ABSTRACT

MILANI, NEIL PATRICK. Performance Optimization of a Hybrid Wind Turbine-Diesel Microgrid Power System. (Under the direction of Dr. Greg Buckner.)

Nearly all off-grid, remote cold-weather facilities utilize diesel-only systems for both thermal and electrical power generation. In areas of minimal to moderate wind resources, these facilities could substantially decrease diesel fuel usage and could additionally provide for thermal energy production via the integration of a wind turbine system combined with resistance heating into the facility. Voltage and frequency grid stabilization could be obtained by using the diesel electrical generating unit as a synchronous condenser and by using incremental resistive load control, respectively. For systems following medium to high wind penetration guidelines, control components are required but no energy storage mechanisms are needed. This thesis investigates a High-Penetration, No Storage Wind Diesel (HPNSWD) system that can utilize available wind resources to minimize diesel fuel costs for the Scott Base facility – all without implementing expensive and maintenance-intensive energy storage devices.
PERFORMANCE OPTIMIZATION OF A HYBRID WIND TURBINE-DIESEL MICROGRID POWER SYSTEM

by

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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

MECHANICAL ENGINEERING

Raleigh, NC

2006

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BIOGRAPHY

Neil Patrick Milani was born in Cleveland, OH and obtained a physics degree from John Carroll University in University Heights, OH (1992) and an electrical engineering degree from Case Western Reserve University in Cleveland, OH (1993).

Upon graduation in 1993, he worked in various capacities on software development for automotive embedded systems and later primarily as a software engineer for cellular phones.

After leaving his job in 2004, he began work on a mechanical engineering degree at North Carolina State University (NCSU) in the area of renewable energy systems. While enrolled at NCSU this included work at the NCSU Solar Center in areas of coastal wind monitoring installations, small residential and commercial PV, coastal wind turbine installations, and western NC ridgeline wind site evaluations.

In the summer of 2005, he was a visiting researcher at the University of Canterbury in Christchurch, New Zealand working on modeling of wind turbines into isolated, diesel-only systems.

Upon graduation from the NCSU Master of Mechanical Engineering program in August 2006, Neil will begin work at GE Energy in the Advanced Career Development Program (ACDP) with the offshore wind turbine group in Greenville, SC.
ACKNOWLEDGEMENTS

I am first, foremost and most deeply indebted to my family – especially my mother and father Carmella and Silvio Milani. It is by their living exemplary lives, leading by example and being the most character-imbued people I know, I can attribute my conviction and passion for pursuing my interest in working on projects that ultimately benefit the greater good for the world ecology and all inhabitants: renewable energy.

In producing this Masters Thesis, I was fortunate to find this serendipitous project via an inquiring email sent halfway around the world to the University of Canterbury in Christchurch New Zealand. A wonderfully welcoming professor named Dr. Susan Krumdiek provided for this opportunity. She offered me the chance to work on this research – without reservation and with unrivaled support – and without her help this would be just another thesis.

I would also like to thank Dr. Buckner, Dr. Leach, Dr. Eckerlin and Dr. Hobbs for their support, assistance and encouragement in helping me complete my work. My generous support in the form of a Research Assistantship from Dr. Hobbs at the NC Solar Center was invaluable in providing hands-on knowledge, relevant work-related projects and excellent technical guidance during the research and development phases.

Saving the most grateful comments for last, I’d like to thank my wife Sara for her constant motivation, support and love – without whom I might not have had the conviction to commit to such a drastic career change by quitting my job and returning to being a full-time student - yet again.
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1 INTRODUCTION

Scott Base Research facility is a New Zealand Antarctic field station located below the Antarctic Circle at the tip of Ross Island, on McMurdo Sound. As with practically all of these remote off-grid facilities, Scott Base currently utilizes diesel-powered generators to supply its electrical and thermal needs. Since these bases are reliant on a diesel fuel specially formulated for these low temperatures, fuel expenses can be quite high. For example, McMurdo Station reported fuel costs of $0.43/litre in 2005 [4] and these could be expected to increase annually. To decrease these costs, many of these research stations engage in vigilant energy-saving strategies in an attempt to continually improve finances but even if Scott Base were to attain 100% energy efficiency by capturing and utilizing all thermal and electrical energy for use on the site, the base fuel consumption would still be 265,000 litres of fuel per year [1].

The objective of this research is to further offset energy usage by implementing a hybrid wind/diesel system to supplement Scott Base’s current energy usage. The specific mechanism investigated is a High-Penetration, No Storage Wind Diesel (HPNSWD) system that can utilize the wind resources and minimize diesel fuel costs for the Scott Base facility – all without the implementation of expensive and maintenance-intensive energy storage devices. These diesel/wind turbine systems are commonly referred to as “hybrid” systems; a graphical representation of such a system is shown in Figure 1.
The facility under study currently utilizes a diesel-only system and the annual fuel consumption is known. The software models created for this research will use the diesel-only system as a baseline, subsequently integrate a wind turbine into the baseline power system, and provide a general power-control mechanism for this hybrid system to determine the amount of fuel that can be saved by maximizing the wind resource via a power control strategy.
2 BACKGROUND

Scott Base was constructed for New Zealand's participation in the International Geophysical Year and was officially opened on January 20, 1957. The base is located on Ross Island only 1 mile away from the US McMurdo Antarctic research facility as shown in Figure 2.

![Figure 2 - Scott Base Topographic Map](image)

The base accommodates up to 85 people during the summer, dropping to a skeleton staff of 10 - 14 during the winter. All-weather corridors link most of its buildings and can be seen in Figure 3.
The energy system at Scott Base exists to support the research activities and the living conditions of the staff. All loads are met by conversion of AN8 fuel oil through internal continuous-use, combustion generators. Scott Base science activities include environmental monitoring, onospheric/auroral observations, meteorological observations (since 1957), offshore marine biology, terrestrial-biology and tide measurement [15].

The base is comprised of 8 main buildings interconnected with a total combined floor area of 2,340 sq m, of which 570 m is used as accommodation [15]. Base power is provided by a 480V, 50 Hz power supply, with a power generation capacity of 600 kW via 2 main generators and 1 auxiliary generator (Figure 4). These generators are fueled with AN8 (aviation turbine fuel) and consume 379,000 liters of fuel annually [1]. Potable water is provided by desalinating seawater (via a reverse osmosis process) and 1,300,000 liters of water are used each year. An on-site wastewater treatment plant performs the sewage treatment/disposal method. Base shipping is done with one re-supply visit per season (in late January) and by support of the McMurdo station, which is 5 km from Scott Base to anchorage. The base uses a variety of means for transportation, which includes a variety of Caterpillar
traverse/field tracked tractors, tracked personnel carriers (Hagglunds), a tracked Kassbohrer PB170/Hiab crane, snowmobiles, tractor/loaders, as well as 4x4 wheeled vehicles [15].

A schematic of energy distribution is presented in Figure 4, which shows the different stages (buildings) and their respective electrical load requirements (percentage). A more detailed listing of the energy usage can be found in [1]. Getting information on Scott Base was critical to thoroughly understanding the data. Details such as the facility layout, building configuration, power ratings for most electrical load devices, thermal load operation, etc. were all important in understanding and validating the load data.

Figure 4 - Scott Base Energy Usage by Structure [1]
Scott Base power is generated in Stage 2 and provides all electrical and thermal requirements for the base.

![Figure 5 - Caterpillar 3406 225 EkW Electrical Generator](image1)

This stage includes 2 diesel electric Caterpillar 3604 electric generators (rated at 225 EkW (prime), 200 EkW (continuous) electrical, 110kW thermal), one running and one on constant standby as shown in Figure 5.

![Figure 6 - Caterpillar Marine Manifold Heat Exchanger](image2)
Heat is obtained via recovery using marine manifold heat exchangers as well as exhaust heat exchangers as shown in Figure 6 [1].

There are also two diesel-fired boilers rated at 98kW each that provide additional thermal energy when required to the main heating loop. Stage 2 originally contained an electric boiler that provided extra load to the generator sets. This electric boiler would be available for use as a dump load if a wind turbine system were implemented. Note that the theoretical incremental efficiency using the electric boilers in the cogeneration situation approaches 85%, which is slightly better than the combustion efficiency of the direct-fired boilers [1].

