Optimizing an Off-Grid Electrical System in Brochet, Manitoba, Canada

by

Prasid Ram Bhattarai (B.Sc., M.E.)

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements for the degree of

MASTER OF NATURAL RESOURCES MANAGEMENT

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FACULTY OF GRADUATE STUDIES

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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 costs. As the existing diesel generators are nearing the end of 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. Three potential power generation options were considered and evaluated, namely: 1) only diesel, 2) only wind, 3) a mix of both. The wind-diesel hybrid system performed best for all the evaluation criteria. While maintaining high reliability, this hybrid system design resulted in 19 % reduction in electricity cost, and 30 % reduction of CO_2 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 replace the existing system.

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I also want to thank my sweet heart, Genevieve Soonike, for inspiring me to pursue my studies here in Canada. Finally, I would like to thank my loving family for their love and support throughout my life.

Dedication

To My Parents.

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CHAPTER 1: INTRODUCTION

This chapter starts with background information on Manitoba's electricity regulatory framework and its utility provider, the status of electricity generation in the province, and the status of electricity generation in Manitoba's off-grid communities. Then, detailed information on the study site, Brochet, along with problems associated with the existing electricity system are presented. These sections are followed by study objectives, rationale, and the chapter summary.

1.1. Background

1.1.1. Regulatory Framework and Utility Provider in Manitoba

Canada's constitution grants the provinces an exclusive authority over electricity generation (Baier, 2005). The electricity market model in Manitoba is vertically integrated and a regulated monopoly. As Manitoba Hydro is the sole provider of electricity in the province, it undertakes all functions: generation, transmission, distribution, wholesale, and retail of electricity supply and service (Manitoba Hydro, 2012). Manitoba Hydro was set up as a Crown Corporation under the *Manitoba Hydro Act* (1988) and is owned by the province (Manitoba Hydro, 2012). Its mandate is to provide continuous, reliable, and economical energy for the residents of the province and is governed by the Manitoba Hydro Electric Board (Manitoba Hydro, 2012). The board is appointed by the provincial cabinet and has the duty to report to the Energy Minister responsible for the *Manitoba Hydro Act* (Manitoba Hydro, 2012). The Manitoba Public Utilities Board, an independent regulatory body representing ratepayers in Manitoba that operates under the Manitoba Public Utilities Board Act, regulates the retail electricity rate (Manitoba Hydro, 2012).

1.1.2. Status of Electricity Generation in the Province of Manitoba

The public utility provides reliable electrical service and also has successfully harnessed Manitoba's abundant renewable resources. Since the first hydroelectric generating station was constructed on the Minnedosa River (now known as the Little Saskatchewan River) in 1900, Manitoba has continually utilized its endowment of natural resources to generate electricity (Manitoba Hydro, n.d.). Today, the installed electricity generation capacity of 5,933 MW in the province comes largely from renewable sources (Manitoba Hydro, 2012). 87.5 % of the electricity in the province is generated from a large network of dams. These dams are mainly located across the northern part of the province and electricity generated is transmitted to the southern part of the province for consumption, where most customers reside (Figure 1-1) (Manitoba Hydro, 2012). In addition, the installed capacity of 258 MW wind power at two wind farms – St. Leon and St. Joseph – in the province further increases the share of renewable sources by 4.35 % (Manitoba Hydro, 2012). The remaining 7.8 % of the total annual electricity production comes from coal and natural gas (Manitoba Hydro, 2012).

As renewable resources dominate the electricity production mix, most Manitobans benefit from clean, low carbon, and low cost electricity. Manitoba has one of the lowest emissions of Greenhouse Gases (GHG) from electricity generation sector in Canada (Manitoba Hydro, 2012) and the lowest electricity rate in North America (Government of Manitoba, 2012). Exports of about 30 % of the total annual electricity production to other Canadian provinces (Saskatchewan and Ontario) and to markets in the USA (North

Dakota and Minnesota) not only brings in substantial trade revenue to the province (Blake & Graydon, 2008), but also allow consumers from other jurisdictions to benefit from clean and low carbon electricity (Manitoba Hydro, 2012).

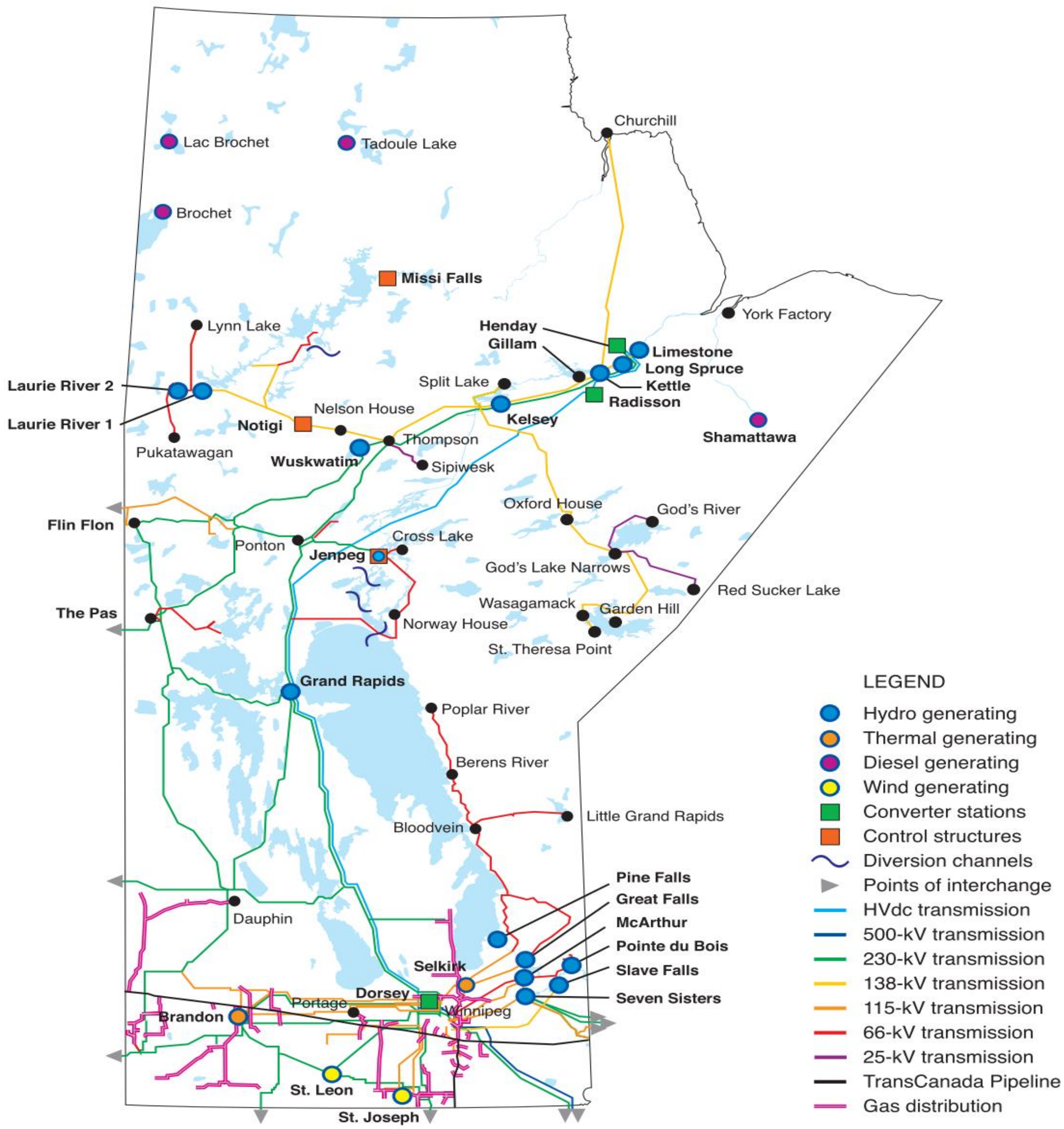

Figure 1-1: Map of Electric Generation Facilities and Transmission Lines in Manitoba. Source: Manitoba Hydro, 2013a (Copyrighted by Manitoba Hydro, 2013)

1.1.3. Status of Electricity Generation in Off-Grid Communities of Manitoba

In contrast to the southern part of the province, four northern communities: 1) Brochet, 2) Lac Brochet, 3) Tadoule Lake, and 4) Shamattawa have yet to benefit from clean, low cost, and low carbon form of electricity (Figure 1-1) (Manitoba Hydro, 2012). In fact, these four communities are off-grid community, which Aboriginal Affairs and Northern Development Canada (AANDC) defines 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" (AANDC, 2012a, para. 1).

The provincial electricity grid has not been extended to these four off-grid communities because the small number of customers served and difficult terrain do not justify the cost of grid extension (Manitoba Hydro, 2008; Manitoba Public Utilities Board, 2010a). Table 1-1 shows the most recent data on the distribution of customers in the four off-grid communities of Manitoba (Manitoba Public Utilities Board, 2010a). As seen in the table below, the community of Shamattawa has the largest number of total customers, whereas the community of Tadoule Lake has the least. Also note that the residential customers' category comprises the majority (almost 80%) of the total customers served in each of the four off-grid communities. In other words, most of the electricity in the off-grid communities is used for household purposes.

Table 1-1: Distribution of Customers in the Off-Grid communities as of 2009.

	Brochet	Lac Brochet	Tadoule Lake	Shamattawa	Total
Residential customers	121	137	114	173	545
Non – Residential customers	43	52	41	42	178
Total customers	164	189	155	215	723

Source: Manitoba Public Utility Board, 2010a

In addition to the small number of customers served, all the four off-grid communities are remote and isolated. As none of the off-grid communities have a permanent access road, these communities use winter roads as their major transport route (Kuryk, 2003). The winter roads are constructed every winter and are usually in operation for only five – six weeks from mid-January onwards (Kuryk, 2003). In addition to this short winter road season, annual cycles of freezing and thawing of ice brings tremendous technical challenges in the design and construction of any physical structures, including that of winter roads (Kuryk, 2003). All these factors makes construction and maintenance of electricity transmission lines over long distances highly expensive (Manitoba Hydro, 2008). Further, total dependence on long transmission line 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.

Instead, Manitoba Hydro operates diesel generators to produce and supply electricity in each off-grid community. Near the generating stations, it also maintains fuel farms to store an estimated two years' worth of fuel as a hedge against any potential supply disruption (Manitoba Hydro, 2008). Each year, fuel required for the generators is trucked in over the winter road (CIER, 2006). For administrative purpose, these four off-grid communities are also collectively referred to as the "Diesel Zone" by Manitoba Hydro (Manitoba Public Utilities Board, 2010a). Table 1-2 shows the total installed capacity and average annual electricity consumption in the Diesel Zone. As seen in Table 1-2, the community of Shamattawa has both the largest installed capacity and the highest annual consumption, whereas the community of Tadoule Lake has the least of both.

Table 1-2: Total Installed Capacity and Average Annual Electricity Consumption in the Diesel Zone Communities of Manitoba.

	Diesel Zone Communities				Total
	Brochet	Lac Brochet	Tadoule	Shamattawa	
Total Installed Capacity (kW)	2,630	2,305	2,130	3,045	10,110
Average Annual Generation (MWh)	2,800	3,300	2,200	4,300	12,600

Source: Manitoba Hydro, 2008.

In each of the four off-grid communities, the residential sector not only comprises of the majority of the number of total customer served (approximately 80 %, as shown earlier in Table 1-1), but also consumes the bulk of the total electricity produced (approximately 80 %) (Manitoba Hydro, 2008). However, the power of electricity supplied to this class is limited to 60 Amps (Manitoba Hydro, 2008). This allows residential customers to use electricity for most domestic activities, except for space heating appliances (Manitoba Hydro, 2008). Manitoba Hydro (2011) notes that "heating with diesel generation is approximately 33 % efficient, whereas efficiencies of approximately 60 % to 86 % can be achieved with low and mid-efficient oil furnaces, respectively". As it is efficient to burn fuel directly, space heating in all the four communities is being met by either fuel oil and/or wooden furnaces (Manitoba Hydro, 2011). If the existing supply restriction continues, Manitoba Hydro projects that the annual community load will grow between the range of 2 ~ 4% (Manitoba Hydro, 2008).

Finally, all the four off-grid communities also have a distinctive tariff rate structure. Manitoba Hydro divides the customers in off-grid communities into three categories: 1) Residential, 2) General Service, and 3) Government and First Nation Education (Manitoba Public Utilities Board, 2010a). Table 1-3 shows the electricity tariff rate in the Diesel Zone for 2011/2012 (Manitoba Hydro, 2013b). As seen in the table below, tariff rate for all electricity consumed by the Residential Customers and the first 2,000 kWh by the General Service Customer is set at par with the grid connected customers in rest of the province. The general service customers are levied a surcharge for all consumption beyond the first 2,000 kWh. The Government and the school pay the highest tariff for all the electricity consumed as the rate includes full cost of service plus applicable subsides to the Residential and the General Service classes (Manitoba Public Utilities Board, 2010a).

Table 1-3: Electricity Tariff Rate for Manitoba's Diesel Zone in 2011/12.

Rate Class	Basic Monthly Charge	Current Rates
Residential (all kWh)	$ 6.85	$ 0.066 / kWh
General Service (< 2,000 kWh)	$ 18.25	$ 0.069 / kWh
General Service (> 2,000 kWh)	$ 18.25	$ 0.35 / kWh
Government and FN Education (all kWh)	$ 18.25	$ 2.13 / kWh

Source: Manitoba Hydro, 2011

1.2. Study Site

Brochet is located at 57°52′47″N 101°40′16″W and is approximately 125 km NW of Lynn Lake. Brochet Airport connects Brochet to the rest of Manitoba throughout the year via Thompson. During the summer months, the community is accessible via boat from Reindeer Lake and via barge from Kinoosao. The winter road from Lynn Lake to Brochet is the major transport route. It is constructed every winter and usually operates for five to six weeks starting from mid – January (Kuryk, 2003).

Unlike the other three off-grid communities (Lac Brochet, Tadoule Lake, and Shamattawa) in Manitoba, which are exclusively First Nation (FN) communities, Brochet is composed of two communities: Barren Lands First Nation (BLFN) under federal jurisdiction and the adjacent Non – FN community under provincial jurisdiction (Figure 1-2).

Figure 1-2: Map of Brochet.
Source: Google Earth, 2013 and NRCAN, 2013

The majority of people at Brochet rely on subsistence fishing, hunting, and trapping (Government of Manitoba, 2003). Table 1-4 shows the distribution of population and facilities in Brochet (Bhattarai & Thompson, 2012). As seen in the table, BLFN community has higher concentration of residential units, whereas the Non – FN community has a higher number of non-residential facilities. All the residential units and non-residential facilities in both communities have connection to the diesel generated electricity (Bhattarai & Thompson, 2012).

As seen in Figure 1-2 above, the diesel generating station and the fuel farm, consisting of 40 storage tanks with 50,000 litres capacity per tank, are both situated on the non–FN side of the community (Manitoba Hydro, 2010). However, the electricity produced is transmitted and distributed to both communities via a single micro-grid configuration. Thus, from an electricity perspective, both communities are treated as a single unit.

Table 1-4: Distribution of Population and Facilities in Brochet, 2011.

	BLFN	Non-FN community	Total
Population	417	120	537
Residential Units	95	31	126
Non-residential Facilities	6	13	19

Source: Bhattarai & Thompson, 2012

1.3. Problem Statement

The existing electricity system in the diesel zone has high economic cost. According to Manitoba Hydro, the total cost to provide service in these communities was $1.069 / kWh, including all depreciation and debt servicing costs; in contrast, the average cost of power generated and distributed on Manitoba Hydro's main grid was approximately 6.0¢ per kWh (Manitoba Public Utilities Board, 2010b). Variable cost represents the majority of the total cost of electricity provided in the Diesel Zone (Manitoba Hydro, 2011). For

2011/12, the total variable cost was estimated at 58.49 ¢ / kWh, and fuel cost alone represents approximately 62 % of this cost (Manitoba Hydro, 2011). In addition to high variable cost, the capital cost of the generating station and fuel farms, as well as expenses towards soil remediation resulting from accidental fuel spillage further increases the cost of electricity produced in the four off-grid communities (Manitoba Hydro, 2008). 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 (shown earlier in Table 1-3) approved by the Manitoba Public Utilities Board. The remaining portion of the total variable cost is cross subsidization by the grid-connected customers (Manitoba Hydro, 2011). 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 (Manitoba Hydro, 2011). Increasing the tariff rate for any customer class to reduce the deficient 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” (Weis & Cobb, 2008). Further, aboriginal poverty in Manitoba is chronic and persistent with rates as high as 42.3 % (Noël & Larocque, 2009).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 (AANDC, 2012b; Manitoba Hydro, 2011).

In addition to the high economic cost, the diesel based system also has high environmental cost. According to Manitoba Hydro (2008), approximately 8,000 tonnes of GHG is emitted from the diesel generating stations in the four off-grid communities. Diesel generation stations are the single largest source of GHG emissions in many off-grid communities (AANDC, 2012b; Bhattarai & Thompson, 2012). Similarly, the remote and isolated location of the off-grid communities also means that transport of fuel over considerable distances results in equally high amount of emissions of GHG and other air pollutants (Fennell & Thompson, 2013). Likewise, spillage and leakage during fuel transport and storage also results in pollution of air, water, and soil (Manitoba Hydro, 2011).

Apart from the economic and environmental cost, the diesel-based electricity system also faces increasing insecurity in its supply chain. The winter roads are open for a shorter period and have become less reliable due to changes in climatic conditions (CIER, 2006; Kuryk, 2003).

This study aims to address the high electricity cost, and emissions that are associated with the existing electricity system at Brochet. It will do this by determining an electricity system design that is low cost, low carbon, and yet has high reliability to replace the existing system.

1.4. Aim and Objectives

The aim of this study is to determine an optimum electricity system design for Brochet. The Merriam Webster dictionary defines optimum as “an act, process, or methodology of making something (as a design, system, or decision) as fully perfect, functional, or effective as possible; specifically: the mathematical procedures (as finding the maximum of a function) involved in this" (Merriam Webster, 2013). In this study 'optimum' is determined by high electric reliability, least cost, and low environmental impact. The study will explore three electricity generation design options for Brochet based on: 1) only fossil fuel, 2) only wind resource, and 3) a mix of both. The specific study objectives are:

1) Evaluate the Existing Micro-grid Configuration;
2) Determine an Optimum Micro-grid System Based Only on Conventional Fossil Fuel;
3) Determine an Optimum Micro-grid System Based Only on Wind Energy; and,
4) Determine an Optimum Wind-diesel Hybrid Micro-grid System.

1.5. Rationale

1. The likelihood of grid extension in the short to medium term to Brochet is considered small. Recently, the federal government denied a funding application of Shamattawa for connection to the provincial electricity grid, citing it as a cost ineffective option (CIER, 2012). This decision has implications for Brochet as it indicates that federal support for grid extension to the remaining off-grid communities in Manitoba seems unlikely (CIER, 2012), particularly as Shamattawa is closer to grid connection than others.

2. Currently the five–year capital plan for replacement of diesel generators in Brochet is under review (personal communication: Delphine Bighetty, BLFN Chief 2011 – 2012). The existing set of diesel generators was installed in 1999 and they are scheduled to be replaced by 2015/2016 (CIER, 2012). Furthermore, the diesel storage

farm in Brochet was constructed around 1989 and is also expected to be replaced around 2016/17 (CIER, 2012).

3. Recently, by Order 10/136, the provincial government gave high priority to reducing/eliminating GHG emissions from electricity generation in the off-grid communities (Manitoba Public Utilities Board, 2010b). As Brochet has multiple levels of governance, it is in a unique position to benefit from various incentive programs for deployment of renewable energy resources at both federal and provincial level (AANDC, 2012b).

4. Although, locally available hydro resources in Brochet have been extensively studied (CIER, 2012; Manitoba Hydro, 2008), the detailed screening of wind resources has not yet been conducted. Further, owing to ongoing improvements in wind turbine efficiency, and with more than a decade of successful operation of small and medium scale wind turbines in similar cold climatic region, such as Alaska, (Baring-Gould & Corbus, 2007), deployment of wind power in Brochet deserves a detailed analysis and serious consideration.

1.6. Significance

As this study is being conducted at a highly critical time, the technical and financial results of this study are expected to provide valuable information to Manitoba Hydro, policy makers at different tiers of government (provincial, federal and First Nations), potential investors, and Independent Power Producers (IPPs).

1.7. Summary

Even though approximately 90 % of the electricity generation in Manitoba occurs in the northern part of the province, four communities (Brochet, Lac Brochet, Shamattawa, and Tadoule Lake) in the province are yet to benefit from this renewable, low carbon source of electricity. Manitoba Hydro operates diesel generating stations in these communities to provide electricity. The existing electricity generation system has very high economic and environmental cost. This study aims at evaluating an optimum electricity system design for Brochet that is low cost, low carbon, and yet has highly reliable electric performance. The study will design and evaluate electrical, economic, and environmental performance of various micro-grids design scenarios based only on conventional fossil fuel, only on wind energy, and a mix of both to determine the optimum electricity system design for Brochet.

CHAPTER 2: LITERATURE REVIEW

This chapter starts by broadly defining and conceptualizing sustainable energy. Then, brief information on energy systems in remote off-grid communities in Canada is provided. This is followed by an introduction to energy system design tools, and the chapter summary is provided at the end.

