [23]. However, as not even partial recovery is included in the tariff rate structure, all the capital expenditure towards electricity generation in the "Diesel Zone" is treated as deficit by the Manitoba Hydro [23]. Increasing the tariff rate for any customer class to reduce the deficit is not a viable alternative. A community energy baseline study done by the Pembina Institute concluded that "aboriginal communities consistently spend higher amounts on energy (on per house and per person basis) that than in non-native communities or when compared to provincial averages" [25]. Further, aboriginal poverty in Manitoba is chronic and persistent with rates as high as 42.3% [26].The local governments are highly dependent on the transfer of welfare payments, therefore high expenditure on energy reduces the budget available for other public work and services such as housing, health, and education [23,27].

In addition to the high economic cost, the diesel-based system has a high environmental impact. According to Manitoba Hydro, approximately 8000 t of GHG is emitted from the diesel generating stations in the four off-grid communities [4]. Diesel generation stations are the single largest source of GHG emissions in many off-grid communities [20,27]. Apart from this direct emissions of GHG from the combustion of diesel, equally high amount of emissions of GHG and other air pollutants occurs while transporting fuel over considerable distances to these remote and isolated off-grid communities [28]. Likewise, spillage and leakage during fuel transport and storage also result in pollution of air, water, and soil [23].

Table 1
Electricity tariff rate for Manitoba's diesel zone in 2014/15.*Source*: Manitoba Hydro, 2011.

Rate class	Basic monthly charge	Current rates
Residential (all kWh)	$7.28	$0.074/kWh
General service (< 2000 kWh)	$19.73	$0.077/kWh
General service (> 2000 kWh)	$19.73	$0.40/kWh
Government and FN education (all kWh)	$19.73	$2.41/kWh

2. Material and method

The Hybrid Optimization Model for Electric Renewables (HOMER) model was applied in this analysis. It was developed by the U.S. National Renewable Energy Laboratory (NREL) to design and compare energy systems with various configurations of both renewable and non-renewable resources [29]. The HOMER model, "allows energy planners and designers to evaluate the design trade-offs and alternative system configurations based on their technical and economic merits" [29]. The HOMER model (v. 2.81) was used to benchmark the existing power configuration as well as to conduct the pre-feasibility of various electricity generation system designs. All the governing equations used in the HOMER are not provided in this method as they have been explained by the model developers in detail in "Micro-power System Modeling with HOMER" [29].

2.1. Load

This study uses the actual power generation log data for 2011 in Brochet applying the 15-min time steps to create the community electricity load profile. This approach is highly accurate as it accounts for distribution and transmission loss as well as for parasitic loads. The entire load was treated as the primary load for the Brochet model. No effort was made to smooth the peak demand value or fill the zero values, which indicates outage. This is because in a real operational scenario, such incidents of disruptions and contingencies are unavoidable. Reliable electricity supply is critical to the survival of communities located in cold climatic regions. Therefore, any proposed power generation design must prove its reliability by being able to withstand the surge in load when power production resumes after a disruption.

2.2. Equipment

a. Diesel generators: an analysis of monthly peak and average load value against the rated output capacity of various sizes of diesel generators was performed to select the diesel generator of suitable size. Information on fuel consumption rate, rated power output, and efficiency of the existing diesel generator was accessed from the homepage of the manufacturer (www.cat.com).
b. Wind turbine: winter temperature in Brochet can fall to −35 °C (Table 3) and only a few wind turbines have the ability to operate in these cold climatic conditions [30]. In addition to the operability issue in cold climatic conditions, another limitation is the winter road from Lynn Lake connects to Brochet. Winter roads have maximum allowable Gross Vehicle Weight for full commercial loads of 37.5 t [31]. Based on these criteria, this study selected Northwind power (NW 100 kW)

and Aeronautica (AW Norwin 29/225 kW). The rated capacity and power curve was provided the in-built library in the HOMER model itself.

c. Battery storage: the possibility of long term bulk storage provided by pumped hydro storage (PHS) was ruled out due to the cold climatic condition and no remarkable variation in elevation in nearby areas [20]. Various studies have concluded that the lead–acid battery provides relatively higher energy and power capacity at minimum cost when compared with other storage options such as flywheel, capacitors, zinc–bromine batteries, and sodium–sulfur batteries, etc. [32,33]. Thus, this study uses lead–acid battery for energy storage.

2.3. Resources: wind resource assessment

For large wind turbines covering wide areas, the preliminary wind regime map can be obtained from Environment Canada's Canadian Wind Energy Atlas (CWEA) website [34]. The map has been generated by using a meso-scale numerical model and has a 5 km resolution coverage for all of Canada [35]. According to the Canadian Wind Energy Atlas (CWEA)'s estimate, the mean annual wind speed in Brochet at 30 m height was 5.36 m/s and at 50 m height was 6.06 m/s [34]. This average mean wind speed is derived from a 43 year period (from 1958 till 2000) [34]. As these values do not provide any high resolution temporal information, its use in actual power system design is fairly limited. Further, power generated by small wind turbines is greatly affected by the local topography and local wind currents [36]. Thus, such large area maps provide rough estimates and need to be validated with on-site measurement [35,36].