Using “dump loads” to provide for supplemental heating is not always available at most hybrid installations but Scott Base provided for two unique mechanisms for doing this: a set of electrical heating elements were incorporated into the heating loop and a resistive “vehicle hitching rail” used for heating the engines of the maintenance vehicles. The vehicle hitching rails account for up to 30% of the electrical power produced [1] during periods of high thermal load requirements.

Many of the loads at Scott Base are required for staff well-being and for performance of tasks. These loads may be separated into two different categories:

- **Mandatory**: on-demand loads, which may not be postponed. Examples of this include workshop tasks, primary heating, etc.
– **Optional**: may be used to match energy production. Primary uses for these types of loads include resistive heating.

To further clarify these optional loads, wind turbine systems must be able to accommodate periods when energy is being produced in excess of load demands. When this occurs the turbine system must either reduce its power production (via blade orientation) or “dump” the excess energy to separate resistive loads. These “dump loads” are essentially large power-dispersing resistors and this energy in the form of heat is usually wasted. Due to the environmental conditions as Scott Base, the dump load scenario is used to provide heat to either the base or a multi-vehicle, resistive engine-block heating unit called a “hitching rail”.

Before deciding on the HPNSWD system approach, a brief consideration of candidate energy storage systems was reviewed and most were deemed infeasible for a variety of reasons. Fuel cells and flywheel systems might prove innovative, practical and effective, as both have been investigated for other wind-diesel systems [9][10]. Nevertheless, issues associated with the transport, reliability, cost effectiveness and maintenance of these alternatives proved to be excessive. Another constraint associated with energy storage systems for Antarctic facilities is the use of chemical batteries. Concerning the simple issue of transport (both in and out), battery systems can be quite heavy and shipping costs are prohibitive. Additionally, the use of batteries can be difficult to manage in these environments since they must be kept indoors and the hydrogen gas produced is quite flammable. Final consideration
against batteries is due the toxic nature of lead and the potential danger of environmental contamination.

Note that the energy system must be designed in order to meet performance objectives through system integration of the supply side and the demand side. The design and integration of a wind turbine to the existing energy system will add renewable energy to the supply side, but the maximum utilization of available wind energy can only be achieved through integration with the demand side in such a way as not to reduce the efficiency of the entire system. For example, the addition of wind turbine electrical resources must not result in the diesel electrical generators running below minimum load requirements. As the wind turbine generates more electricity, the load monitoring feedback into the diesel generator will reduce generator output to maintain the current electrical load. The diesel output must not be reduced below a certain minimum value (usually 30% of maximum load). Otherwise this will result in a marked reduction in the lifetime of the diesel generator and will also increase maintenance costs. Therefore, the wind resource must be used in an efficient, system-wide manner.

3 PREVIOUS RESEARCH

Much research has been done in the area of integrating wind turbines into previously diesel-only systems, mostly from the perspective of power controls [21] and those utilizing on-site energy storage mechanisms [22][23]. Far less has been done in the area of what is known as High-Penetration, No-Storage, Wind-Diesel (HPNSWD)
systems [24]. As indicated by the name, these systems do not utilize energy storage devices but rather rely on effective and timely power system management to provide for system stability. Some of the existing research is quite impressive, as exemplified by the creation of the MATLAB/Simulink SimPowerSystems™ module – created specifically to model transients for these types of systems. Although excellent work in this area continues, little attention has been given to those systems that rely on diesel generators for their thermal capacity [18-20]. For example, most of the Antarctic systems rely solely on diesel generators to provide for both their thermal and electrical needs. When a wind turbine system is added, the use of the diesel generators is minimized but this also reduces or entirely eliminates the thermal supply for these facilities. As a result, these facilities typically rely on fossil-fueled boilers for their thermal needs.

This research investigates the usage of available wind resources to supply thermal resistance heating and the usage of variable-resistance (VR) loads for maintaining frequency power conditioning during periods of reduced wind resource. Research involving the utilization of variable resistance loading for frequency control has been done by Black [25] and Schweppe, et al. [26]. A balance of resistive power controls frequency, therefore VR load can be increased or decreased to stabilize grid frequency. This mechanism also assists in decreasing the required diesel start up time – effectively controlling the grid frequency long enough for the diesel to start up and provide load control.
4 METHODS

The approach to this project is multifaceted in an attempt to produce research data that is more pragmatic than abstruse. To accomplish this, a decision was made to use three different software-modelling tools: Hybrid2™, Homer™ and MATLAB/Simulink. Following the description of the software-modelling tools, an evaluation of how to determine an “optimal” system will be discussed.

As an overview of the modelling process, Hybrid2™ was used to model the baseline diesel-only system and validate extrapolated electrical load data to see if this load data mirrors known annual diesel fuel usage. Next, after successfully validating the electrical load data, Homer™ was used to size and optimise the system according to system constraints such as fuel costs, wind resource, number of turbines, etc. With the Homer™ data, a suitable model was obtained to predict a range of annual fuel usage by the implementation of numerous wind turbine arrays and other system factors. Finally, the feasibility of implementing a power control strategy with a HPNSWD system was investigated using MATLAB/Simulink, effectively simulating transient conditions of diesel power up/power down during periods of fluctuations in wind resources.

With the hourly electrical load data validated with Hybrid2™, the sizing of the proposed hybrid wind system components was conducted prior to the MATLAB/Simulink system modelling. With the existing diesel-only configuration, the addition of a properly sized single or multiple wind turbine array would be
mandatory, as to ensure a final configuration that is properly sized and economically reasonable. For this part of the research, the Homer™ software simulation package was chosen to effectively size and subsequently perform the system modelling to determine annual fuel usage.

In order to properly size the wind turbine for this application, a few criteria must be evaluated to determine the optimal hybrid configuration. When incorporating renewable-based systems into remote stand-alone systems, the amount of energy that can be obtained from the resource must be determined in order to properly size the added components. The percentage of renewable energy or renewable penetration can be classified in the following ways as per Drouihet [28]:

\[
\text{Instantaneous Penetration} = \frac{\text{Wind Power Output (kW)}}{\text{Primary Electrical Load (kW)}}
\]

\[
\text{Average Penetration} = \frac{\text{Wind Power Energy Output (kWh)}}{\text{Primary Electrical Load (kWh)}}
\]

For the Scott Base system with a 2004 average annual electrical load of 137 kW and a maximum electrical load of 172 kW, the instantaneous penetration ranges from 0% (calm winds) to nearly 310% (windiest periods). The average penetration is a figure more commonly used when referring to renewable penetration percentages. For 2004, the simulations run with Homer™ indicate the average penetration values of 63%. The system design constraints were such that the percentage of renewable
energy would be below 40% of load demand. This 40% threshold was chosen because at percentages above this value, short term energy systems such as flywheels, batteries or hydrogen fuel cells are usually required [7]. Additionally, similarly sized wind-diesel systems without storage were found to provide the greatest fuel savings when either no or very small battery storage systems were used [10].

Therefore, the research gathered for this project will provide for system estimates based from a range of control parameters. For example, a plot of the number of wind turbines can be obtained as a function of both diesel price and renewable energy fraction. Using this approach, an evaluation can be made as to how the number of turbines may change, in addition to the amount of renewable energy fraction when the fuel price fluctuates.

Although a reasonable consideration, it must be noted that the financial feasibility of this project was not a primary concern of this project. A brief note regarding the estimated costs of integrating a wind turbine system into the current configuration is included in the CONCLUSION.

5 SYSTEM/FIELD DATA

The data utilized for this project came from research gathered from the University of Canterbury (UoC) Antarctic research archives. Additionally, the UoC Library has an extensive Antarctic research section, as well as Scott Base Energy Audit [1] and the Scott Base Building Services Manuals [2,3]. As the author of the Scott Base Energy
Audit, Dave Hume was available to clarify questions about electrical loads. Finally, the Scott Base manager was available via email to answer any remaining questions.

At the onset of the project, hourly electrical load information was available for each of the Scott Base stages (Figure 4) but only for a three-day period. Because hourly data for an entire year was needed, this data was constructed based on discussions with the UoC staff from the three-day dataset and annual electrical load vs. temperature data. It must be noted that comparable data was used when those for Scott Base were unavailable. For example, temperature data for Scott Base was acquired from a variety of sources including the Scott Base Energy Audit, the Scott Base weather website [15], the Global Climate Observing System website, and the National Climatic Data Center/NOAA website. However, the only complete set of annual temperature data was from the nearby McMurdo Base. For this reason, the McMurdo Base temperature data was used for the analysis in this project.