2.1. Sustainable Energy

Sustainable development is defined as, “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland & others, 1987). The concept of sustainable development, or sustainability, has being gaining increased attention in the context of energy. To highlight this importance, the United Nations (UN) General Assembly designated the year 2012 as the ‘International Year of Sustainable Energy for All’(United Nations, 2011). Sustainable development within a society demands a sustainable supply of energy resources (that, in the long term, is readily and sustainably available at reasonable cost and can be utilized for all required tasks without causing negative societal impacts) and its effective and efficient utilization (Dincer, 2000).

In Canada, a sustainable energy strategy is divided into two groups: 1) energy efficiency, and 2) renewable energy (Liming, Haque, & Barg, 2008). Energy efficiency can be applied to both the supply and demand side by reducing energy wastage/leakage during generation and transmission and by increasing efficiency of the appliances on the demand side (end-users) (Kreith & Goswami, 2007; Liming et al., 2008). Whereas, renewable energy strategy can be applied to the supply side by incorporating local renewable energy sources (Thompson & Duggirala, 2009; Weis & Ilinca, 2008).

From a system's perspective, a society can achieve sustainable development and energy security only when its energy sources and systems are diversified and localized (Li, 2005).

2.2. Energy System in Remote Off-grid Communities of Canada

In almost all of the remote off-grid communities (more than 300 communities) in Canada, electricity is generated in the community itself (AANDC, 2012a; Kim & Leng, 1999). Although, the electricity is produced locally and near the electricity load, the electricity system is not sustainable. This is because electricity in all the off-grid communities is generaed by diesel powered generators (Kim & Leng, 1999). From a system prespective, the cost of electricity produced is primarily affected by three main components: 1) Investment and capital cost; 2) Operation and Maintenance cost; and 3) Fuel cost (Rad, 2011). Although, the diesel based system has low capital cost, the cost of electricity produced in remote locations is extremely high due to high fuel prices and heavy transportation and storage costs (Wies, Johnson, & Agrawal, 2012).

Incorporating locally available renewable resources such as wind, solar, and biomass in the electricity mix can be a cost effective alternative in many such remote off-grid communities (Freris & Infield, 2008; Pinard & Weis, 2003; Thompson & Duggirala, 2009; Weis & Ilinca, 2008). Harnessing wind resources decreases reliance on fossil fuels, reduces emissions of GHG gases, creates clean energy jobs, and has high potential in bringing revenue to the local communities (IRENA, 2012; Jamison et al., 2007). However, there is no 'one-size-fits-all' in the context of renewable energy systems because each community has a different load profile and the availiablity of renewable resources itself is site dependent (Cochran, Bird, Heeter, & Arent, 2012). As, the availability of renewable energy sources strongly depends on local weather and climatic conditions (Freris & Infield, 2008; Weis & Ilinca, 2010), the associated economic, technical, and geographical constraints must be considered in detail while designing an electric system that incorporates renewable resources (Hamilton, 2012). Generally, renewable energy technologies are characterized by higher initial capital cost (Lund, 2006). According to a recent survey, in addition to the higher capital cost, operating cost is also perceived as one of the most significant barriers preventing wide scale deployment of renewables in off-grid communties in Canada (Weis, Ilinca, & Pinard, 2008).

In many areas, where renewable energy resources cannot sufficiently meet the required electricity demand at a reasonable cost, or a very high reliability in electricity supply is needed, energy planners often design a hybrid energy system (Elhadidy & Shaahid, 2000). A hybrid renewable energy system is composed of at least one renewable and at least one conventional energy source in a stand alone or grid connected model (Rad, 2011). Hybrid energy systems based on renewables capitalize on the strengths of both conventional and renewable energy systems (Deshmukh & Deshmukh, 2008). By coupling both sources and coordinating the dispatch strategy, such systems provides reliable and high quality electricity at a lower cost (Lilienthal, Lambert, & Gilman, 2004). Hybrid design also helps diversify energy sources and eventually helps communities become more energy secure and sustainable (Li, 2005).

To date, 38 off-grid First Nations communities in Canada have successfully used hybrid electricity system by integrating either hydro or wind or natural gas in their electricity mix (AANDC, 2012a). A recent study identified that a large number of remote off-grid communities in Canada have high technical potential to integrate renewable energy in their electricity mix (Weis & Ilinca, 2010). A key driver in wide deployment of renewable energy technologies in many of these remote communities would be financial incentives and other regulatory strategies that reduce the cost of renewables (Weis et al., 2008; Weis & Ilinca, 2010).

2.3. Renewable Energy System Design Tool

Due to recent technological innovations, smart policy measures, and decreasing manufacturing cost, renewable energy has prolificated around the world (IRENA, 2012). This has also led to the development and application of various types of computer software in planning sustainable energy systems throughout the world (Bazmi & Zahedi, 2011). Electrical power systems are studied by simulating actual phenomena using models that reflect the physical elements of the system (Sallam & Malik, 2011). A review of myriads of different computer software and tools available to analyze integration of renewable energy is documented by various authors (Markovic, Cvetkovic, & Masic, 2011; Connolly, Lund, Mathiesen, & Leahy, 2010). As concluded by Connolly, Lund, Mathiesen, & Leahy (2010), “there is no energy tool that addresses all issues related to integrating renewable energy, but instead the ‘ideal’ energy tool is highly dependent on the specific objectives that must be fulfilled”. In the present study, two popular energy models: the RETScreen and HOMER models were initially considered in detail.

RETScreen ‘Clean Energy Project Analysis software’, developed by Natural Resource Canada, is a Microsoft Excel based spreadsheet model (NRCan, 2009). It allows comparisions between a ‘base case’, typically the conventional technology, and a ‘proposed case’ which is typically the clean energy technology (Markovic et al., 2011).

RETScreen uses a physical accounting methodology to provide techno-economic feasibility of application of a local single clean energy technology (Markovic et al., 2011).

The Hybrid Optimization Model for Electric Renewables (HOMER) model, developed by National Renewable Energy Laboratory (NREL), is used to design and compare energy systems with various configurations of both renewable and non-renewable resources (HOMER Energy LLC, 2012). HOMER is more detailed than the RETScreen software and concurrently considers several renewable technologies. HOMER reports both optimal and near optimal solutions.

As the objective of this study is to determine an optimum electricity system design on the basis of three major criteria - technical, economic, and environmental merit - the HOMER model was found to be the most suitable tool. Various studies have used the HOMER model, across Canada and around the world in a number of different applications (HOMER Energy LLC, 2012). Some major and widely cited studies in Canada include: “Pre-Feasibility Analysis of Wind Energy for Inuvialuit Region in Northwest Territories” (Pinard & Weis, 2003), “A feasibility study of a zero energy home in Newfoundland” (Iqbal, 2004), “Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland” (Khan & Iqbal, 2005), “Off-Grid Diesel Power Plant Efficiency Optimization and Integration of Renewable Energy Resources” (Lautier, Prevost, Ethier, & Martel, 2007), and “Assessing the potential for a wind power incentive for remote villages in Canada” (Weis & Ilinca, 2010).

2.4. Summary

Currently electricity in most of the remote communities in Canada is provided by diesel generators. This electricity generation system solely based on fossil fuel is highly unsustainable. Societies can benefit from low cost and low carbon electricity by incorporating renewable energy resources such as solar, wind, and biomass in the electricity generation mix. This helps make their energy systems sustainable and is a major step towards of sustainable development. There are a myrid of computer softwares to help design and analyze electricity systems based on renewable resources. Although both RETScreen and HOMER are energy pre-feasibility assessment softwares that are widely used to evaluate energy production, life-cycle costs, and greenhouse gas emission reductions for various types of renewable energy technologies, the HOMER model is considered best suited to meet the thesis objectives.

CHAPTER 3: RESEARCH METHODS

This chapter starts with a brief overview of the HOMER model as provided in its user's manual. Then, each study objective is re-stated along with the questions it seeks to answer and an outline of key steps taken in the energy modelling process. Next details on input data, collection method, and steps taken in data analysis are provided. Following this, details on how different electricity system designs were simulated in the HOMER model are provided. Finally, the study assumptions and limitations are presented.

3.1. Overview of the HOMER Model

The developers of the HOMER model have provided a detailed description of the HOMER model in "*Integration of Alternative Sources of Energy"* (Lambert, Gilman, & Lilenthal, 2005) and "*Computer Modeling of Renewable Power Systems"* (Lilienthal et al., 2004). As stated by Lambert et al. (2005), 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". The HOMER model is highly flexible and can model both off-grid and grid connected micro-grid power systems serving electric and thermal loads (Lambert et al., 2005). It can simultaneously model both AC and DC in the design system with any combination of PV modules, wind turbines, small hydro, biomass power, reciprocating engine generators, micro turbines, fuel cells, batteries, and hydrogen storage (Lambert et al., 2005). Input to the HOMER model includes:

1. Loads: primary, deferrable and thermal load.

2. Components: PV, wind turbine, hydro, diesel generators, grid, battery, converters, electrolyzers.
3. Resources: solar, wind, hydro, biodiesel, ethanol, propane.
4. Economics: annual real interest rate, project lifetime, cost of unmet load, fixed capital cost, fixed operation and maintenance cost, carbon tax.
5. System controls: Dispatch strategy (load following, cycle charging), which determines how the generator(s) charge the battery bank.
6. System constraints: operating reserve, maximum annual capacity shortage, and minimum renewable fraction.
7. Optimization: values of each optimization variable (such as fuel price and wind speed) that are used to build the set of all possible system configurations.

The HOMER model performs three principal tasks: 1) simulation, 2) optimization, and 3) sensitivity analysis and their functional relationship is graphically represented in Figure 3-1 below (Lambert et al., 2005).

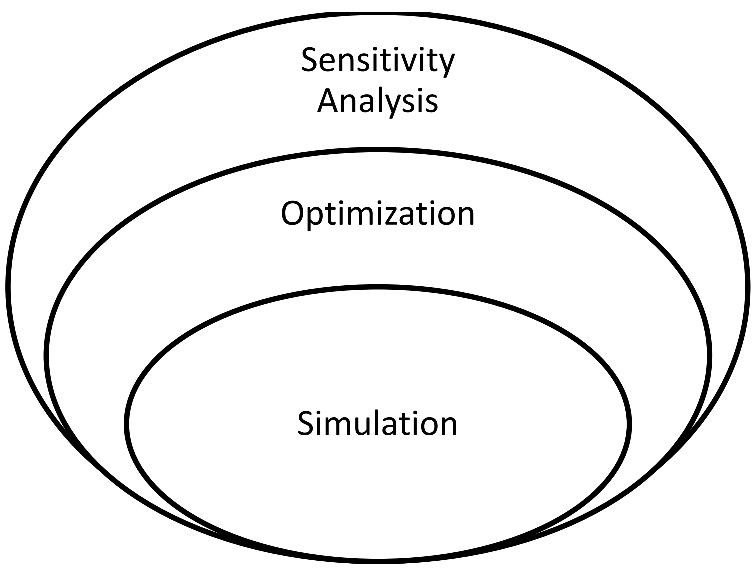

Figure 3-1: Conceptual Relationship of Various Functions of the HOMER Model. Source: Lambert et al. (2005).

As shown in Figure 3-1 above, the HOMER model performs multiple simulations for a single optimization process, and multiple optimizations for the sensitivity analysis process. The HOMER model simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year and performs optimization and simulation analysis in time steps of up to one minute resolution (Lambert et al., 2005). This fine resolution greatly increases the robustness of the model as it allows the energy designer to evaluate the performance ability of the HOMER model close to a real world scenario. In the optimization process, multiple simulations are performed and the results are presented for in three broad performance categories: 1) electrical, 2) economic, and 3) environmental impact (Lambert et al., 2005). The electrical performance category provides information on production and consumption of electricity and gives detailed analysis of percent of excess electricity, unmet electric load, and capacity shortage across various temporal scales (Lambert et al., 2005). In the economic modeling, the HOMER model performs lifecycle cost analysis that incorporates all capital and operating costs that occur within the life span of the system (HOMER Energy LLC, 2012). The economic performance provides net present and annualized cost summary and cash flow (Lambert et al., 2005). In the environmental impact category, the HOMER model evaluates emissions of pollutants such as carbon dioxide, carbon monoxide, unburned hydrocarbon, particulate matter, sulfur dioxide, and nitrogen oxide (Lambert et al., 2005). Finally, in the sensitivity analysis or 'what-if' analysis, multiple optimizations are performed to analyze the sensitivity of output results for changes in the input variables. The basic version of the HOMER model can be freely downloaded from HOMER Energy's webpage (www.homerenergy.com).

3.2. Objectives and Steps

The aim of this study is to determine an optimum electricity system design for Brochet on the basis of high electric reliability, least cost, and low environmental impact. In the first step, the community load was investigated to understand the exact nature of the electricity demand in Brochet. Then, the existing system is benchmarked to establish reference points to measure performance. Afterwards, the study will explore three electricity generation options for Brochet based on: 1) only fossil fuel, 2) only wind, and 3) a mix of both. The questions that each objective aims at answering and the outline of steps taken in the HOMER model is categorically presented below:

<u>First Objective</u>: Evaluate the Existing Micro-grid Configuration.

The purpose of the first objective is to find answers to the following questions:

1) What is the type and characteristic of electricity load in Brochet on a temporal scale?

2) What is the electricity performance, economics and emissions of the existing micro-grid configuration?

To answer the first question, the actual electricity power produced at the Brochet generating station was analyzed. It will provide information on the nature of the load as well as identify daily, monthly or seasonal variations. This annual load information along with other technical and economic information of the existing diesel generating system will then be simulated in the HOMER model. The simulation results (electrical, economic, and environmental performance) will help standardize the results the existing system and facilitate comparison of results with various other design scenarios. The outline of the steps relating to the first objective is presented in a graphical form in Figure 3-2 below:

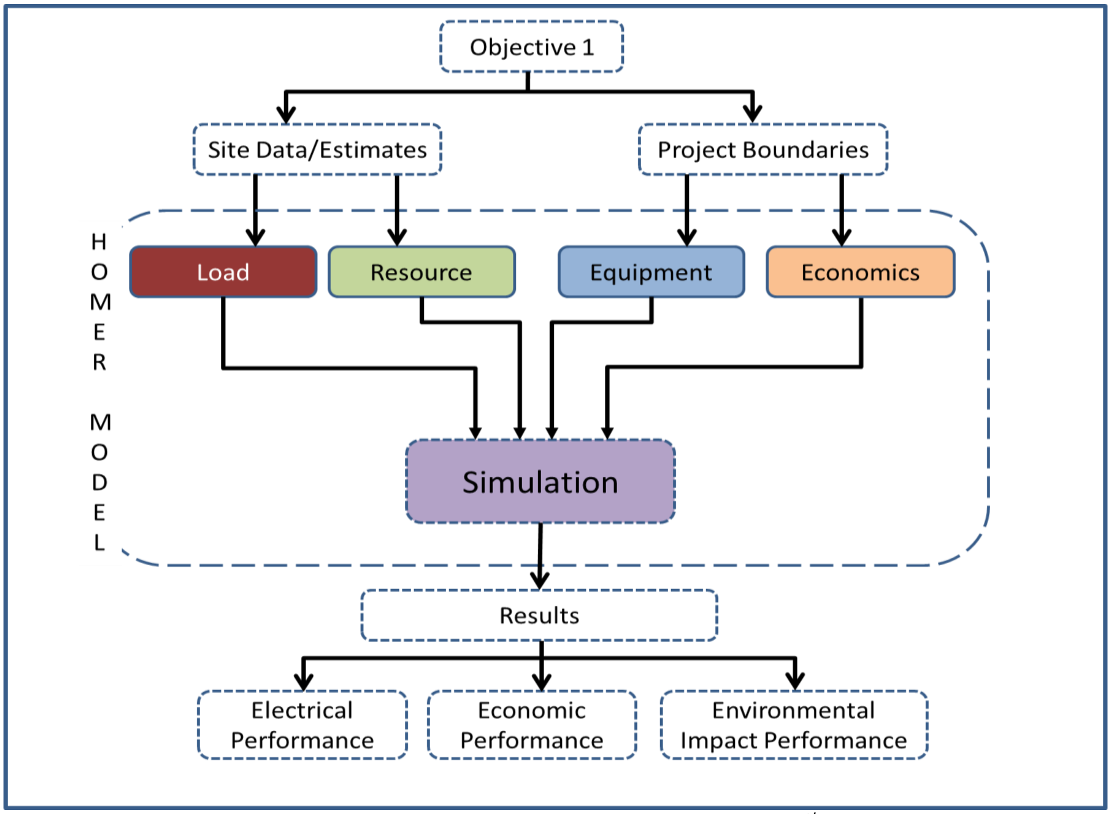

Figure 3-2: Schematics of HOMER Model in Relation to the 1st Objective. Modified from Furtado, 2012

<u>Second Objective</u>: Determine an Optimum Micro-grid System Based Only on Conventional Fossil Fuel.

The purpose of the second objective is to find answers to the following questions:

1) What is the optimum size and unit configuration of diesel generators that meets the electricity demand for Brochet?

2) Does such system provide benefits of lower cost of electricity and reduced emissions?

As discussed earlier, many remote communities have excess installed capacity; including the existing system at Brochet. Among various reasons for oversized systems, lack of reliable and high resolution load data is one of the most important and frequently occurring factors (Elma & Selamogullari, 2012). To avoid this problem, the actual power generation data log for 2011 at Brochet Generating Station that was used in the benchmarking step was reassigned to determine an optimum microgrid system based only on diesel fuel. As this objective explores the scenario of multiple reduced sized diesel generators to replace the existing power generation system at Brochet, all the inputs used in the benchmarking process were reassigned, except for the existing equipment. Instead, discrete size of diesel generators that closely matches the actual electricity demand at Brochet were analyzed and simulated in the HOMER model. Then, the optimization run in the HOMER model was used to determine the optimum configuration of such a system. Finally, the economic, electrical and environmental performance results of the optimized system were compared with the existing configuration to determine if the optimized configuration reduces the cost of electricity produced as well as the emission of pollutants. As seen in Figure 3-3, all the steps taken to achieve the second objective are similar to the first objective except that in this step instead of directly analyzing the simulation results; optimization run were first performed.

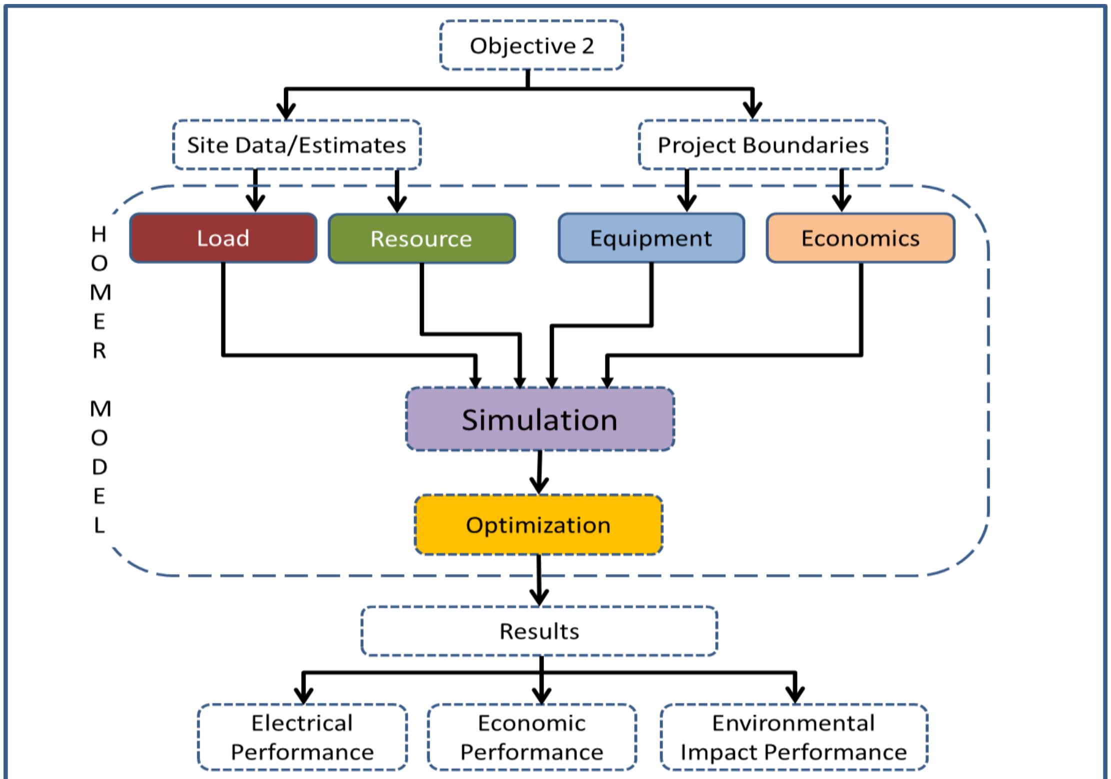

Figure 3-3: Schematics of HOMER Model in Relation to the 2nd Objective. Modified from Furtado, 2012

Third Objective: Determine an Optimum Micro-grid System Based Only on Wind Energy.

The purpose of the third objective is to find answer to the following question:

1) Is sufficient wind resource locally available at Brochet to design a wind only system?

