Feasibility of Utilizing Hydrogen Fuel Cell Systems in Hybrid Energy Systems In Stand-Alone Off-Grid Remote Northern Communities of Canada

Signature Project

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Abstract

Feasibility of Utilizing Hydrogen Fuel Cell Systems in Hybrid Energy Systems

In Stand-Alone Off-Grid Remote Northern Communities of Canada

By

Garth Simmons, P.Eng.,BScME., MBA (candidate)

April 2011

Hydrogen production represents one of the most promising solutions for solving the intermittency in electricity generation that is produced by renewable resources, such as wind. Recent studies have suggested that a potential solution for the storage of excess energy generated by a hybrid energy system is to use a hydrogen fuel cell system operating in parallel with wind turbines (Cotrell and Pratt, 2002; Khan and Iqbal, 2004).

This study examined whether a small-scale hybrid system working in parallel with a fuel cell system had reached a commercially viable stage. More specifically, the study investigated under what conditions (wind speed, fuel cell system capital cost, and diesel price) it would be economically feasible to use a wind-hydrogen fuel cell system to replace wind-diesel-battery generated electricity for off-grid applications in remote northern regions of Canada. HOMER (computer software simulation tool) was used to conduct the aforementioned sensitivity analysis as well as for sizing and optimization.

The average monthly wind speeds for Iqaluit were used to represent the wind regime potential of a remote northern community. A projected electrical load of 630 kilowatt hours per day with a corresponding peak load of 143 kilowatts was chosen to represent the electrical power requirements of 30 residents for an off-grid small residential development in a remote northern community of Canada. This load requirement was calculated by scaling up, by a factor of 30, the author’s own monthly household electrical consumption of 21kWH with a peak demand of 4.76 kilowatts.

The analysis revealed that a wind-diesel-battery system is presently the most economically viable solution. However, with a reduction in fuel cell systems (electrolyzer, fuel cells, and hydrogen storage tanks as defined in the Glossary) to approximately 50% of their current costs these systems begin to become cost effective when coupled with a wind-diesel-battery system. It is not until the fuel cell system costs reduce to 20% and wind speeds exceed 7.7 m/s that it is economically justifiable to eliminate the diesel-battery components entirely. Anticipated advances in fuel cell system research and development are needed to enable the fuel cell system technology to become an economically viable option.

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1.0 Introduction

1.1 Overview

The practice of harnessing wind energy can be traced back to 5000 BC. Wind was being used to propel vessels along the Nile River. Simple windmills were first utilized in the Middle East and China around 200 BC for drawing water and grinding grains. It wasn't until the development of electricity in the 19^{th} Century that windmills began to be used to generate power. In recent years large scale wind turbines connected to an established electrical grid have been proven to be economically viable where favorable wind regimes exist. Excellent example of these systems can be found here in North and West Cape, Prince Edward Island and in Grand Bend, Ontario.

Hydrogen production represents one of the most promising solutions for solving the intermittency in electricity generation that is produced by renewable resources, such as wind (Cotrell and Pratt, 2002). Furthermore, it is a clean energy carrier that can be produced by electrolysis of water using excess energy produced from wind turbines (Beccali, Brunone, Cellura and Franzitta, 2007). Electrolysis of water is the decomposition of water (H_2O) into it constituent parts, oxygen (O_2) and hydrogen gas (H_2), as a result of passing an electric current through the water.

This study will examine the feasibility of using small scale hybrid systems involving a fuel cell system for use in small, remote, off-grid communities. For the purposes of this study a hybrid energy system was defined as a primary renewable resource working in parallel with a standby non-renewable component and a storage unit. The renewable resource, wind, is being converted into electricity via wind turbines. A fuel cell system was defined as a system consisting of an electrolyzer, hydrogen storage tank and fuel cell used to produce electricity.

Recent advances in fuel cell system technology and the associated cost reductions can provide an opportunity to use hydrogen to store excess energy produced by turbines. It is hoped that a hybrid system utilizing this advancing technology may prove to be an economically viable solution for small, stand-alone electrical systems. Assuming that reliable systems characterized by an uninterrupted power supply and low operating costs can be designed, their rate of adoption is anticipated to be high in remote communities. For these communities, burdened with high electricity costs, it is not feasible to connect to power grids that service large urban areas.

1.2 Background

The reverberating cadence of diesel generators producing electricity is a familiar sound too many residents living in Canada's remote northern communities. Less familiar is the sight of hybrid energy systems, typically characterized by swirling turbine blades. But renewable energy installations are beginning to take root in places like Nunavut and the Yukon. These hybrid systems are starting to supplement or even replace diesel generators. That being said, only a limited number of hybrid energy systems currently operate north of the 60th parallel in Canada, but research into their future potential usage is continuing (Ascher, 2002). The requirements of isolated communities may increase the probability of hybrid energy systems becoming economically feasible. Isolated communities incur increased diesel fuel costs as a result of long transport distances and are often located in very hostile environments. However some have the advantages of excellent wind regimes, which are a renewable resource.

Hybrid energy systems diminish the risk of diesel-related environmental damage and related remediation costs (Ascher, 2002). Diesel generators emit greenhouse gases, and leaks from fuel storage tanks can contaminate soil and potable water supplies. Furthermore, tanker truck accidents on ice roads are increasing due to global warming, both after freeze-up and prior to spring thaw. The extrication efforts to retrieve tanker trucks that have broken through the ice can result in additional fuel spills.

Despite these environmental benefits, hybrid energy system utilization in remote northern communities is not without challenges. Northern community populations are typically low and scattered and their power needs are proportionately small relative to more densely populated areas. This creates challenges when attempting to gain cost advantages from economies of scale.

Various combinations of wind turbines, diesel generators, batteries, power converters, and fuel cell systems were simulated in an effort to find the most cost effective system to satisfy the given electrical load requirements. Within the content of this study, a fuel cell system is defined as a system consisting of the following three components: electrolyzers, hydrogen storage tanks, and fuel cells (see Glossary).

1.3 Purpose and Aim Research

The purpose of the study was to investigate under what conditions (wind speed, fuel cell system capital cost, and diesel price) it would be economically feasible to use wind and a hydrogen fuel cell system to replace wind-diesel-battery generated electricity for off-grid applications in remote regions of Canada.

This is of personal interest because I expect that significant reductions in emissions can be achieved when, and if, hydrogen can be used to store and produce energy more cost effectively than a diesel-battery system. If it can, it will be a much cleaner form of energy production.

Unfortunately, with our North American culture I am doubtful that this technology will be widely adopted without an economic stimulus. Thus, this study will concentrate on the feasibility of utilizing a wind-fuel cell system in place of a wind-diesel-battery system to produce energy.

2.0 Literature Review

2.1 Focus and Intent

To ensure this study is based on the most recent and relevant information in the public domain, a literature review was conducted to learn more about hybrid energy systems involving both wind-diesel-battery systems as well as wind-fuel cell systems.

2.2 Large-Scale Grid-Connected versus Stand-Alone Off-Grid

Dutton, Bleijs, Dienhart, Falchetta, Hug, Prischich, and Ruddell (2000) posit that large-scale, grid-connected wind turbines exceeding 1 Megawatt in size have proven to be economically viable in most regions of the world. However, they proceed to indicate that the development of small-scale, stand-alone power sources for use in remote off-grid communities has yet to reach commercial viability.

2.3 Wind-Fuel Cell Hybrid Energy System

In a hybrid energy system a wind turbine is used to provide the primary power source. Because wind energy is of an intermittent nature, energy must be supplied by other sources during times of low wind speeds. During times of high wind speeds, excess energy can be converted into hydrogen using an electrolyzer. An electrolyzer is a vessel or system of vessels filled with an electrolyte in which electrodes (cathodes are connected to the negative poles of a direct-current source while anodes are connected to the positive pole) are used to carry out electrolysis. During periods of low wind speeds, stored hydrogen can be converted back to electricity using fuel cells. An electronic power converter is required to allow the electricity to flow between the AC components (wind turbines) and the DC components (fuel cells).

A hydrogen fuel cell system is depicted in Figure 2.1.

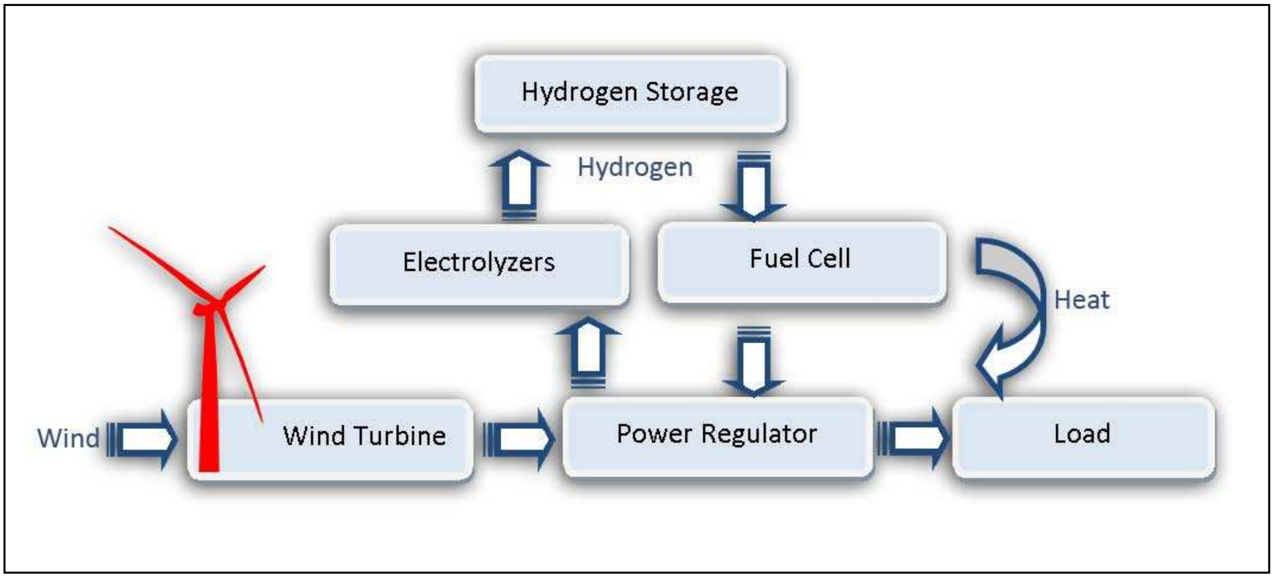

Figure 2.1 Fuel Cell System Working in Parallel with Wind Turbine

2.4 Present and Future Fuel Cell Costs

2.4.1 Reduced Cost of Renewable Energy Systems

With the anticipated reduction in component costs and gains in efficiencies as a result of advancements in technology, attention is turning towards renewable energy alternatives for electricity generation in stand-alone applications. This momentum is drawing interest from all corners of the globe. Wind technology is expected to be at the forefront of the various renewable stand-alone systems being considered (Mann, 2003). This, combined with recent advancements in full cell and electrolyzer technology, is creating viable options for utilizing hydrogen to store the excess energy being generated with the intermittent wind (Beccali, Brunone, Cellura and Franzitta, 2007). A hybrid energy system, utilizing improved fuel cell and electrolyzer technology, and operating in parallel with wind turbines may prove to be an economically viable solution for small-scale power generation (Dutton et al 2000).

2.4.2 Cost of Fuel Cells

A fuel cell is defined as an electrochemical device consisting of three basic components (anodes, cathodes, and electrolytes) used to produce electricity and heat from a fuel (often hydrogen). Based on previous studies, the high cost of fuel cells has caused these systems to be less economically viable than the traditional diesel-battery system for supplying backup power for wind turbines when unfavorable wind conditions persist. The cost of fuel cells varies depending on the technology deployed (Cotrell, 2003). The Fuel Cell Report to Congress (2003) and Ballard Power Systems Inc. (2010) indicate that fuel cell costs vary from $3000 to $6000/kW. However, current research, driven by the desire to develop low-cost electric vehicles, is expected to reduce this to as low as 6.5% of the current lowest costs. Fuel cell prices are expected to reach costs ranging from $195 to 300/kW in the near future (Fuel Cell Report to Congress, 2003). Simbeck and Chang (2002) and Pratt (2002) have also reported similar findings for current and future fuel cell costs. The cost of fuel cells varied depending on scale, power electronics requirements, and reformer requirements. Three fuel cells were identified that were priced between $3,000 and $6,000/kW.

One fuel cell technology under development was expected to reduce the installed fuel cell cost to $400/kW by extending the useful operating life of the cell to over 40,000 hours. It was expected to be available for commercial distribution within 5 years (Fuel cell Report to Congress, 2003). Based on the actual and projected fuel cell costs, capital, replacement, and operational and maintenance costs (see Glossary for definitions) utilized in this study were $3000/kW, $2500/kW, and $0.020/h respectively.

2.5 Component Efficiencies and Costs

Equipment operating efficiencies and costs (capital, replacement, and operational and maintenance) have been based on website information, discussion with equipment manufactures, and information from literature reviews of academic and professional journals. With regard to academic journals, the following authors provided excellent insight into the costing and performance of the various components involved in this study: Cotrell and Pratt, 2002; Simbeck and Chang, 2002; Pratt, 2002; and Khan and Iqbal, 2004. In addition, personal conversation with two Professional Engineers working with the P.E.I. Energy Corporation; Estabrooks, 2010 and Victor, 2010 were invaluable in confirming the accuracy of the costs and efficiencies being used to model the system.

2.6 Diesel Prices in Remote Northern Communities

Costs for diesel fuel used to generator power in remote northern communities are known to be high. Alaska provides one example. Alaska has more than 200 small communities that have no link to the power grids serving the main urban areas and are thus reliant on diesel-driven generators. Diesel costs for operating generators are inflated by the high transportation costs involved to deliver fuel. Remoteness of these communities, coupled with a lack of roads, result in diesel fuel prices ranging, from $.26 to $.79/litre (Drouilhet and Shirazi, 2002). The average price of a barrel of oil has tripled ($22/barrel to $88/barrel) from 2002 to 2010. Based on this increase, the 2010 price of diesel in these communities would range from $.78 to $2.37/litre. Victor (2010) indicated that the subsidy adjusted price for diesel fuel delivered to Nunavut in the fall of 2010, for the purpose of generating electricity, was $.85/litre.