Next, the intention was to validate this data and determine its accuracy. Upon review, this data was found to be incomplete and was also determined to have a few instances of suspect data. It was later determined that the original electrical load information was gathered manually and contained data gaps, zero electrical loads, and cases of discontinuous data at 2 and 3 times the generator capacity. This data was then modified to correct for these errors and was used as the baseline electrical load for the model. For 2004, Scott Base had the electrical load statistics shown in Table 1:
Table 1 - Scott Base Electrical Load Statistics

<table>
<thead>
<tr>
<th>Daily Average (kW)</th>
<th>Annual Maximum (kW)</th>
<th>Annual Minimum (kW)</th>
<th>Load Factor (Average Load/Peak Load)</th>
<th>Daily Average Load (kWh/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>138</td>
<td>217</td>
<td>52</td>
<td>0.636</td>
<td>3312</td>
</tr>
</tbody>
</table>

Thermal load data was obtained from the Scott Base Energy Audit and was quite helpful. This data was used to define the thermal characteristics of the Scott Base facilities and was used to calculate building heat loss. The thermal data was used to determine how often secondary heating was provided by Beacon 98 kW boiler as shown in Figure 7.

![Figure 7 - Beacon 98 kW Boiler [1]](image)

The 2004 McMurdo daily temperature data for 8 discrete times (2 each of 3:00, 6:00, 9:00 and 12:00) was used for the simulation. Since the simulation can accept hourly data, the 8-times/day data was extrapolated to alleviate any periods of zero thermal loads. For example, for each time period when data was available (3:00), this data was also used for the subsequent two time periods (4:00 and 5:00).
The Scott Base 2004 hourly load data is imported, including a default daily (9.71%) and hourly (0.879%) noise factor as shown in Figure 8. Thermal load data is also imported, utilizing the temperature data (obtained from the nearby McMurdo weather data) for the time period and the respective thermal load as per Equation 1. Default daily (6.8%) and hourly (3.7%) noise data was added to the thermal calculations. The thermal load profile can be seen in Figure 9. Note that an option is selected to use the excess electricity to support thermal loads.
Next, the 2004 hourly wind data was imported into Homer™, along with the Weibull (0.978) and autocorrelation (0.878) factor as shown in Figure 10. The boiler information is entered and 85% efficiency is selected as per [1].

**Figure 10 - Scott Base Wind Resource Data for Homer™ Model**

The Scott Base energy audit provided excellent data for calculating thermal loads. The correlation between thermal load (kW) and temperature (°C) can be seen Figure 11. It can be clearly seen that the thermal loads are highest during the winter months (June-August) and lowest during the summer months (December-February).

**Figure 11 - Scott Base Thermal Load vs. Temperature [1]**
The data was helpful for accurate calculations obtained from a Least Mean Square (LMS) curve fit of thermal power vs. temperature as seen in Figure 12.

![Figure 12 - Scott Base Thermal Load vs. Temperature – Linearized](image)

It is this trend line that was used for the correlation of the temperature and thermal heating used in the calculation for the simulation. The plot for the 2004 data can be extended to intercept the temperature axis, so that the X and Y intercepts can be clearly determined. The linear relation from this can then be determined, which resulted in a thermal load of $y = -2.7798x + 103.68$, where X is the hourly temperature as shown in Figure 13.

![Figure 13 - Linearized Thermal vs. Temperature Correlation](image)
These calculations include a noise and variance factor of $X$ and $Y\%$ to compensate for the linear nature of the data used. Therefore the Scott Base thermal load is calculated as:

\[
\text{Thermal Load} = -2.7798(\text{Temperature}) + 103.68 \, ^\circ C
\]

Equation 1 - Scott Base Thermal Load Calculation

Annual wind data was also obtained for 2004 and was taken via a data acquisition system from an unknown weather station at Scott Base. The wind data contained both 10-minute wind averages and standard deviation for those averages. This data was also reviewed and determined to have no data gaps or discontinuous segments. To work with the modelling software, this 10-minute wind data was subsequently processed, producing hourly wind speed averages, as well as respective values for standard deviation over the hourly period. A plot of the Scott Base 2004 annual wind speed can be seen in Figure 14.

![Scott Base Annual Wind Speed - 2004](image)

Figure 14 - Scott Base Annual Wind Resource
For 2004, Scott Base had the following wind resource statistics as shown in Table 2:

<table>
<thead>
<tr>
<th>Wind Average (m/s)</th>
<th>Peak Wind (m/s)</th>
<th>Dominant Wind Direction</th>
<th>Weibull (k)</th>
<th>Calm Wind (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.48</td>
<td>36</td>
<td>NNE and NE</td>
<td>0.978</td>
<td>13.8</td>
</tr>
</tbody>
</table>

From the wind resource data gathered, it shows the average wind resource to be ~4.5 m/sec and a relatively moderate percentage of calm winds (13.8%). With these relatively low wind speed averages, a wind turbine with a lower cut-in speed is required as well as one with a power curve favoring low wind speed averages.

It must be noted that the wind speed average of 4.48 m/s is considered to be a relatively poor wind resource and the specifics of this data (i.e. from what height data recorded, orientation of the monitoring tower, etc.) could not be determined. Considering that many parts of the coastal Antarctic areas experience katabatic winds or winds that are gravity-driven and flow down from the elevated center of the continent to the lower coastal regions, a coastal site with poor wind resource was not expected. By comparison, the Australian Mawson Station in Eastern Antarctica experiences katabatic winds, providing for an annual wind speed of 11.4 m/s [6]. Additionally, wind data information taken at the 20-meter height by the neighboring McMurdo Station at the nearby Crater Hill location indicates an average wind speed of 8.3 m/sec [4], a value substantially higher than the Scott Base readings of 4.48 m/sec. Regardless of the magnitude, the Scott Base data was used for all calculations but the Homer™ results were plotted for different wind speeds to accommodate for possibility of higher average wind speeds.
6 SOFTWARE SIMULATION TOOLS

The software tools utilized for this project were those available “off the shelf”, to maintain consistency in results. The specific software tools used for the system modeling were MATLAB/Simulink as well as NREL’s Homer™ and Hybrid2™. To do this, a software package was chosen to simulate the diesel-only system and produce an estimate of the annual fuel consumption. Since the fuel consumption for Scott Base was known, this would effectively validate the hourly electrical load information. For this task, the NREL Hybrid2™ software package was chosen.

The annual, hourly electrical load data obtained for 2004 was generated using Matlab. This data was imported into Homer™ and subsequently plotted as shown in Figure 15.

![Scott Base Annual Electrical Load - 2004](image)

Figure 15 - Scott Base Annual Electrical Load
Initially, it was conceived that a single software package could possibly be used to model the entire hybrid system. A choice was made early in the development stages in selecting MATLAB/Simulink SimPowerSystems™ module to perform the transient modelling. This module contains accurate models of electrical and power components that can be configured to provide an accurate simulation of power systems as shown in Figure 16.

![Figure 16 - Simulink Wind-Diesel System Model](image.png)

After developing a preliminary model of the hybrid diesel/turbine system using SimPowerSystems™, it was soon realized that this tool could not be used effectively to estimate the systems annual fuel usage. This is due to the fact that a 10-second model of a transient system using SimPowerSystems™ took about 60 seconds to run via computer simulation. For the application of these types of electrical and power components, the tool is configured such that the sampling time is quite short (i.e. 0.001 seconds for some components) so it is quite effective in modelling transient conditions but not very useful in modelling long-term processes. As a result, the
research for this project utilized three different software packages that were necessary in order to properly design the system.

First, the parameters for the baseline system (diesel only) were modelled using the Hybrid2™ software package, which allowed for verification of the electrical load and fuel consumption data. The load data and system parameters (i.e. system configuration, diesel fuel consumption, diesel generator performance data, etc.) were entered into the Hybrid2™ model. A simulation was then performed and the resultant model provided an annual fuel consumption, which matched the actual annual fuel consumption to within 1%.