In the first step, meteorological data collected at the Brochet Airport were analyzed to assess available wind resource. Due to the lack of good wind (results presented later in Section 4.3.1) and any viable bulk energy storage option (analysis and discussion given later in Section 4.3.1), micro-grid system based only on wind energy was not analyzed.

Fourth Objective: Determine an Optimum Wind-diesel Hybrid Micro-grid System.

The purpose of the fourth and final objective is to find answers to the following questions:

1) What is the optimum configuration of wind-diesel hybrid system that is economic, has high electricity performance, and has low emission of pollutants?

2) How does it compare to earlier scenarios in terms of cost of electricity, emission of pollutants, and electricity performance?

3) How does the variability in fuel price and wind speed affect the economics of the system?

In this scenario, multiple reduced size diesel generators, various size and capacity of wind turbine models and storage options were simulated in the HOMER model according to the following steps:

1. The actual load information (used in objective 1) and all the relevant inputs used in exploring objectives 2 and 3 were re-assigned to the HOMER model. Multiple reduced size diesel generators, various capacity of generic wind turbine model and storage option were simulated in the HOMER model.

2. Optimization run was performed in the HOMER model and the optimum configuration of the hybrid model was selected on the basis of least cost of electricity. The results (electrical, economic, and environmental performance) were compared with previous results obtained under objective 1 – 3.

3. Sensitivity analysis on escalation of fuel price and variation in wind speed were conducted to determine the effects on cost of electricity produced as well as emissions of the optimum wind-diesel hybrid system. All the steps taken to achieve this fourth study objective are exactly the same as the one followed to achieve the second objective except for the additional component of sensitivity analysis (shown in Figure 3-4).

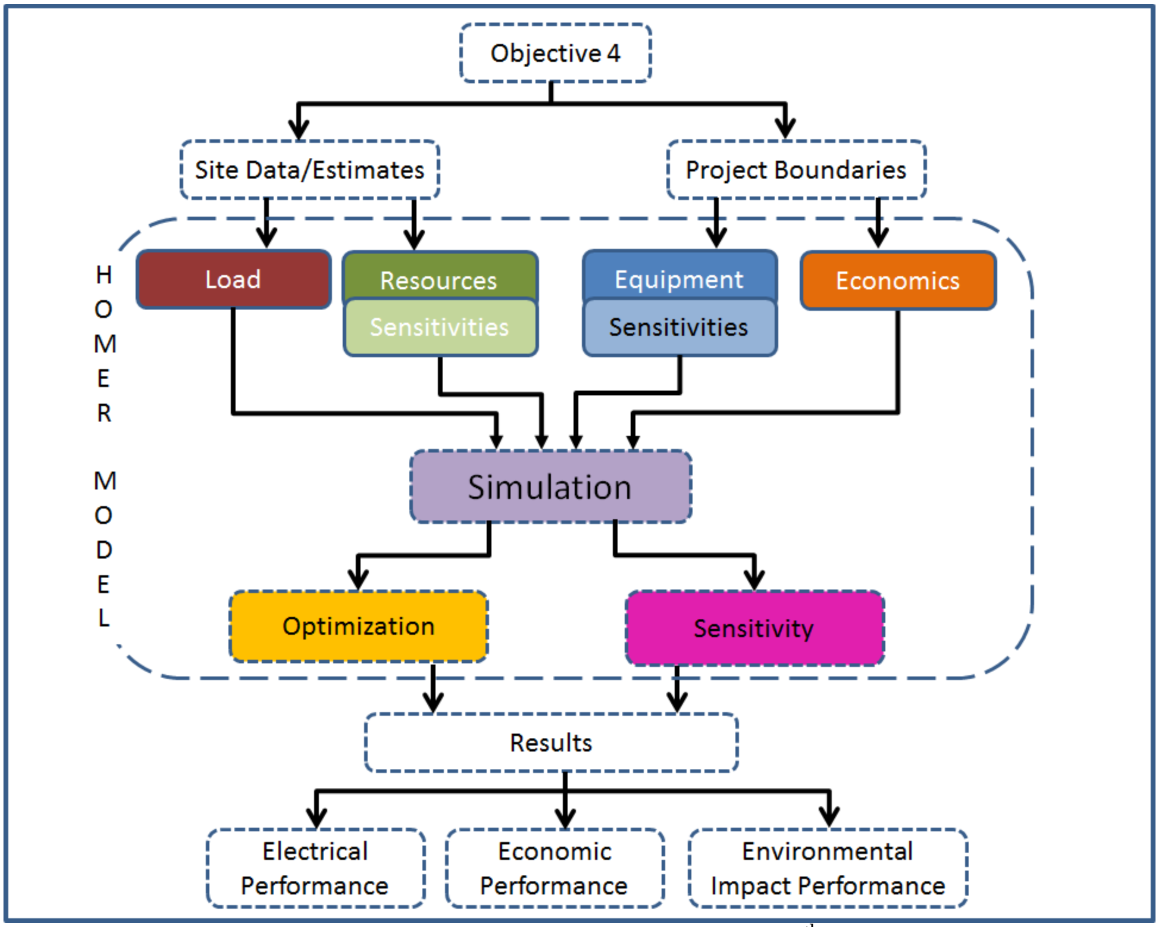

Figure 3-4: Schematics of HOMER Model in Relation to the 4th Objective. Modified from Furtado, 2012

3.3. Input Data

The HOMER model (Version 2.81) was used to benchmark the existing power configuration as well as to conduct the prefeasibility of various electricity generation system designs as outlined in the section of objectives 2 – 4 above. The following sections provide detailed information and analysis on various inputs used in the HOMER model as well as their data sources and collection method.

3.3.1. Load

Load profile represents electricity usage pattern for a given period (Jain, 2011). Accurately constructing and predicting a load profile is a very challenging task as actual amount of electricity consumed in a community is determined by various factors such as number and type of buildings, occupancy rate, income level, local climatic conditions, and number of end appliances (Devine, 2005; Ihbal, Abd-alhameed, & Jalboub, 2012). This study uses actual 15 – minute time step power generation log data for 2011 from Brochet (provided by Manitoba Hydro under Non – Disclosure Agreement) to create the community electricity load profile. This top down approach was chosen because it is highly accurate as it accounts for distribution and transmission loss as well as parasitic loads. Microsoft Excel (Version 10) was used to pre – process the data and organize it in the format accepted by the HOMER 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 the 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.

3.3.2. Equipment

a) Diesel Generators: An analysis of monthly peak and average load value against the rated output capacity of various sizes of diesel generator 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) and is provided in Appendix A. Cost information on capital, replacement, and Operation and Maintenance (O&M) are based on a study done by Manitoba Hydro (2008).

b) Wind Turbine: This study used two major criteria, as strongly suggested in "Expert Group Study on Wind Energy Projects in Cold Climates" (Laakso, Tallhaug, & Ronsten, 2005), to screen the wind turbines with potential of deployment in Brochet: 1) ability to operate in cold climatic conditions and 2) transport logistics. Figure 3-5 shows that winter temperature at Brochet can fall to – 35 °C and only a few wind turbines can withstand such cold temperatures (Laakso et al., 2005).

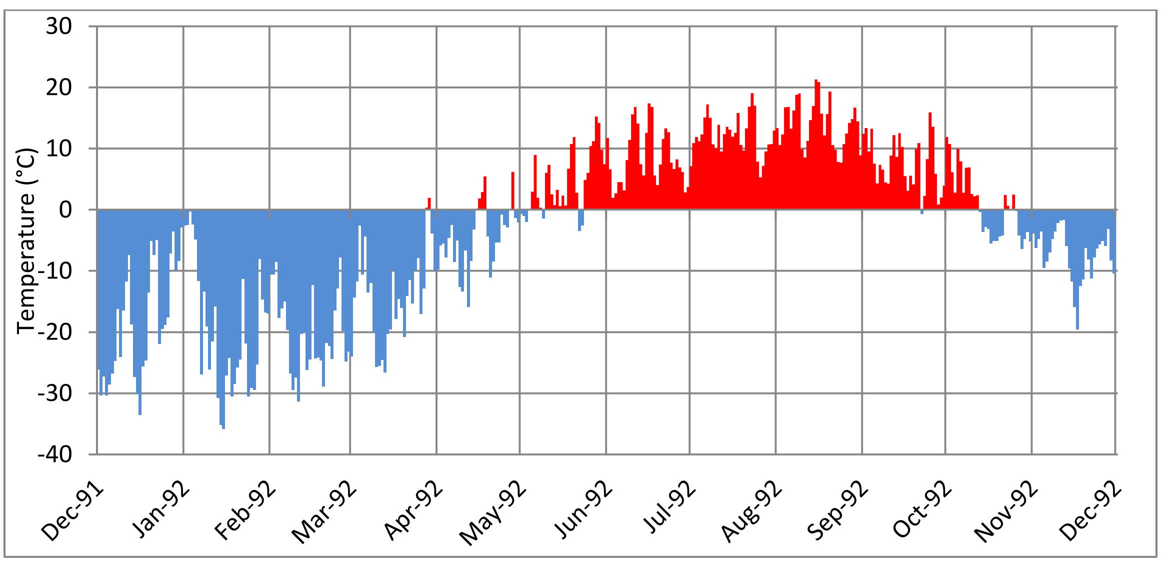

Figure 3-5: Hourly Temperature Profile from December 1991 to November 1992 at Brochet, Manitoba.
Data Source: NOAA, 2012

In addition to the operability issue in cold climatic conditions, the issue of transport logistics is also critical. The permanent road from Winnipeg extends only up to Lynn Lake and from there onwards a winter road connects to Brochet (Figure 3-6). The map was drawn using ESRI ArcGIS (Version 10.0). Unlike most provincial highways, winter roads constructed over the packed snow have lower allowable maximum vehicle load limits (Government of Manitoba, 2013a). The maximum Gross Vehicle Weight (GVW) permitted on winter roads for full commercial loads is 37.5 tonnes (Government of Manitoba, 2013a). In addition to the weight constraint, transporting wind turbines to Brochet also face a bridge-width restriction of 4.25 m (Government of Manitoba, 2013a).

Based on these criteria's, this study selected Northwind power (NW 100kW) and Aeronautica (AW Norwin 29/225 kW). The rated capacity and power curve were accessed from the in-built library in the HOMER model itself. The cost information was estimated after reviewing other studies and interviewing local wind turbine dealers and suppliers.

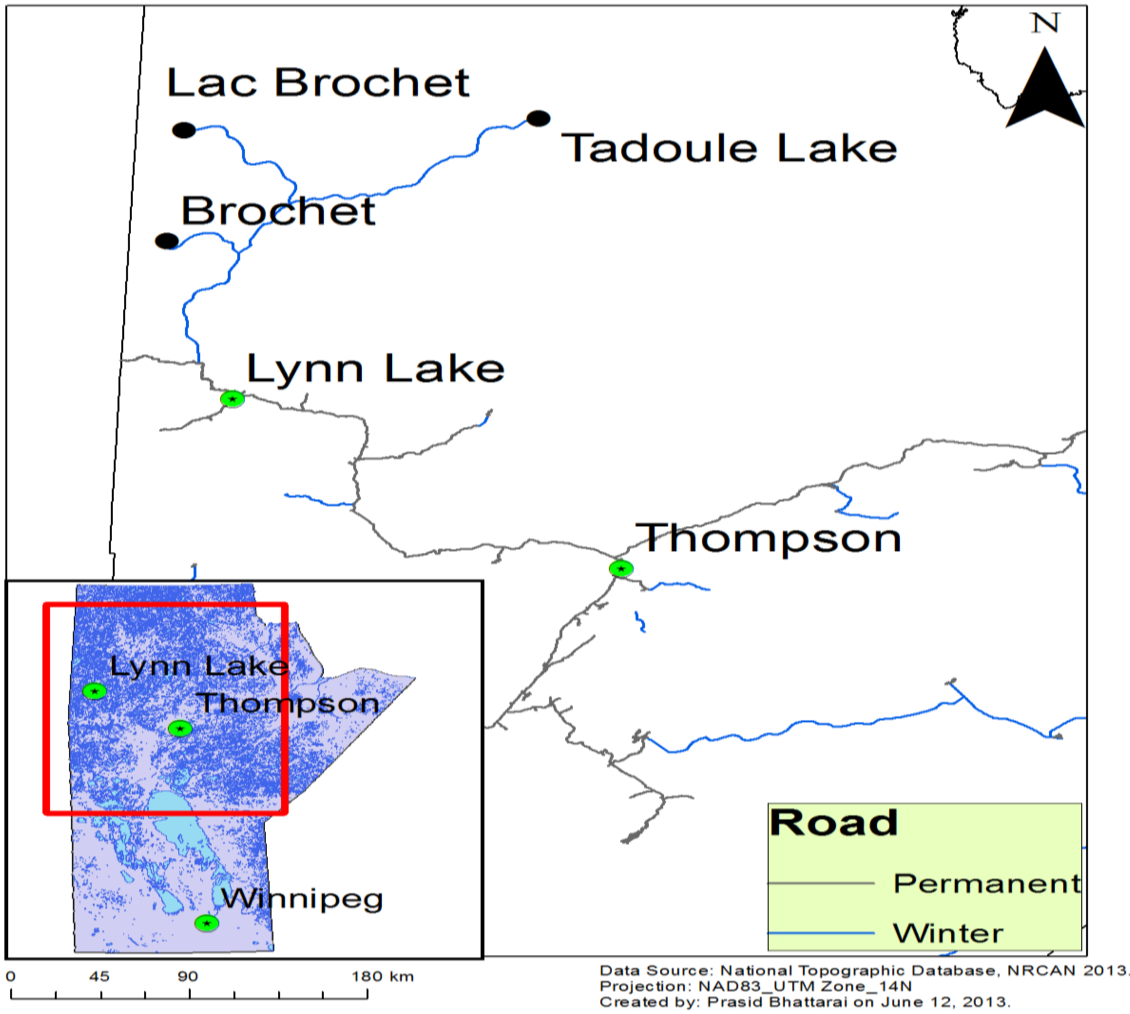

Figure 3-6: Winter Road Map from Lynn Lake to Brochet.

c) Battery Storage: 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. (Ibrahim, Ilinca, & Perron, 2008; Ross, Hidalgo, Abbey, & Model, 2010). Thus, this study also uses Lead-Acid Battery for energy storage. Information on various sizes and capacity of storage and conversion medium was obtained by reviewing various documents and interviewing local suppliers.

3.3.3. Resources

a) Diesel: In a recent study done by Manitoba Hydro in the context of off-grid communities, an average annual delivered fuel price of $0.86 per liter was assigned for Brochet (Manitoba Hydro, 2008). That report cited "2006 Manitoba Hydro 20-year diesel price forecast for fiscal year 2006 to 2026" as the source of the fuel price information. This landed fuel price is surprisingly low. Figure 3-7 shows the historical rack rate of average monthly diesel price index for Winnipeg.

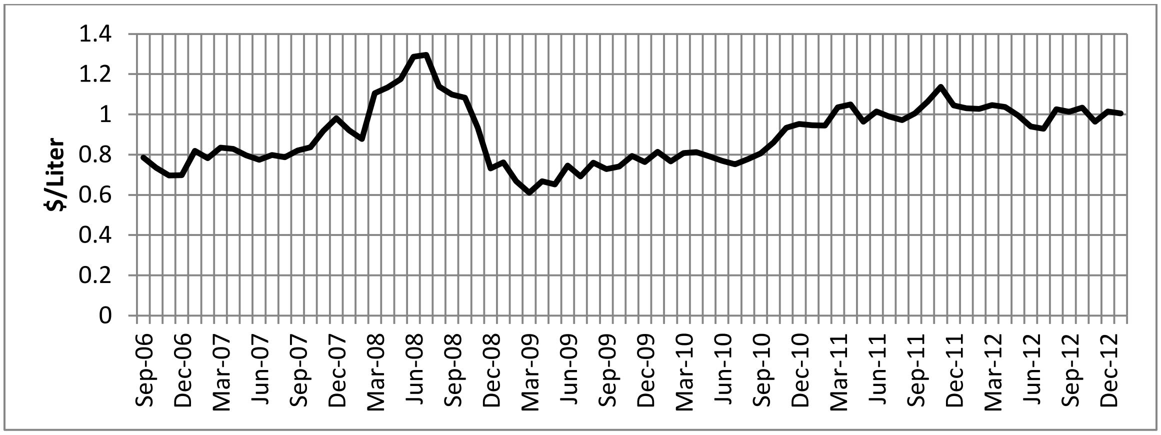

Figure 3-7: Monthly Average Diesel Fuel Price Index for Winnipeg.
Data Source: Government of Manitoba, 2013a

As seen in the figure above, in the recent years, the average diesel price has been above $0.86/liter. Initially, it was thought that perhaps Manitoba Hydro benefits from the economics of scale while procuring the fuel. Every fall, Manitoba Hydro calls for tender to procure fuel to the Diesel Zone communities for the forthcoming winter (Manitoba Public Utilities Board, 2011). However, as Manitoba Hydro is charged the applicable rack rate at the time of actual fuel shipment (Manitoba Public Utilities Board, 2011), the initial assumption was ruled out. Another possible explanation for the low cost used by Manitoba Hydro in its calculation is that the transportation cost is fully subsidized by various agencies and thus is not directly calculated in the cost of electricity produced. As the original report ("2006 Manitoba Hydro 20-year diesel price forecast for fiscal year 2006 to 2026") referred in Manitoba Hydro's study is not publicly available and could not be accessed, its basic assumptions and methodology could not be analyzed in detail. Interestingly, a study by Kuryk (2003) estimated the normal winter road fuel hauling cost for Brochet at $0.25/liter but unfortunately did not give any details on the applicable amount of subsidy. In addition, the federal and provincial tax exemption to the reserve community also reduces the fuel cost in these communities (AANDC, 2010). Considering the escalation in recent fuel price (as seen in Figure 3-7 above), this study cautiously assumes that the landed cost of diesel at Brochet to be at an average of $1.00/litres. This study uses default fuel properties of diesel that is provided in the HOMER model (Appendix A).

b) Wind Resource: As the cost of electricity produced is highly dependent upon the availability of useful wind resource, energy planners should give detailed consideration in assessing the wind resource and properly understanding and analyzing its spatial and temporal variations (Jain, 2011).

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. The map has been generated by using a meso-scale numerical model and has a 5 km resolution coverage for all of Canada (Yu et al., 2006). 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 (Environment Canada, 2003). This average mean wind speed is derived from a 43 year period (from 1958 till 2000) (Environment Canada, 2003). 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 (Jain, 2011). Thus, such large area maps can be considered only as indicative and need to be validated with on-site measurement (Jain, 2011; Yu et al., 2006).

As in many remote communities, there is no dedicated meteorological station at Brochet (CIER, 2012). However, the local Brochet Airport maintains manual records on wind speed, wind direction, and temperature data. One such recent dataset from April 2009 to the end of March 2011 was initially analyzed. The dataset consisted of only four records made at 7 a.m., 9 a.m., 11 a.m., and 2 p.m. for five working days per week. This sparse data could only be used to arrive at the monthly average wind speed. When monthly average values are entered in the HOMER model, the model assumes that the value is true for each hour of each day for the entire month. This is a very gross exaggeration as wind speed shows high inter and intra daily variations.

The only available continuous hourly meteorological record at Brochet was from November 1991 till December 1992. The data was collected at Brochet Airport (tower height 10 m) and was accessed from National Oceanic and Atmospheric Administration (NOAA)'s National Climatic Data Center website.

In the absence of sufficient wind data from the site of interest, one common industry practice is to correlate the available data with concurrent records from a nearby station (preferably within 100 km) to generate predictions (Gipe, 2004; Jain, 2011). The nearest meteorological station is Lynn Lake Airport which is at a distance of 125 km south of Brochet. Environment Canada's National Climate Data and Information Archive (www.climate.weatheroffice.gc.ca) maintains hourly records of wind speed, temperature, wind direction and other related parameters for the Lynn Lake station. Following the recommendation of Jain (2011), seasonal and diurnal variations in wind speed, correlation of raw wind speed and wind direction for the concurrent period at both sites were analyzed to determine if the sites are similar in which case would allow using recent data from Lynn Lake as a surrogate.

However, meteorological data at Lynn Lake Airport (as shown in the Appendix B) was found to be significantly different to Brochet in direction as well as wind speeds according to correlation and other analysis and so it was not applied.

This study used the historical meteorological data covering a year from 1991 to 1992 from Brochet based on literature stating that one year wind speed sufficiently predicts the long term wind profile of the region. “One statistically developed rule of thumb is that one year of record data is generally sufficient to predict long-term seasonal mean wind speeds within an accuracy of 10 % with a confidence of 90 %” (Aspliden, C. I., Elliot, D. L., Wendell, (1986) in Manwell, McGowan, & Rogers (2002) pp. 26)

Data were pre-processed using Microsoft Excel (Version 2010). The archived data were categorically organized and then evaluated for data completeness. Table 3-1 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. 8,760 hours. As seen in the table below, the available data is fairly complete.

Table 3-1: 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	2,443	90.7	1,103

In the original data, missing values (denoted by blank cells) ranged from a single value to the maximum of three consecutive days (72 hours). However, the HOMER model required a complete set of 8,760 hours to represent a full year and doesn't allow 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.

As the data set was fairly complete, averaging to fill the missing value for two – three days is assumed to have less impact on the overall evaluation of the wind resource in Brochet. The best practice would have been to ignore such data for further analysis (Jain, 2011). For the wind direction, the averages were smoothed out to reflect the wind directions in the receding hours. As no information on standard deviation was available, detailed statistical analysis could not be performed. Also, as temperature data are not directly used as an input in the HOMER model, no further analysis was performed.