2.7 Cost of Electricity (COE) in Remote Northern Communities

High diesel fuel prices have a direct influence on the cost of electricity (COE) in remote communities. Additionally, Drouilhet and Shirazi (2002) have suggested that high operating and maintenance costs of diesel generators contribute to high electrical cost in Alaska. These costs can range from $0.40 to $1.00/kWh. Estabrooks (2010) indicated that the cost of electricity in remote Canadian communities ranged from $.50 to $.70/kWh. It should be noted that the Canadian COE can also be influenced by government diesel fuel price subsidization given to remote communities.

3.0 Methodology

3.1 Research Design

The main objective of this study was to assess the economic feasibility of utilizing fuel cell systems to replace the diesel-battery components in a hybrid energy system involving wind turbines. A computer simulation was conducted to answer the research question presented in Section 1.3. Simulation involves the use of mathematical models to recreate a situation so that the likelihood of a range of outcomes can be more accurately predicted (Ross, 2002). This study will report the data analysis results of various hybrid energy systems simulated in the study. Critical independent variables (hereinafter referred to as a sensitivity analysis) are proposed to be wind speed, diesel prices, and fuel cell system costs. Each of these variables will be simulated or tested for within the following specified range: wind speeds 6.0 to 9.5 m/s, diesel prices $.85 to $1.50/litre, and fuel cell system costs 100% to 10%. This will enable the study to identify the effects that a change in one of these variables has on the feasibility of the overall system. Table 3.1 provides a definition, as well as the unit and scale of measure, for each of these variables.

Independent Variable	Definition	Units of Measure	Scale of Measure
Wind speed	Average monthly wind speed	Meters/second	Ratio
Diesel price	Cost per litre of diesel	$/litre	Ratio
FC System Capital Multiplier	Percentage of present fuel cell system costs	%	Ratio

Table 3.1 Independent or Sensitivity Variables

3.2 Method of Analysis

HOMER, a computer model developed by the United Stated National Renewable Energy Laboratory (NREL) is available for downloading free of charge, will be used to analyze the feasibility of two hybrid energy systems. The HOMER software enables the user to create a model of the power system. This model incorporates both the physical behavior of the system and its life-cycle costs. The life-cycle cost is the total cost of installing and operating the system over its expected life. It includes costs for capital, replacement, operation and maintenance, fuel, and interest. The two off-grid hybrid energy systems being compared are a wind-diesel-battery system and a wind-fuel cell system. Both are used to generate electricity to satisfy an electrical load of 630 kilowatt hours per day with a corresponding peak load of 143 kilowatts.

HOMER utilizes algorithms to perform three principal tasks: simulation, optimization, and sensitivity analysis. In the simulation process, HOMER models the performance of a submitted configuration to determine the technical feasibility and life-cycle costs of the system. In the optimization process, HOMER simulates many different system configurations to identify the one that best satisfies the technical constraints at the lowest life-cycle cost. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of inputted assumptions to allow the user to gauge the effects of changes to the model. Sensitivity analysis helps the designer assess the effects that changes in the variables, which can't be controlled by the modeler, have on the system design. The independent variables considered in this study were: wind speeds, diesel prices, and fuel cell system costs. HOMER was used to simulate system configurations for the range of: wind speeds (6.0 to 9.5 m/s), diesel prices ($.85 to $1.50/litre), and fuel cell system costs (100% to 10% of current costs).

HOMER enables the user to evaluate many different system configurations based on technical and economic merit. It also enables the user to better understand and to quantify the effects of changes to the inputted variables discussed in Section 4.0.

HOMER was used to simulate the operation of a power system by making energy balance calculations for each of the 8760 hours in a year. For each hour, HOMER used the electric demand for that hour and calculated the flows of energy to and from each component in the hybrid energy system. For the systems being considered, HOMER computed on an hourly basis whether to operate the generator or turbine and/or to charge or discharge the batteries. It provided optimal calculations for the turbine, fuel cell, and hydrogen storage tank system.

3.3 Data Sources

HOMER utilizes algorithms to perform the simulation, optimization, and sensitivity computations. To obtain the input data utilized by HOMER in modeling the various hybrid systems, data was collected from the following sources: academic and professional journals, written reports, websites, government agencies, various service providers, and personal communication with representatives from component equipment manufacturers.

The costs, sizes, efficiencies, and life expectancies of the various hybrid energy system components were additional dependent variables in this study. A detailed description of these dependent variables is presented in Section 4.0.

4.0 Hybrid Energy Systems and Associated Variables

A hybrid energy system was defined as a primary renewable resource working in parallel with a standby, non-renewable component and a power storage unit. The renewable resource component is the wind turbine. Other components that make up the hybrid system are the diesel generator, electrolyzer, hydrogen storage tank, fuel cell, power converter, and the battery storage units as shown in Figure 4.1.

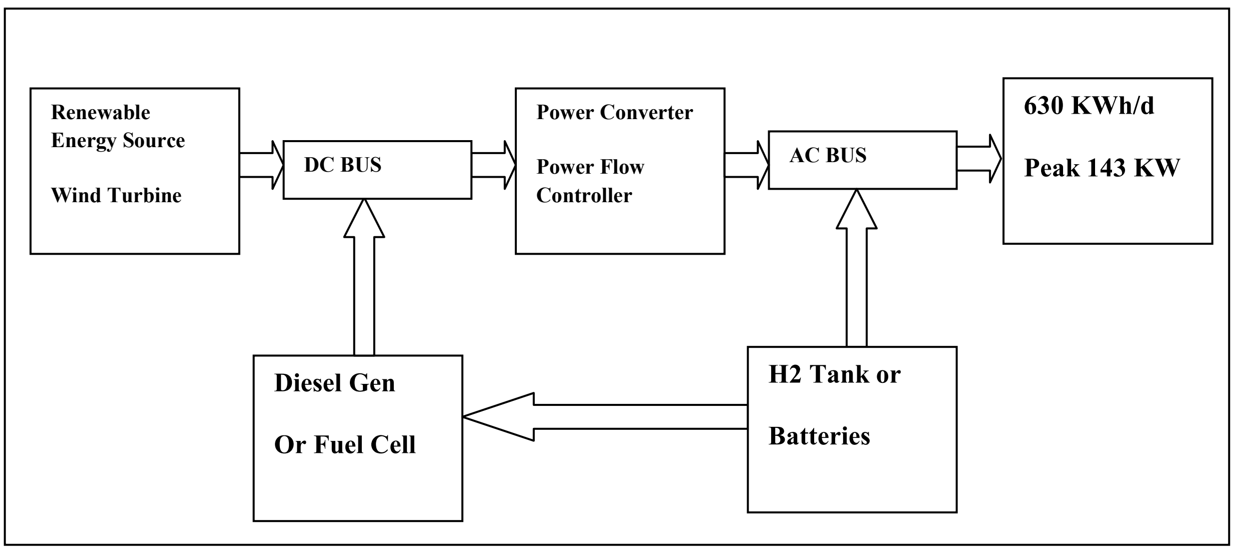

Figure 4.1 Hybrid Energy Systems Configuration

The research specific schematic inputted into the HOMER simulation software is shown in Figure 4.2.

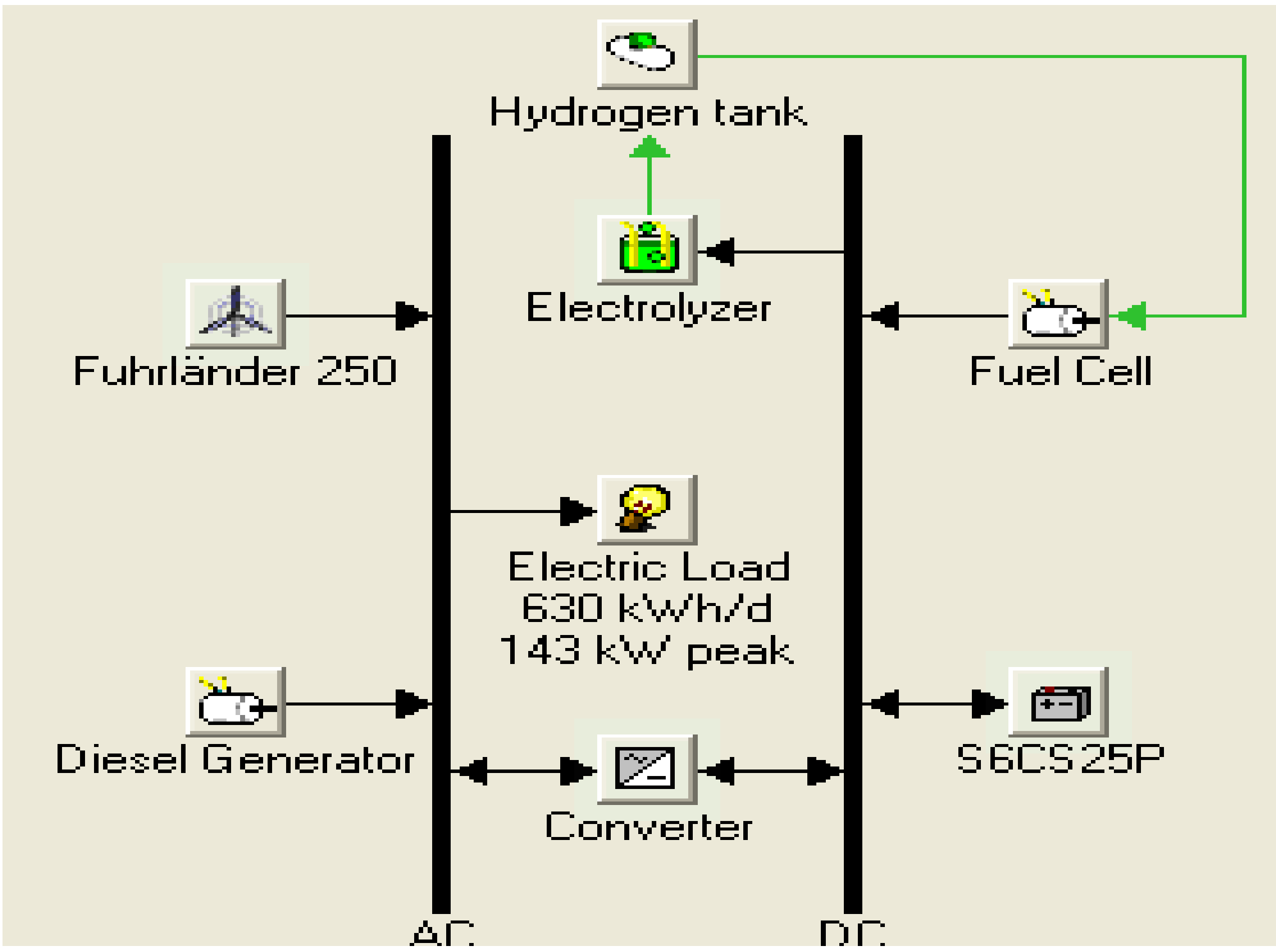

Figure 4.2 Hybrid Energy System Configuration Inputted into HOMER

A detailed description of each component along with the associated costs, number of units being considered, and the operating life follows. These inputs were analyzed in the HOMER simulation program to determine the most economically feasible option to meet the 630kWh/d primary load.

4.1 Electrical Load

The electrical load to be feasibly satisfied in this study was 630 kilowatt hours per day (kWh/d) with a corresponding peak load of 143 kilowatts (kW). This load was scaled up using the author's own monthly household electrical consumption of 21kWH with a peak demand of 4.76 kilowatts. This consumption is based on general household consumption for a family of four with residential heat being provided by an oil fired boiler. This, assumed to be representative sample, was scaled up by a factor of 30 to represent the electrical power requirements of 30 residents for an off-grid small residential development in a remote northern community of Canada. It is acknowledged that this electrical load could be expected to vary depending on the user profile and the community being considered. The daily load profile being used in this study is shown in Figure 4.3. The daily energy consumption is expected to be higher during early morning, mid day, and again in the evening.

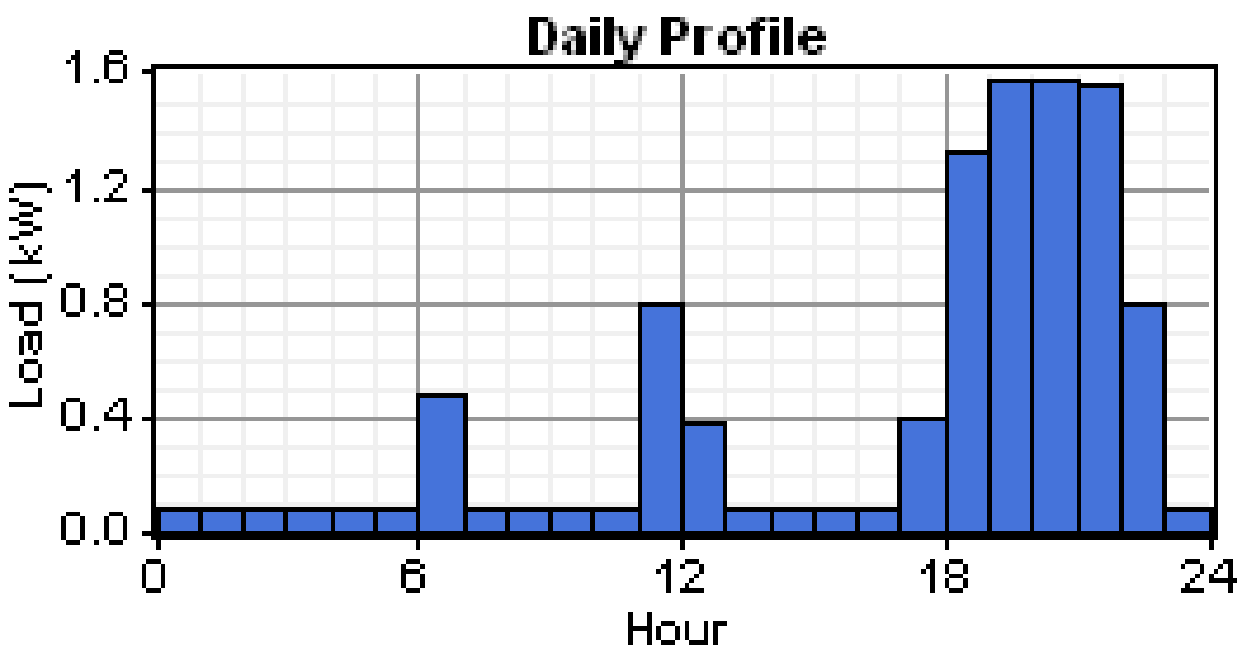

Figure 4.3 Daily Load Profile

The daily load profiles for a one year period are shown Figure 4.4. Lower load demands are expected during the summer months from June through to the end of August.