The most recent hourly meteorological data collected at Brochet Airport (tower height 10 m) was accessed from National Oceanic and Atmospheric Administration (NOAA)'s National Climatic Data Center website. Data were pre-processed using Microsoft Excel (Version 2010). The archived data were categorically organized and then evaluated for data completeness. Table 2 provides summarized result of data pre-processing on missing data, data completeness, and number of gaps from the hourly data of selected meteorological variables from December 1991 through November 1992. The values given under the label "Data completeness (%)" were obtained by dividing the total number of hourly data by the total number of hours in a year i.e. 8760 h.

As seen in the table below, the available data is fairly complete. In the original data, missing values (denoted by blank cells) ranged from a single value to the maximum of three consecutive days (72 h). However, the HOMER model required a complete set of 8760 h to represent a full year without any blank values. When three or less consecutive hourly values were missing, interpolation from previous and the next available hourly values were used to fill in the missing values. If more than three consecutive values were missing, then each hourly value was determined by averaging the wind speed from the exact hour three days before and after the missing date. Averaging to fill the missing value for two to three days is assumed to have little impact on the overall evaluation of the wind resource in Brochet. The best practice would have been to ignore such data for further analysis [36]. For the wind direction, the averages were smoothed out to reflect the wind directions in the receding hours.

As seen in the summarized monthly data (Table 3) of the relevant meteorological parameters, wind speed in spring and fall seasons have stronger winds than in the summer and winter. The table also clearly shows strong inverse relationship between air temperature and air density in the winter and spring seasons. This means that cold, dense wind blowing in the winter and spring has higher potential to supply large amounts of renewable electricity (Fig. 2).

Generally, wind speed is dependent on solar radiation and therefore, many places have high wind speed around noon when the solar radiation is at its highest [36]. However, stronger wind speed was recorded in the late afternoon hours at Brochet. The diurnal wind speed distribution pattern shows that average maximum wind occurred from 17 to 20 h of the day for the data period (Fig. 3). Similar diurnal pattern of maximum wind occurring at late hours has been observed in other communities such as Clark's Point, Naknek, and Koliganek all located in the high latitudes [37]. As Brochet is also located at high latitude (57°), incoming solar radiations are high in summer and days in the summer months have greater number of day light hours. As only daily values of solar irradiation could be obtained for Brochet, a detailed investigation on its effect on diurnal wind pattern could not be performed. The diurnal strength pattern was calculated to be 0.118. Auto-correlation factor was calculated at 0.841, signaling

Table 2
Analysis of data completeness of major meteorological variables at Brochet.

	Number of missing hourly data	Data completeness (%)	Number of gaps
Speed	770	91.2	336
Direction	940	89.3	452
Temperature	733	91.6	315
Total	2443	90.7	1103

Table 3
Summary of climatic conditions at Brochet Airport for a year in 1991–1992.Data source: NOAA, 2012.

Year	Month	Wind speed (m/s)			Temperature (°C)			Air density (kg/m³)		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1991	Dec	3.79	0	14.31	−18.4	−40	1.1	13.92	12.62	15.34
1992	Jan	3.75	0	10.28	−19.8	−37.8	1.1	13.99	12.76	15.16
1992	Feb	3.19	0	10.73	−20.4	−37.7	−3.9	14.09	12.98	15.21
1992	Mar	3.51	0	12.96	−14	−37.2	7.8	13.74	12.64	15.11
1992	Apr	3.92	0	14.31	−4.6	−23.9	13.9	13.25	12.25	14.35
1992	May	4.19	0	15.78	4.2	−8.9	23.3	12.79	11.9	13.48
1992	Jun	4.14	0	15.2	8.6	−2.2	27.2	12.55	11.73	13.15
1992	Jul	3.64	0	12.96	12.1	1.1	26.5	12.38	11.76	12.94
1992	Aug	3.12	0	12.52	13.9	1.1	26.8	12.33	11.7	13.01
1992	Sep	5.27	0	17.88	7.5	−2.2	20	12.54	11.93	13.13
1992	Oct	4.05	0	14.31	0.9	−12.8	21.7	12.92	11.89	13.69
1992	Nov	4.19	0	12.52	−7.3	−27.2	1.1	13.36	12.72	14.58
All Data		3.89	0	17.88	−3	−40	27.2	13.15	11.7	15.34

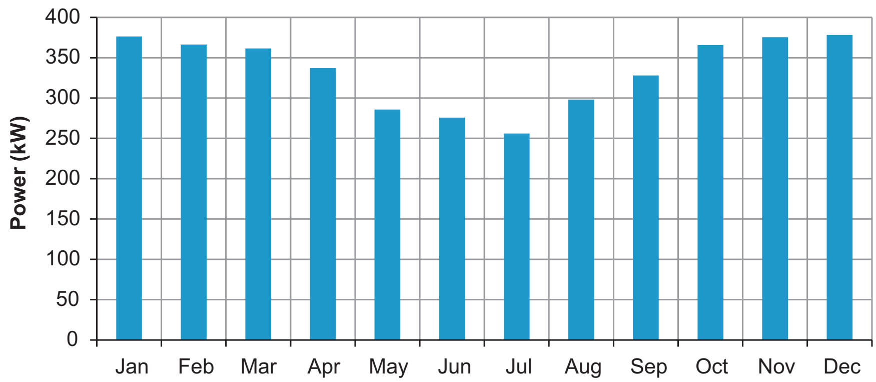

Fig. 2. Average monthly electricity production in 2011 at Brochet. Data source: Manitoba Hydro, 2012.