3.3.4. Economics

This study used the project life time of 20 years and interest rate of 6 %. Table 3-2 shows the cost of components used in this study. The diesel costing was based on the study done by Manitoba Hydro (2008). Cost information of two models of wind turbines (AW Norwin 225 kW and Northern Power NW 100 kW), Surrettee Battery Pack (6CS25P) and converter were all based upon review of literature and by interviewing local suppliers in Winnipeg.

Table 3-2: Assumed Cost of Components Used in the HOMER Model.

Components	Cost		
	Capital	Replacement	O & M
Diesel Generator [1]	$1,300/ kW	$594/kW	$33.16/hr
AW Norwin 225 kW [2]	$675,000/turbine	$562,500/per turbine	$2,000/year
Northernpower NW 100 kW[3]	$550,000/turbine	$500,000/per turbine	$2,000/year
Surrettee Battery Pack (6CS25P) [4]	$1,250/unit	$1,100/unit	$15/year
Converter[5]	$800/kW	$750/ kW	$10/year

(Source: [1] Manitoba Hydro, 2008; [2-5] Literature review & interview with local suppliers)

3.3.5. System Control

This study uses a 60 minute simulation time step. In addition, the following system controls in the HOMER model for Brochet (Table 3-3).

Table 3-3: System Controls Used in the HOMER Software.

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

3.3.6. System Constraint

This study assigned the following system constraints to the HOMER model (Table 3-4).

Table 3-4: Spinning Reserve Inputs to the HOMER Software.

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

3.3.7. Optimization and Simulation

This study assigned the following values during the simulation of the optimum wind-hybrid system to under-stand how wind speed and diesel price affects the cost of electricity produced.

Table 3-5: Variables of Wind Speed and fuel price used in the simulation run.

Wind (m/s)	Diesel ($/L)
5	1
5.5	1.2
6	1.4
6.5	1.6
7	1.8

3.4. Micro-grid design in the HOMER model

1) Existing System at Brochet: The diesel generating station at Brochet has an installed capacity of 2.63 MW consisting of two Caterpillar 3512B gen sets, each rated 1015 kW at 1200 rpm, and one Caterpillar 3508B gen set, rated 600 kW at 1200 rpm (Figure 3-8) (Poweronline.com, 2000). During normal operations, only one 1015 kW gen set is used while the other 1015 kW gen set is constantly kept on stand-by (Manitoba

Hydro, 2008). 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 (Manitoba Hydro, 2008).

Figure 3-8: Existing Diesel Generators at Brochet.
Source: Poweronline.com, 2000

In the HOMER model, one 1015 kW gen set was forced to run all the time, while the operational mode of the other unit of 1015 kW was set as optimized, and the backup unit of 600 kW was kept as stand-by (Figure 3-9). When operation of the gen set 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.

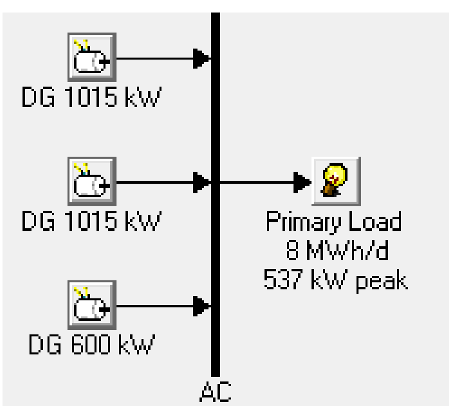

Figure 3-9: Representation of the Existing System in the HOMER Model.

2) Determination of Optimum Diesel System: In this scenario, multiple reduced sized diesel generators were considered to replace the existing power generation system at Brochet. As discussed earlier, many remote communities have excess installed capacity; including the existing system at Brochet (as shown later in Figure 4-4). Among various reasons for oversized systems, lack of reliable and high resolution load data is one of the most important and frequently occurring factors (Elma & Selamogullari, 2012). To avoid this problem, the actual power generation data log for 2011 at Brochet Generating Station that was used in the benchmarking step was reassigned to determine an optimum microgrid system based only on diesel fuel.

As shown in Figure 3-10 below, the electricity system based only on conventional fuel has the same components as the existing system. In this system, a single unit of 500 kW, 750 kW, and 830 kW and dual units of 455 kW, and 600 kW were simulated in the HOMER model. To ensure no capacity shortage occurred, the selection of these discrete sizes of gen sets was based upon their rated output and the average and peak load at Brochet. Further, similar to the existing configuration, one unit of 600 kW was configured to be an ultimate backup.

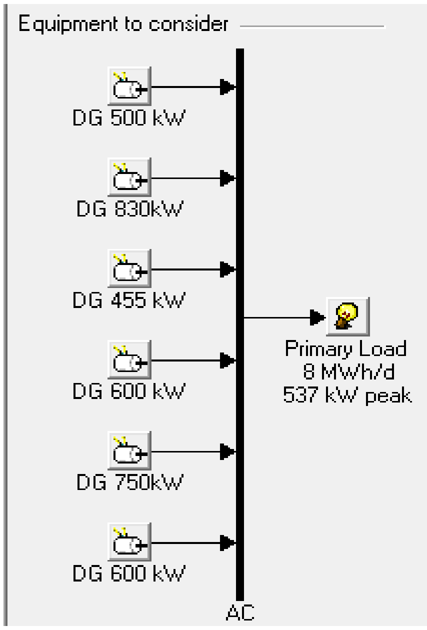

Figure 3-10: Simulation of the Multiple Reduced Sized Generators in the HOMER model.

Table 3-6 shows the choices of various discrete generator sizes that were entered in the HOMER model to determine the optimum size of the gen set. Assigning 0 in the sizes allows the HOMER model to discard a certain gen set specification from the optimization result, if it does not meet the constraint assigned.

Table 3-6: Sizes to Consider for Various Generators Used in the HOMER Model.

455 kW	500 kW	600 kW	600 kW	750 kW	830 kW
0	0	600	0	0	0
455	500		600	750	830
910					

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. The fuel consumption values of varying generators considered in the study are given in Appendix A. Economics and system constrains entered while benchmarking the existing system were reused in this system (provided in Appendix A).

3) Determination of Optimum Wind-Diesel Hybrid System: This wind-diesel hybrid micro-grid system considers power generation from a mix of conventional diesel generators and wind turbine as an alternate to the existing system. As seen in Figure 3-11, the wind diesel hybrid system has dual units of 600 kW capacity gen set, two wind turbine models (Northern Power 100 kW and AW Norwin 225 kW), battery storage, and converter. As in the earlier scenarios, one unit of 600 kW generator was configured as the ultimate back up and the other was configured to run at an optimized mode. Both wind turbines 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. Further information on cost, fuel consumption, power output and emissions are provided throughout Appendix A.

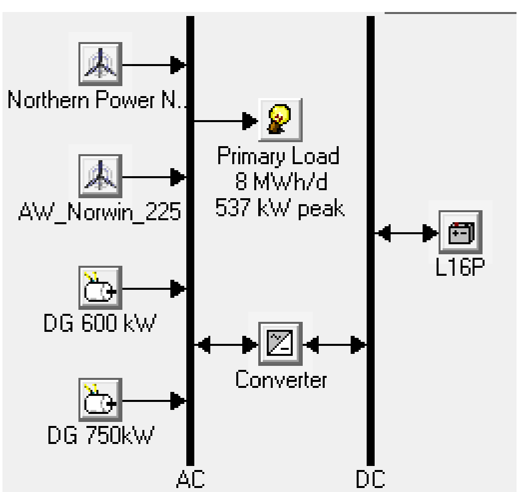

Figure 3-11: Representation of Wind-Diesel Hybrid System Design in the HOMER Model.

Table 3-7 shows the size choices of various components that were entered in the HOMER model to determine the optimum wind-diesel system. As mentioned earlier, assigning 0 in the sizes allows the HOMER model to discard that component altogether from the optimization result if certain constraints are not met.

Table 3-7: Sizes to Consider for Various Components for the Hybrid System.

AW Norwin (225 kW)	NW (100 kW)	Surrettee (6CS25P)	Converter	600 kW	600 kW
0	0	0	0	0	600
1	1	1	50	600	
2	2	2	100		
3	3	3			
4		4			
5		5			
		6			
		7			
		8			
		9			

3.5. Assumptions

Most electric systems are designed to accommodate an estimated future load growth. But, this study assumed that the current electricity supply constraint will continue in the future. This is because the HOMER model assumes that the electricity load is constant throughout the project lifetime. One way to approximately solve this issue is to construct a discrete HOMER model for the growth anticipated year. Then, the results of all such HOMER models are aggregated in a separate spreadsheet. In addition, the total electricity generated at Brochet station is considered as only base load. This means that any design systems under consideration must immediately meet this primary electricity demand to avoid unmet electricity load. Wind data collected at the local Brochet Airport is assumed to be reliable and representative of the local conditions.

3.6. Limitations

As mentioned earlier, the existing generators at Brochet were installed in 1999 and are schedule to be replaced in 2015/2016 (CIER, 2012). In the absence of information on current emission rate of the existing diesel generators (hereafter referred to as 'gen sets'), emission rates of new gen sets of same specification were entered while benchmarking the existing system in the HOMER model. Thus, emission results recorded by the HOMER model in the benchmarking stage were that of new gen sets for existing specifications. Although, the HOMER model uses life cycle costing, it does not consider fuel storage and clean-up cost for diesel based system. If such cost is further incorporated in the model, then the cost of the electricity produced by diesel generator would be significantly higher. Further, the cost of wind turbine varies depending on the mode of transport, number of turbine, local geology which in turn affects the cost of the tower foundation. As generalized economic values have been used in this study, the results might vary when a detailed economic assessment is performed. This study will not evaluate power quality, life cycle assessment, social acceptability of the results, and business model and financing options of the proposed energy designs. All of those topics deserve an in-depth study in their own merit. In addition, energy savings resulting from energy efficiency measures will not be modeled because of the simulation inflexibility of the HOMER model.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter starts by evaluating the detailed temporal variations (intra-annual, seasonal, daily, and diurnal) of the electricity load at Brochet. Then, the existing system is first simulated in the HOMER model and the results (electrical, economic, and environmental performance) are categorically presented to form a basis for subsequent analysis. In Section 4.2 and Section 4.3, results of objective 2 and 4 are categorically presented. In Section 4.3 a detailed analysis on locally available wind resource at Brochet is provided. Finally, in Section 4.5, overall study results are discussed.

4.1. Evaluate the Existing Micro-grid Configuration.

4.1.1. Analysis of Electricity Load in Brochet

The intra-annual variation of the electricity produced at Brochet Generating Station was analyzed by using actual log data of 15 – minute time step (provided by Manitoba Hydro) from year 2007 until 2011. In the first step, electric load values for all the years were analyzed. During the study period, the annual average load was fairly consistent at 320 kW, whereas the annual average peak load was in the range of 520 – 595 kW. In addition, a load duration analysis for each year was performed by constructing load duration curve that shows the power output verses the number of hours in a year. The results showed that the most recent power generation data did not vary from the load profiles of previous years from 2007 – 2010 and for all the years, the diesel generators produced power in a consistent manner (results not shown for proprietary reasons)*. The result also validates that the power generation data of 2011 is representative of long term electricity load at Brochet.

Figure 4-1 shows the average monthly electricity production for 2011at Brochet. As seen in Figure 4-1, high electricity production coincided with the winter months from October till April, whereas a lower amount was generated during summer months from May till July.

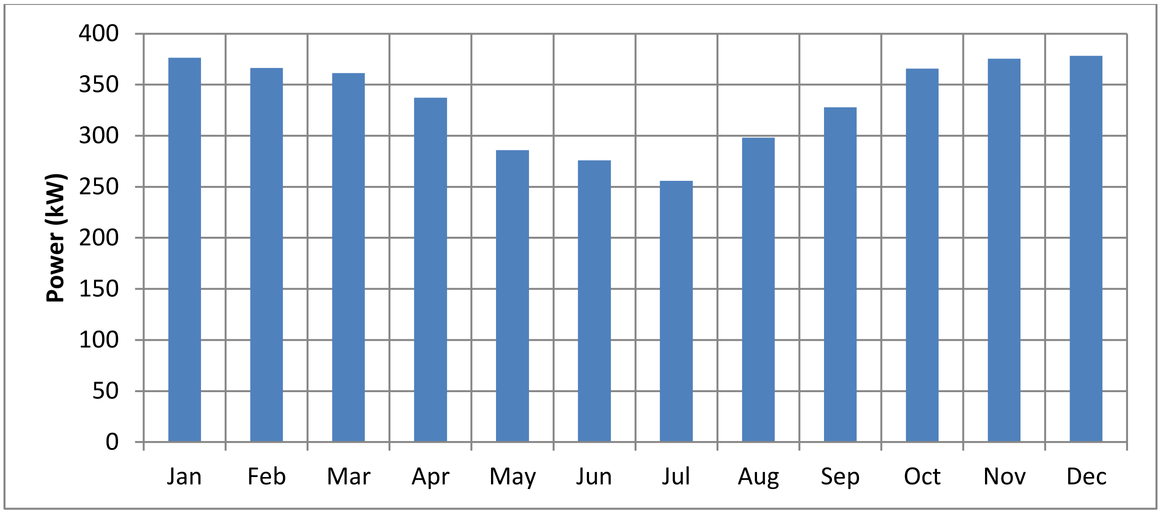

Figure 4-1: Average Monthly Electricity Production in 2011 at Brochet.
Data Source: Manitoba Hydro, 2012

Brochet lies just below the arctic circle and its climate is characterized by short, mild summers and long, cold winters (Furgal & Prowse, 2008). As Brochet is located in high latitude (57°), it has high variation of incoming solar radiation (Figure 4-2). The data was obtained from National Aeronautics and Space Administration's (NASA) Surface Meteorology and Solar Energy website (http://eosweb.larc.nasa.gov/sse/). As seen in Figure 4-2 below, the summer months are characterized by high amounts of incoming radiation, whereas the winter months have less. Thus, higher amount of

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electricity production could be due to the increase in demand for lighting and other domestic purposes in the longer dark hours of the winter months.

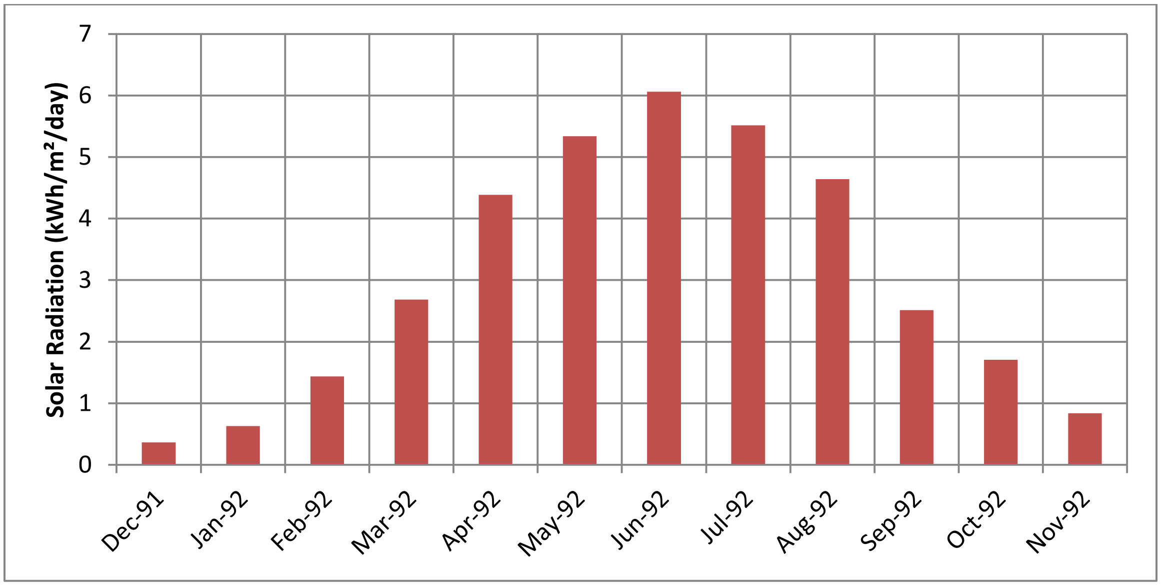

Figure 4-2: Average Daily Solar Radiation for a year in 1991-1992 at Brochet.
Data Source: NASA, 2012

Figure 4-3 shows the average heating and cooling degree days at Brochet. Heating degree days are the cumulative number of degrees in a month by which the average daily temperature falls below 18 °C, whereas cooling degree days are the cumulative number of degrees in a month by which the average daily temperature rises above 18 °C.

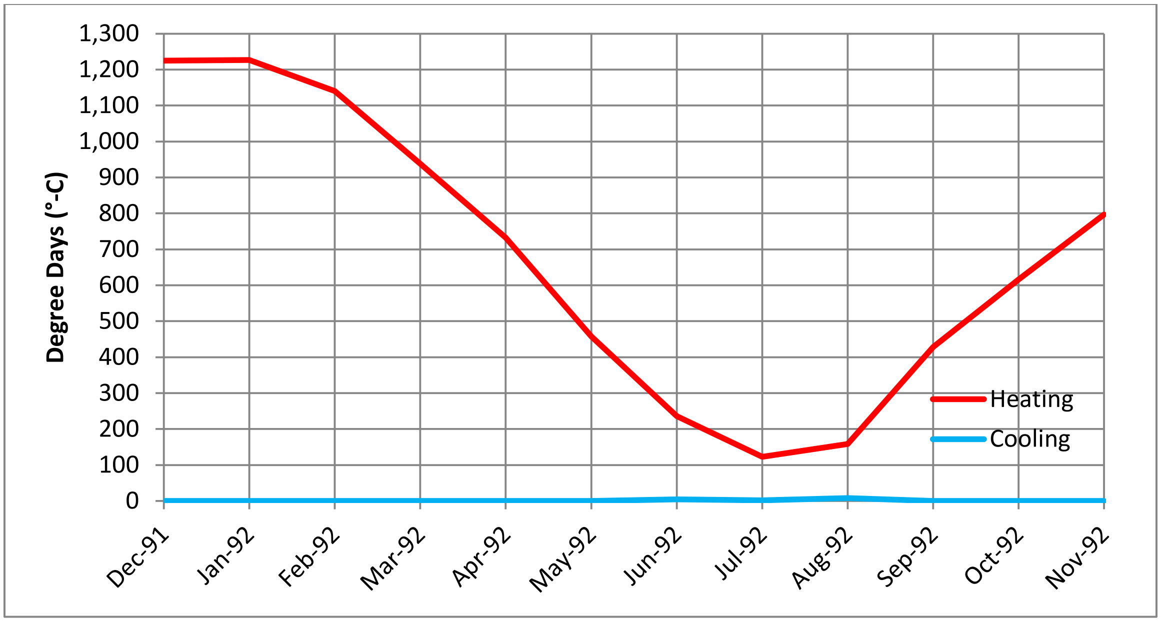

Figure 4-3: Average Monthly Heating and Cooling Degree Days at Brochet for a year in 1991-1992.
Data Source: NOAA, 2012

As seen in Figure 4-3, there are very few cooling degree days at Brochet. So, the electricity demand for cooling in the summer months is small. On the other hand, other seasons have high heating degree days. The highest values of heating degree days were recorded for the winter months. Despite sharp increase in the demand for heat, the winter months did not show corresponding increase in electricity production (shown earlier in Figure 4-1). This is because according to Manitoba Hydro's policy "using electricity for space heating appliances is restricted" (Manitoba Hydro, 2008). Instead, the heating need in the community is met either by wooden or oil furnace (Bhattarai & Thompson, 2012). Thus, electricity generation and its subsequent consumption at Brochet is not highly weather dependent.

Seasonal diurnal variations of power production showed that the load in summer seasons had unimodal peak occurring around noon whereas the winter months had bimodal distribution. During the winter months, peak load was observed mostly in the evening (6 p.m.) and sometime just before noon (11 a.m.). The daily base and peak load in the winter season was higher by about 100 kW than the summer season. High consumption in winter time may be due to the occurrence of high energy consuming activities, such as cooking and using domestic hot water, around the peak hours.

Monthly diurnal variations shows that electricity load at Brochet tends to vary in a fairly regular way over the day, often reaching a maximum around noon and falling to a low from midnight onwards until early morning hours (result not shown for proprietary reasons)[*]. The monthly diurnal profiles were created by averaging electricity generation for each hour over every day of the month.

A weekday and weekend energy production analysis showed no substantial variations in the electricity demand (results not shown for proprietary reasons)[*]. It shows that the non-residential sector, which consumes only about 20 % of the total electricity produced (Manitoba Public Utilities Board, 2010a), had less effect on the total community load. As only the power generation data provided by Manitoba Hydro was not divided as per various user groups, the exact energy demand from each sector could not be further investigated.