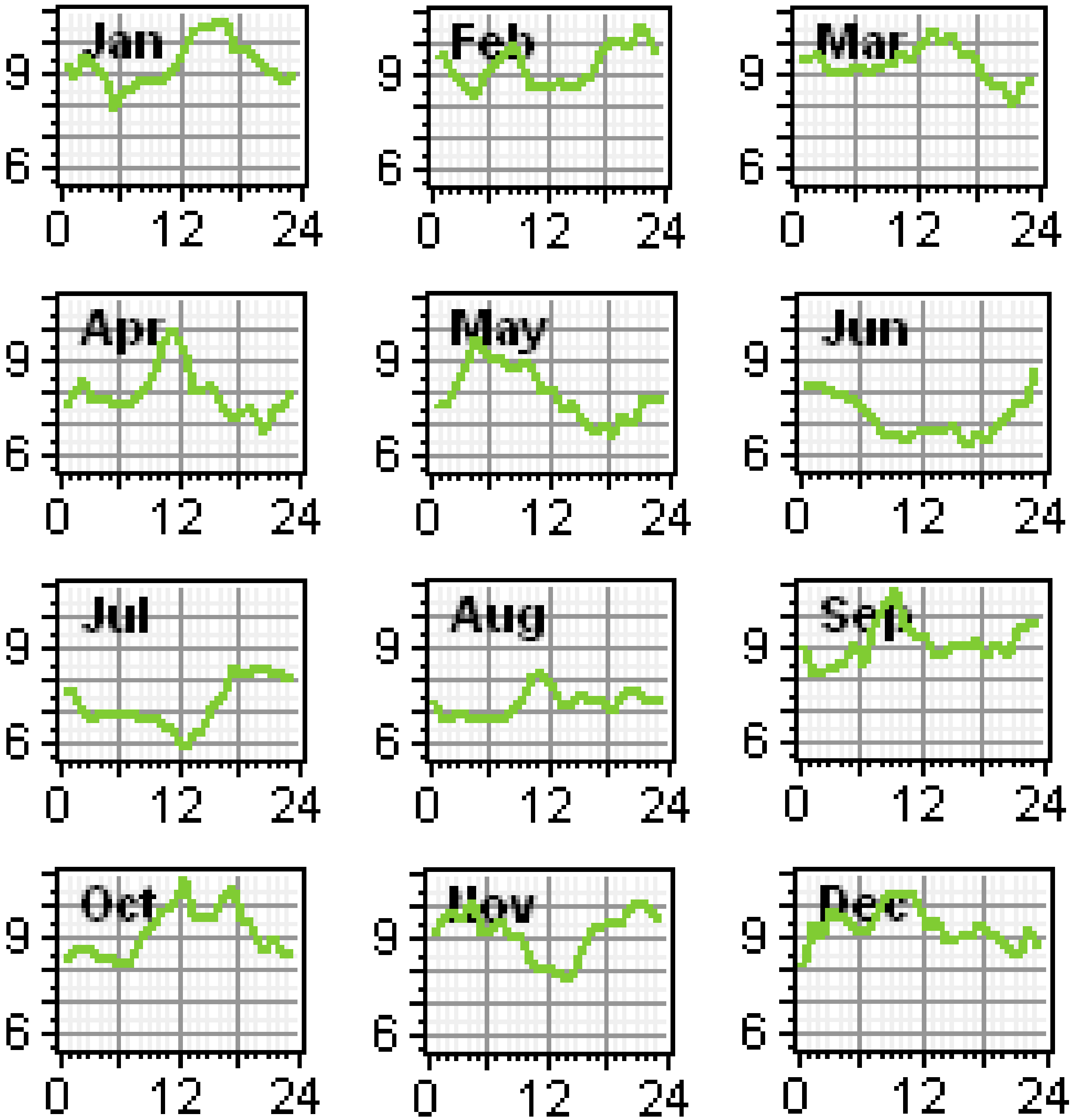

Figure 4.4 Daily Load Profile for a One Year Period

The profile of the seasonal electrical consumption was chosen to be a reasonably consistent electrical demand for the entire season as shown in Figure 4.5.This will vary depending on the specific community location. If, for instance, the community utilized electrical heat, the winter load demand would rise accordingly. For the given load profile the hourly variation was 10.2% while the daily variation was 10.5%.

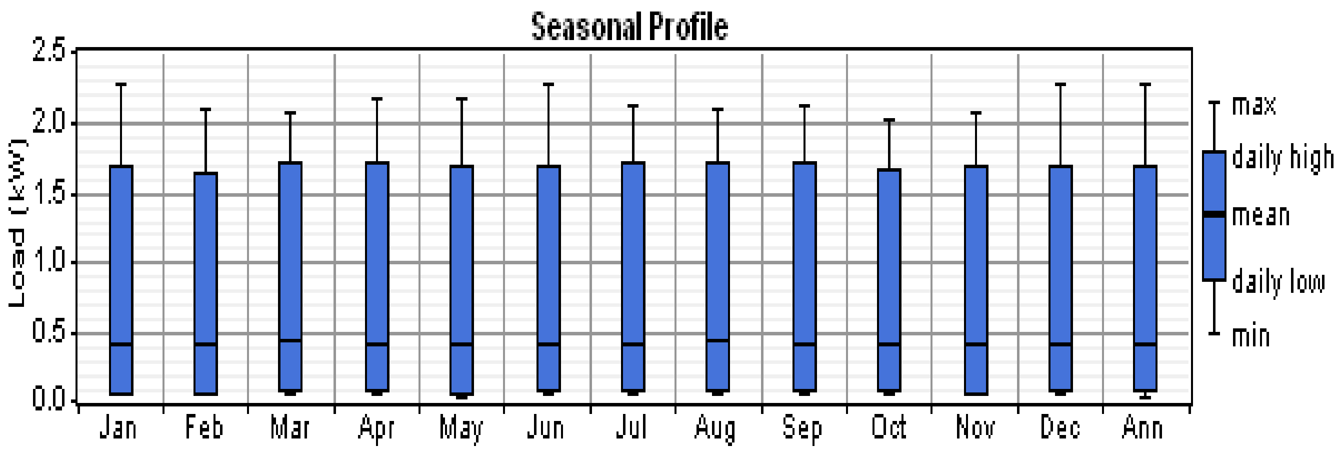

Figure 4.5 Seasonal Load Profile

4.2 Renewable Resource

Iqaluit's (latitude = 62.656 and longitude = 69.505) average monthly wind speed was 6.49 metres per second. Iqaluit was chosen to be a representative sample of Northern Canada's wind potential (See Appendix A- Iqaluit Average Wind Speeds). The Weibull distribution (k) was 1.16, indicating the distribution of wind speed over a one year period. The randomness in wind speed was calculated to be .967 while the daily variation in wind speed was found to be .0323. The average wind speed is highest in the fall and winter season at 6.98 and 7.10 m/s respectively. The spring and summer seasons the average wind speeds were measured to be 6.06 and 5.51m/s respectively as shown in Figure 4.6.

To ensure the study provided an overview for communities with varying wind regimes, the following range of average wind speeds was considered in the sensitivity analysis: 6.0, 6.49, 7.0, 7.7, 8.0, 8.5, 9.0, and 9.5 m/s. This range of wind speeds was chosen in an attempt to represent the varying wind resources that could exist in remote Northern Canadian communities.

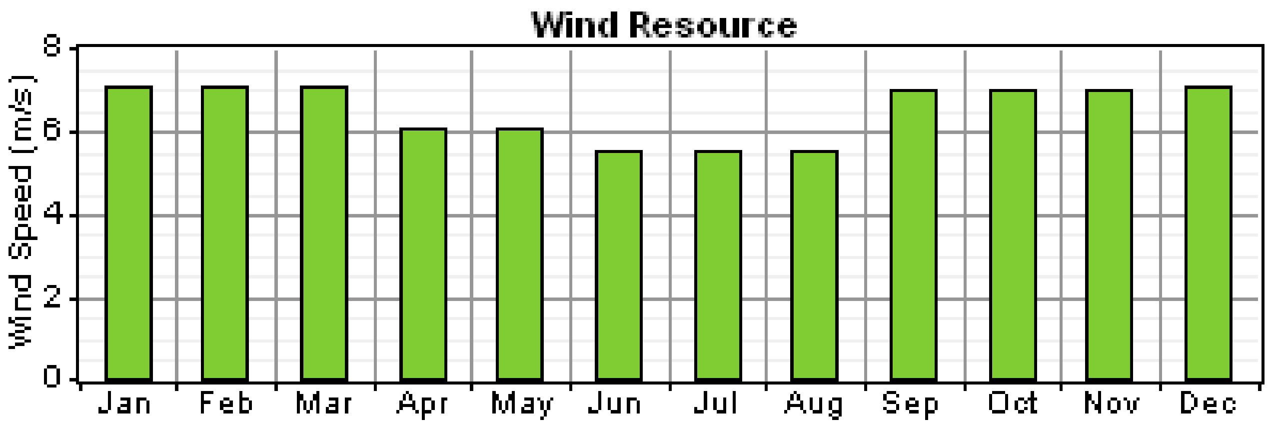

Figure 4.6 Average Monthly Wind Speed for Iqaluit

4.3 Hybrid System Components

The hybrid system components being considered are as follows: diesel generators, wind turbines, fuel cells, electrolyzers, hydrogen storage tanks, batteries, and power converters. Research has been conducted to determine the costs (capital, replacement, and operating and maintenance) of each of these components. Additionally, the number of units or size of each component was researched to determine what was needed to service the aforementioned electrical load of 630 kWh/d with a corresponding peak load of 143 kilowatts.

4.3.1 Diesel Generator

The cost of a commercially available generator can range from $200 to $500/kW (Cotrell, 2003). The larger units are more economical to purchase. Since the peak demand for the generator was 143 kW the lowest current price was used as the input price. Replacement, as well as operational and maintenance costs, were projected to be $150/kW and $.10/hr respectively. Options for generator use were inputted into the HOMER Model to use no generator (0) as well as, 25, 75, 150, and 250 kW. The operating life of the generator was set at 10,000 hours (Cotrell, 2003).

Diesel price was used in the sensitivity analysis portion as it was hypothesized at the outset of this study to be an important factor in determining when fuel cells would become economically viable over diesel generators. As such, the following diesel prices were chosen: $.85, $1.00, $1.25, $1.50 and $1.75/litre. The $.85/litre cost was chosen as the base price as it was the known commercial bulk price for diesel fuel delivered to Nunavut in late 2010 (Victor, 2010).

4.3.2 Wind Turbine

Availability of energy from a wind turbine is directly rated to the consistency of the wind speed and is referred to as the capacity factor of the turbine. The Fuhrländer turbine, with a rated capacity of 250 kW was chosen to service the electrical load discussed in section 4.2. The turbine rating can be misleading as it is generally much higher than the actual output delivered. Indeed, the mean output was calculated to be just 89.5kW based on a capacity factor of 35.8% as indicated in Figure 4.7. The capacity factor is influenced by intermittent wind speed, as there are periods when the wind speeds are to low or high (cut out speeds) to allow the turbine to generate electricity (Estabrooks, 2010).

Variable	Value	Units
Total rated capacity	**250**	**kW**
Mean output	**89.5**	**kW**
Capacity factor	**35.8**	**%**

Figure 4.7 AC Wind Turbine: Fuhrländer 250 Output

The cost of the turbine was set at $600,000 while the replacement costs were considered to be $450,000 (Estabrooks, 2010). The operating and maintenance costs were estimated to be $2000/yr. The operating life of the turbine was taken to be 20 years (Estabrooks, 2010). To enable the HOMER simulation software to identify an optimum system the number in the turbine search space was inputted at 0 to allow no turbine to be chosen as well as at 1, 2, 3, and 4.

4.3.3 Fuel Cell

A fuel cell is an electrochemical device consisting of three components an anode, cathode, and electrolyte used to produce electricity and heat from a fuel (often hydrogen). Researchers such as Cotrell and Pratt (2002), Simbeck and Chang (2002), Pratt (2002), Khan and Iqbal (2004), and Beccali et al (2007) found that fuel cell costs are known to vary greatly depending on the technology chosen. They indicated that variances ranging from $3000 to $6000/kW are typical. However, the cost of fuel cells is projected to decline sharply based on the emphasis being given to this technology in the effort to develop economically viable electric vehicles. Some studies are projecting that fuel cell cost will reach $200 to $300/kW in the near future (Beccali et al 2007). Based on this research, the capital cost was inputted at $3000/kW which is the lowest currently available price. The corresponding replacement cost utilized was $2500/kW where as the operating and maintenance cost was inputted at $.02/kW. A fuel cell efficiency of 60% was chosen to represent the higher range of the efficiencies available.

Three different fuel cell sizes were used in the simulation to ensure accurate sizing of the fuel cell to the electrical load requirement. The search space was given the following sizes: 0, 150, and 175 kW. The zero (0) provided the HOMER optimization algorithm the option to choose no fuel cell if it was the most economical choice to meet the load requirements. Based on other studies, it was proposed that the most significant cost in commercializing a hybrid energy system was the fuel cell system (fuel cells, electrolyzer, and hydrogen storage tank). To test this proposition the components were linked in the analysis so that the capital cost multiplier (see Glossary) was applied to the three components simultaneously. A sensitivity analysis was carried out with the cost multiplier factor for each of these components (hereinafter "FC Capital Cost Multiplier") computed at 100%, 65%, 45%, 20%, and 10% while the wind speeds and diesel prices were computed within a range of 6.0 to 9.5 m/s and $.85 to $1.50/litre, respectively.

4.3.4 Electrolyzer

An electrolyzer is a vessel or system of vessels filled with an electrolyte in which electrodes are used to carry out electrolysis. Beccali et al (2007) indicated that the current costs for electrolyzers were similar to fuel cells in that they were dependent on the technology chosen, and that they can range from \$1500 to \$3000/kW. With projected improvements in technology, these costs were also expected to decrease within the next few years (Beccali et al 2007). Electrolyzer capital costs were inputted at \$1500/kW while the replacement cost was inputted at \$1200/kW, as shown in Figure 4.8. Operations and maintenance costs were projected to be minimal and thus were given a nominal value of \$20/year.