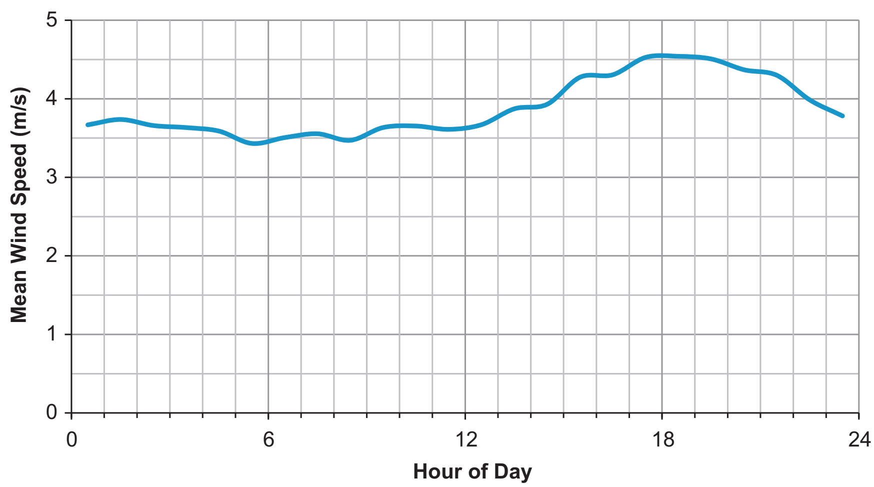

Fig. 3. Diurnal wind speed profile for Brochet over a period of a year in 1991–1992. Data source: NOAA, 2012.

the wind blowing in a certain hour was not highly dependent on wind from previous measured hour.

The probability distribution of the wind speed occurring at Brochet shows that the wind speed at Brochet is marginal with most of the wind speeds lower than 4 m/s (Fig. 4). The cumulative distribution analysis showed that about 65% of the winds are less than 4 m/s and 100% of the winds are less than 11 m/s; hence the time frequency of wind speeds suitable for energy production in Brochet is approximately 35% or about 2500 h.

The corresponding Weibull scale parameter (c) and shape parameter (k) for 10 m of height was calculated as $c=3.73$ m/s and $k=1.54$, respectively. Values of k typically range from 1 to 3.5, with the higher values indicating a narrower frequency distribution (i.e., a steadier, less variable wind) [38]. As seen in Fig. 4 below, the Weibull parameters have a relatively good fit with the observed wind speed distribution at Brochet. The wind data was collected at only one height, wind shear could not be directly calculated. As, Brochet has few surface roughness elements such as tall trees or buildings and a winter snow pack usually from November till May of each year, the mean power law shear exponent of 0.08 was used in the HOMER model.

Fig. 5 shows the seasonal wind rose graph with wind speed for various corresponding directions at Brochet for the 1991–1992 period. As seen in the figure below, the wind blew from both north and south directions in the spring season, whereas in the summer season most of the wind blew from the southeast direction. As the fall season progressed, most wind blew from the southeast direction and in the winter season, the easterly was the most dominant one. These seasonal variations are the typical characteristics of wind direction in artic and sub-arctic regions [39]. Thus, any potential wind turbine deployed at Brochet should be oriented towards this direction to effectively capture most of the wind.

A detailed statistical analysis on wind resource was limited as continuous hourly data was available from only one mast height and there was no information on standard deviation. The nearest meteorological station is at Lynn Lake, located 125 km south of Brochet. Analysis of wind speed, diurnal variation, wind direction, and seasonal distribution of wind data collected at Airports in Brochet and Lynn Lake showed that the wind resources are distinct in both places due to topographical variations (Lynn Lake airport is surrounded by forest) [20].

2.4. System setup

For the existing system, in the HOMER model, one 1015 kW diesel generator was forced to run all the time, while the operational mode of the other 1015 kW unit was set for optimization, and the backup unit of 600 kW was kept as stand-by (Table 4). When operation of the generator is configured as optimized in the HOMER model, the HOMER model will decide when to operate the gen set based on the least cost of operation factor.