Hybrid2™ software is developed by the University of Massachusetts and NREL. Hybrid2™ is a time-series, probabilistic model that uses time-series resource and load information combined with statistical analysis and manufacturers' data for hybrid system equipment to accurately predict the performance and cost of hybrid power systems. Hybrid2™ allows direct comparison of many different renewable and non-renewable power system designs in a user-friendly format in which off-the-shelf equipment is incorporated into potential power systems.

Hybrid2™ has several capabilities not present in the HOMER™ software: it can simulate systems with multiple diesel generators, perform simulations with time steps smaller than one hour, consider the variability of resource and load values within a single time step, simulate a mixture of AC and DC loads and simulate a number of
dispatch strategies. A dispatch strategy is a set of rules used to control the operation of the diesel generator and the store, e.g. a battery bank, whenever there is insufficient renewable energy to supply the load. Actual usage of Hybrid2™ required more effort than originally planned. Although Hybrid2™ is released with a users manual (63 pages) and also a theory of operation manual (235 pages), details on actual calculations are conspicuously absent. For example, the Unmet Load threshold is calculated by derating the generator Rated Power by 20%. During Hybrid2™ calculations for Scott Base, the 245 EkW generator is derated by 20%, resulting in an Unmet Load threshold upper limit of 196 kW. Therefore, any load values in excess of 196 kW will be considered an Unmet Load. There is nothing in either manual that would indicate any power derating used in the calculated results. Similarly, thresholds for Excess Dump Loads are calculated from Minimum Allowed Power but also not alluded to in either manual. Specific system parameters must be defined for each Hybrid2™ configuration and simulations must be run separately. Therefore, in order to obtain results, which show a range of input parameters, multiple simulations must be generated and the results compiled separately.

With the load data verified with the Hybrid2™ software package, a second software package was used to quantify the amount of wind energy resource that can be reasonable extracted at the Scott Base site and also to optimise the required turbine system. For this task, the Homer™ software package was used to properly size the wind turbine system, based on the desired percentage of energy supplied by the wind resource or more commonly referred to as “wind penetration”. The calculations
provided by Homer™ also include economic factors such as fuel and turbine costs, turbine sizing and number of turbines.

Homer™ is a computer model also provided by NREL that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation (DG) applications. Homer™ optimization and sensitivity analysis algorithms allow the evaluation of the economic and technical feasibility for a large number of technology options and to account for variation in technology costs and energy resource availability. Homer™ models both conventional and renewable energy technologies.

As shown Figure 17, Homer™ can generate an output based off of a range of parameters instead of discrete value. This graph show many important correlations, including how wind speed dictates the number of wind turbines needed, as well as diesel usage. It has been determined that the Scott Base modeling will utilize

Figure 17 - Homer™ Surface Plot Example for Scott Base
Homer™ instead of Hybrid2™, due to the greater flexibility, ease of use, accuracy and range of control parameters.

Note that the Homer™ model produces a variety of configurations, each dependent upon system parameters such as diesel fuel cost (which effects hybrid system cost recovery), desired renewable energy fraction (which effects the number of turbines required), wind resource (which determines both number of turbines and fuel usage), etc. Therefore, there is no “optimum” system and determining a suitable configuration is entirely dependent on the criterion by which the system should be measured. For this research however, the primary consideration for the Scott Base system is to minimize fuel usage.

Due to the fact that Hybrid2™ does not provide for much of the detailed results necessary for this research, it was used to simply determine the accuracy of the electrical load model. With the baseline load model verified, the subsequent results will be obtained for Homer™ and MATLAB/Simulink. Note that the Simulink model is used only for the transient response condition of the diesel turning off during periods of high wind penetration and turning the diesel on during periods of low wind penetration. The results obtained for the Homer™-modeled hybrid case will be compared to the Homer™-modeled, diesel-only case.
The Homer™ hybrid model required much more in terms of configuration compared to the baseline Homer™ model. Initially Homer™ requires the selection of system equipment such as Components (Turbine/Generator), Loads (Primary/Thermal) and Grid as shown in Figure 18.

The Homer™ model also allows for the selection of a thermal load. These thermal loads are dependent upon the outside temperature and provide for a more complete model compared to Hybrid2™. Note also that the Homer™ model calculates total and electrical efficiency of the system, as well as the diesel starts and the operational life. These results will be compared to the hybrid model and can be found in the ANNUAL RESULTS - HOMER™ section. In terms of thermal considerations, Homer™ uses both thermal loading and efficiency in the model. Additionally, Homer™ allows for the usage of any excess electrical energy supplied by the renewable energy resource to be used to supplement the thermal load.
Homer™ proved to be far easier to use than Hybrid2™ and provided more flexible
data, allowing for more detailed combinations of different configurations. Each
simulation can be run which utilize a range of values, with results showing how one
parameter can change relative to another.

Finally, with a verification of the electrical load data and a properly sized diesel-wind
system, the resultant configuration was then modelled by using MATLAB/Simulink
software. The Simulink interface provides a graphical representation of the system
and allows for real-time monitoring of a variety of system parameters, such as
diesel/turbine output power, grid frequency, fuel consumption, wind speed, etc. To
properly model Scott Base and attempt to predict annual fuel consumption accurately,
a software tool would be necessary that would allow the flexibility of customizing
(programming) certain aspects of the system but would also provide for a suitable
graphical interface so that transient effects could be viewed and evaluated.

The MATLAB/Simulink model simulated a fixed-speed wind turbine, which operates
within a relatively narrow RPM range. It must be noted that the actual Enercon E-33
is a variable speed wind turbine and an Enercon variable-speed power profile is used
for the model. These Enercon parameters, although different from the actual unit,
were ultimately chosen due to the desirable nature of this turbine and its proven
performance in demanding, cold-weather installations.
The MATLAB/Simulink software also has the added benefit of having a module that specifically addresses the mechanical and electrical characteristics of wind turbines. This SimPowerSystems™ module allows for the user to model and simulate electrical power systems and drives within the Simulink environment.

7 POWER SYSTEM COMPONENTS

The main components for hybrid wind-diesel system are of course the turbine and diesel generator however additional power control mechanisms are necessary during transient conditions and are discussed in the following section.

7.1 WIND TURBINE

Wind turbines of various sizes were considered but to achieve an electrical average annual renewable energy fraction of at least 30%, a 330kW Enercon E33 was chosen as the baseline turbine. This particular turbine was chosen for the following reasons:

- Suitable low-speed power profile
- E33 model has proven reliability in another Antarctic installation [6]
- Gearless to reduce maintenance/improve reliability

The 330 kW size is appropriate for Scott Base to achieve electrical annual average renewable energy fractions exceeding 30% per turbine. If for example the smaller 50 kW AOC 15/50’s turbines were used, this configuration would require the installation of 6 turbines to achieve a renewable energy fraction exceeding 30%.
The power curve of the Enercon E-33 wind turbine that was used for the Scott Base model is shown in Figure 19. This curve shows the output power of the wind turbine in relation to the given wind speed and turbine rotor speed. The maximum power point available at each wind speed produces a parabolic profile (shown in dark blue) and intersects each constant-wind speed profile at various turbine RPM’s and is outlined in [27]. For fixed-speed wind turbines, the turbine is operating within a narrow frequency range (1600-2000 RPM), so the maximum power for the turbine is not produced until the winds reach speeds between 10-13 m/sec.

The inclusion of the wind turbine required a power profile so that the correlation between wind and power output could be determined. The chosen turbine for this application is the Enercon E-33, which appears to be a more common choice for cold-
environment applications due in part to its gearless design (reducing maintenance), proven reliability and low wind cut-in speed. A power curve for the E-33 can be seen in Figure 20.