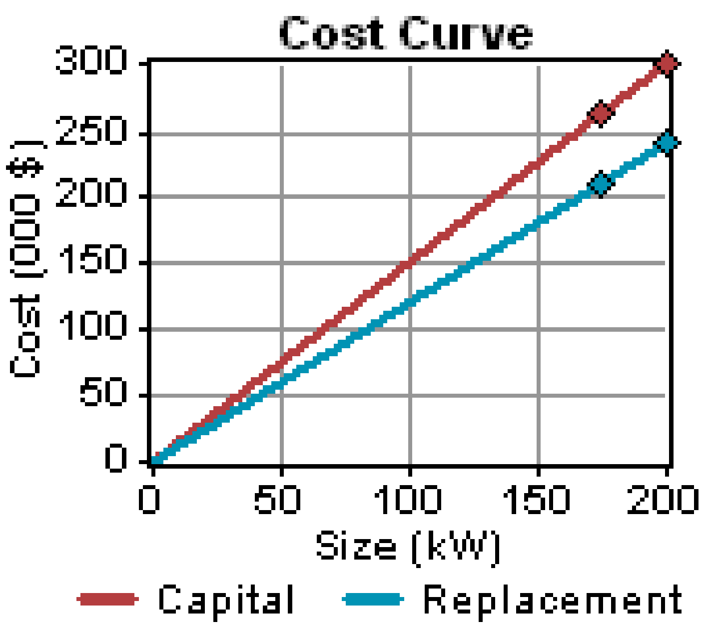

Figure 4.8 Electrolyzer Capital & Replacement Costs

Different sizes of electrolyzers (0, 175, and 200 kW) were inputted into the HOMER simulation software for optimum sizing. Operating life was considered to be 25 years while the efficiency was projected to be 75%. A sensitivity analysis was carried out with the cost multiplier factor coupled to the FC capital multiplier. They were computed at 100%, 65%, 45%, 20%, and 10% of the original capital cost.

4.3.5 Hydrogen Storage Tank

A hydrogen storage tank is a large (usually metallic) pressure vessel used for storing hydrogen gas. The hydrogen storage tank was also included in the fuel cell system as it was utilized to store the hydrogen produced by the electrolyzer. The hydrogen storage tank was included at $1300/kg with a corresponding replacement cost of $1200/kg and a 15 year life-cycle, as depicted in Figure 4.9 (Beccali et al 2007). Four different sizes (0, 200, 250, and 400/kW) were included in the HOMER search space field to allow for the selection of the most cost effective configuration. A sensitivity analysis was carried out with the capital multiplier factor coupled to the FC capital multiplier. Again they are being inputted at 100%, 65%, 45%, 20%, and 10%.

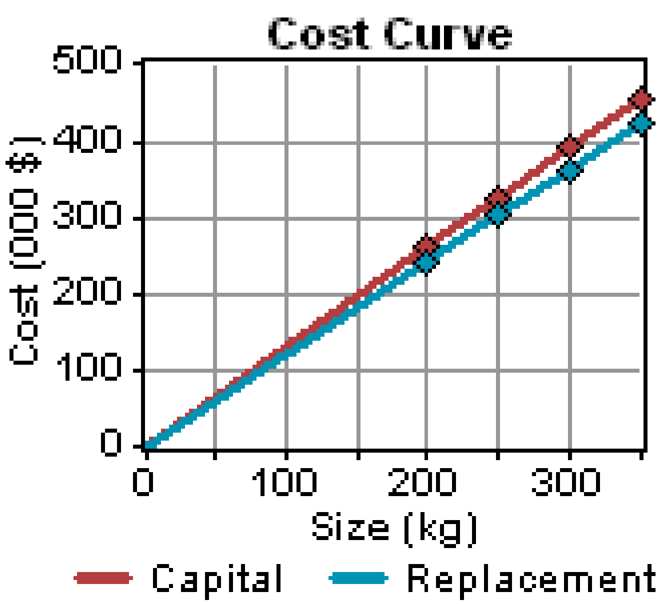

Figure 4.9 Hydrogen Storage Tank Capital & Replacement Costs

4.3.6 Battery Component

To enable a comparison to the electrolyzer and hydrogen storage tank configuration, a conventional battery stack was included in the study. Model 6CS25P manufactured by Surrette Batteries was chosen. This battery had the following nominal voltage and capacity 6V, 1156 Ah. Its rated life throughput was inputted at 9645 kWh. As shown in Figure 4.10, the capital and replacement cost of each 6CS25P battery was inputted at $900 and $850 respectively. The operating and maintenance cost was projected to be $.10/kWh. The battery stack size selection options were inputted for 0, 600, 650, 700 batteries to be utilized.

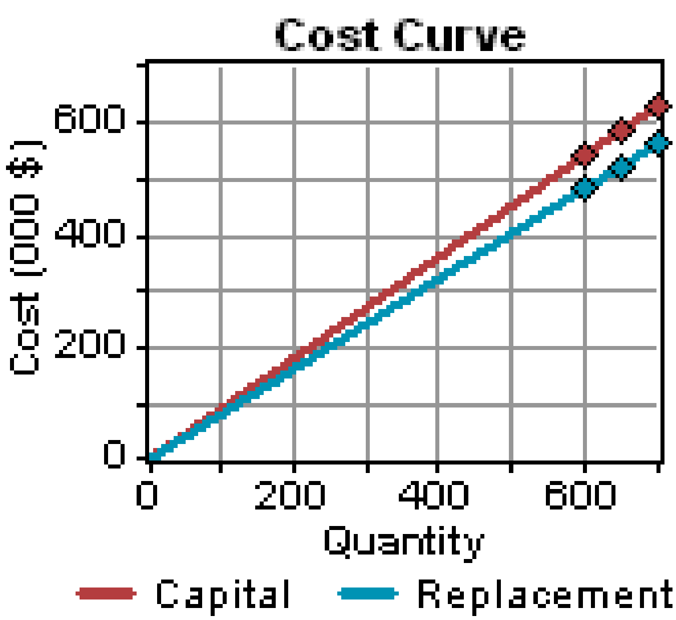

Figure 4.10 Battery Capital & Replacement Costs

4.3.7 Power Converter

An electronic power converter was required to allow the electricity to flow between the AC components (wind turbine and diesel generator) and the DC components (fuel cell and batteries) to service the 630kWh/d AC load, and to allow for storage of any excess energy for future use. The converter capital costs were inputted at $800/kW while the replacement costs were included at $750/kW, (see Figure 4.11). The operational and maintenance cost was considered negligible over the life of the project. The converter sizes inputted into the simulation for optimization were: 0, 300, and 500kW.

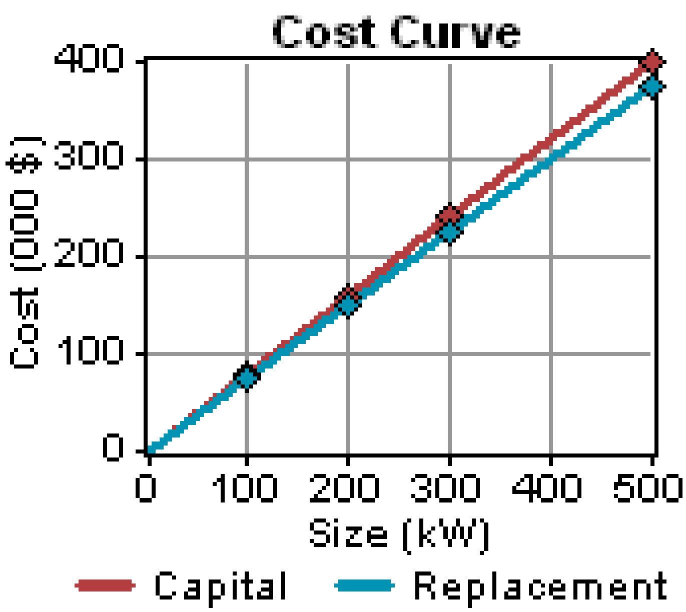

Figure 4.11 Power Converter Capital & Replacement Costs

4.4 Economics and Constraints

The project life was taken to be 25 years with an annual interest rate assumed to be 5% over the life of the project. Capital costs, as well as operating and maintenance costs, were included with the system components detailed above. No additional fixed or operational costs were therefore needed to ensure all costs were accounted for. No federal, territorial, or municipal government subsidies were considered.

Constraints were as follows: the maximum allowable annual electrical capacity shortage was restricted to 2% while the operating reserve was required to be 6% of the hourly load requirements.

4.5 Summary Table of Hypothesized Critical Sensitivity Variables

Table 4.1 contains all the sensitivity variables that were inputted into the HOMER Model in an attempt to determine what combination of winds speeds, diesel price increases, and fuel cell component capital costs would make the wind turbines-fuel cell system the most economically viable option.

Diesel Price	Wind Speed	Fuel Cell Component Capital Cost Multiplier
($/litre)	**(m/s)**	**Fraction of capital cost**
0.85	**6.00**	**1.00**
1.00	**6.49**	**0.65**
1.25	**7.00**	**0.45**
1.50	**7.70**	**0.20**
1.75	**8.00**	**0.10**
	8.50	
	9.00	
	9.50	

Table 4.1 Sensitivity Variables

4.6 Summary Table of Variables for Optimization

Table 4.2 presents a summary of all the aforementioned sizing options that were inputted into the HOMER simulation software to determine the optimum number and size of each component needed to satisfy the electrical load.

Turbine	FC	Diesel Gen	Batteries	Converter	Electrolyzer	H2 Tank
No to Use	Size(kW)	Size(kW)	No to Use	Size(kW)	Size(kW)	Size(kg)
0	0	0	0	0	0	0
1	150	25	300	300	175	250
2	175	75	325	500	200	400
3		150	350			
4		250				

Table 4.2 Optimization Variables

5.0 Results

5.1 Sensitivity Results

As summarized in Table 4.1, three different sensitivity variables (wind speed, diesel price, and fuel cell component costs) were considered. To ensure every opportunity was considered when searching for the optimum combination of technology and system configuration, various combinations of sizes and technologies were simulated. The sizes and numbers of each component that were considered are summarized in Table 4.2.

For each of the sensitivity variables the HOMER Model does a simulation for all the sizes and numbers of each component identified in Table 4.2. HOMER calculated an hourly time series simulation for every possible system size and configuration over a one year period. A feasible system was considered to be any system that satisfied the electrical load of 630 kWh/d with a corresponding peak of 143kW. HOMER retained all feasible combinations and sorted them in ascending order according to their net present costs. Net present cost is the summation of all costs discounted back to present value using an expected real interest rate of 5% over a project lifetime of 25 years.

A total of 225 or (9x5x5) sensitivity cases were considered in the simulation. This number was simply a product of each of the wind speeds, diesel prices, and fuel cell system costs considered in Section 4.5.

The search space for the number of wind turbines to be used, fuel cell size, diesel generator size, number of batteries to be used, power converter size, electrolyzer size, and hydrogen tank size was inputted at (4x3x5x4x3x3x3). This enabled 6480 sizing options to be considered as detailed in Section 4.6.

In total, 1.5 million (225 x 6489) different systems were simulated by HOMER to find the most feasible system configuration for each of the 225 sensitivity cases or independent variables.

Optimization models for different sensitivity parameters are shown in Figures 5.1 to 5.3 inclusive. For ease of reading the levelized cost of energy in $/kW was superimposed on each of the models presented. The levelized cost of electricity was the average cost per kWh of useful electricity produced by the system.

5.1.1 Wind versus Diesel with FC Multiplier at 1

In Figure 5.1, the sensitivity of wind speed in m/s was plotted again diesel prices in $/litre. The third sensitivity variable, fuel cell system capital cost multiplier (faction of capital cost), was fixed at 1. This model indicated that at current fuel cell system cost (FC capital multiplier fixed at 1) the most economically feasible solution for wind speeds ranging from 6.0 to 9.5 m/s and diesel prices ranging from $.85 to $1.25/litre is a wind-diesel-battery system.

Considering the fuel cell system costs at present cost, diesel prices to be $.85/litre, and the average wind speed to be 8m/s the net present cost of the system, capital cost, and the cost of energy was found to be $1,935,339, $1,396,500 and $.60/kW respectively.

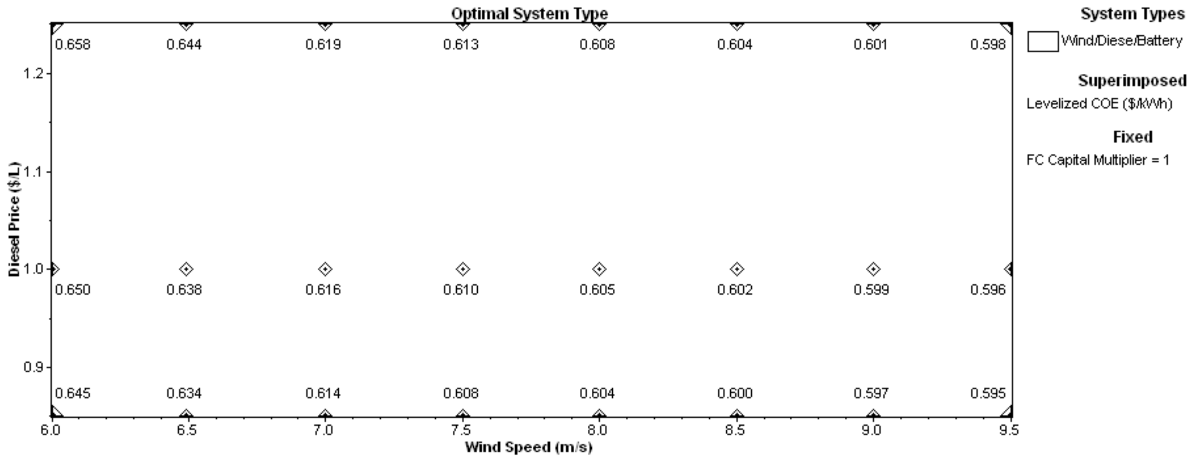

Figure 5.1 Wind Speed versus Diesel Price with FC System Capital Multiplier at 1

5.1.2 Wind versus FC Costs with Diesel Price at $.85/L

In Figure 5.2, the sensitivity of wind speed in m/s was plotted against the fuel cell capital cost multiplier (faction of capital cost). The third sensitivity variable, diesel price was fixed at $.85/litre. This model indicated that the fuel cell system begins to be utilized in combination with a diesel generator when the fuel cell system capital costs were reduced to approximately 50% their current costs. This is consistent across the entire wind speed range being considered (6.0 to 9.5m/s).

It also indicated that when the fuel cell system capital costs falls to 20% of their current costs and the average wind speed is equal to or greater than 7.7 m/s, the diesel generation can be eliminated from the configuration. When this point is reached, all the energy demands can most feasibly be satisfied by the wind turbine-fuel cell system (no diesel-battery components required).