For the first scenario of reduced-sized diesel only system, all the inputs used in benchmarking the existing system were reassigned. To ensure no capacity shortage occurred, various discrete sized gen sets were selected based upon their rated output and matched against the average and peak load at Brochet. Units of various sizes of diesel generators used in the model are given in

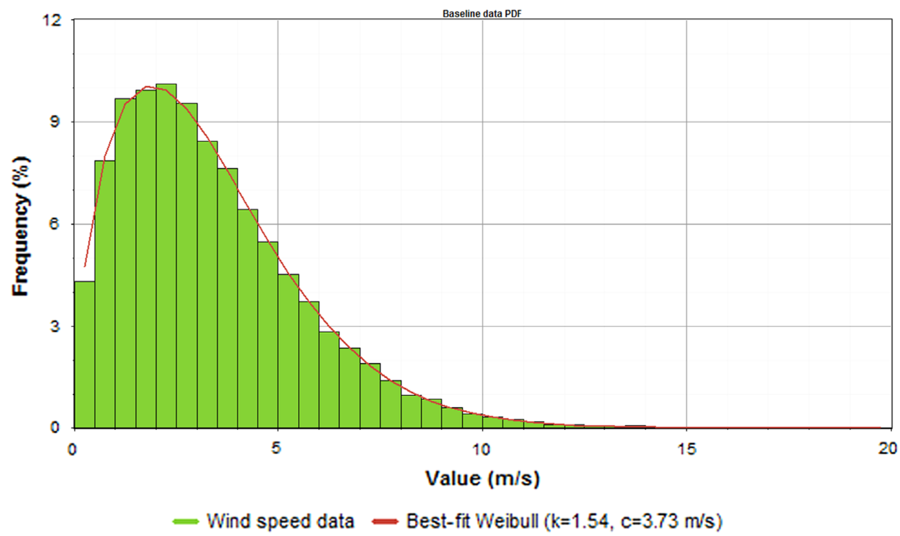

Fig. 4. Probability distribution function of wind speed at Brochet Airport. Data source: NOAA, 2012.

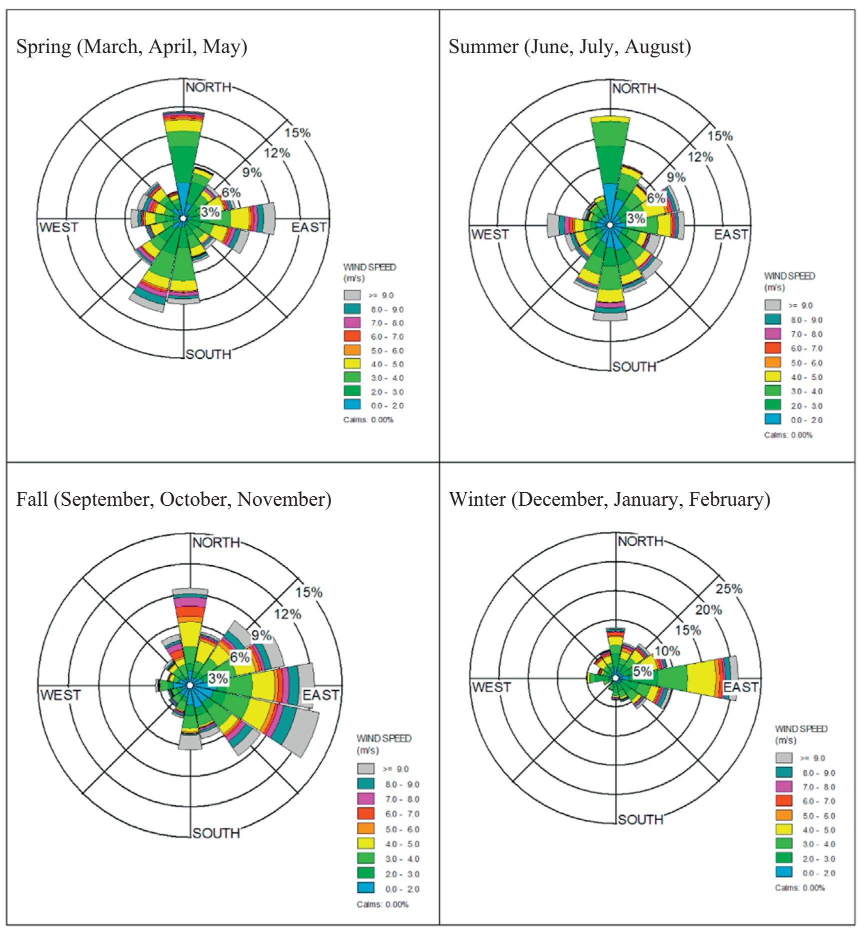

Fig. 5. Seasonal wind direction profile at Brochet Airport over a year in 1991–1992. Data source: NOAA, 2012.

Table 4. Assigning 0 in the unit of sizes allows the HOMER model to discard a certain gen set specification from the optimization result, if it does not meet the constraint assigned. Further, similar to the existing configuration, one unit of 600 kW was configured as a backup gen set. All diesel generators were configured to operate at an optimized schedule. This allows the HOMER model to consider electricity load, rated capacity of each generator, and fuel consumption at varying loads and finally decide whether to operate a single unit or multiple units in parallel on a least cost basis.

For the second scenario of wind–diesel hybrid system, the optimum reduced sized diesel configuration obtained from first scenario was selected and additional components for the wind system were added to the simulation. Units of various components considered in the wind–diesel system design are given in Table 4. Similar to the existing system, one 600 kW capacity generator was configured as a backup and the other unit was configured to run at an optimized mode. Both wind turbine models (Northern Power 100 kW and AW Norwin 225 kW) were assumed to have a life-time of 20 years and be installed on a 40 m tower. The hybrid system uses cycle charging facility so that whenever the generators operate, they will operate at their full or near maximum rated capacity and charges the battery with excess.