4.1.2. Electrical Performance

For 2011, the average electricity produced at Brochet was 7,959 kWh/day. The average power production was 332 kW with minimum and maximum values of 50.8 kW and 537 kW, respectively. The load factor, which is determined by average load divided by the peak load, was calculated to be 0.62. The standard deviation in the sequence of

[*] Non-Disclosure Agreement with Manitoba Hydro
[*] Non-Disclosure Agreement with Manitoba Hydro

daily averages i.e. day-to-day variation of electricity load, as calculated by the HOMER model, was found to be 4.8 %. The standard deviation in the difference between the hourly electricity data and the daily average load profile denoted by time-step to time-step variability, as calculated by the HOMER model, was found to be 7.2 %. The HOMER model also calculated the total annual diesel consumption to be 866,150 litres/year, and the specific fuel consumption at 0.298 litres/kWh. The mean electrical efficiency of the system was 34.1 %.

However, the existing power generation system at Brochet has very high reliability. There were very few incidents of power outage in the entire year. When power generation is resumed after a period of outage, a spike in demand follows. For example, in one power outage incidence, the surge in demand on resumption of power generation was more than 40 % before the outage. The primary diesel generator of 1015 kW capacity effectively met this surge in demand by ramping up the power generation until the load eventually tailed off. The existing system not only met all the electricity demanded but also had no capacity shortage. As reciprocating engines are operated under load following cycles, the production of excess electricity was virtually nil (Table 4-1).

Table 4-1: Electrical Performance of the Existing System as Estimated by the HOMER Model.

Production	kWh/yr	%
DG 1015 kW	2,905,368	100
DG 1015 kW	0	0
DG 600 kW	0	0
Total	2,905,368	100
Consumption	kWh/yr	%
AC primary load	2,904,955	100
Total	2,904,955	100
Quantity	kWh/yr	%
Excess electricity	413	0.01
Unmet electric load	0	0
Capacity shortage	0	0

The existing system has excess installed capacity. As mentioned earlier, in the existing system, one 1015 kW gen set is constantly operating, while another is on stand-by. This means that a single 1015 kW gen set is capable of producing 8,891 MWh /yr (gen set capacity of 1015 kW multiplied by 8,760 hours of operation in a year) electricity in a year. However, the total electricity produced at Brochet in 2011 was only 2,905 MWh/yr (shown earlier in Table 4-1). This means that the existing diesel system is producing electricity at approximately one-third of its operating capacity.

To identify the actual operating range of the 1015 kW gen set, a load frequency variation analysis was conducted. Figure 4-4 shows that 65 % of the total electric production occurred in the range of 250 kW to 400 kW (Figure 4-4). Thus, in comparison to the electricity demand, the existing diesel generator of 1015 kW capacity is highly oversized and is always forced to operate well below its optimum capacity.

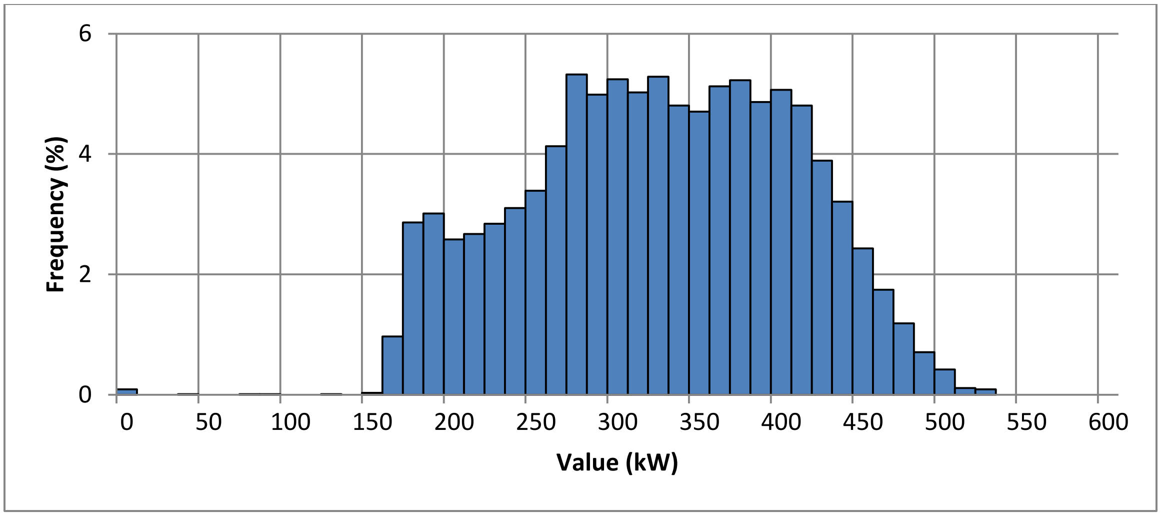

Figure 4-4: Electric Load Frequency Variation in 2011 as Recorded by the HOMER Model.

4.1.3. Economic Performance

The Levelized Cost of Electricity (LCOE) for the existing system was $0.605/kWh, which is equal to the full cost rate as given in the “current electricity rate for diesel zone” (Manitoba Hydro, 2011). Total net present cost of the existing system was calculated as $ 20,160,924 and the operating cost was $ 1,459,637/year. The estimated cash flow summary shows that fuel costs alone represent almost 65 % of the total variable cost of $ 3,331,803 of the existing system (Figure 4-5). The total fixed cost of the existing system was calculated to be $3,419,000.

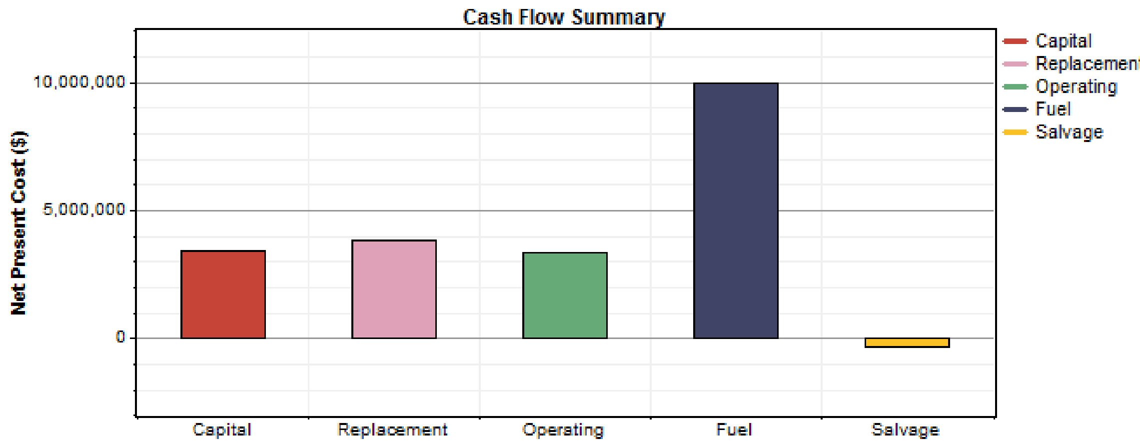

Figure 4-5: Cash Flow Summary of the Existing System at Brochet as Estimated by the HOMER model.

4.1.4. Environmental Impact Performance

Emissions from the existing diesel generating system across six pollutant categories, as estimated by the HOMER model, are presented in Table 4-2. As discussed earlier in the limitation section of Chapter 1, the following results are from new gen sets and underestimate the actual emissions at Brochet.

Table 4-2: Emissions from the Existing System at Brochet as Estimated by the HOMER Model.

Pollutant	Emissions (kg/yr)
Carbon dioxide	2,416,330
Carbon monoxide	2,472
Unburned hydrocarbons	824
Particulate matter	531
Sulfur dioxide	4,841
Nitrogen oxides	70,053

4.2. Determine an Optimum Micro-grid System Based Only on Conventional Fossil Fuel.

4.2.1. Optimization Results as given by the HOMER model

The HOMER model performed 48 distinct simulation runs to determine the optimal gen set configuration based on the least cost of electricity produced. As seen in Figure 4-6 below, the electricity system design consisting of dual units of 600 kW gen sets, one unit of which is always operating (denoted by 8760 hours in the first row of figure 4-6) and the other unit as a back-up (denoted by 0 hours in the first row), was ranked most optimal design configuration. Figure 4-6 also shows the ranking of other near optimal system configurations again based on low cost of electricity produced.

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		

Figure 4-6: Optimization Results of the Multiple Reduced Sized Generators in the HOMER Model.

4.2.2. Electrical Performance

As seen in Figure 4-7 below, 100 % of the total electricity production throughout the year was handled by the single unit of 600 kW generator.

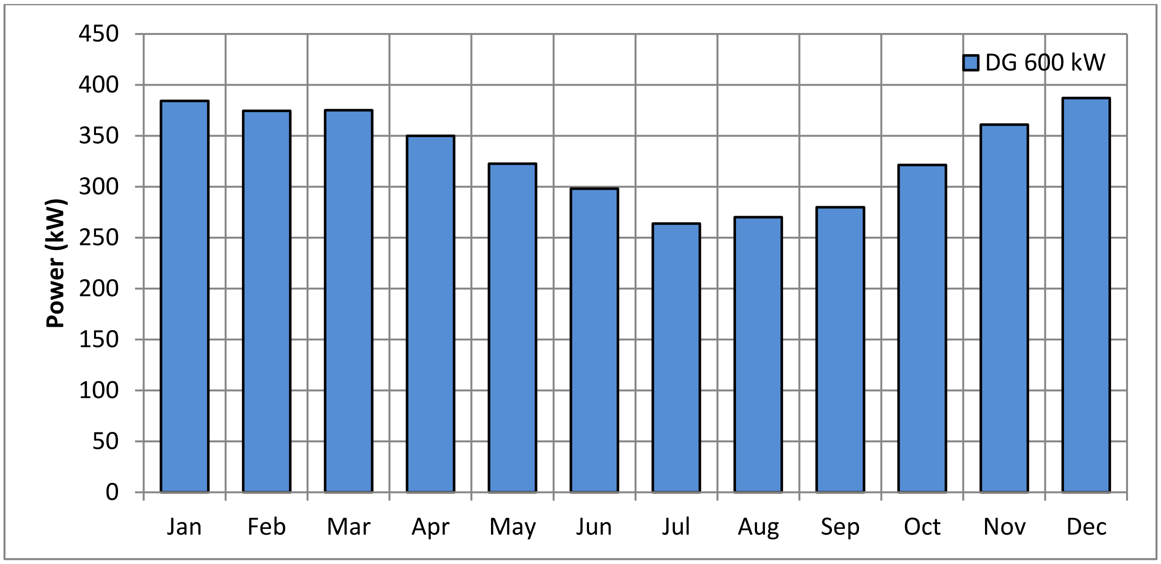

Figure 4-7: Monthly Average Electricity Production of the Optimized Diesel System at Brochet as Estimated by the HOMER Model.

This optimized system had very low levels of excess electricity (Table 4-3). Total fuel consumption of this system was 877,076 litres/year and the average mean electrical efficiency was 33.7 %. As the new diesel generation system was configured to meet full range of electricity load, there was neither any unmet electric load nor any capacity shortage.

Table 4-3: Electrical Performance of the Optimized Diesel System at Brochet as Estimated by the HOMER Model.

Production	kWh/yr	%
DG 600 kW	2,907,195	100
DG 600 kW	0	0
Total	2,907,195	100

Consumption	kWh/yr	%
AC primary load	2,904,955	100
Total	2,904,955	100

Quantity	kWh/yr	%
Excess electricity	240	0.01
Unmet electric load	0	0
Capacity shortage	96.2	0

4.2.3. Economic Performance

Total net present cost of the optimized system was calculated as $ 17,070, 622 and the operating cost was $ 1,352,287/year. Detailed cost breakdown as per each component of the existing system is shown in Table 4-4. The levelized cost of electricity (LCoE) for the optimized DG system was calculated to be $0.512/kWh. When compared to $0.605/kWh of LCoE of the existing system, this is 15.2 % reduction.

Table 4-4: Cost summary of the Optimized Diesel System at Brochet as Estimated by the HOMER Model.

Component	Capital ($)	Replace-ment ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
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

4.2.4. Environmental Impact Performance

Table 4-5 shows emissions from the optimized diesel system as estimated by the HOMER model. Across all the pollutant categories, the optimized diesel generating system design had lower emissions that the existing system at Brochet. This is because of the higher efficiency of the 600 kW gen set when compared to the 1015 kW generator (Table 4-6).

Table 4-5: Emissions from Optimized Diesel System as Estimated by the HOMER Model.

Pollutant	Emissions (kg/yr)
Carbon dioxide	2,319,936
Carbon monoxide	421
Unburned hydrocarbons	9
Particulate matter	509
Sulfur dioxide	4,642
Nitrogen oxides	51,221

As discussed earlier, the benchmarked emissions values are that of new gen sets with same specifications as the existing gen sets in Brochet, which are near their useful lifetime and are going to be replaced in 2015/2016. Thus, the HOMER model under predicted the actual amount of emissions that is being given off by the existing gen sets at Brochet.

Table 4-6: Emissions from Different Sized Caterpillar Generators.

Emissions	1015 kW[1]	600 kW[2]
NOx (g/hp-hr)	7.65	5.84
CO (g/hp-hr)	2.7	0.48
HC (g/hp-hr)	0.09	0.01
PM (g/hp-hr)	0.058	0.035

Source: [1] Altorfer Inc., 2013; [2] Caterpillar, 2013

4.3. Determine an Optimum Micro-grid System Based Only on Wind Energy.

4.3.1. Analysis of Wind Resources in Brochet

The most recent hourly meteorological data collected at Brochet Airport from the period of December 1991- November 1992 was analyzed to assess and characterize the wind resources at Brochet.

Figure 4-8 shows the monthly mean wind speed records at Brochet Airport from 1991-1992. As seen in Figure 4-8 below, spring and fall seasons have stronger winds than summer and winter, with the strongest wind was recorded in the month of September.

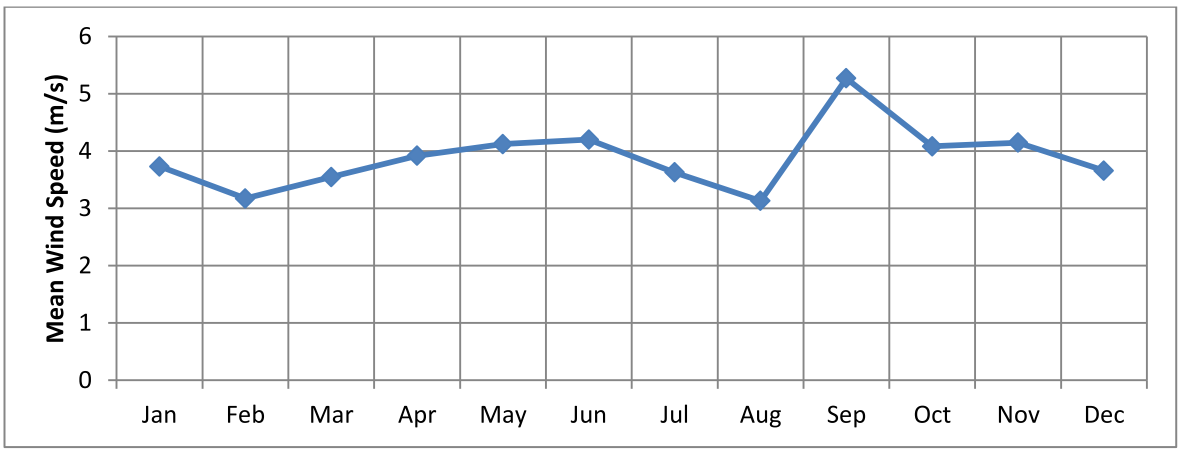

Figure 4-8: Monthly Mean Wind Speed Profile at Brochet Airport for a year in 1991-1992.
Data Source: NOAA, 2012

Table 4-7 shows the summary of the relevant meteorological parameters at Brochet Airport for the study period. As seen in the table below, the maximum wind speed of 17 m/s was recorded in the month of September. 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 amount of renewable electricity.

Table 4-7: Summary of Climatic Conditions at Brochet Airport for a year in 1991-1992.

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

Data Source: NOAA, 2012

The hourly wind speed profile for the study period of one year (total 8,760 data points) is shown in Figure 4-9. The highest wind speed of 17.88 m/s was recorded at 4 p.m. on 14th September, 1992.

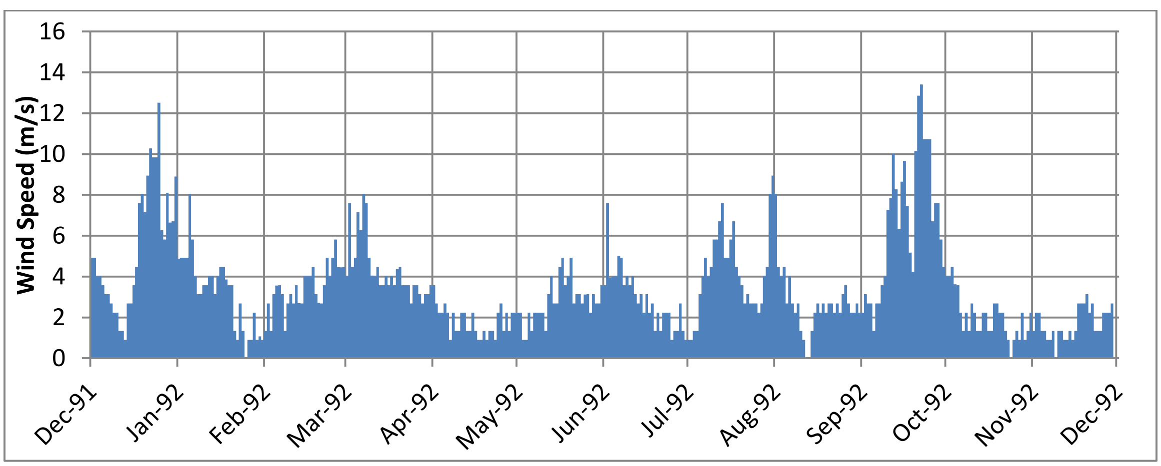

Figure 4-9: Hourly Records of Wind Speed Profile at Brochet Airport for a year in 1991-1992.
Data Source: NOAA, 2012

The diurnal wind speed distribution pattern shows that average maximum wind occurred from 17 – 20 hours of the day for the data period (Figure 4-10). The diurnal strength pattern was calculated to be 0.118. Generally, wind speed is dependent on solar radiation and therefore, many places have high wind speed around noon when the solar radiation is at highest (Jain, 2011). However, stronger wind speed was recorded in the later afternoon hours at Brochet. This means that the solar radiation has less effect on the wind regime at Brochet. Auto-correlation factor was calculated at 0.841, signalling the wind blowing in a certain hour was not highly dependent on wind from previous measured hour.

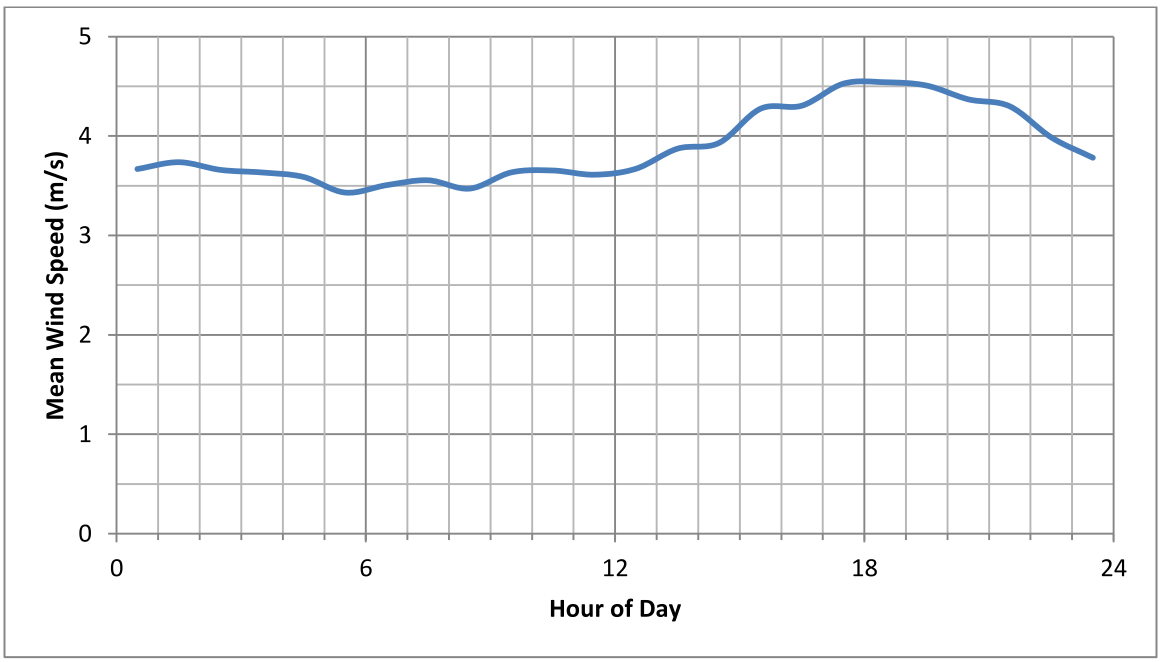

Figure 4-10: Diurnal Wind Speed Profile for Brochet over a period of a year in 1991-1992.
Data Source: NOAA, 2012

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 5 m/s (Figure 4-11). 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, the higher values indicating a narrower frequency distribution (i.e., a steadier, less variable wind) (AWS Truepower, 2010). As seen in Figure 4-11 below, the Weibull parameters have a relatively good fit with the observed wind speed distribution at Brochet.