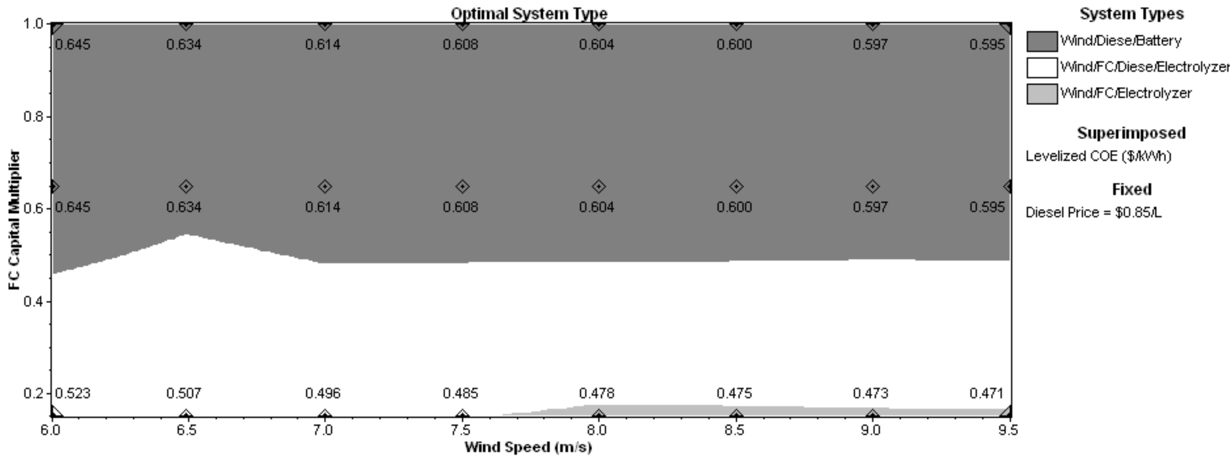

Figure 5.2 Wind Speed versus FC System Capital Multiplier and Diesel Fixed at $.85/L

5.1.3 Wind versus Diesel with FC Capital Multiplier at .2

In Figure 5.3, the sensitivity of wind speed in m/s was plotted against the fuel cell capital cost multiplier (faction of fuel cell system capital cost). The third sensitivity variable, wind speed, was fixed at 7.7 m/s. This model more clearly indicates that when the average wind speed exceeds 7.7 m/s and the fuel cell systems reach 20% of their current capital costs it was economically feasible to meet the electrical load without the diesel generator component. Furthermore, this model indicated that this result was almost completely independent of the price of diesel within the range of $.85 to $1.75/litre. Considering the fuel cell system capital costs to be 20% of present costs, diesel prices to be $.85/litre, and the average wind speed to be 7.7m/s, the net present cost of the system, capital cost, and the cost of energy (COE) was found to be $1,606,500, $1,614,356, and $.50/kW respectively.

With a reduction in fuel cell system costs to 50% of their present capital costs, the fuel cell system (electrolyzer, hydrogen storage tank, and fuel cells) began to be utilized in combination with the turbine -diesel generator components. As discussed earlier, this was consistent across the entire wind speed range being considered (6.0 to 9.5m/s). This would result in a considerable reduction in carbon emissions and reduce community dependency on fossil fuels. However, neither of these benefits was factored into the feasibility models presented.

These results clearly identify that the major drawback in using a fuel cell system for storing excess energy from the intermittent winds was the high cost of the system. However, all was not lost, as the literature review indicated that fuel cell systems are projected to reduce to as low as 6.5% of their current capital costs. If this were to occur, the system would become feasible at wind speeds in excess of approximately 7.7 m/s.

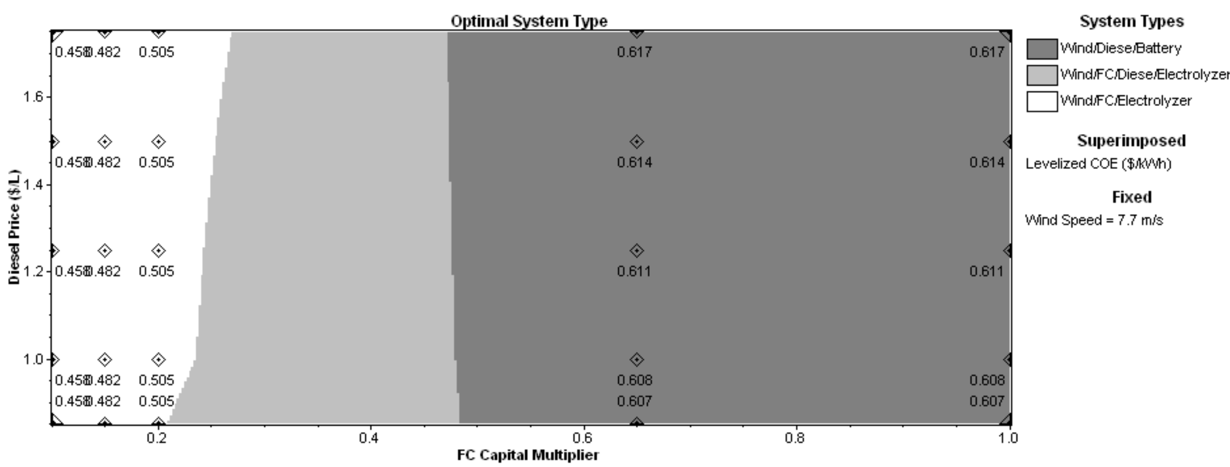

Figure 5.3 Wind Speed versus FC System Capital Multiplier and Wind Speed at 7.7m/s

5.2 Optimization Results

5.2.1 Wind, Diesel, and FC Capital Multiplier Fixed at (6.49, .85, 1)

With the wind speed fixed at 6.49m/s, the diesel price fixed at $.85/litre, and the fuel cell system capital multiplier fixed at 1 (current cost) the following system configuration was identified as the most economically feasible: one 250kW turbine, one 150kW diesel generator, 600 Surrette batteries and a 300kW power converter. The net present cost of this system, yearly operating costs, and yearly cost of energy were $2,053,977, $45,585, and $.63/kWh (See Appendix B-Optimization Results at [6.49, .85, and 1]). These numbers were specifically targeted as they represent Iqaluit's current average wind speed, diesel price, and fuel cell system costs respectively. As noted, at current fuel cell systems costs the most economically feasible system is a wind-diesel-battery configuration.

5.2.2 Wind, Diesel, and FC Capital Multiplier Fixed at (7.7, .85, .45)

With the wind speed fixed at 7.7m/s, the diesel price fixed at $.85/litre, and the fuel cell system capital multiplier fixed at .45 of current costs the following system configuration was identified as the most economically feasible: one 250kW turbine, one 150kW fuel cell, one 25kW generator, one 300kW power converter, one 175kW electrolyzer, and one 250kg hydrogen storage tank. The optimum system configuration in this scenario has both the fuel cell system and the diesel generator. The net present cost of this system, yearly operating costs, and yearly cost of energy were $1,903,868, $39,103, and $.59/kWh. (See Appendix C-Optimization Results at [7.7, .85, and .45]).

5.2.3 Wind, Diesel, and FC Capital Multiplier Fixed at (7.7, .85, .20)

With the wind speed fixed at 7.7m/s, the diesel price fixed at $.85/litre, and the fuel cell system capital multiplier fixed at .2 of current cost the following system configuration was identified as the most economically feasible: one 250kW turbine, one 150kW fuel cell, one 300kW power converter, one 175kW electrolyzer, and one 250kg hydrogen storage tank. The net present cost of this system, yearly operating costs, and yearly cost of energy were $1,614,356, $38,872, and $.50/kWh. (See Appendix D-Optimization Results at [7.7, .85, and .20]).

6.0 Conclusions

6.1Findings

The emphasis of this study was on determining whether the advances in fuel cell system technologies had reached a point where the system could be cost competitive with the conventional wind-diesel-battery system being utilized in some remote off-grid communities in northern Canada. As of 2010, it was found that the fuel cell system (fuel cell, electrolyzer, and hydrogen storage tank) was not a cost competitive alternative compared to the conventional wind-diesel-battery systems. However, with a reduction in fuel cell systems to about 50% of their current costs these systems begin to become cost effective when coupled with a wind-diesel system. It was not until the fuel cell system costs reduce to 20% that it was economically justifiable to eliminate the diesel-battery component entirely. Anticipated advances in fuel cell system research and development are needed to enable the fuel cell system technology to become an economically viable option. Beccali et al (2007) were predicting that hydrogen produced by non-fossil, renewal energy sources would be technically, economically, and ecologically relevant in the near future.

6.2 Limitations of Study

Large, off-grid remote communities with higher energy loads may change the economies of scale but is it not known whether this would result in a more favorable outcome for the use of fuel cell systems. Additionally, the study did not consider subsidies for either emission reduction or diesel fuel prices which could significantly impact the feasibility of various systems.

This was a generic study intended to provide a starting point for further investigation into the use of hybrid systems involving fuel cell systems. Site specific wind speed should be measured at 15 minute intervals. Estabrooks (2010) indicated this would cost approximately $50,000. Based on this cost projection, it was considered to be beyond the limited budget of this study. If completed, it would provide more precise data to enable the system designer to more accurately match the wind regime characteristics to the performance characteristics of commercially available turbines.

The lack of local expertise in remote communities available to maintain a diesel generator may significantly increase the operating costs of the diesel-battery systems as they typically require more maintenance and attention than fuel cell systems. Use of other renewable resources such as photovoltaic, geothermal, biomass, and micro-hydro were considered to be beyond the scope of this research but may be explored in future studies. The size and corresponding costs could impact the optimum system type identified in the HOMER Model. The results of this study are intended to provide a starting point in identify where a hybrid energy system may be feasible but, ultimately, each system should be analyzed on a case-by-case basis.

7.0 Recommendations

Before proceeding with the installation of any hybrid system it is recommended that a detailed study be carried out to more accurately profile the wind speeds. Wind speeds should be measured at 15 minutes intervals to create an hourly profile for a one year period to ensure the wind resource is constant enough to warrant a hybrid system involving a wind turbine. Average wind speeds can be misleading if the high average wind speeds are a result of extreme highs and lows. If that was the case, the wind turbine may be less feasible as the turbines have cut out wind speeds at both extremes where they do not generate electricity.

Detailed modeling and hardware testing should be conducted to determine whether the economically optimum system identified in this study can be successfully operated in the harsh weather conditions anticipated in remote northern communities. Attention should be given to the technical capabilities of the inhabitants of the community in which a hybrid system is being considered. Increased initial capital costs may be justified to purchase a less maintenance-intensive system if the skill set is not available locally to maintain and service the various components (wind turbines, fuel cells, electrolyzers, storage tanks, power converters) that make up a hybrid system.

Glossary

Capital cost The initial purchase price or capital cost of a piece of equipment.

Capital cost multiplier A percentage of the capital cost to purchase a piece of equipment. Used to adjust the future purchase price downward based on anticipated technological or manufacturing improvements.

Electrolyzer A vessel or system of vessels filled with an electrolyte in which electrodes (cathodes are connected to the negative poles of a direct-current source while anodes are connected to the positive pole) are used to carry out electrolysis.

Electrolysis of water The decomposition of water (H_2O) into it constituent parts, oxygen (O_2) and hydrogen gas (H_2), as a result of passing an electric current through the water.

Fuel cell An electrochemical device consisting of three components (anodes, cathodes, and electrolytes) used to produce electricity and heat from a fuel (often hydrogen).

Fuel cell system A system consisting of an electrolyzer, hydrogen storage tank and fuel cell used to produce electricity.

Fuel cell system capital multiplier A percentage of present fuel cell system cost.

Hybrid energy system- A primary renewable resource working in parallel with a standby non-renewable component and a storage unit. The renewable resource, wind is converted in electricity.

Hydrogen fuel cell An electrochemical device that uses hydrogen as its fuel and oxygen (from the air) as its oxidant to produce electricity.

Hydrogen storage tank A large (usually metallic) pressure vessel used for storing hydrogen gas.

Life-cycle cost The total cost of installing and operating a system over its expected life. It includes capital, replacement, operation and maintenance, fuel and interest costs.

Net present cost The summation of all costs discounted back to present value using the expected real interest rate of 5% for a project lifetime of 25 years.

Operational and maintenance cost The annual cost of operating and maintaining a piece of equipment.

Project lifetime The number of years over which the net present cost of the project is calculated.

Replacement cost The cost of replacing a piece of equipment at the end of its useful life.

Search space The number of component sizes inputted into the HOMER Model for consideration in identifying the hybrid energy system configuration with the minimum total life-cycle.

Simulation The use of mathematical models to recreate a situation so that the likelihood of a range of outcomes can be more accurately predicted.