The graphic representation of the existing system, scenario one of reduced-sized diesel only system, and scenario two of wind–diesel hybrid system is presented in Fig. 6.

2.5. Economics

This study applies a project life-time of 20 years and an interest rate of 6% for economic analysis. The cost of components was estimated after reviewing literature and by interviewing local suppliers in Winnipeg (Table 5). Due to lack of information on actual fixed and operating cost of the existing diesel generators (mentioned earlier in Section 1.1), economic analysis on net pay back, benefit/cost analysis could not be performed. Instead, the

Table 4
Generator sets (Genset) considered in the system design in the HOMER model.

Existing system										
	Unit									
Backup Genset (600 kW)	1									
Genset (1015 kW)	1									
Genset (1015 kW)	1									
Scenario 1 (Reduced sized diesel generator system)										
Genset (455 kW)	0	1	2							
Genset (500 kW)	0	1	2							
Backup Genset (600 kW)	1									
Genset (600 kW)	0	1	2							
Genset (750 kW)	0	1	2							
Genset (830 kW)	0	1	2							
Scenario 2 (Wind diesel hybrid system)										
AW Norwin (225 kW)	0	1	2	3	4	5				
NW (100 kW)	0	1	2	3						
Surrettee (6CS25P)	0	1	2	3	4	5	6	7	8	9
Converter	0	50	100							
Gen set (600 kW)	0	1								
Backup Gen Set (600 kW)	1									

Table 5
Assumed cost of components used in the HOMER model.

Components	Cost		
	Capital	Replacement	O & M
Diesel generator	$1300/kW	$594/kW	$33.16/h
AW Norwin 225 kW	$675,000/ turbine	$562,500/per turbine	$2000/yr
Northernpower NW 100 kW	$550,000/ turbine	$500,000/per turbine	$2000/yr
Surrettee battery pack (6CS25P)	$1250/unit	$1100/unit	$15/yr
Converter	$800/kW	$750/kW	$10/yr

Table 6
System controls used in the HOMER model.

Parameters	Options	Options used
Cycle charging	Yes or no	Yes
Apply set point	Yes or no	Yes
Load following	Yes or no	Yes
Multiple generators can operate in parallel	Yes or no	Yes
Allow system with two types of wind turbine	Yes or no	Yes

Table 7
Spinning reserve inputs to the HOMER model.

Parameters	Value (%)
Percent of annual peak load	5
Percent of hourly load	10
Percent of hourly wind output	40

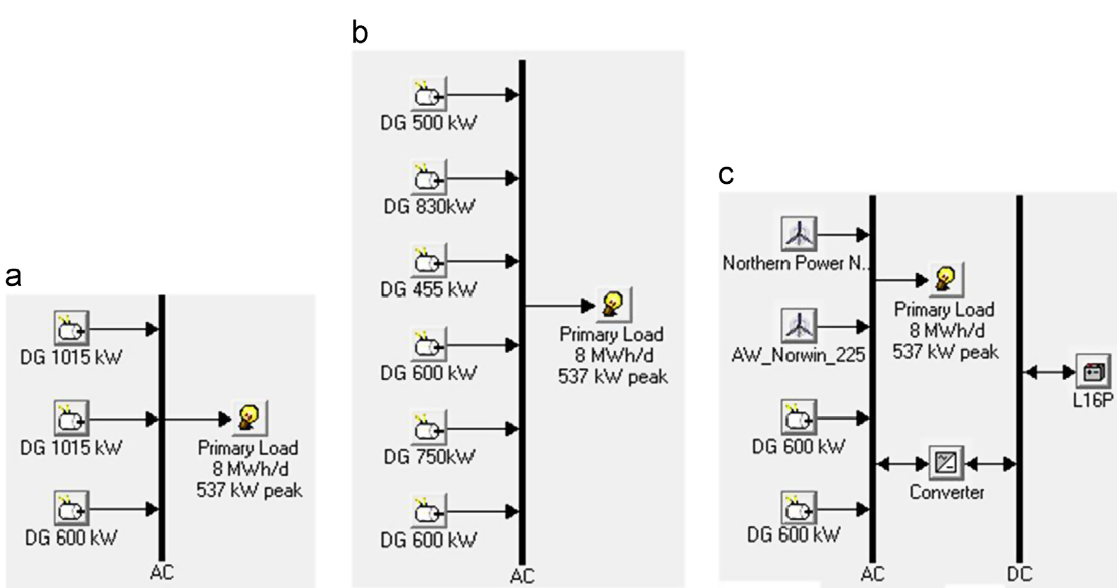

Fig. 6. Graphic representation of various micro-grid systems for Brochet in the HOMER model.

study uses levelized cost of electricity (LCOE) over the full life cycle of the energy system as the main economic parameter [29].

2.6. System control and constraints

This study uses a 60 min simulation time step. The system controls and constraints assigned to the HOMER model are shown in Tables 6 and 7.