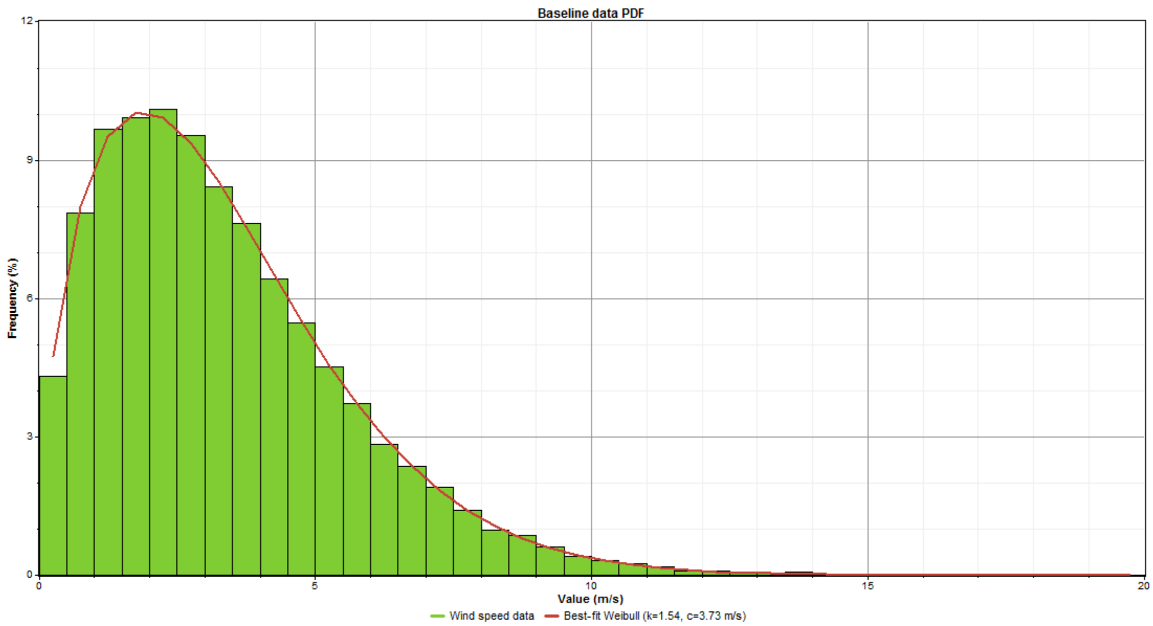

Figure 4-11: Probability Distribution Function of Wind Speed at Brochet Airport.
Data Source: NOAA, 2012

The cumulative distribution function is another way to understand the probability distribution function. Note that in the annual data set, represented below, 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 % (Figure 4-12) or about 2,500 hours (Figure 4-13).

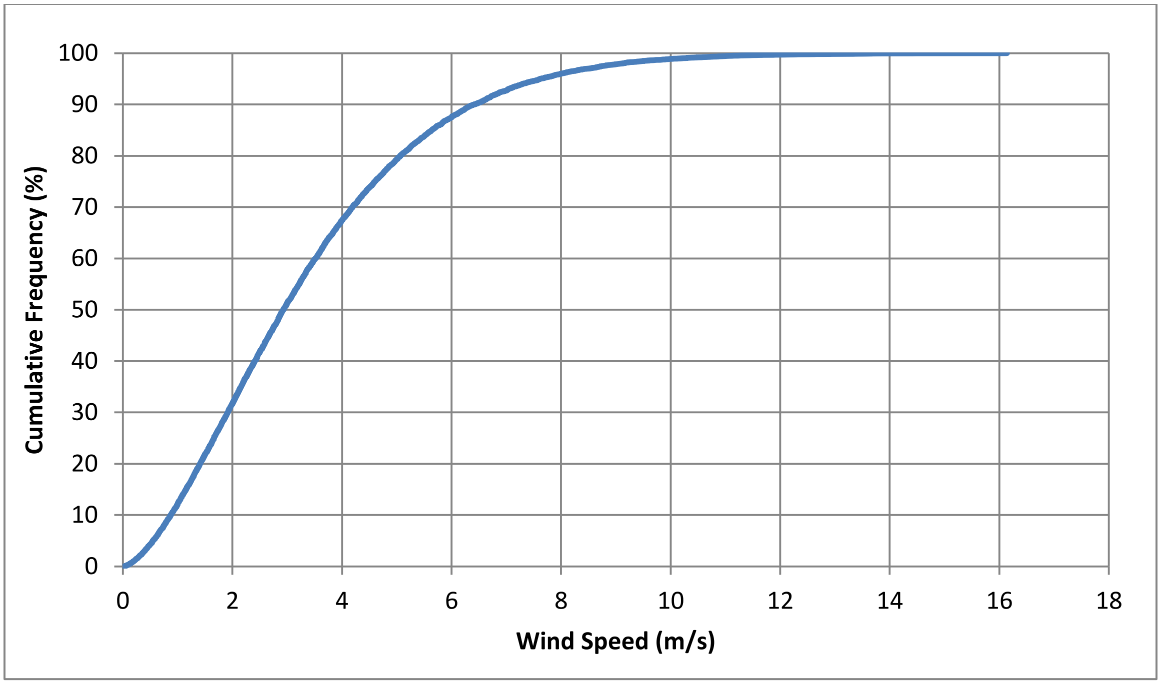

Figure 4-12: Cumulative Frequency Distribution Function of Wind Speed at Brochet Airport over a year in 1991-1992.
Data Source: NOAA, 2012

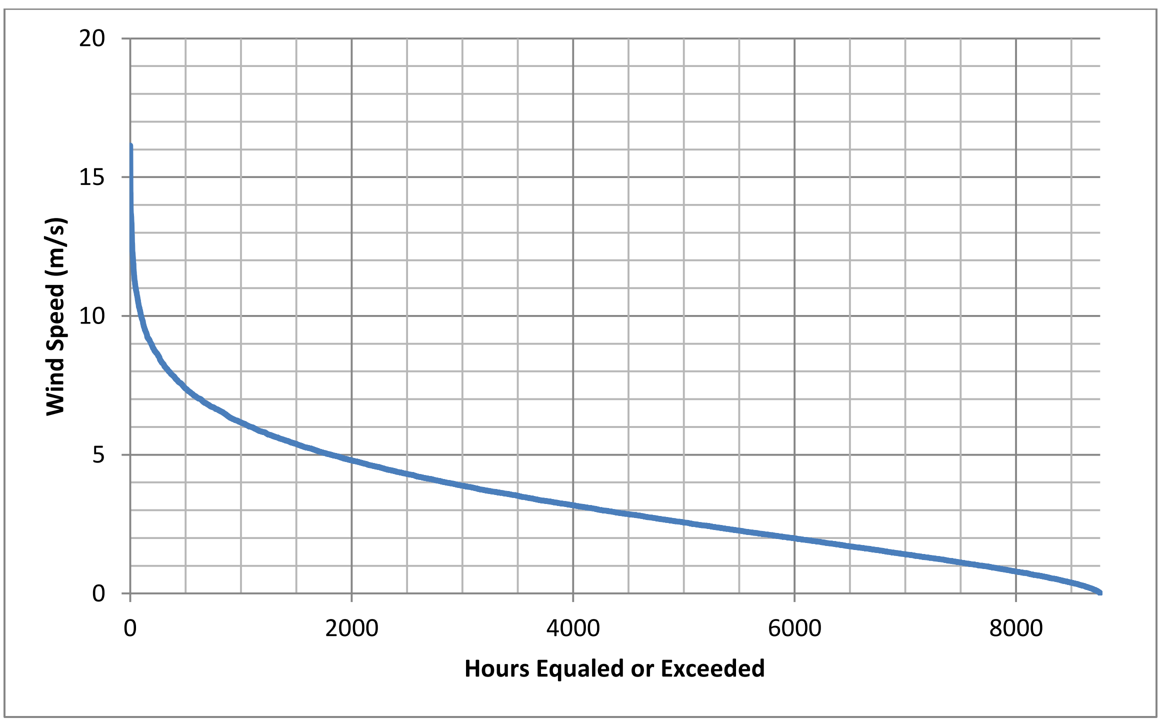

Figure 4-13: Wind Speed Duration Curve at Brochet Airport over a year in 1991-1992.
Data Source: NOAA, 2012

Figure 4-14 shows the seasonal wind rose graph with wind speed for various corresponding directions at Brochet from 1991-1992. 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 the wind blew from the southeast direction and in the winter season, the easterly was the most dominant one.

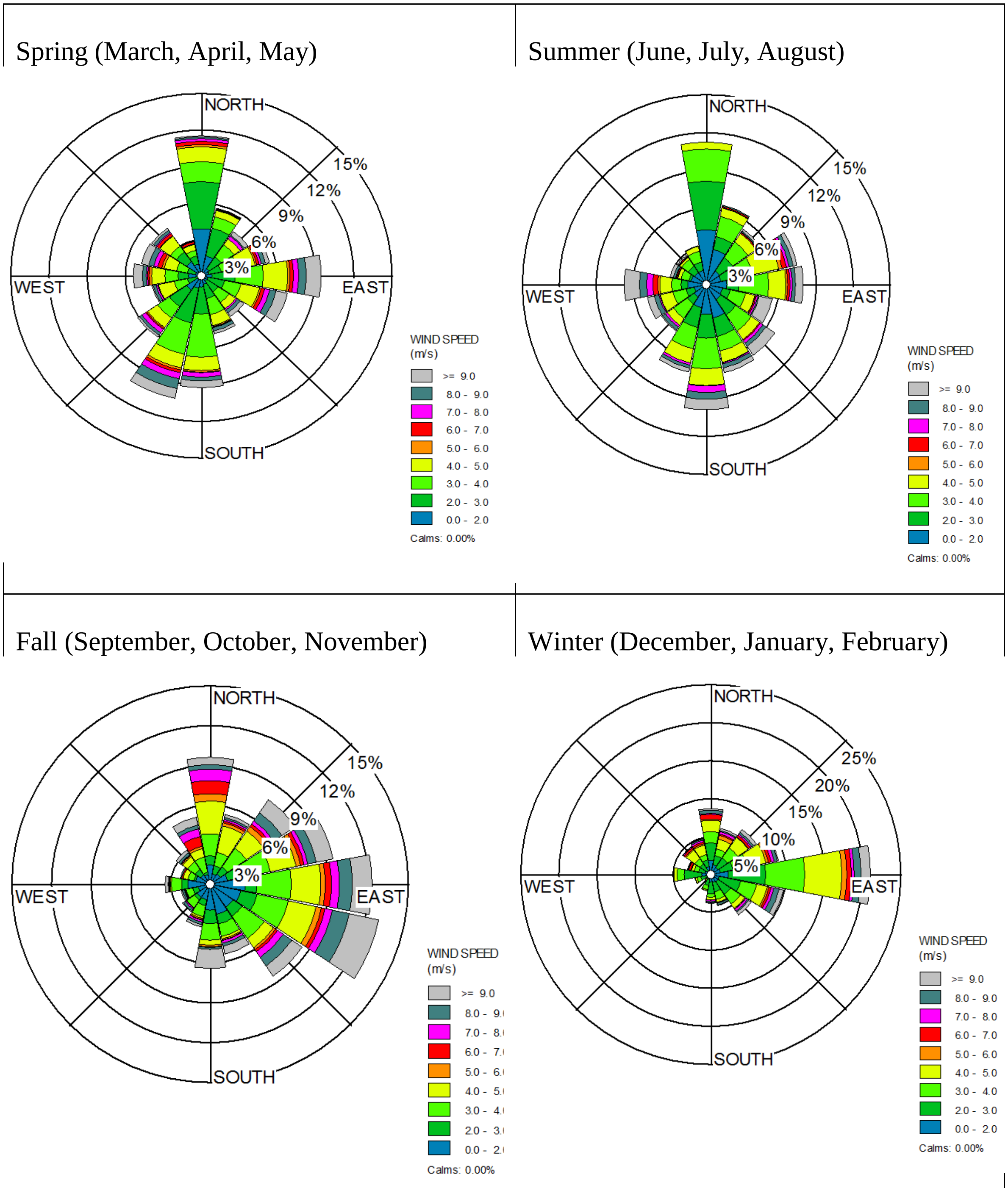

Figure 4-14: Seasonal Wind Direction Profile at Brochet Airport over a year in 1991-1992.
Data Source: NOAA, 2012

Figure 4-15 shows the wind direction histogram in Brochet for a year in 1991-1992. The wind direction data was divided into 16 bins with each having a bin size of 22.5° to show frequency of occurrence at each direction. As seen in the figure below, majority of the wind in Brochet blew from western direction i.e. easterlies was dominant. This is typical nature of wind direction in artic and sub-arctic regions (Vickers, Buzza, Schmidt, & Mullock, 2001). Thus, any potential wind turbine deployed at Brochet should be oriented towards this direction to effectively capture most of the wind.

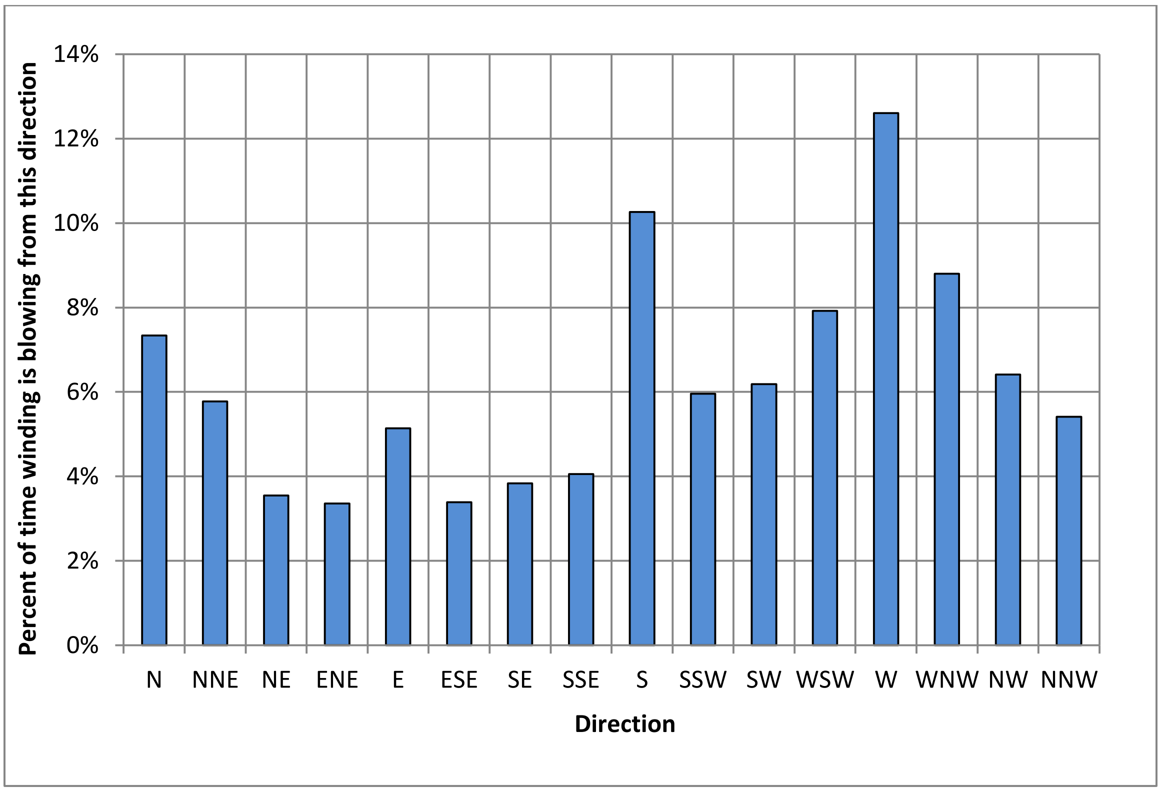

Figure 4-15: Wind Direction Histogram at Brochet for a year in 1991-1992.
Data Source: NOAA, 2012

4.3.2. Discussion

Wind turbines work only in a certain range of wind speeds. Most wind turbines do not begin to generate power until the wind speed at its hub height reaches 4 m/s, also known as the “cut – in” wind speed (Jain, 2011). Most wind turbines stop generating power at a “cut – out” wind speed of 25 m/s (Jain, 2011). As the wind profile at Brochet has marginal wind speed, this study did not consider building the whole electricity design based only on wind power. Although, large commercial wind turbines with high tower heights and a cold climate pack could be installed at Brochet to capture wind at higher altitudes, in the event of failure, the survival of the community can be at risk. Total dependence on any single source of energy severely reduces the energy security of a community (Li, 2005). Given the logistical constraints in transporting over the winter road (as discussed in the method section), large wind turbines deployment would face tremendous obstacles.

In addition, wind resources are not controllable and electricity generation by wind is independent of demand. To meet the amount of electricity demand at all times, wind-only electricity system requires an effective storage component. To illustrate, if the community load at a certain point is 400 kW and suddenly the wind stopped blowing, then that electricity demanded should be met by the storage system to avoid blackout. In such a system, when wind energy produces power that is excess of demand, it is used to charge the storage and when the demand is higher than the production of renewable energy, the storage were discharged (Rabiee, Khorramdel, & Aghaei, 2013). To effectively meet the community demand all the time, the system must also have a long term bulk storage provision. There are various mechanical and electrical storage technologies such as battery storage, capacitors, and flywheel that are mostly used for short and mid-term period ranging from 5 – 10 minutes. But, for long term bulk storage, pumped hydro storage (PHS) and compressed air electricity storage (CAES) are the most suitable and economic (Kreith & Goswami, 2007). Figure 4-16 shows the elevation contour map of Brochet. As seen in the figure below, the nearby areas do not have any remarkable variations in height (the highest hill is 370 m, which is 30 m higher than the site elevation of 340 m). Further, the cold climatic conditions also means that water bodies freeze up (in early to mid-November) and break up (in mid to late April) (Vickers et al., 2001). Owing to these two factors, the possibility of pumped hydro storage at Brochet is ruled out. The other option of compressed air electricity storage system has only been installed in two facilities – one in Germany and the other in USA (Fertig & Apt, 2011). So, considering the lack of maturity and proven ability to perform in cold climatic conditions like at Brochet, CAES was also ruled out for Brochet.

Thus, due to marginal wind and lack of effective storage option, wind-only micro-grid system seems unfeasible for Brochet.

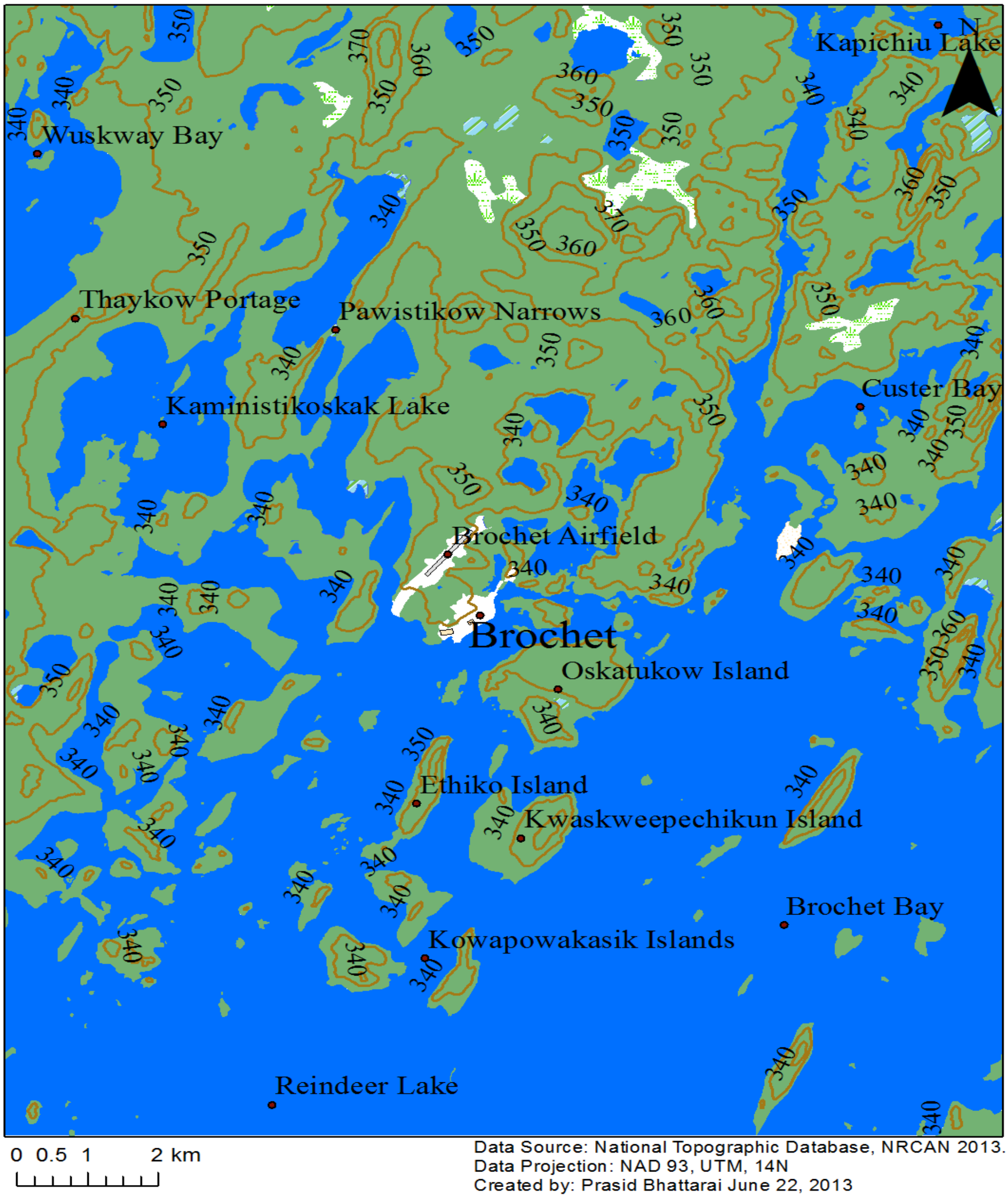

Figure 4-16: Elevation Contour Map of Brochet.