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Appendices

Appendix A – Iqaluit Average Wind Speeds

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Iqaluit Average Wind Speeds

Latitude = 62.656, longitude = -69.505

Numerical Values at 10m

Period	Mean Wind Speed	Mean Wind Energy	Weibull shape parameter (k)	Weibull scale parameter (A)
Annual	6.44 m/s	329.25 W/m2	1.61	7.19 m/s
Winter (DJF)	7.10 m/s	465.50 W/m2	1.54	7.89 m/s
Spring (MAM)	6.06 m/s	290.25 W/m2	1.54	6.73 m/s
Summer (JJA)	5.51 m/s	203.69 W/m2	1.62	6.15 m/s
Fall (SON)	6.98 m/s	405.13 W/m2	1.65	7.80 m/s

Retrieved on December 4, 2010 from http://www.windatlas.ca

Appendix B - Detailed Financial Analysis

Wind @ 6.49; Diesel @ .85; FC System Capital Multiplier @ 1

Appendix B – Financials Wind @ 6.49; Diesel @ .85; FC System Capital Multiplier @ 1

Sensitivity Variables

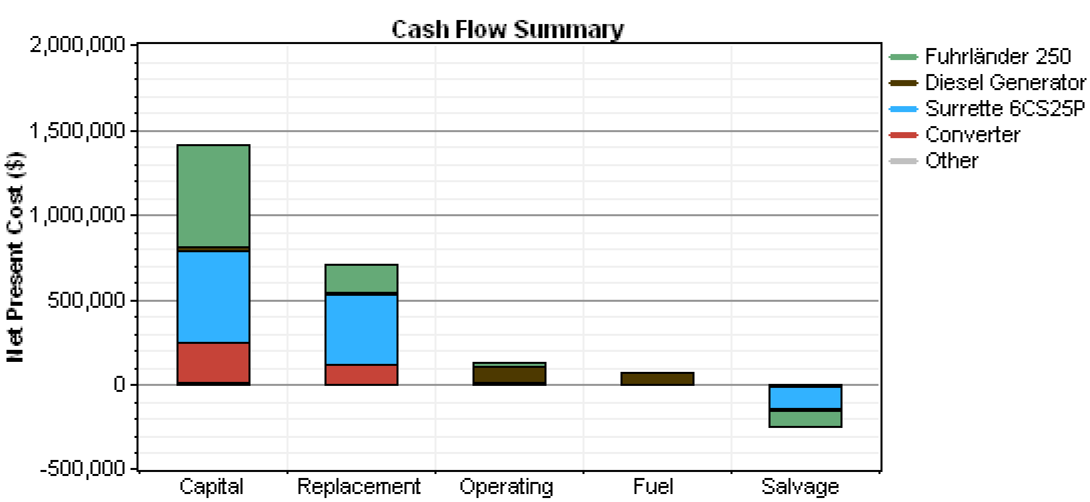
Wind Data Scaled Average:	**6.49 m/s**
Diesel Price:	**0.85 $/L**
Fuel Cell Capital Cost Multiplier:	**1**
Fuel Cell Replacement Cost Multiplier:	**1**
Electrolyzer Capital Cost Multiplier:	**1**
Electrolyzer Replacement Cost Multiplier:	**1**
Hydrogen Tank Capital Cost Multiplier:	**1**
Hydrogen Tank Replacement Cost Multiplier:	**1**

System Configuration

Wind turbine	1 Fuhrländer 250
Diesel Generator	150 kW
Battery	600 Surrette 6CS25P
Inverter	300 kW
Rectifier	300 kW
Dispatch strategy	Load Following

Cost Summary

Total net present cost	$ 2,053,977
Levelized cost of energy	$ 0.634/kWh
Operating cost	$ 45,585/yr

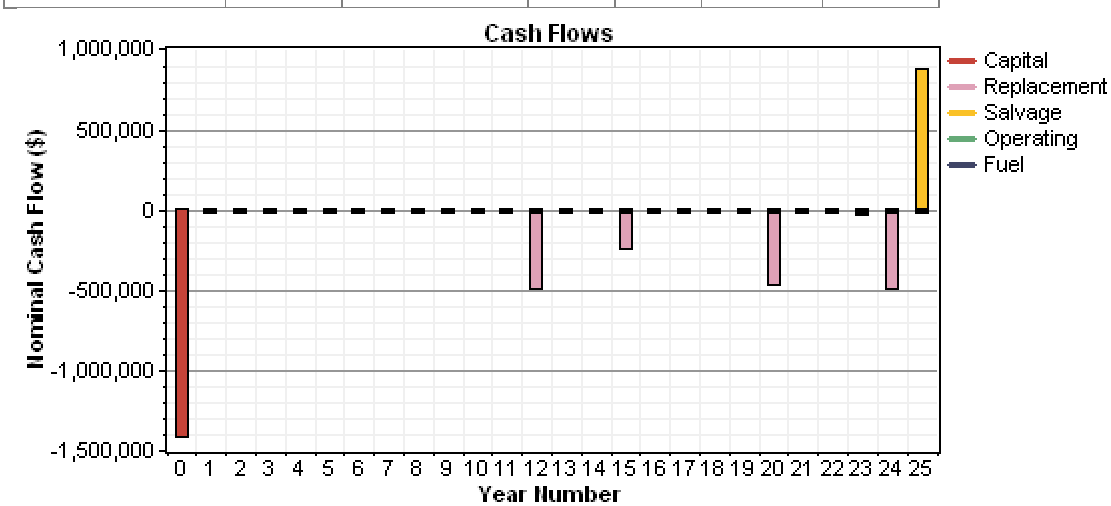


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
Fuhrländer 250	600,000	169,600	28,188	0	-99,665	698,124
Diesel Generator	30,000	7,682	95,980	71,921	-5,747	199,836
Surrette 6CS25P	540,000	416,115	846	0	-129,933	827,027
Converter	240,000	108,229	0	0	-22,148	326,081
Other	1,500	0	1,409	0	0	2,909
System	1,411,500	701,626	126,423	71,921	-257,493	2,053,977

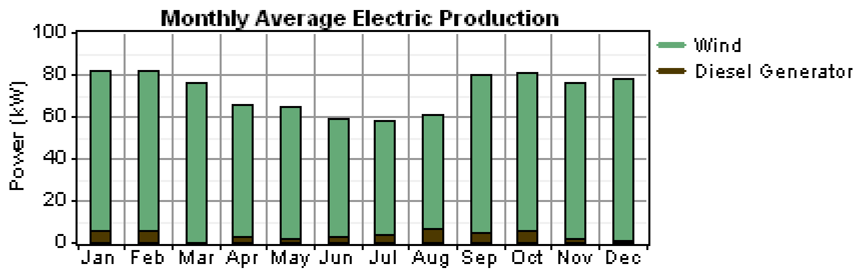
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
Fuhrländer 250	42,571	12,034	2,000	0	-7,071	49,534
Diesel Generator	2,129	545	6,810	5,103	-408	14,179
Surrette 6CS25P	38,314	29,524	60	0	-9,219	58,680
Converter	17,029	7,679	0	0	-1,571	23,136
Other	106	0	100	0	0	206
System	100,149	49,782	8,970	5,103	-18,270	145,735



Electrical Load

Component	Production	Fraction
	(kWh/yr)	
Wind turbine	599,469	95%
Diesel Generator	30,913	5%
Total	630,382	100%



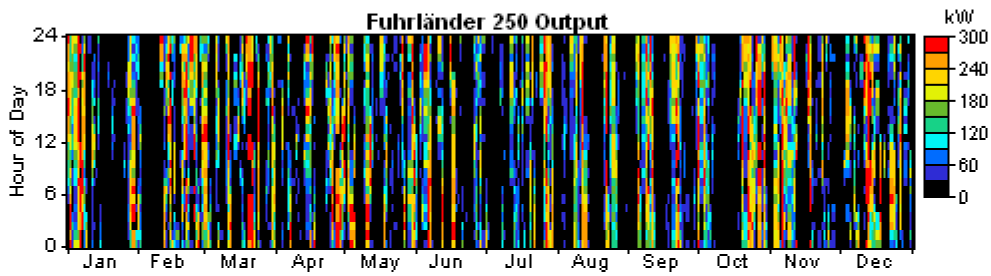
Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	229,950	100%
Total	229,950	100%

	Value	Units
Excess electricity	358,759	kWh/yr
Unmet load	-0.0000567	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	0.951	

AC Wind Turbine: Fuhrländer 250

Variable	Value	Units
Total rated capacity	250	kW
Mean output	68.4	kW
Capacity factor	27.4	%
Total production	599,469	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	300	kW
Wind penetration	261	%
Hours of operation	6,759	hr/yr
Levelized cost	0.0826	$/kWh

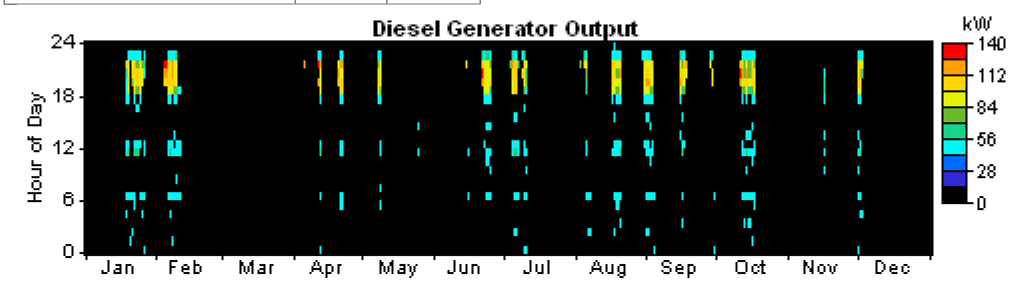


Diesel Generator

Quantity	Value	Units
Hours of operation	454	hr/yr
Number of starts	203	starts/yr
Operational life	22.0	yr
Capacity factor	2.35	%
Fixed generation cost	26.2	$/hr
Marginal generation cost	0.0340	$/kWhyr

Quantity	Value	Units
Electrical production	30,913	kWh/yr
Mean electrical output	68.1	kW
Min. electrical output	45.0	kW
Max. electrical output	132	kW

Quantity	Value	Units
Fuel consumption	6,004	L/yr
Specific fuel consumption	0.194	L/kWh
Fuel energy input	59,075	kWh/yr
Mean electrical efficiency	52.3	%

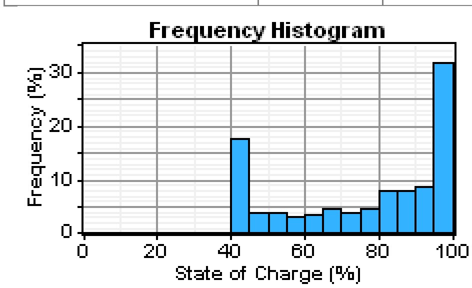


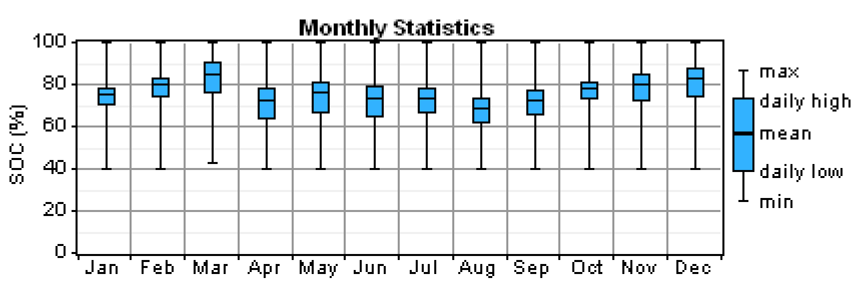
Battery

Quantity	Value
String size	2
Strings in parallel	300
Batteries	600
Bus voltage (V)	12

Quantity	Value	Units
Nominal capacity	4,162	kWh
Usable nominal capacity	2,497	kWh
Autonomy	95.1	hr
Lifetime throughput	5,787,120	kWh
Battery wear cost	0.093	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	129,608	kWh/yr
Energy out	105,285	kWh/yr
Storage depletion	1,790	kWh/yr
Losses	22,533	kWh/yr
Annual throughput	117,712	kWh/yr
Expected life	12.0	yr

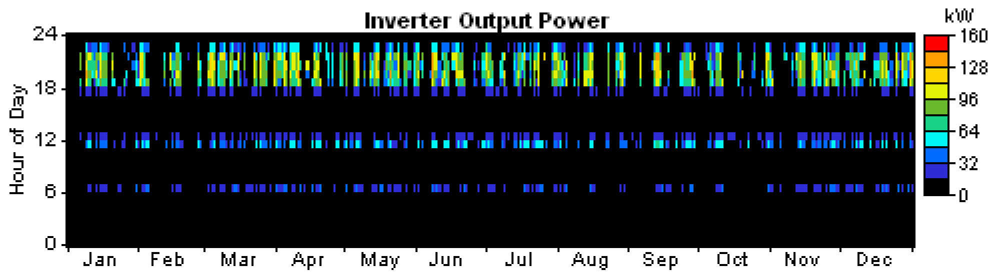


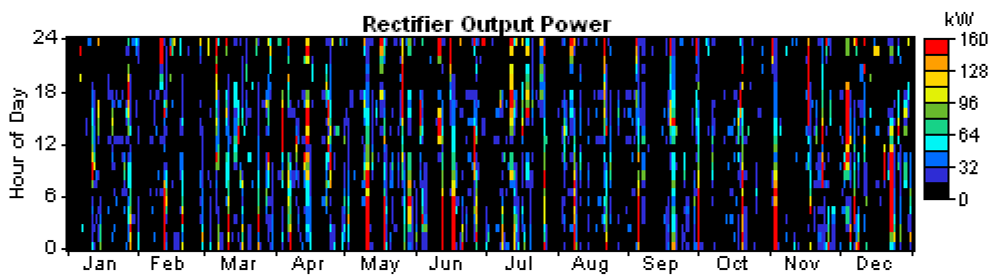


Converter

Quantity	Inverter	Rectifier	Units
Capacity	300	300	kW
Mean output	11	15	kW
Minimum output	0	0	kW
Maximum output	143	148	kW
Capacity factor	3.6	4.9	%

Quantity	Inverter	Rectifier	Units
Hours of operation	3,810	4,638	hrs/yr
Energy in	105,285	136,429	kWh/yr
Energy out	94,757	129,608	kWh/yr
Losses	10,529	6,821	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	15,809
Carbon monoxide	39
Unburned hydrocarbons	4.32
Particulate matter	2.94
Sulphur dioxide	31.7
Nitrogen oxides	348

Appendix C - Detailed Financial Analysis

Wind @ 7.70; Diesel @ .85; FC System Capital Multiplier @ .45

Appendix C –Financials Wind @ 7.70; Diesel @ .85; FC System Capital Multiplier @ .45

Sensitivity Variables

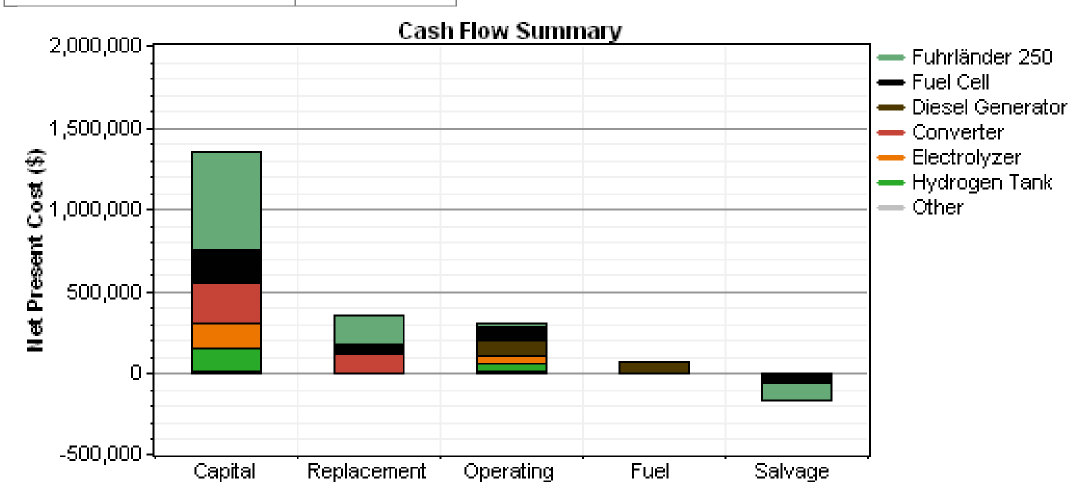
Wind Data Scaled Average:	**7.7 m/s**
Diesel Price:	**0.85 $/L**
Fuel Cell Capital Cost Multiplier:	**0.45**
Fuel Cell Replacement Cost Multiplier:	**0.45**
Electrolyzer Capital Cost Multiplier:	**0.45**
Electrolyzer Replacement Cost Multiplier:	**0.45**
Hydrogen Tank Capital Cost Multiplier:	**0.45**
Hydrogen Tank Replacement Cost Multiplier:	**0.45**