3. Result and discussion

3.1. Benchmarking existing system

The benchmarking of the existing system in the HOMER model revealed its high electrical performance and reliability, but at a high economic and environmental cost (Table 8). In the model, the fuel cost was the key determinant of the economics of the existing system. Other studies [6,40–42] have also concluded that typically diesel-based electricity systems in off-grid communities have a high economic and environmental cost due to the common design flaw from excess installed capacity. Although, Manitoba Hydro projects that the annual community load in the off-grid communities of Manitoba to grow between 2% and 4% per year, the size of diesel generators installed in each community is far larger than the average load [4]. In the case of Brochet, a load frequency variation analysis shows that 65% of the total electric production from the 1015 kW gen set occurred in the range of 250–400 kW. This means the 1015 kW gen set was forced to run at approximately one-third of its operating capacity, which is far below its optimum range. These large oversized diesel generators, operating far below their optimum efficiency, result in high fuel consumption, greater wear and tear, and higher operation and maintenance cost [5,41].

3.2. Determination of optimum diesel system

The HOMER model performed 48 distinct simulation runs to determine the optimal gen set configuration and ranked them based on the least cost of electricity produced. The optimum diesel system determined by the HOMER model consisted of one 600 kW unit as lead and the other 600 kW unit operating as standby (Table 9). As expected, when the diesel generators are sized to closely match the electricity demand, it results in reduced cost per unit of electricity produced (Table 8). As fuel cost dominates the economics of the diesel-based system, this reduction in cost per unit of electricity produced is largely due to reduced fuel consumption (Table 8).

When compared to the existing gen sets at Brochet, optimized reduced sized diesel gen sets resulted in slightly reduced GHG and other emissions. This is because the reduced sized gen sets operate at higher efficiency (33.7%) when they produce power near their rated capacity and thus preventing incomplete fuel combustion and efficiently burning fuel. Incomplete combustion results in higher emissions of carbon monoxide and unburned hydrocarbons, as evident in Table 8.

The large diesel gen sets are sized to meet the maximum peak load plus some regulatory requirement [6]. In the case of Brochet, the peak load was almost twice the average load, however, in some communities it can be as high as five to 10 times the average load [6]. And, like in the case of Brochet, the peak values usually occur for a small fractions of the total year [43]. Thus, using multiple diesel gen sets with different sizes would help maximize fuel efficiency and allow greater integration of renewables in the electricity mix [41].

Table 8
Summary of estimates by Homer model for various electricity system designs.

	Existing system	Optimized diesel system	Optimized wind diesel system
Electrical (kWh/yr)			
Production	3,100,638	2,906,302	3,839,191
Consumption	2,904,981	2,904,981	2,904,955
Excess electricity	195,615	1289	874,409
Unmet electric load	0	0	0
Capacity shortage	0	0	0
Economic			
LCOE ($/kWh)	$0.622	$0.487	$0.492
Fuel consumption (L/yr)	915,736	804,407	527,287
Emissions (kg/yr)			
Carbon dioxide	2,416,370	2,118,270	1,695,364
Carbon monoxide	2472	421	308
Unburned hydrocarbons	824	579	7
Particulate matter	531	394	22
Sulfur dioxide	4841	4253	3392
Nitrogen oxides	70,054	46,656	37,175

3.3. Determination of optimum wind–diesel hybrid system

The HOMER model performed 1440 simulation runs to determine the optimum wind–diesel hybrid system configuration. As seen in Fig. 7, 47% of the total electricity production came from wind turbines and the rest from the 600 kW gen set. The above Table 8 also clearly showed that the wind–diesel hybrid system can effectively provide the high reliability offered by the existing diesel generating system. Out of all the design scenarios, the hybrid system design had the least cost of electricity produced (19% reduction compared to the existing system, and 4% compared to the optimized diesel system), least amount of fuel consumption (39% reduction compared to both existing system and optimized diesel system), and least amount of emissions (30% reduction in CO_2 emissions compared to existing system, and 27% when compared with optimized diesel system). Finally, as the GHG emission during the transport of the fuel to the community was not considered, the net environmental benefit of integrating wind resources would be far greater than that determined by the HOMER model. The cost component of the optimum wind–diesel hybrid system is presented in Table 10.

On the basis of the evaluation criteria for electrical, economics, and environmental component, the study concludes that wind–diesel hybrid system is an optimum electrical system for Brochet. A sensitivity analysis on variation of wind speed and fuel price was performed to understand how changes in these factors affect the levelized cost of electricity and CO_2 emissions of the optimum wind–diesel hybrid system. Fig. 8 shows the simulated wind speeds (m/s) along the *X*-axis and simulated diesel price ($/L) along the *Y*-axis. The color gradient shows that the levelized cost of electricity produced has a positive relationship with the cost of fuel price and an inverse relationship with the wind speed. In addition, the figure also has values of CO_2 emission (kg/yr) for any given price and wind speed at the different variations. If the annual wind speed was 5.5 m/s and the fuel price escalated to $1.8/liter, then the levelized cost of electricity produced will be $0.64/kWh with annual CO_2 emissions of almost 1.5 million kg/yr. The figure shows that capturing larger amount of wind energy further reduces both annual CO_2 emissions and levelized cost of electricity produced.