![Power Curve](image)

**Figure 20 - Enercon E-33 Power Curve [31]**

### 7.2 DIESEL GENERATOR

The diesel generators used at Scott Base provide all electrical and thermal requirements for the base. Each of the Caterpillar 3604 electric generators (rated at 225 EkW (prime), 200 EkW (continuous) electrical, 110kW thermal) utilize a governor control system utilizes a feedback mechanism, which receives the speed and voltage from engine and motor respectively, comparing the mechanical output (kW) and terminal voltage (V) to reference per unit (pu) or normalized values. The governor is responsible for maintaining the output speed of the mechanical drive shaft at a fixed RPM which is 1800 for a 60 Hz system and 1500 for a 50 Hz system as shown in Figure 21. For our simulations, a 60 Hz system is used.
As the electrical load increases, this in turn induces a mechanical resistance on the output shaft, effectively slowing it down to something less than 1800 RPM. The governor attempts to maintain the target RPM and in response, increases fuel to the diesel engine thereby increasing the mechanical output and restoring the output shaft back to 1800 RPM.
Using information obtained from the Caterpillar distributor, the power, fuel consumption and efficiency information was entered into a lookup table so that fuel consumption could be recorded. The performance characteristics for the Caterpillar 3406 diesel generator can be seen in Figure 22. With a few modifications of the model parameters, the fuel consumption measurements of the diesel model were essentially the same (< 1%) compared to those given by the manufacturer at the specified power output increments of 15kW.

### 7.3 SYSTEM CONTROL MECHANISMS

In order to maintain a properly functioning thermal and electrical system, a thorough control strategy must be developed. To address the electrical control strategy, the need is threefold: frequency, voltage and power factor control. Additionally, general power control and system load control will be briefly discussed.

The diesel governor performing its task via careful control of fuel consumption maintains a constant 60 Hz grid frequency. As the frequency decreases, the fuel rate to the diesel is increased and vice versa. Similarly, frequency can also be maintained by a complementary method as outlined in [25,26]: instead of increasing fuel, sometimes the option exists to decrease the resistive load to accomplish the same result. Since grid frequency is dependent only upon resistive loads, a controllable dump load can be configured to add or subtract a resistive load to help stabilize the grid frequency.

By comparison, grid voltage is controlled via maintaining a balance of reactive power [28]. This can be accomplished by a variety of mechanisms, which may include static
or dynamic power factor correction mechanisms, which provide for capacitive compensation for inductive loads. For this research, reactive power correction is obtained via the use of the diesel electrical generator operating as a synchronous condenser. The system configurations explored in the previous section utilized some form of power factor (PF) mechanism correction to maintain grid frequency and voltage. To properly understand these mechanisms, a brief explanation of system power will be reviewed.

A consideration that must be addressed is the issue of the system power, which can be classified in terms of true, reactive and apparent power. True power (W) is a function of only the resistive components of the system and is measured in watts.

\[ P = \text{True Power} = P = I^2 R = \frac{E^2}{R} \text{ (Watts)} \]

Reactive power (Q) is a function of both capacitive (and more commonly inductive) system components and is measured in VAR’s.

\[ Q = \text{Reactive Power} = Q = I^2 X = \frac{E^2}{X} \text{ (Volts-Amps Reactive or VAR)} \]

Apparent power (S) is the combination of the reactive and true power of the system [33] as shown by the “Power Triangle” in Figure 23.
With purely resistive loads, the grid current and voltage are always in-phase and the resultant PF is maintained at 1.0 as shown in Figure 24.

The addition of inductive loads and also inductive power-generating devices, the PF is lowered due to the current lagging behind the voltage. The resultant power generation is diminished when PF is below unity shown in Figure 25.
To address this issue, numerous trials were conducted in an attempt to optimize the transient response or minimize the duration of the frequency fluctuations and stabilize the system voltage during these periods. Most of the mechanisms currently available are those of static or one-time configurable nature, which included fixed and switched capacitors, as well as static VAR compensators. Additionally a dynamic approach is the utilization of the diesel generator as a synchronous condenser was also considered.

Fixed capacitors have a single VAR rating and are used primarily to correct relatively constant, low PF issues due to purely inductive loads [16]. Switched capacitors are simply a bank of fixed capacitors, configurable for conditions when the system VAR rating changes, in the case of the addition or elimination of inductive loads. As with the fixed capacitors they are used primarily to correct relatively constant, low PF issues due to purely inductive loads [16]. Static VAR compensators are essentially a power rectifier bridge, which directs the VAR’s from a capacitor bank onto either the electrical grid or dissipates the VAR’s across a set of inductors to maintain proper PF.
control. Although static VAR compensators are very flexible and have excellent transient response, they can be very expensive and require a complex maintenance schedule [16]. A capacitor bank was integrated into the grid and was tested with a purely capacitive load, as well as with a small inductive load. In all cases, the transient response was markedly worse than without the capacitor bank. As a result, no capacitive PF correction was used in either transient model.

The best performing mechanism proved to be the simplest: usage of the diesel’s synchronous induction generator as a rotating synchronous condenser. In this mode, the synchronous induction motor normally driven by the diesel engine is allowed to spin freely during periods when the diesel engine is not running. It operates by automatically providing reactive power in either absorbing or generating VAR’s as needed by the system and providing rapid and accurate voltage correction.

Recommendations on the amount of voltage variance include a ±10% range [17]. According to the European Standard EN 50 160, the average value of the fundamental frequency measured over 10 seconds in distribution systems with no synchronous (grid) connection is to be within 50 Hz ± 2% (i.e. 49 Hz to 51Hz) for 95% of the week or 50 Hz ± 15% (i.e. 42.5 Hz to 57.5Hz) for 100% of the week [17]

Power control strategies are required during transient periods when the system is switching between prime movers: from the diesel off/on when the wind resource diminishes to diesel on/off when the wind resource picks back up again. In addition to the rapid response of zero-switching SCR’s, a more long-term control strategy
should be included also. For example, to prevent a diesel from cycling on and off repeatedly in a short time frame, a hysteresis threshold should be maintained to include a minimum diesel on time under these conditions.

Due to the fact that a wind resource is a highly fluctuating power source, a few different approaches are necessary to interface wind energy with small, isolated diesel-only systems to create hybrid systems. These approaches are needed to permit acceptable frequency/load control and also to minimize diesel start/stop cycling. In this section, consideration for some of these options will be considered.

One way to accommodate the load demands of a facility is to designate loads into different categories, namely mandatory and optional loads. As discussed in the BACKGROUND section, these loads are separated into those whose demands must be met at all times (mandatory) and those that can be deferred until a later time (optional). In the Scott Base system, the optional loads - also designated as dump loads - will be the vehicle hitching rail and the resistive heating boiler.

Load control has the benefit of being used for effective control of the grid frequency. By using load control to remove loading (preferably optional loads) as wind resource decreases, the time it takes to reach critical frequency levels is delayed, effectively giving the system more time to engage the diesel system and accommodate the increase in net load. Load control has been used in operating two small island communities since 1982 and has proved to be effective [14].
Another option that can be used with other load-control alternatives is the inclusion of an element of hysteresis. This mechanism is used to minimize diesel cycling and assumes that the cycling results primarily from changes in the wind turbine output rather than changes in system load [14]. Hysteresis strategy involves the determination of a fixed power surplus of wind resource above the current load before the diesel is switched off.

Still another option many include defining a minimum diesel run-time, which provides for an easy way to reduce the average start/stop cycling rate [14]. Essentially, this means that once a diesel generator has started, it will continue to run for a pre-defined duration, independent on load or wind resource variations.

8 SYSTEM CONTROL DESIGN

In order to properly model Scott Base, a diagram of the facility was initially drawn. This began as a sketch of the individual buildings, the diesel generator and wind turbine prime movers, system components, etc.

![Figure 26 - Scott Base Control Model](image)
From this initial drawing, a classical control model was obtained as shown in Figure 26. This control model shows the base in the simplest form. Primary loads are defined as the mandatory or normal “everyday” loads used by the base. The wind-diesel system must provide for these loads at all times. Secondary loads are defined as optional or those used as “dump” loads by the system to utilize the excess energy in the system due to periods of wind produced electricity in excess of demands. The resistive heater and vehicle-hitching rail will be defined as secondary loads. The scope of the research for this project includes a brief mention of a recommended control system for the hybrid system, although a thorough design solution is beyond the scope of this research.

Not shown in the control diagram are the thermal components of the system. These components include the diesel-fired boiler and resistive heater (both used for supplemental heat), as well as the indoor and outdoor base temperatures. These additional components require that the controller maintain not only the electrical stability of the system but also the indoor base temperature. It is these thermal aspects that differentiate this HPNSWD system from most others.