System Configuration

Wind turbine	1 Fuhrländer 250
Fuel Cell	150 kW
Diesel Generator	25 kW
Inverter	300 kW
Rectifier	300 kW
Electrolyzer	175 kW
Hydrogen Tank	250 kg

Cost Summary

Total net present cost	$ 1,903,868
Levelized cost of energy	$ 0.588/kWh
Operating cost	$ 39,103/yr

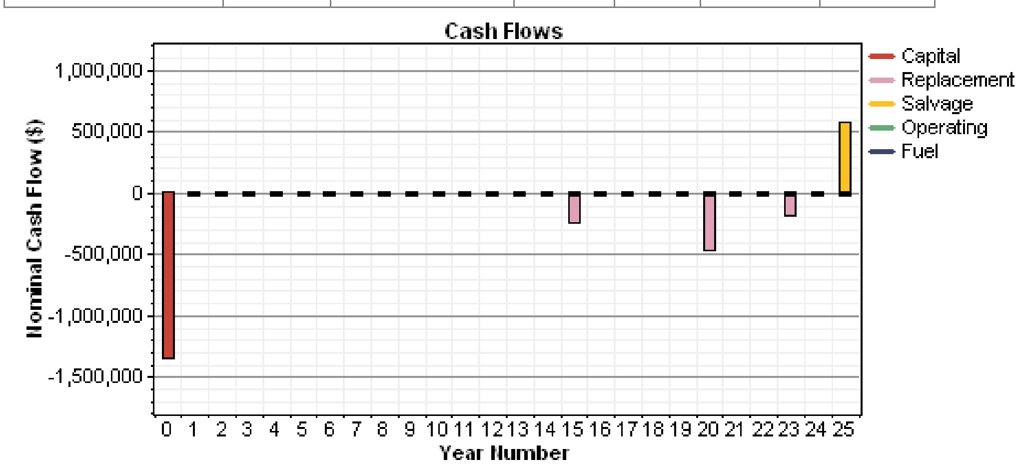


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
Fuhrländer 250	600,000	169,600	28,188	0	-99,665	698,124
Fuel Cell	202,500	55,324	73,993	0	-45,161	286,657
Diesel Generator	5,000	12,701	97,565	68,986	-86	184,166
Converter	240,000	108,229	0	0	-22,148	326,081
Electrolyzer	157,500	0	49,329	0	0	206,829
Hydrogen Tank	146,250	0	52,852	0	0	199,102
Other	1,500	0	1,409	0	0	2,909
System	1,352,750	345,855	303,337	68,986	-167,059	1,903,869

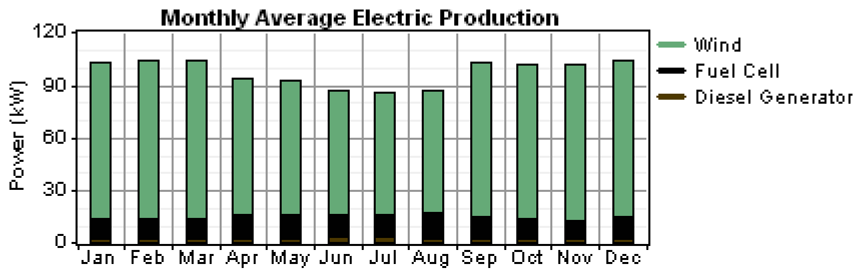
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
Fuhrländer 250	42,571	12,034	2,000	0	-7,071	49,534
Fuel Cell	14,368	3,925	5,250	0	-3,204	20,339
Diesel Generator	355	901	6,923	4,895	-6	13,067
Converter	17,029	7,679	0	0	-1,571	23,136
Electrolyzer	11,175	0	3,500	0	0	14,675
Hydrogen Tank	10,377	0	3,750	0	0	14,127
Other	106	0	100	0	0	206
System	95,981	24,539	21,523	4,895	-11,853	135,084



Electrical

Component	Production	Fraction
	(kWh/yr)	
Wind turbine	721,150	85%
Fuel Cell	107,291	13%
Diesel Generator	22,820	3%
Total	851,261	100%



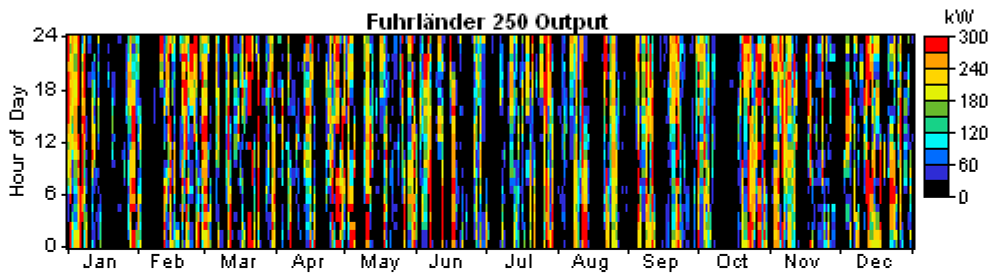
Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	229,894	44%
Electrolyzer load	290,975	56%
Total	520,869	100%

Quantity	Value	Units
Excess electricity	304,348	kWh/yr
Unmet load	55.8	kWh/yr
Capacity shortage	141	kWh/yr
Renewable fraction	0.973	

AC Wind Turbine: Fuhrländer 250

Variable	Value	Units
Total rated capacity	250	kW
Mean output	82.3	kW
Capacity factor	32.9	%
Total production	721,150	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	300	kW
Wind penetration	314	%
Hours of operation	6,938	hr/yr
Levelized cost	0.0687	$/kWh

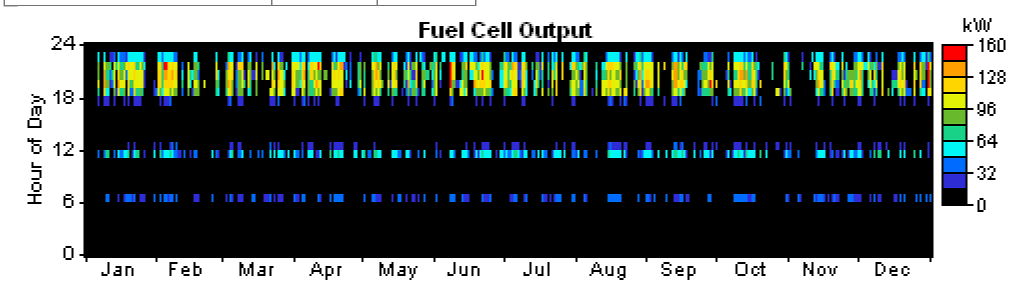


Fuel Cell & Electrolyzer

Quantity	Value	Units
Hours of operation	1,750	hr/yr
Number of starts	662	starts/yr
Operational life	22.9	yr
Capacity factor	8.17	%
Fixed generation cost	7.22	$/hr
Marginal generation cost	0.00	$/kWhyr

Quantity	Value	Units
Electrical production	107,291	kWh/yr
Mean electrical output	61.3	kW
Min. electrical output	0.00976	kW
Max. electrical output	150	kW

Quantity	Value	Units
Hydrogen consumption	5,365	kg/yr
Specific fuel consumption	0.050	kg/kWh
Fuel energy input	178,819	kWh/yr
Mean electrical efficiency	60.0	%

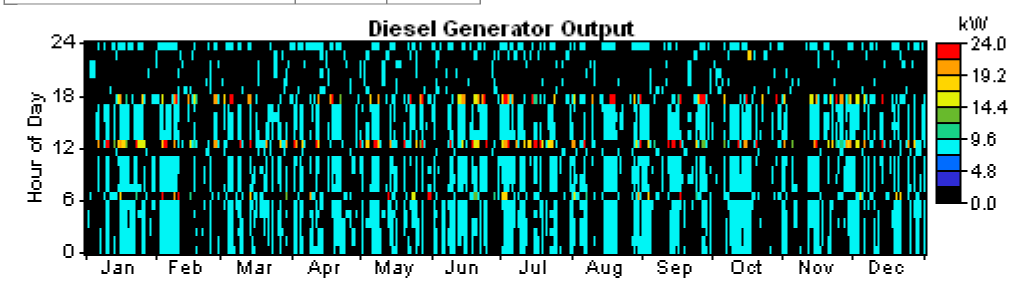


Diesel Generator

Quantity	Value	Units
Hours of operation	2,769	hr/yr
Number of starts	953	starts/yr
Operational life	3.61	yr
Capacity factor	10.4	%
Fixed generation cost	4.36	$/hr
Marginal generation cost	0.0340	$/kWhyr

Quantity	Value	Units
Electrical production	22,820	kWh/yr
Mean electrical output	8.24	kW
Min. electrical output	7.50	kW
Max. electrical output	23.4	kW

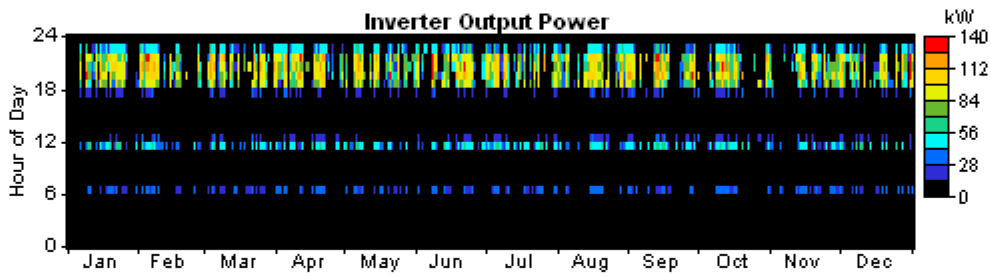
Quantity	Value	Units
Fuel consumption	5,758	L/yr
Specific fuel consumption	0.252	L/kWh
Fuel energy input	56,663	kWh/yr
Mean electrical efficiency	40.3	%

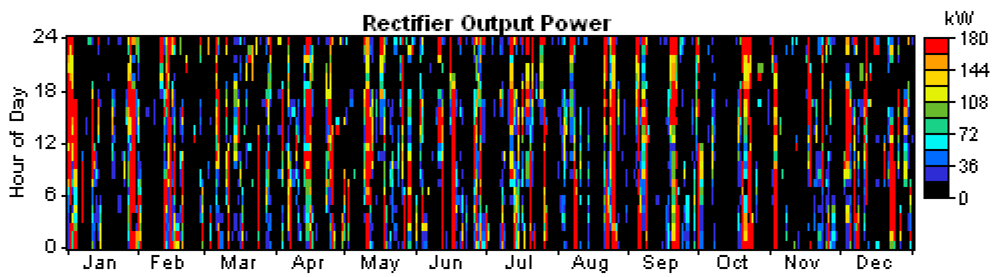


Converter

Quantity	Inverter	Rectifier	Units
Capacity	300	300	kW
Mean output	11	33	kW
Minimum output	0	0	kW
Maximum output	135	175	kW
Capacity factor	3.7	11.1	%

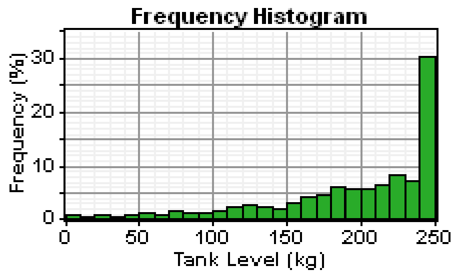
Quantity	Inverter	Rectifier	Units
Hours of operation	1,627	5,284	hrs/yr
Energy in	107,291	306,289	kWh/yr
Energy out	96,562	290,975	kWh/yr
Losses	10,729	15,314	kWh/yr

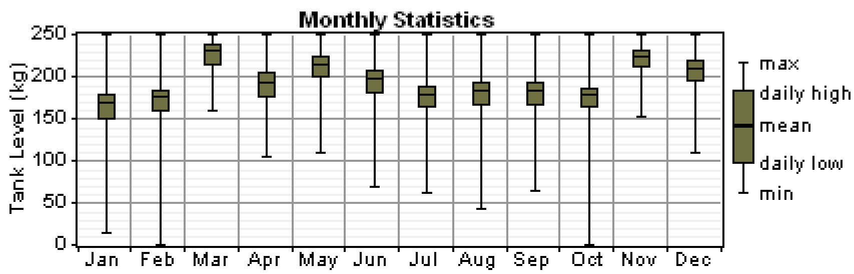


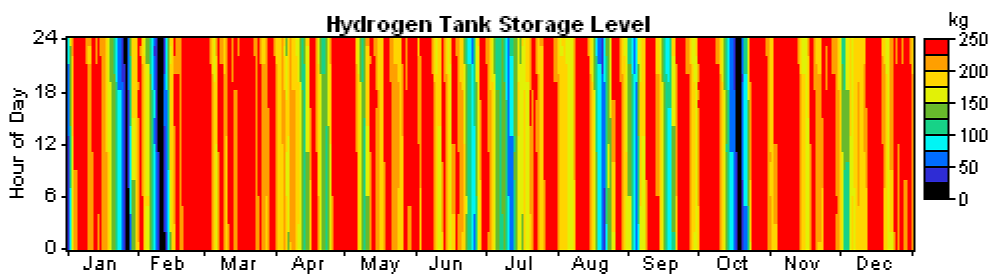


Hydrogen Tank

Variable	Value	Units
Hydrogen production	5,533	kg/yr
Hydrogen consumption	5,365	kg/yr
Hydrogen tank autonomy	317	hours







Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	15,109
Carbon monoxide	72.3
Unburned hydrocarbons	8.01
Particulate matter	5.45
Sulphur dioxide	30.5
Nitrogen oxides	645