Table 9
Optimization results of the multiple reduced sized generators in the HOMER model.

Rank	455 (kW)	500 (kW)	600 (kW)	600 (kW)	750 (kW)	830 (kW)	Initial capital	Operating cost ($/yr)	Total NPC	COE ($/kWh)	Renewable fraction	Diesel (L)	455 (hrs)	500 (hrs)	600 (hrs)	600 (hrs)	750 (hrs)	830 (hrs)
1			600	600			$1,560,000	1,352,287	$17,070,622	0.512	0	877,076			8,760	0		
2				600	750		$1,755,000	1,403,748	$17,855,874	0.536	0	879,981				0	8,760	
3			600	600	750		$2,535,000	1,340,108	$17,905,934	0.537	0	877,089			8,750	0	10	
4			600	600		830	$2,639,000	1,338,861	$17,995,632	0.54	0	877,141			8,750	0		10
5	455		600	600			$2,879,500	1,336,558	$18,209,714	0.547	0	877,187	10		8,760	0		
6		500	600	600			$2,879,500	1,336,611	$18,210,320	0.547	0	877,240		10	8,760	0		
7				600		830	$1,859,000	1,431,621	$18,279,582	0.549	0	881,462				0		8,760
8				600	750	830	$2,834,000	1,380,653	$18,669,982	0.56	0	877,836				0	8,171	589
9	455			600	750		$3,074,500	1,365,106	$18,732,156	0.562	0	805,863	6,333			0	2,427	
10			600	600	750	830	$3,614,000	1,326,949	$18,834,004	0.565	0	877,089			8,750	0	10	0
11	455			600		830	$3,178,500	1,377,001	$18,972,588	0.569	0	813,452	6,180			0		2,580
12		500		600	750		$3,074,500	1,387,686	$18,991,144	0.57	0	879,981		0		0	8,760	
13		500	600	600	750		$3,854,500	1,324,046	$19,041,204	0.571	0	877,089		0	8,750	0	10	
14	455		600	600	750		$3,854,500	1,324,046	$19,041,204	0.571	0	877,089	0		8,750	0	10	
15		500	600	600		830	$3,958,500	1,322,799	$19,130,902	0.574	0	877,141		0	8,750	0		10
16	455		600	600		830	$3,958,500	1,322,799	$19,130,902	0.574	0	877,141	0		8,750	0		10
17	455	500	600	600			$4,199,000	1,320,496	$19,344,984	0.581	0	877,187	10	0	8,760	0		
18		500		600		830	$3,178,500	1,415,559	$19,414,852	0.583	0	881,462		0		0		8,760
19	455			600	750	830	$4,153,500	1,349,050	$19,626,998	0.589	0	806,928	6,180			0	2,424	156
20		500		600	750	830	$4,153,500	1,364,591	$19,805,252	0.594	0	877,836		0		0	8,171	589
21	455	500		600	750		$4,394,000	1,349,044	$19,867,426	0.596	0	805,863	6,333	0		0	2,427	
22		500	600	600	750	830	$4,933,500	1,310,887	$19,969,274	0.599	0	877,089		0	8,750	0	10	0
23	455		600	600	750	830	$4,933,500	1,310,887	$19,969,274	0.599	0	877,089	0		8,750	0	10	0
24	455	500		600		830	$4,498,000	1,360,939	$20,107,858	0.603	0	813,452	6,180	0		0		2,580
25	455	500	600	600	750		$5,174,000	1,307,984	$20,176,474	0.606	0	877,089	0	0	8,750	0	10	
26	455	500		600			$3,419,000	1,468,559	$20,263,260	0.608	0	812,732	7,398	2,424		0		
27	455	500	600	600		830	$5,278,000	1,306,737	$20,266,172	0.608	0	877,141	0	0	8,750	0		10
28	455	500		600	750	830	$5,473,000	1,332,988	$20,762,266	0.623	0	806,928	6,180	0		0	2,424	156
29	455	500	600	600	750	830	$6,253,000	1,294,825	$21,104,544	0.633	0	877,089	0	0	8,750	0	10	0
30	910			600			$3,419,000	2,106,753	$27,583,288	0.828	0	878,159	8,760			0		

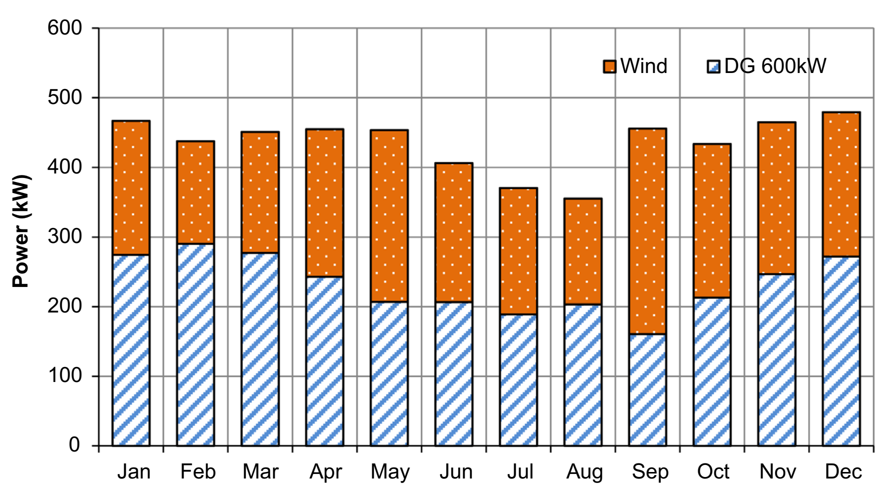

Fig. 7. Monthly average electricity production from the wind–diesel hybrid system as estimated by the HOMER model.