4.4. Determine an Optimum Wind-diesel Hybrid Micro-grid System.

4.4.1. Electrical Performance

The HOMER model performed 1440 simulation runs to determine the optimum wind-diesel hybrid system configuration. As seen in Figure 4-17 below, 47 % of the total electricity production came from wind turbines and the rest from 600 kW capacity diesel generator. Another unit of 600 kW unit was kept as backup as it is in the existing system.

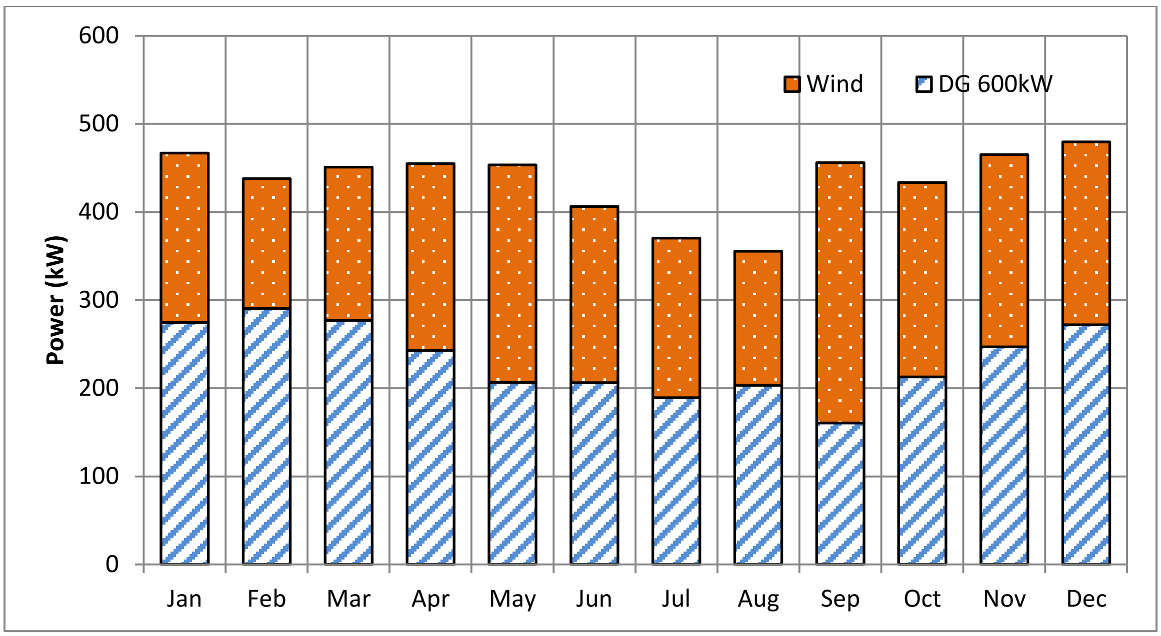

Figure 4-17: Monthly Average Electricity Production from the Wind-Diesel Hybrid System as Estimated by the HOMER Model.

There was no unmet electric load and no capacity shortage for this wind diesel system. Instead this system had excess electricity production (Table 4-8). The total fuel consumption was 640,950 litres per year.

Table 4-8: Electrical Performance of the Wind Diesel Hybrid System as Estimated by the HOMER Model.

Production	kWh/yr	%
Wind Turbines	1,787,407	47
DG 600 kW	0	0
DG 600 kW	2,028,144	53
Total	3,815,551	100

Consumption	kWh/yr	%
AC primary load	2,904,955	100
Total	2,904,955	100

Quantity	kWh/yr	%
Excess electricity	910,493	23.9
Unmet electric load	0	0
Capacity shortage	0	0

4.4.2. Economic Performance

The cash flow summary of the wind diesel hybrid system shows that the cost of 600 kW diesel generator has the largest share in the total system (Figure 4-18). The Levelized Cost of Electricity (LCoE) for the optimized hybrid system was $0.492/kWh. This is a reduction of 19 % when compared to the existing rate of $0.605/kWh and of 4 % when compared to the optimized diesel only micro-grid system. The total net present cost of the system was $16,402,547 (Table 4-9) and the operating cost was $ 1,046,764 per year.

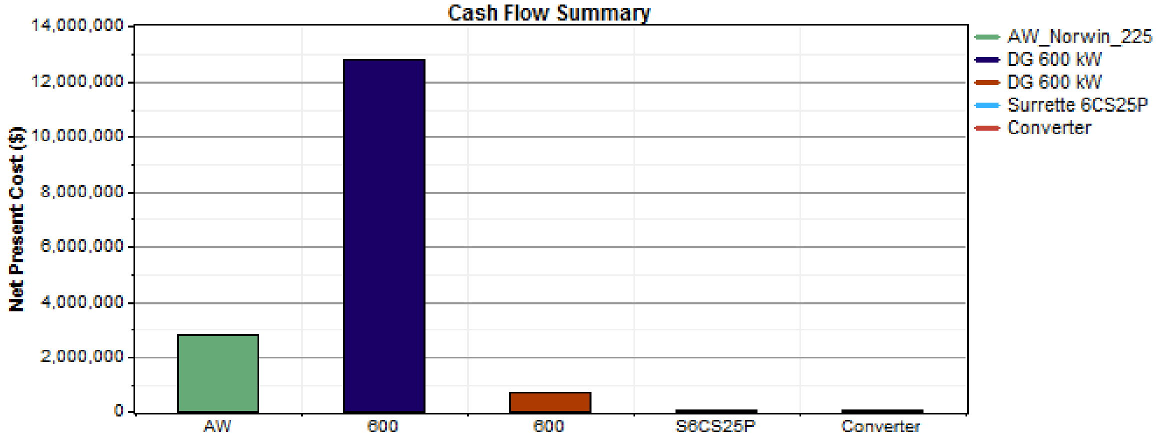

Figure 4-18: Cash Flow Summary of the Hybrid System as Estimated by the HOMER Model.

Table 4-9: Cost Component of the Hybrid System as Estimated by the HOMER Model.

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
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 600kW	780,000	0	0	0	-108,905	671,095
Surrette 6CS25P	56,250	24,600	7,742	0	-5,145	83,447
Converter	80,000	0	11,470	0	-7,795	83,675
System	4,396,250	1,881,661	2,914,098	7,351,651	-141,107	16,402,553

4.4.3. Environmental Impact Performance

When compared with the existing system at Brochet, incorporating wind turbines in the power system resulted in the reduction of emissions across all measured pollutant categories (Table 4-10). In addition, as the hybrid system consumed lower amount of fossil fuel than both existing system and optimized diesel system, implementing this design will result in lower emissions of GHG during fuel transport.

Table 4-10: Emissions Results from Hybrid System as Estimated by the HOMER Model.

Pollutant	Emissions (kg/yr)
Carbon dioxide	1,695,364
Carbon monoxide	308
Unburned hydrocarbons	7
Particulate matter	22
Sulfur dioxide	3,392
Nitrogen oxides	37,175

4.4.4. Sensitivity Analysis

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. Figure 4-19 shows 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. For example, if the annual wind speed occurred at 5.5 m/s and the fuel price escalated to $1.8/liter, then the annual CO_2 emission would be 1,492,195 kg/year.

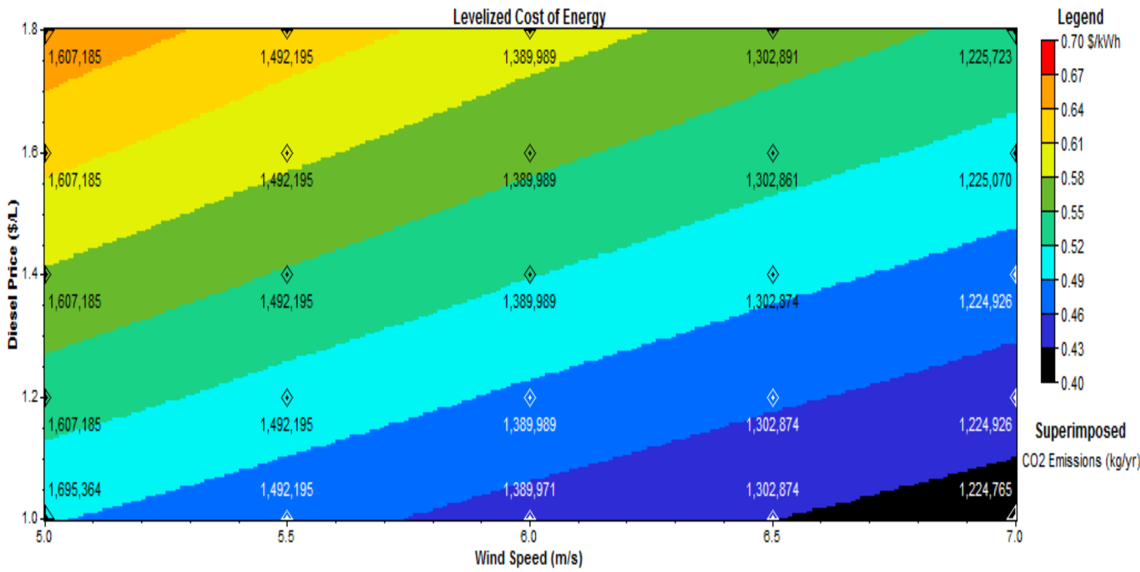

Figure 4-19: Sensitivity Results of the Hybrid System as Estimated by the HOMER Model.

4.5. Discussion

The aim of this study was to determine an optimum electricity system design for Brochet, an off-grid community in northern Manitoba, on the basis of high electrical reliability, least cost, and lower carbon. The study considered three electricity microgrid scenarios based on: 1) only conventional fossil fuels, 2) only wind, and 3) a mix of both to replace the existing system.

The power generation log data for the past five years (from 2007-2011) at Brochet in 15 – minute timescale was successfully analyzed. This revealed that for each year, the average amount of electricity produced was constant, although slight variations in peak generation occurred from year to year. Annual power generation data showed that higher amounts of electricity were produced in the winter months than in the summer months. As Brochet is located at a high latitude (57°), the incoming solar radiation is thought to have an effect on the electricity demand. Days in the summer months have greater number of the day light hours than the winter months. Thus, less amount of electricity is demanded for lighting purposes in the summer months and vice versa. A diurnal analysis also showed that the winter months had a bimodal peak. The first one occurred in the evening hour (coinciding dinner time) and the second around noon (coinciding lunch time).

Power generated by the diesel generator at Brochet seems to be highly affected by domestic electricity usage pattern, such as lighting and use of other household appliances. Residential customers comprise 80 % of the total number of customers served in each off-grid community, and consume 80 % of the total electricity produced in each off-grid community (figures shown earlier in Chapter 1 Section 1.1.3).

The amount of power generated at Brochet did not show a strong relationship with outside temperature (especially in winter). This lesser degree of dependence is due to the restriction of using electricity for space heating appliances. So, without demand for electricity for heat in the winter months, the amount of electricity produced in the winter months was relatively constant. The remaining off-grid communities of Manitoba are also under load restriction and using electricity for space heating appliances is not permitted (Manitoba Hydro, 2008). Given, the similarities of geographical location, size of community, load restriction, proportional number of residential customers; the load characteristics seen in Brochet are very likely to represent the load characteristics of all the remaining three off-grid communities in Manitoba.

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. In the model, fuel cost was the key determinant of the economics of the existing system. Other studies have also concluded that typically diesel gen sets have a high economic and environmental cost (Katiraei & Abbey, 2007; Kim & Leng, 1999; Lautier et al., 2007; Lipman, 1994). A common design flaw for diesel based electricity systems in off-grid communities are its excess installed capacity (Schofield, 2011; Weis & Ilinca, 2010). This is true in the case of Diesel Zone communities of Manitoba as well (refer to Table 1-2 that shows total installed capacity and average annual production). This study not only quantifies the inefficient operation of diesel generations but also shows the actual range of power generation (detail in section 4.1.4).

Electricity system design with optimized reduced sized diesel gen sets, and optimized wind-diesel hybrid system design are summarized in Table 4-11 below. As expected, when the diesel generators are sized to closely match the electricity demand, it results in reduced cost per unit of electricity produced. 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. When compared to the existing gen sets at Brochet (specifications of new gen sets were actually entered as new gen sets in the HOMER model), 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 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 4-11.

Table 4-11: Summary of the Results of Various Electricity System Designs as Estimated by the HOMER Model.

	Existing System	Optimized Diesel System	Optimized Wind Diesel System
	Electrical (kWh/yr)		
Production	2,905,368	2,907,195	3,839,191
Consumption	2,904,955	2,904,955	2,904,955
Excess electricity	0	240	874,409
Unmet electric load	413	0	0
Capacity shortage	0	96.2	0
	Economic		
LCOE ($/kWh)	$0.605	$0.512	$0.492
Fuel consumption (L/year)	866,150	863,747	527,287
	Emissions (kg/yr)		
Carbon dioxide	2,416,330	2,319,936	1,695,364
Carbon monoxide	2,472	421	308
Unburned hydrocarbons	824	9	7
Particulate matter	531	509	22
Sulfur dioxide	4,841	4,642	3,392
Nitrogen oxides	70,053	51,221	37,175

The above table 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 % when 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). Thus, the wind-diesel hybrid is an optimum electrical system for Brochet.

As the benchmark results of the existing system earlier showed that Brochet directly pays high economic and environmental costs due to its fossil-fuel based electricity system. The community also has to deal with indirect economic and environmental cost such as high cost of goods and services, and poverty due to high energy expenses, and also spillage and leakage of fuel that pollutes their land and threatens their livelihood. In addition to the impacts from the diesel based system, Brochet is also impacted by Hydro development in Saskatchewan. Brochet is about 20 km east of the Saskatchewan border on the north shore of Reindeer Lake. Whitesand Dam was constructed in 1942 to regulate water flow to the Island Falls Dam located in its downstream (both located in Saskatchewan). This increased the water level at the Reindeer Lake by one and half meters and flooded large areas and disrupted the life style of many communities including Brochet (Waldram, 1993). Unfairly, Brochet has borne the cost of hydro development without benefitting from it.

Carefully engaging with the local stakeholders in designing a suitable and acceptable community energy system is urgently needed at Brochet. In this process, the HOMER model can be a highly effective tool to aid decision makers, energy planners and modellers. Further, the HOMER model can also be applied to design an energy system that meets the space heating need of Brochet. Currently, Brochet is also reliant on wooden/oil furnaces to meet its heating needs. Integrating combined heat and power (CHP) based on biomass would allow Brochet to meet both its electrical as well as heating needs.

Many off-grid communities have undertaken research on different renewables but this data is not shared or accessible for everyone’s benefit. Reviews of various public utilities board hearing minutes and Manitoba Hydro reports only show summarized results of various electricity options such as small hydro, wind, and grid connection (CIER, 2012; Manitoba Hydro, 2008, 2010). Most of these original reports are confidential and not available to the public. As identified during this study, there is a lack of central repository for information on off-grid communities. This publicly available research fills, to some degree, this knowledge gap.

A survey of stakeholders' prespective on barriers to remote wind-diesel power plants in Canada by Weis et al., (2008) showed that the utility providers are still not confident in wind-diesel hybrid system despiteconflicting message from government and academia. This applies to Manitoba, in particular, as Manitoba's electricity market is a regulated monopoly. This means Manitoba Hydro is not obligated to purchase or deliver electricity produced from private developers. As a result, Manitoba Hydro is a key stakeholder in the community energy planning process and it too would benefit from optimization for economic reasons and to decrease their carbon footprint.

There are over 300 off-grid communities in Canada that are totally dependent on diesel generated electricity (Kim & Leng, 1999). These systems have similar configurations to that of Brochet, usually one or two large diesel gen sets operating in parallel to meet the electricity load and a third gen set, that is generally kept as a backup (Schofield, 2011). The large diesel gen sets are sized to meet the maximum peak load plus some regulatory requirement (Lipman, 1994). 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 ten times the average load (Lipman, 1994). And, like in the case of Brochet, the peak values usually occur for a small fractions of the total year (Pelland et al., 2012).

Thus, using multiple diesel gen sets with different sizes would help maximize fuel efficiency and allow greater integration of renewables in the electricity mix (Katiraei & Abbey, 2007).

As shown in this study, the HOMER model can be effectively applied to achieve these goals. Various studies have used the HOMER model to evaluate and design hybrid systems based not only on wind but also on hydro, solar, and grid connection in remote communities (Ibrahim, Younès, Ilinca, Dimitrova, & Perron, 2010; Katiraei & Abbey, 2007; Lautier et al., 2007; Weis & Ilinca, 2008). In addition to these steps of efficient operation of gen sets and integration of renewable energy in the electricity mix, the HOMER model can also be used to evaluate how the demand side can be managed to balance with its supply. For example, instead of treating all community electricity demand as base load, the load can be divided into critical and non-critical categories. This information would further allow sizing diesel generators to closely match the load (Pelland, Turcotte, Colgate, & Swingler, 2012). For in-depth analysis, the HOMER model can be coupled with other electricity models such as MATLAB and SIMULINK to investigate how voltage and frequency variations affects power quality supplied by electricity system with increased penetration of renewable energy (especially wind) (Islam, 2012). Thus, the HOMER model could be a highly valuable tool to evaluate various electricity system design configurations to make the transition towards sustainable energy system.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Brochet is a remote off-grid community located in northern Manitoba which would benefit from energy optimization. The basic electricity need of Brochet is currently being met by a diesel generating station. The existing system is characterized by high economic and environmental costs. In addition, total reliance on imported fossil fuel also makes the community highly vulnerable to any disruption in the supply chain for diesel. The generators installed in Brochet are near the end of their operational life span and are expected to be replaced soon in 2015 – 2016. This study was conducted to determine the optimum electricity system design at Brochet based on high electric reliability, least cost and lower carbon emissions. The study explored three potential power generation options based on: 1) diesel only, 2) wind only, and 3) a mix of both. The results showed that the proposed wind-diesel hybrid system results in substantial reduction in the cost of electricity produced as well as reduction in the fuel consumed. The system also resulted in lower emissions of GHG while maintaining the high reliability that the existing system offers.

The reduced sized diesel system design with dual 600 kW gen sets also resulted in lower cost of electricity than the existing system. This system also had emissions than the existing system, which is due to burning smaller amounts of diesel. Moreover, this option is not recommended as the system is completely dependent on imported fossil fuel and equally exposed to disruptions in fuel supply. For the first time, the electricity load at Brochet was also analyzed to understand its temporal variation. The results clearly showed that the demand in Brochet is more or less constant and the planned supply limitation means that amount of power generated is not weather dependant. In addition, the load analysis also shows that the existing diesel system at Brochet is highly oversized and is operating well below its rated optimum capacity.

The study also analyzed wind data from various public sources to understand both its temporal and spatial variation. The result shows that the wind speed at Brochet is marginal and the nature of Brochet's wind is different from the nearest meteorological station located 125 km to the south. The wind-only microgrid system was not evaluated due to the logistic challenges of transporting large wind turbines to Brochet and lack of any feasible long term bulk energy storage option. Further, this study also highlights that any wind energy project in the north should only be planned after carefully considering the logistics involved. As the winter roads are in operation for a short period (five to six week from January onwards), the project should have a very well developed time-line to avoid project overrun.

To improve confidence of the study results, a meteorological tower should be installed in Brochet to acquire high resolution wind data. Data from an anemometer at various heights would provide information on wind shear and turbulence intensity as well. As Lac Brochet is also less than 100 km north from Brochet, such data can be very helpful in assessing wind resource at Lac Brochet as well.

This study considered technical, economic, and environmental aspects of electricity supply but not its social aspect. Especially in the context of isolated regions, the social aspect also plays a crucial role when choosing power supply from renewable energy source (Georgilakis, 2006). The next step should include a preliminary community perspective to determine the acceptability of wind energy. This step could include the community in the planning process and ensure that their values, needs and community development are also represented.

The two main barriers to deployment of wind energy in the electricity mix are: (1) the perceived intermittency of winds, and (2) the difficulty in identifying good wind locations (Archer & Jacobson, 2005). This study shows that using conventional energy storage and coupling existing diesel generator can help address the problem of intermittency. Similarly, using available public data (airport meteorological data collected at 10 m height) can provide good indication of the wind. Independent power producers, community organizations, and as well as other interested agencies can easily follow the methods used in this thesis to design an energy system, use a variety of data sets (both private and public), and further refine the existing model that best fits their needs. For example, the HOMER model could be used to evaluate how incentives for renewable energy (for example, eco-Energy program supported by federal government) can be leveraged to make deployment of renewable energy more profitable and attractive.

Energy optimization needs to be considered in combined heat and power analysis. Although not considered in this study, the contribution of renewable energy resources especially combined heat and power (CHP) generation based on biomass should be further explored and evaluated to determine how much it can contribute to meet the community's electricity and heating needs in a sustainable manner. When it comes to energy security, diversity is the key (Li, 2005).