At low wind speeds both the induction generator and the diesel-driven synchronous generator are required to feed the load. When the wind power exceeds the load demand, it is possible to shut down the diesel generator. In this all-wind mode, the synchronous machine is used as a synchronous condenser and its excitation system provides the reactive power needed to maintain the grid voltage at its nominal value. A secondary resistive load bank is used to regulate the system frequency by
maintaining a balance of real (purely resistive) power, effectively absorbing any excess wind power above consumer demand.

The wind Turbine block uses a 2-D Lookup Table to compute the turbine torque output as a function of wind speed and turbine speed. The Secondary Load block consists of eight sets of three-phase resistors connected in series with GTO (Gate Turn Off) thyristor switches. The nominal power of each set follows a binary progression so that the load can be varied from 0 to 446.25 kW by steps of 1.75kW. Ideal switches simulate the GTOs in the system.

The Discrete Frequency Regulator block controls the frequency. This controller uses a standard three-phase Phase Locked Loop (PLL) system to measure the system frequency. The measured frequency is compared to the reference frequency (60 Hz) to obtain the frequency error. This error is integrated to obtain the phase error. The phase error is then used by a Proportional-Differential (PD) controller to produce an output signal representing the required secondary load power. This signal is converted to an 8-bit digital signal controlling switching of the eight three-phase secondary loads. In order to minimize voltage disturbances, switching is performed at zero crossing of voltage.
The largest part of the software system modeling was done using MATLAB/Simulink. Using the SimPowerSystems™ toolbox, a baseline Simulink demo was used as shown in Figure 27. This demo utilized some base components that were very similar to those needed for Scott Base – namely a wind turbine, a diesel generator and system-controllable loads. In the demo model, the wind turbine is comprised of an asynchronous machine connected to a wind turbine gearbox and control system and receives a fixed wind speed as shown in Figure 28.
The diesel generator in the demo is essentially used only as a synchronous condenser and does not provide electrical power to the system but rather provides reactive power to the system and is shown in Figure 29.

The loads are purely resistive and controlled via a discrete frequency regulator to provide variable amounts of load for maintaining grid frequency and dump loads as shown in Figure 30.
Although the main loads are resistive, the reactive components of the turbine and diesel generator require a capacitive power factor (PF) correction component to balance the reactive components of the prime movers. The inclusion of the capacitive PF component can be seen in Figure 31.

Using this demo as a baseline, the Scott Base model required that this system be modified in the following manner:

- Diesel governor control system
- Accurate model of Caterpillar 3406 diesel generator
- Creation of control mechanism to maintain grid voltage and frequency
• Wind turbine characteristics of Enercon E33 turbine

Note that the operation of the MATLAB/Simulink Scott Base model is strictly a transient model and as a result the following items were not considered:

• Measurement of diesel fuel usage
• Simulation of outdoor temperature variations
• Scott Base annual load data used as programmable load

9 SIMULATION RESULTS

In this section, the Homer™ software simulations for both the baseline and hybrid configurations are compared and the annualized results are reviewed. Additionally, the MATLAB/Simulink simulation, which demonstrates the transient response of the system, is investigated.

9.1 ANNUAL RESULTS - HOMER™

The software simulations began by first running a Hybrid2™ simulation to validate the 2004 hourly electrical load model. Using our electrical load profile, the Caterpillar power vs. fuel usage profile and no wind turbine, the results indicate an annual fuel usage of 361,018 litres/year. This differs from the actual 2004-measured value of 379,000 by 4.7%, which is considered acceptable. Hybrid2™ produces a report in text format but for comparison purposes, a tabular format similar to that produced by the Homer™ software was used and can be seen in Table 3.
Table 3 – Diesel-Only Annual Electric Energy Consumption for Hybrid2™ Model

<table>
<thead>
<tr>
<th>Load</th>
<th>Consumption (kWh/yr)</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC primary load</td>
<td>1,212,193</td>
<td>100%</td>
</tr>
<tr>
<td>Total</td>
<td>1,212,193</td>
<td>100%</td>
</tr>
</tbody>
</table>

Next, the Homer™ simulations began, first with a baseline trial using only the current Scott Base configuration without a wind turbine system. With the baseline diesel-only system, the following results were obtained:

Table 4 - Diesel-Only Annual Electric Energy Consumption for Homer™ Model

<table>
<thead>
<tr>
<th>Load</th>
<th>Consumption (kWh/yr)</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC primary load</td>
<td>1,209,684</td>
<td>100%</td>
</tr>
<tr>
<td>Total</td>
<td>1,209,684</td>
<td>100%</td>
</tr>
</tbody>
</table>

From Table 4, the AC primary load fraction is 100%, of course comprising 100% of the total electrical energy load.

Figure 32 - Diesel Only Annual Thermal Energy Production for Homer™ Model

The annual thermal energy production calculation shows a few instances of thermal load being supplied by the 98kW boiler during April, May, August and September.
These brief periods can be seen at the extreme bottom of the chart in Figure 32. These boiler-supplemented periods occurred during instances of low electrical loading and high thermal load.

The percentage of time in which the boiler is active is far less than 1% (0.076%) as outlined in Table 5.

**Table 5 - Diesel-Only Annual Thermal Energy Production for Homer™ Model**

<table>
<thead>
<tr>
<th>Component</th>
<th>Production (kWh/yr)</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat Gen</td>
<td>1,774,912</td>
<td>100%</td>
</tr>
<tr>
<td>Boiler</td>
<td>1,350</td>
<td>0%</td>
</tr>
<tr>
<td>Total</td>
<td>1,776,262</td>
<td>100%</td>
</tr>
</tbody>
</table>

The Homer™ model provided for much more detail in the results for the diesel generator. For the breakdown of the Caterpillar 3406 generator, the specifics can be seen in Table 6.

**Table 6 - Diesel-Only Caterpillar 3406 Generator for Homer™ Model**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours of operation:</td>
<td>8,760</td>
<td>hr/yr</td>
</tr>
<tr>
<td>Number of starts:</td>
<td>1</td>
<td>starts/yr</td>
</tr>
<tr>
<td>Operational life:</td>
<td>1.71</td>
<td>yr</td>
</tr>
<tr>
<td>Average electrical output:</td>
<td>138</td>
<td>kW</td>
</tr>
<tr>
<td>Minimum electrical output:</td>
<td>67.5</td>
<td>kW</td>
</tr>
<tr>
<td>Maximum electrical output:</td>
<td>217</td>
<td>kW</td>
</tr>
<tr>
<td>Average thermal output:</td>
<td>203</td>
<td>kW</td>
</tr>
<tr>
<td>Minimum thermal output:</td>
<td>120</td>
<td>kW</td>
</tr>
<tr>
<td>Maximum thermal output:</td>
<td>295</td>
<td>kW</td>
</tr>
<tr>
<td>Annual fuel usage:</td>
<td>363,460</td>
<td>L/yr</td>
</tr>
<tr>
<td>Specific fuel usage:</td>
<td>0.300</td>
<td>L/kWh</td>
</tr>
<tr>
<td>Average electrical efficiency:</td>
<td>33.8</td>
<td>%</td>
</tr>
<tr>
<td>Average total efficiency:</td>
<td>83.5</td>
<td>%</td>
</tr>
</tbody>
</table>
The total annual fuel consumption as calculated by the Homer™ model was 363,460 litres/year. This compares to the actual usage of 379,000 litres/year within 4.1%, which is a slight improvement over the Hybrid2™ model of 360,430 litres/year.

Table 7 - Diesel-Only Emissions for Homer™ Model

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions (kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>957,537</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>2,362</td>
</tr>
<tr>
<td>Unburned hydrocarbons</td>
<td>262</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>178</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>1,923</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>21,081</td>
</tr>
</tbody>
</table>

Due to the priority concerning the environmental impact of modeling this system, a brief note on diesel emissions will be provided to quantify the reduction of emissions with the use of a renewable energy resource. The baseline emissions as calculated by the Homer™ model can be seen in Table 7. Following the results for the baseline case, a simulation model for the hybrid case was performed but only for the Homer™ model.