4. Conclusion

Brochet is a remote off-grid community located in northern Manitoba, which would benefit from energy optimization. Analysis of the existing configuration of gen sets against the electricity load shows that the existing system at Brochet is highly oversized and the diesel generators are operating well below their rated capacity. With the existing systems coming to the end of their operational life span in 2015–2016, this study analyzed two hypothetical scenarios of reduced sized diesel-based electricity system and wind–diesel hybrid electricity system.

This study concludes that using multiple diesel gen sets with discrete sizes that closely match with the average demand would help lower fuel consumption, cost of electricity, and emissions. The

Table 10
Cost summary of the various scenarios as estimated by the HOMER model.

Component	Capital ($)	Replace ment ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
a. Optimized diesel only system:						
DG 600 kW	780,000	2,263,297	3,331,803	10,059,996	−35,561	16,399,534
DG 600 kW	780,000	0	0	0	−108,905	671,095
Total system	1,560,000	2,263,297	3,331,803	10,059,996	−144,465	17,070,628
a. Optimized wind–diesel hybrid system:						
AW Norwin (225 kW)	2,700,000	0	91,759	0	0	2,791,760
DG 600 kW	780,000	1,857,061	2,803,126	7,351,651	−19,262	12,772,576
DG 600 kW	780,000	0	0	0	−108,905	671,095
Surrette 6CS25P	56,250	24,600	7742	0	−5145	83,447
Converter	80,000	0	11,470	0	−7795	83,675
Total system	4,396,250	1,881,661	2,914,098	7,351,651	−141,107	16,402,553

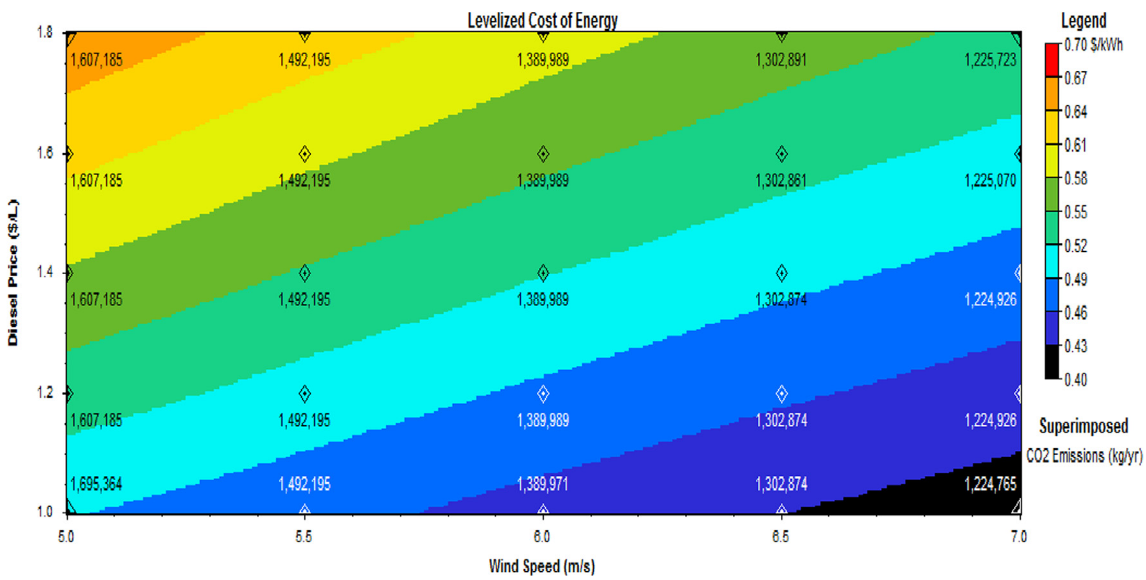

Fig. 8. Sensitivity results of the hybrid system as estimated by the HOMER model.

study also concludes that integration of this reduced sized diesel system with wind energy, despite the wind resources being marginal, resulted in significant reduction of cost, emissions and yet provided high electrical reliability. This gradual step, first increasing energy efficiency and then integrating renewable energy, is critical in successful deployment of renewable energy and also in achieving sustainable energy system. When it comes to energy security, diversity is the key [44].

Finally, the study shows that the HOMER model is a very robust feasibility level modeling tool and has the capacity to simulate the real electricity system and also various design scenarios. To improve the confidence in the study, a meteorological tower should be set up at Brochet to obtain high resolution data. The electrical, financial and environmental performance results given by the HOMER model could be a highly effective and valuable tool to aid decision makers, energy planners and modelers to help communities achieve a sustainable energy system.

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