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APPENDIX A

Additional Information Used in the HOMER Model:

Calculation of non-fuel O & M cost for gen sets: Manitoba Hydro (2008) reports that the non-fuel O & M cost for Brochet is $290,177 per year. This divided by total electricity produced (2,905,368 kWh/yr for 2011) gives the $0.1/kWh of O & M. As, average electric output for the same period was 332 kW, the O&M entered in the HOMER model is $33.16/hr.

Table A-1: Default Fuel Properties provided in the HOMER model.

Diesel Fuel	Value
Lower Heating Value	43.2 MJ/kg
Density	820 kg/m^3
Carbon content	88 %
Sulfur content	0.33 %

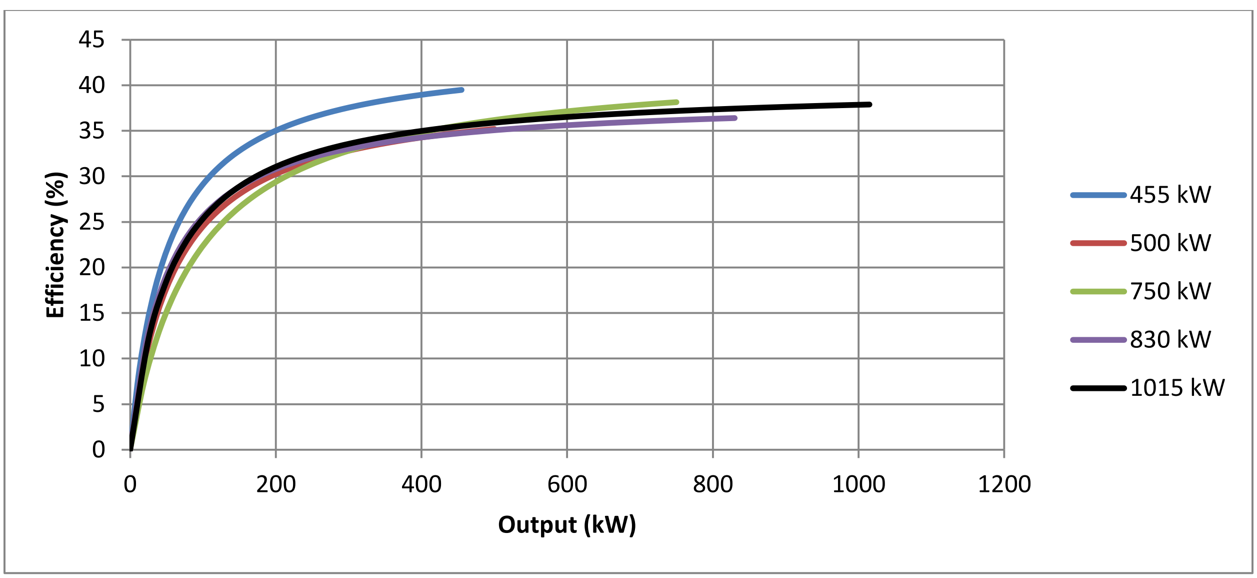

Figure A-1: Fuel Efficiency Curves of varying sizes of Caterpillar diesel generators.
Data Source: Caterpillar, 2012

Table A-2: Output power, fuel consumption, intercept, and slope of various sizes of diesel generators entered in the HOMER model.

	1015 kW Genset		830 kW Genset	
	Output power (kW)	Fuel Consumption (L/hr)	Output power (kW)	Fuel Consumption (L/hr)
	1,015.00	273	830	232.1
	761.25	206.5	622.5	176.5
	507.5	144.2	415	122.9
Intercept (L/hr/kW)	0.01448		0.0161	
Slope (L/hr/kW)	0.2538		0.2631	
	750 kW Genset		600 kW Genset	
	Output power (kW)	Fuel Consumption (L/hr)	Output power (kW)	Fuel Consumption (L/hr)
	750	200.3	600	161.6
	562.5	154.4	450	129.8
	375	111.2	300	91.7
Intercept (L/hr/kW)	0.02887		0.03808	
Slope (L/hr/kW)	0.2376		0.233	
	500 kW Genset		450 kW Genset	
	Output power (kW)	Fuel Consumption (L/hr)	Output power (kW)	Fuel Consumption (L/hr)
	500	144.6	455	117.3
	375	111.7	341.25	90.4
	250	80.3	227.5	64.6
Intercept (L/hr/kW)	0.0315		0.02575	
Slope (L/hr/kW)	0.2572		0.2316	

Output Power and Fuel Consumption Data Source: Caterpillar, 2012; Intercept and Slope was calculated by using the HOMER Model.

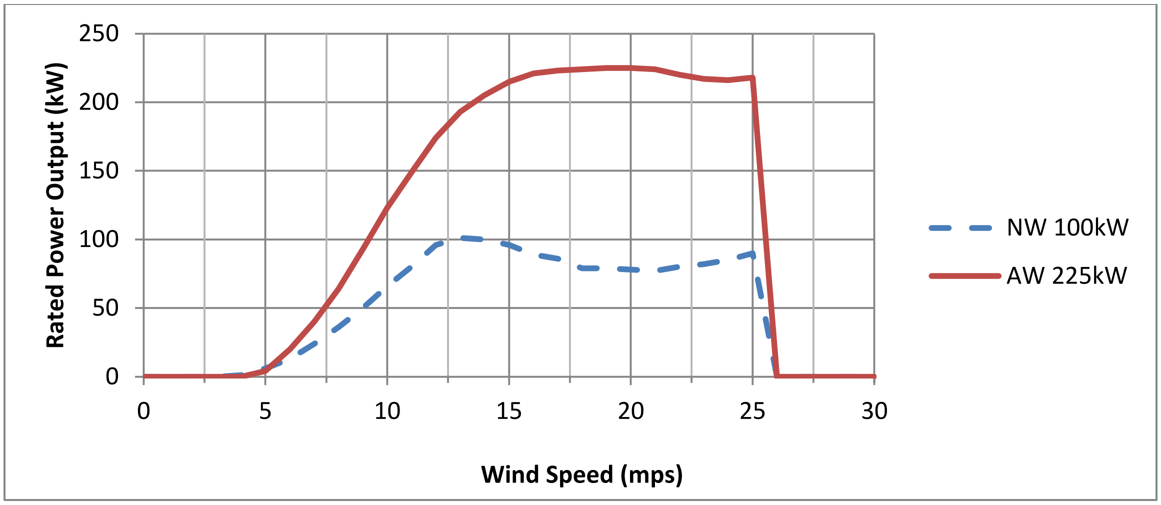

Figure A-2: Rated Power Output of two wind turbine models used in the study.
Source: HOMER Model, 2013.

APPENDIX B

Comparison of meteorological records at Lynn Lake and Brochet Airport:

Figure B-1 shows the comparison of monthly average wind speed between Brochet and Lynn Lake for a year in 1991-1992. As seen in the figure below, wind speed occurring at Brochet shows distinct seasonal fluctuations and for most of the period is higher than recorded at Lynn Lake.

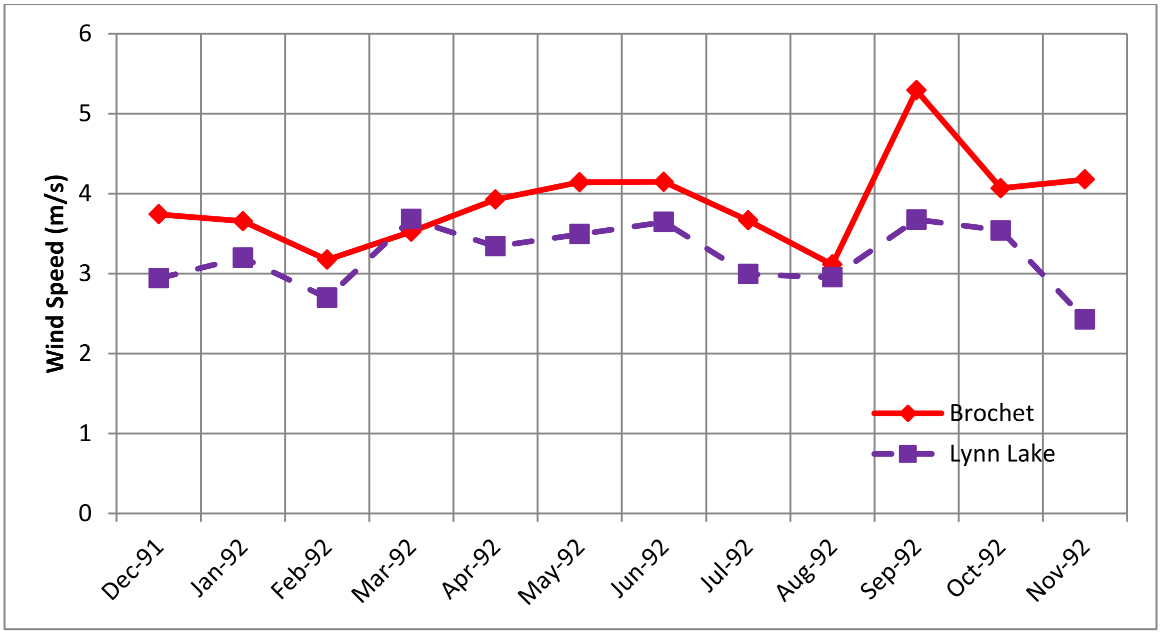

Figure B-1: Monthly Mean Wind Speed Profile at Brochet and Lynn Lake for a year in 1991-1992.
Data Source: NOAA, 2012

In Figure B-2 below, the diurnal variations in mean speed at Brochet and Lynn Lake for a year in 1991-1992 is shown. As seen in the figure, the hour of peak wind speed at Brochet occurred much later in the day that at Lynn Lake.

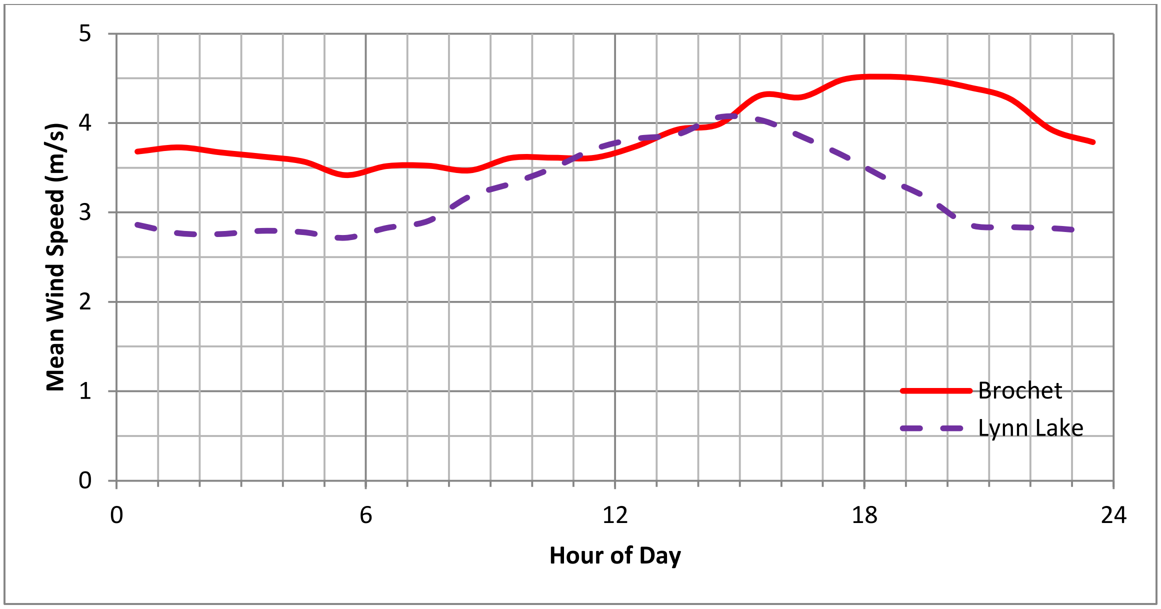

Figure B-2: Diurnal Variation in Mean Wind Speed at Brochet and Lynn Lake for a year in 1991-1992.
Data Source: NOAA, 2012

In Figure B-3, hourly mean wind speeds at Brochet and Lynn Lake Airport for the period of 1991-1992 is plotted in a scatter diagram. Each dot shows corresponding wind speed occurring at a certain hour at Brochet (represented in the X-axis) against wind speed occurring at the same hour and date at Lynn Lake (represented in the Y-axis). As seen in the figure below, there was no significant correlation between the wind speed occurring at Brochet and Lynn Lake. Also note that calm period occurred more frequently at Lynn Lake as represented by greater number of dots occurring along the X-axis. This is because spotty and stunted trees at Brochet also means that the surface winds are stronger and unlike Brochet, the meteorological station at Lynn Lake is surrounded by forests (Vickers et al., 2001).

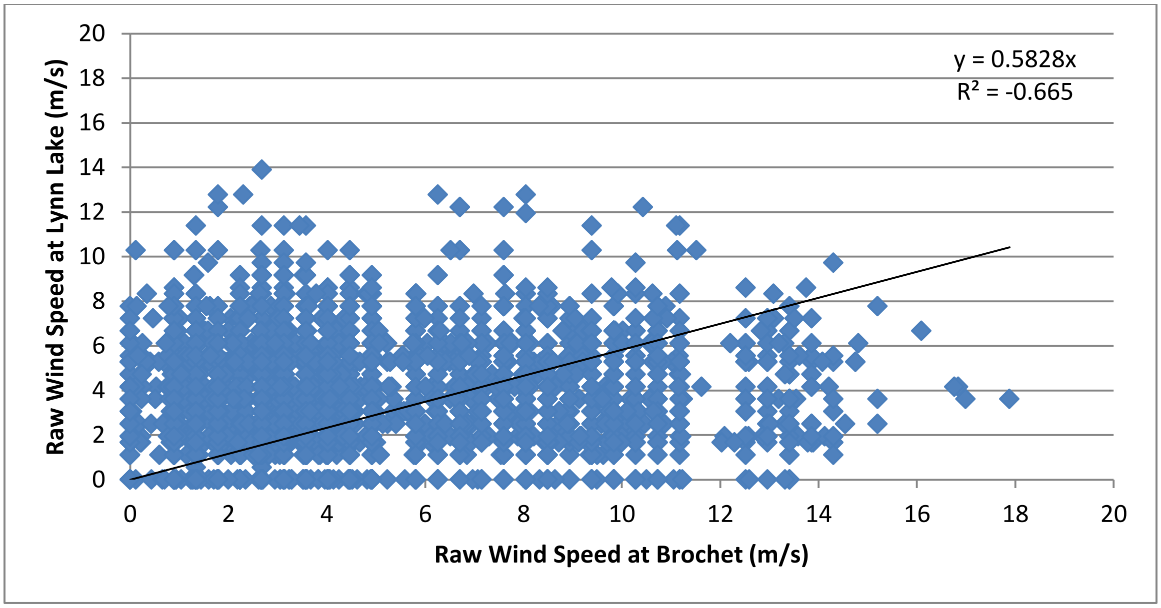

Figure B-3: Correlation of Hourly Mean Wind Speed Data collected at Brochet and Lynn Lake for a year in 1991-1992.
Data Source: NOAA, 2012)

Finally, Figure B-4 shows the wind rose of percentage of wind direction at both Brochet and Lynn Lake Airport for the period of 1991-1992. As seen in the figure, southerly was dominant in Brochet, whereas easterly was dominant in Lynn Lake.

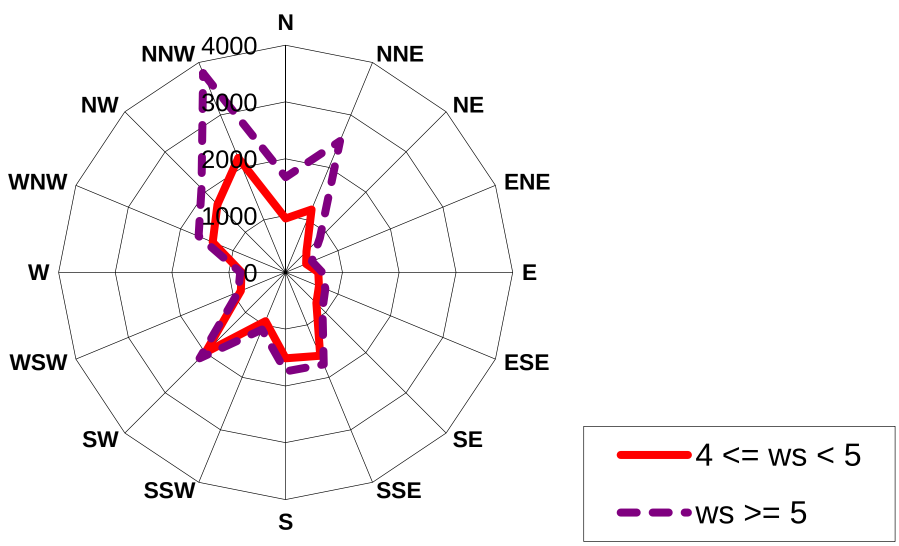

Figure B-4: Variation in Wind Directions at Brochet and Lynn Lake for a year in 1991-1992.
Data Source: NOAA, 2012

All the results of temporal variations (seasonal and diurnal), correlation of raw wind speed records, and wind direction shows that the Lynn Lake and Brochet sites are not similar. Thus, recent hourly data from Lynn Lake meteorological station were not used in this study.

APPENDIX C
ETHICS PROTOCAL # J2012:012

INFORMED CONSENT FORM

Study Title: Evaluation of an Optimum Electricity System Design in Brochet, Manitoba.

Principal Investigator: Prasid Ram Bhattarai, Master in Natural Resources Management Candidate, Natural Resources Institute, Clayton H. Riddell Faculty of Environment, Earth, and Resources, University of Manitoba, 204-474-7174, bhattapr@umanitoba.ca

Research Supervisor: Dr. Shirley Thompson, Associate Professor, Natural Resources Institute, Clayton H. Riddell Faculty of Environment, Earth, and Resources, University of Manitoba, 204-474-7174, s_thompson@umanitoba.ca

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Project description: I, Mr. Prasid Ram Bhattarai, am conducting this study as part of the partial requirement for my degree in Master of Natural Resource Management at Natural Resources Institute, University of Manitoba, under the supervision of Dr. Shirley Thompson. The purpose of this research is to evaluate an optimum electricity design in Brochet, Manitoba. The feasibility of the design will be assessed in terms of reliability, low cost, and low carbon emissions.

Study Procedure: If you choose to participate in this study, you will be asked to answer several questions about the economic cost of various components of power generation system.

Location and Time Requirement: The interview will take approximately twenty – thirty minutes and would take place during regular office hours (9am to 4:30pm). During the interview, I would be taking notes by hand.

Participation in this project is strictly voluntary and you may decline to answer any question or withdraw from the study without any negative consequences.

Confidentiality: I will keep any information gathered in this research strictly confidential. All data will be identified only by code number and kept in a locked filing cabinet in my University office. Only the researcher will have access to the data. You will not be named or identifiable in any reports of this study. If any statement you made during this interview is used in a research report it will be attributed to an anonymous source. Information containing personal identifiers (e.g., this consent form) will be destroyed as soon as it is no longer necessary for scientific purposes, approximately 09/2013. Interview notes will be deleted and/or destroyed by shredding once the project reaches its conclusion, approximately by September, 2013.

Compensation: Your participation is voluntary and no compensation in any form/kind will be provided to you.

Result Dissemination: Information provided by you may be published in a thesis at the University of Manitoba Natural Resources Institute and academic journals. A copy of the Master's thesis, a summary of findings, as well as any other publications resulting from this research will be shared with the community-based organizations, participating regional government offices, as well as with any participant requesting these materials.

Risks and Benefits: There is no risk to you from participating in this research. In the long-term, you/your organization <u>may</u> benefit <u>if</u> the findings of this research results in deployment of a new energy system in Brochet.

Feedback: If you would like to have a copy of the notes that I took today during the interview, I can provide it to you by email. A copy of the brief summary of results will be provided to you upon request either by email or postal mail after September, 2013.

Consent: Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence.

Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at your research records to see that the research is being done in a safe and proper way.

This research has been approved by the Psychology/Sociology Research Ethics Board. If you have any concerns or complaints about this project you may contact Dr. Shirley Thompson, (thesis advisor) at 474-7170 during business hours (M-F, 9:00 A.M. - 5:30 P.M.) or the Human Ethics Secretariat at 474-7122, or e-mail margaret_bowman@umanitoba.ca. A copy of this consent form has been given to you to keep for your records and reference.

____

Participant's Signature   Date

____

Researcher's Signature   Date

Email or surface mail address to which a summary of findings and written reports (at your option) should be sent:

Sample Questions:

Participant Interview Guide to power generation system dealers/suppliers

Date: ____________________

Location: ______________________

Interviewee: ____________________

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1. In general, how much is the installed cost per kilowatt of a specified power capacity of wind turbine/battery/diesel generator at a northern Manitoba?

2. What is the operation and maintenance cost per year for those systems?

Participant Interview Guide to Energy Suppliers/Importers

Date: ____________________

Location: ______________________

Interviewee: ____________________

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1. What kind of fuel (gasoline, diesel, others) do you supply to Brochet?

2. Was air or land transport used to supply the fuel?

3. What is the approximate average landed cost of fuel per liter?