For the future development of Scott Base, the primary consideration for this project is to reduce the diesel fuel usage. Financial consideration must of course be weighed in light of this usage but reduced fuel consumption is paramount. The motivation for this primary factor is threefold, namely:

- Decrease environmental impact and to showcase renewable energy systems, thereby setting new standard for Antarctic research facilities
- Decrease dependency on McMurdo, which supplies Scott Base’s diesel fuel
- Decrease dependency on diesel fuel in general in light of price volatility
This last point is of interesting concern, as Scott Base is currently being supplied diesel fuel by McMurdo at one point at an inordinately inexpensive price ($0.50/litre as per discussions with David Hume in July 2005). Whether or not this pricing continues, it most certainly will not remain as such in the near future. As a result, the optimum system chosen for Scott Base utilized two Enercon E-33’s, with hub heights of 50 m to provide for a renewable electrical energy fraction of 49.8%. The renewable electrical energy fraction is the total electrical production that is produced by renewable sources.

As shown in Figure 33, the majority of excess energy can be used to provide a sizeable portion of the thermal load for the facility, with the boiler and generator providing the balance. With the hybrid system configured, the following results were obtained.

**Table 8 - Hybrid Annual Electrical Energy Consumption from Homer™ Model**

<table>
<thead>
<tr>
<th>Component</th>
<th>Production (kWh/yr)</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbines</td>
<td>1,434,640</td>
<td>69%</td>
</tr>
<tr>
<td>Cat Gen</td>
<td>632,126</td>
<td>31%</td>
</tr>
<tr>
<td>Total</td>
<td>2,066,766</td>
<td>100%</td>
</tr>
</tbody>
</table>
From Table 8, the AC primary load fraction is now broken down into the electrical energy provided by the wind turbine (69%) and the energy supplied by the diesel generator (31%). As per our previous descriptions of energy penetration, Homer™ includes a total renewable energy fraction that included both thermal and electrical components. For the two-turbine hybrid system configuration, the total renewable energy fraction is 49.8%.

![Monthly Average Electric Energy Production for Homer™ Model](image)

**Figure 34 - Monthly Average Electric Energy Production for Homer™ Model**

With the inclusion of the wind turbine – specifically the dump loads being used to supplement the thermal loads - the annual thermal energy production calculation shows an increased number of instances where thermal load is supplied by the 98kW boiler as shown in Figure 35.

![Primary Thermal and Boiler Output for Homer™ Model](image)

**Figure 35 - Primary Thermal and Boiler Output for Homer™ Model**
These increased periods of boiler usage can be seen during periods of high wind energy penetration and as a result, lower or no thermal contributions from the diesel generators. Boiler usage is increases dramatically from 0.076% to 22% but the generator operating time is down from 100% to 27% as shown Table 9.

Table 9 - Hybrid Annual Thermal Energy Production for Homer™ Model

<table>
<thead>
<tr>
<th>Component</th>
<th>Production (kWh/yr)</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat Gen</td>
<td>454,189</td>
<td>27%</td>
</tr>
<tr>
<td>Boiler</td>
<td>360,405</td>
<td>22%</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>857,088</td>
<td>51%</td>
</tr>
<tr>
<td>Total</td>
<td>1,671,681</td>
<td>100%</td>
</tr>
</tbody>
</table>

The average output of the two-turbine system is 164kW, which is slightly more than the annual 137 kW load average, for a total output of 119% compared to the baseline system as shown in Table 10.

Table 10 - Hybrid System with Enercon E-33 Wind Turbine for Homer™ Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity:</td>
<td>670 kW</td>
<td></td>
</tr>
<tr>
<td>Average output:</td>
<td>164 kW</td>
<td></td>
</tr>
<tr>
<td>Minimum output:</td>
<td>0.0 kW</td>
<td></td>
</tr>
<tr>
<td>Maximum output:</td>
<td>670 kW</td>
<td></td>
</tr>
<tr>
<td>Wind penetration:</td>
<td>119 %</td>
<td></td>
</tr>
<tr>
<td>Capacity factor:</td>
<td>24.4 %</td>
<td></td>
</tr>
<tr>
<td>Hours of operation:</td>
<td>6,782 hr/yr</td>
<td></td>
</tr>
</tbody>
</table>

Recall that the wind penetration calculation is the average power output of the wind turbines divided by the average primary load and the capacity factor is the average power output of the wind turbines divided by the total wind turbine capacity.
The Homer™ model provided for much more detail in the results for the diesel generator. For the breakdown of the Caterpillar 3406 generator, the specifics can be seen in Table 11. The Homer™ model allows for the selection of a thermal load as shown in Figure 9. These thermal loads are dependent upon the outside temperature and provide for a more complete model compared to Hybrid2™. Note also that the Homer™ model calculates total and electrical efficiency of the system, as well as the diesel starts and the operational life. These results will be compared to the hybrid model found in the following section.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Diesel System Value</th>
<th>Hybrid System Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours of operation:</td>
<td>8,760</td>
<td>5,683</td>
<td>hr/yr</td>
</tr>
<tr>
<td>Number of starts:</td>
<td>1</td>
<td>516</td>
<td>starts/yr</td>
</tr>
<tr>
<td>Operational life:</td>
<td>1.71</td>
<td>2.64</td>
<td>yr</td>
</tr>
<tr>
<td>Average electrical output:</td>
<td>138</td>
<td>111</td>
<td>kW</td>
</tr>
<tr>
<td>Minimum electrical output:</td>
<td>67.5</td>
<td>67.5</td>
<td>kW</td>
</tr>
<tr>
<td>Maximum electrical output:</td>
<td>217</td>
<td>208</td>
<td>kW</td>
</tr>
<tr>
<td>Average thermal output:</td>
<td>203</td>
<td>79.9</td>
<td>kW</td>
</tr>
<tr>
<td>Minimum thermal output:</td>
<td>120</td>
<td>56.1</td>
<td>kW</td>
</tr>
<tr>
<td>Maximum thermal output:</td>
<td>295</td>
<td>133</td>
<td>kW</td>
</tr>
<tr>
<td>Annual fuel usage:</td>
<td>363,460</td>
<td>196,120</td>
<td>L/yr</td>
</tr>
<tr>
<td>Specific fuel usage:</td>
<td>0.300</td>
<td>0.310</td>
<td>L/kWh</td>
</tr>
<tr>
<td>Average electrical efficiency</td>
<td>33.8</td>
<td>32.8</td>
<td>%</td>
</tr>
<tr>
<td>Average total efficiency:</td>
<td>83.5</td>
<td>56.3</td>
<td>%</td>
</tr>
</tbody>
</table>

For the hybrid system, the total annual fuel consumption as calculated by the Homer™ model was 239,210 litres/year. This breaks down to 196,120 litres/year for the diesel generator and 43,090 litres/year for the boiler. This total usage compares to the actual usage of 379,000 - a 36.9% reduction in fuel usage over the baseline model.
The Homer™ model calculates the expected decrease in emissions compared to the baseline model and can be seen in Table 12.

**Table 12 – Diesel-Only vs. Hybrid Emissions for Homer™ Model**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Diesel Only Emissions (kg/yr)</th>
<th>Hybrid Emissions (kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>957,537</td>
<td>630,459</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>2,362</td>
<td>1,275</td>
</tr>
<tr>
<td>Unburned hydrocarbons</td>
<td>262</td>
<td>141</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>178</td>
<td>96.1</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>1,923</td>
<td>1,270</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>21,081</td>
<td>11,375</td>
</tr>
</tbody>
</table>

### 9.2 TRANSIENT RESULTS - MATLAB/SIMULINK

With the Hybrid2™ and Homer™ software, simulation models were constructed to reveal long-term performance and trends of the system. What is also required to provide for a complete representation of the system, is to determine the transient response of the system - during periods when the diesel is either turning off (in the case of a decreasing wind resource) or on (in the case of an increasing wind resource). The MATLAB/Simulink SimPowerSystems™ block allows for such a transient model, to determine how quickly the system might respond to such operating conditions and also the extent of the effects of these changes. For example, the transient response will indicate how much the grid frequency will change before the diesel generator will either turn on (for the case of decreasing wind) or turn off (for the case of increasing wind)
The Simulink model used to simulate the transient response when wind resource is decreasing is shown in Figure 36. At $t = 6.0$ sec. the wind resource instantaneously decreases 15%, from 8 m/s. to 6.8 m/s. to evaluate the system performance for a 125 kW resistive load during a period of decreasing wind resource.