Appendix D - Detailed Financial Analysis

Wind @ 7.70; Diesel @ .85; FC System Capital Multiplier @ .20

Appendix D-Financials Wind @ 7.70; Diesel @ .85; FC System Capital Multiplier @ .20

Sensitivity Variables

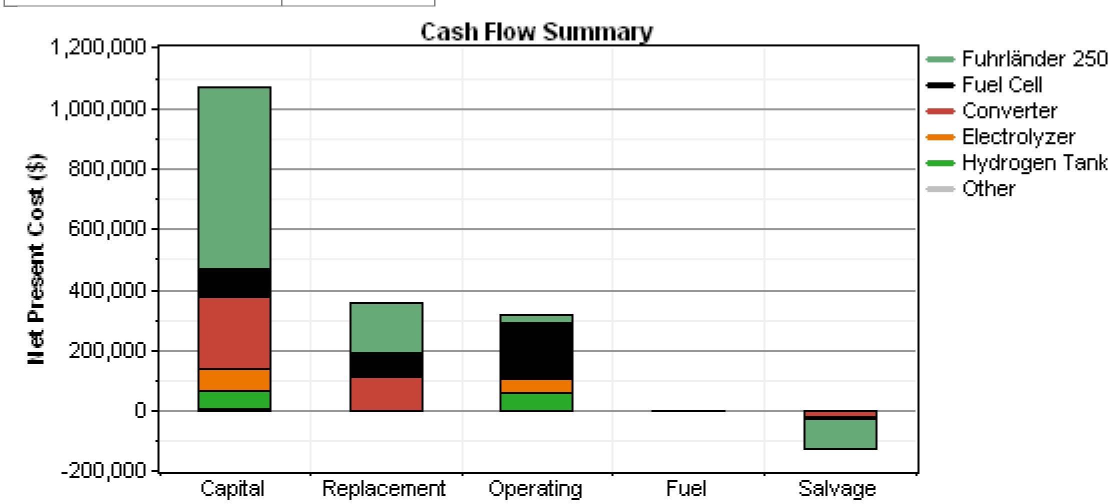
Wind Data Scaled Average:	**7.7 m/s**
Diesel Price:	**0.85 $/L**
Fuel Cell Capital Cost Multiplier:	**0.2**
Fuel Cell Replacement Cost Multiplier:	**0.2**
Electrolyzer Capital Cost Multiplier:	**0.2**
Electrolyzer Replacement Cost Multiplier:	**0.2**
Hydrogen Tank Capital Cost Multiplier:	**0.2**
Hydrogen Tank Replacement Cost Multiplier:	**0.2**

System Configuration

Wind turbine	1 Fuhrländer 250
Fuel Cell	150 kW
Inverter	300 kW
Rectifier	300 kW
Electrolyzer	175 kW
Hydrogen Tank	250 kg

Cost Summary

Total net present cost	$ 1,614,356
Levelized cost of energy	$ 0.505/kWh
Operating cost	$ 38,872/yr

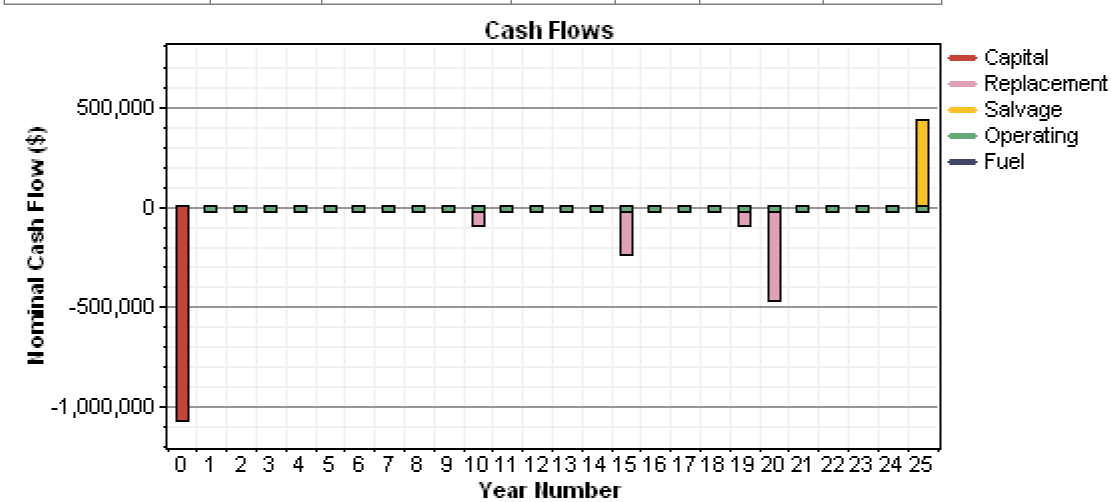


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
Fuhrländer 250	600,000	169,600	28,188	0	-99,665	698,124
Fuel Cell	90,000	79,109	186,378	0	-5,426	350,061
Converter	240,000	108,229	0	0	-22,148	326,081
Electrolyzer	70,000	0	49,329	0	0	119,329
Hydrogen Tank	65,000	0	52,852	0	0	117,852
Other	1,500	0	1,409	0	0	2,909
System	1,066,500	356,938	318,157	0	-127,239	1,614,357

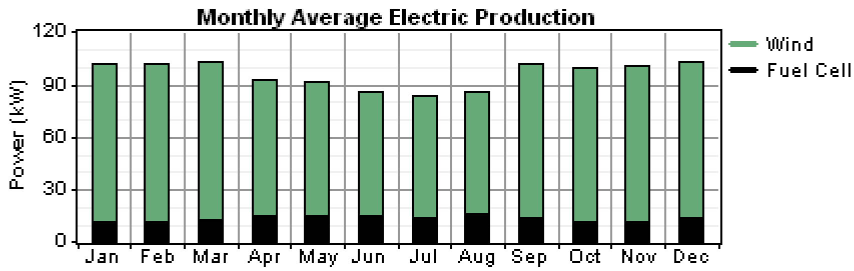
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
Fuhrländer 250	42,571	12,034	2,000	0	-7,071	49,534
Fuel Cell	6,386	5,613	13,224	0	-385	24,838
Converter	17,029	7,679	0	0	-1,571	23,136
Electrolyzer	4,967	0	3,500	0	0	8,467
Hydrogen Tank	4,612	0	3,750	0	0	8,362
Other	106	0	100	0	0	206
System	75,671	25,326	22,574	0	-9,028	114,543



Electrical

Component	Production (kWh/yr)	Fraction
Wind turbine	721,150	86%
Fuel Cell	117,429	14%
Total	838,579	100%



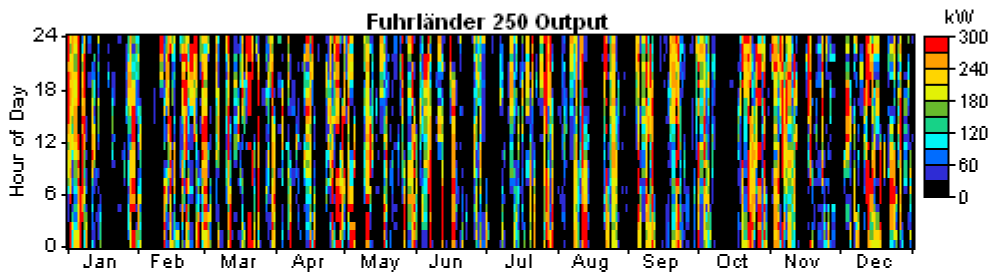
Load	Consumption (kWh/yr)	Fraction
AC primary load	226,766	42%
Electrolyzer load	317,322	58%
Total	544,088	100%

Quantity	Value	Units
Excess electricity	266,046	kWh/yr
Unmet load	3,184	kWh/yr
Capacity shortage	3,669	kWh/yr
Renewable fraction	1.000	

AC Wind Turbine: Fuhrländer 250

Variable	Value	Units
Total rated capacity	250	kW
Mean output	82.3	kW
Capacity factor	32.9	%
Total production	721,150	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	300	kW
Wind penetration	314	%
Hours of operation	6,938	hr/yr
Levelized cost	0.0687	$/kWh

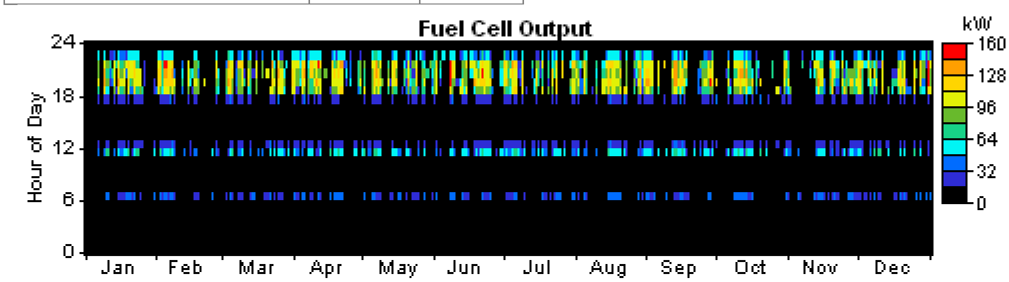


Fuel Cell & Electrolyzer

Quantity	Value	Units
Hours of operation	4,408	hr/yr
Number of starts	626	starts/yr
Operational life	9.07	yr
Capacity factor	8.94	%
Fixed generation cost	4.88	$/hr
Marginal generation cost	0.00	$/kWhyr

Quantity	Value	Units
Electrical production	117,429	kWh/yr
Mean electrical output	26.6	kW
Min. electrical output	0.0000000745	kW
Max. electrical output	150	kW

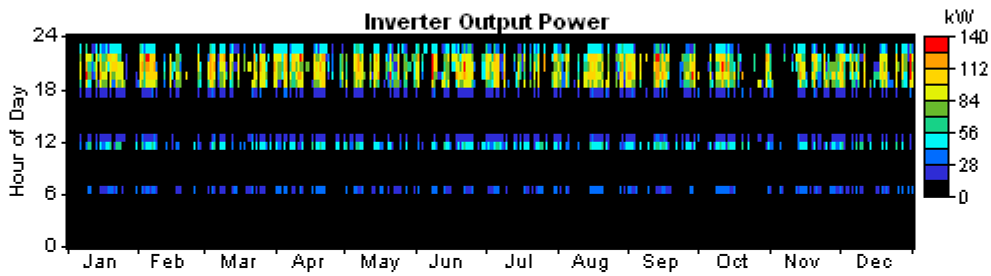
Quantity	Value	Units
Hydrogen consumption	5,871	kg/yr
Specific fuel consumption	0.050	kg/kWh
Fuel energy input	195,715	kWh/yr
Mean electrical efficiency	60.0	%

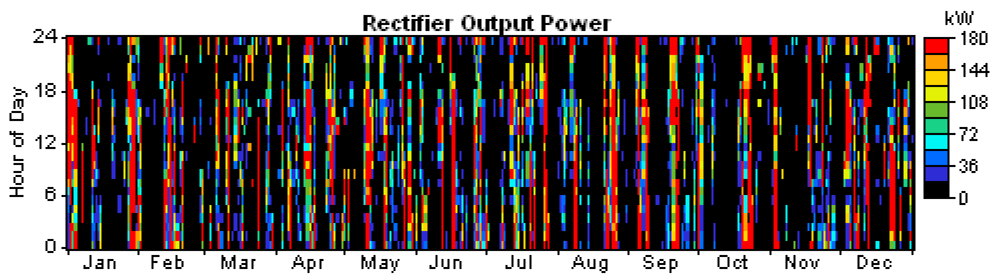


Converter

Quantity	Inverter	Rectifier	Units
Capacity	300	300	kW
Mean output	12	36	kW
Minimum output	0	0	kW
Maximum output	135	175	kW
Capacity factor	4.0	12.1	%

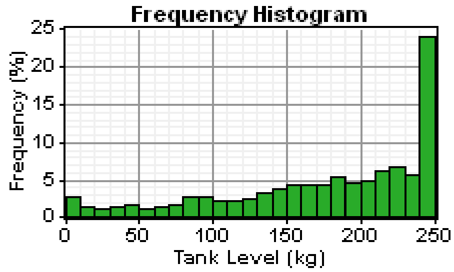
Quantity	Inverter	Rectifier	Units
Hours of operation	3,743	3,654	hrs/yr
Energy in	117,429	334,023	kWh/yr
Energy out	105,686	317,322	kWh/yr
Losses	11,743	16,701	kWh/yr

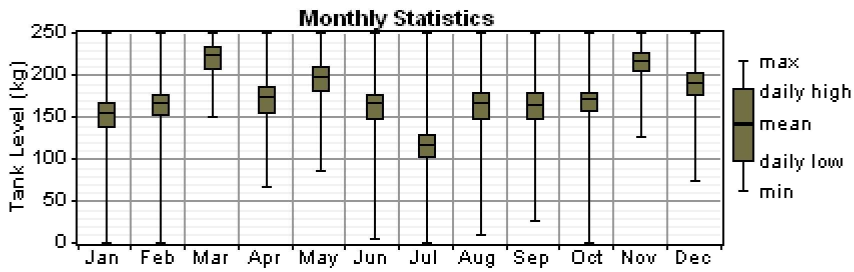


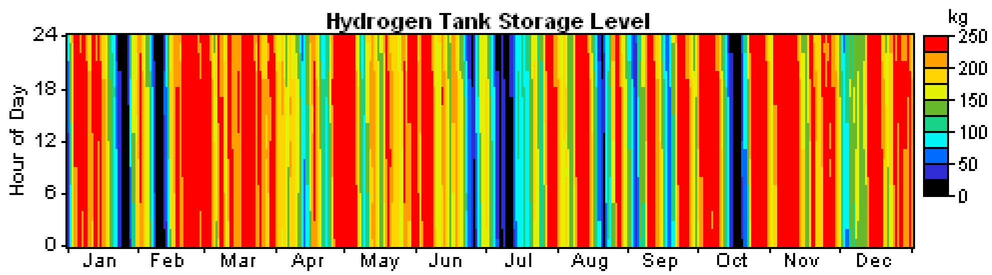


Hydrogen Tank

Variable	Value	Units
Hydrogen production	6,034	kg/yr
Hydrogen consumption	5,871	kg/yr
Hydrogen tank autonomy	317	hours







Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	-60
Carbon monoxide	38.2
Unburned hydrocarbons	4.23
Particulate matter	2.88
Sulphur dioxide	0
Nitrogen oxides	341