At $t = 6.1$ sec. the diesel generator is switched on and it takes ~ 2.0 sec. for the diesel generator to provide the necessary power to supplement the loss due to the decrease
in wind resource. The grid frequency dips 0.7 Hz within a ~3.0 sec. period and the wind turbine stabilizes its output power within ~2.0 sec as shown in Figure 37.

It is important to note that for the decreasing wind transient response, the wind turbine power is generating “negative” power for a short period of time, reaching a peak of –35 kW. This negative power is a combined result of two simultaneous mechanisms: the turbine decreasing power and the diesel generator increasing power. When the wind resource suddenly decreases, the wind turbine slows down and naturally generates less power to the grid. At the same time the diesel generator quickly increases power and essentially “drives” the wind turbine. The turbine is effectively absorbing power from the diesel generator for a short period of time during this transient period. Once the diesel generator and wind turbine quickly stabilize to accommodate the load, both the wind turbine and diesel generator maintain their respective share of the power required by the grid.

Frequency control of the system is addressed with multiple mechanisms. For this model the diesel generator is initially idle but still acts as a synchronous condenser by providing approximately 100 kVAR of reactive power for the grid voltage control during non-transient periods. Additionally, the programmable load control provides for grid frequency control, consuming 10 kW of resistive load. When the diesel generator is switched on, the programmable load control is no longer needed to provide frequency control and is simultaneously disconnected from the system. The diesel generator is then controlling grid frequency and voltage via the speed governor.
mechanism. System response under these conditions was quite acceptable. Voltage fluctuations ranged from 497V (+3.54% change) down to 450V (-6.25% change) and the grid frequency decreased to 59.3 Hz (-1.18% change).

Trials were performed with different delay times between when the wind resource decreased and when the diesel generator was switched on. For this particular configuration 0.1 sec delay was optimal. Note that an instantaneous 15% decrease in wind resource is an extreme design criterion and would easily characterize a “worst case” situation. A more accurate representation would be a more gradual, ramped-decrease but this scenario was not investigated for this research.

In another scenario, the wind resource instantaneously increased 20% at $t = 6.0$ sec. from 6 m/s to 7.2 m/s to evaluate the system performance for a 200 kW resistive load during a period of increasing wind resource. The Simulink model for this configuration can be seen in Figure 38.

![Figure 38 - Simulink Increasing Transient Response Model](image-url)
In this case, the diesel generator is initially running and controlling grid frequency so the programmable load control not required. No system intervention is required and the diesel generator automatically regulates the system frequency and voltage to conform to the changing conditions.

As expected, system response under these conditions was much improved over the decreasing wind scenario, since the abrupt engagement of the diesel prime mover was not required. Voltage fluctuations were less than 1% in both directions and the grid frequency increased to 60.4 Hz (+0.7% change), stabilizing within 3 seconds. The transient performance for the increasing wind model can be seen in Figure 39.

![Figure 39 - Simulink Increasing Wind Transient Response Model](image)

10 SYSTEM INTEGRATION

Turbine power integration strategies will require the largest amount of consideration for the hybrid system – especially with renewable energy fractions exceeding 40%
and a lack of any energy storage devices [5]. Typically, the amount of wind penetration characterizes the system as small, medium or large.

For small systems (< 20% energy penetration), the diesel run time is not decreased but loading levels are decreased. As a result, fuel savings are minimal. These systems typically require minimal component control and there is minimal impact on plant operations [28]. High penetration systems (>50% energy penetration) have a larger impact on fuel savings and diesel runtime but require increased system sophistication due to the additional components (i.e. synchronous condensers, dump load controllers, etc.) for frequency and voltage regulation [28]. Under these criteria, the two-turbine, Scott Base model would probably be characterized as a high-penetration system.

Control and optimization of the wind turbine output is controlled by power regulation electronics, provided by the wind turbine manufacturer. These power regulation strategies must include regulating the dump loads, as well as maintaining proper at least a 30% electrical load of the diesel generators.

11 CONCLUSION

The research presented in this paper provided for a threefold approach to modeling a remote HPNSWD system: field data verification, modeling of long-term operating conditions and modeling of short-term transient conditions. The field data was found
to closely follow the modeled data, as did the long-term operating conditions. The short-term transient response performed well within acceptable requirements.

Homer™ was used to properly size the system based on wind energy penetration, for which a two-turbine system was determined to be optimal. The combination of excess wind resource, electrical load profile and thermal requirements allowed for a system able to provide a total renewable energy fraction of 49.8%.

Using the long-term Homer™ model, total annual fuel usage was decreased 36.9% from 379,000 to 239,210 litres/year, while average electrical efficiency for the diesel generator decreased 1.0% (from 33.8 to 32.8%) and average total efficiency decreased (83.5 vs. 56.3%) due to lower generator loading. It can be seen in Figure 22 that the generator efficiency is reduced considerably at the lower output power range.

Diesel operational life was increased 54% from 1.71 to 2.64 years as the operating hours decreased 35% from 8,760 to 5,683 hr/year. The number of diesel starts for the year was calculated to be 516 or 1.4 times/day. If required, this number could be improved with a load and control optimization strategy as outlined in the SYSTEM CONTROL MECHANISMS section with a minimum increase in fuel usage. Pollutant emissions for the Homer™ model show a 34.2% decrease in CO₂, and a 46% decrease in CO. Similar reductions were found in unburned hydrocarbons (46.2%), particulate matter (46%), sulfur dioxide (34%) and NOₓ (46%).
Frequency control was obtained by PLL control of a resistive dump load and voltage control was obtained via using the diesel electrical generator as a synchronous condenser. During periods of high-wind penetration, diesel operation was suspended and using the dump load to provide electrical resistance heating, as well as the supplementary use of a 98 kW boiler provided for all required thermal capacity.

The calculations generated for this research were obtained by using the Scott Base annual wind speed of 4.48 m/sec. This wind resource is relatively poor by most standards and wind penetration values could be increased considerably by siting the wind turbines at a location with a higher annual wind speed.

Nearby areas studied by McMurdo research [4] cite locations with excellent wind resources such as Crater Hill (8.71 m/sec @ 20m) or Twin Craters (7.89 m/sec @ 20m). Wind speeds at the 50 m hub height would be even greater. The Crater Hill area is within 2000 meters of Scott Base and turbines could be easily installed at these locations for connection to the Scott Base grid. The increased wind resource would also further reduce fuel usage and similarly reduce base pollutant emissions.

The research performed for Scott Base will lay the groundwork for developing new methods for HPNSWD systems, which will become important for remote energy systems with acceptable wind resources around the world. The situation at Scott Base provides an excellent opportunity for the design of larger scale energy systems that must operate as efficiently as possible, produce as little waste as possible, reduce fuel
use to a minimum, optimise utilization of renewable components, and also function to provide desired system performance within system and supply constraints.

This project provided for excellent, hands-on experience, working with actual electrical load and wind resource data. Scott Base is properly sized to allow for complete evaluation of load information and design a suitable hybrid system that is within reasonable small-scale engineering projects. Additionally, Scott Base is ideally suited for the addition of a renewable wind turbine system, allowing it to reduce its reliance solely on AN8.

12 FUTURE WORK

In light of the relatively poor wind resource data collected from Scott Base, more studies would likely indicate even greater gains in fuel savings and lower fuel costs by choosing a nearby area with an improved wind resource, as per data collected from McMurdo field studies [4]. Increasing the heat recovery from the diesel generators from the current value of 35% to 50% would have a pronounced effect on diesel consumption (~20,000 litres/year in most cases), requiring less boiler operational time and would increase both diesel and system efficiency. Design of a control system (PD or PID) similar to one shown in Figure 26 would demonstrate the accuracy of the transient models outlined in this research. Load optimization and control strategies as outlined in the SYSTEM CONTROL MECHANISMS section would investigate the possibility for even greater improvements to the transient responses and diesel start/stop cycling rate. Additionally, applying a Performance Objective Design
approach as outlined in [11] would further improve and quantify fuel saving from a
demand perspective. These savings would be accomplished via control of mandatory
and optional loads, depending on available wind resource. Finally, an economic
evaluation would be highly desirable and would enable the quantification of the
conversion of Scott Base to a HPNSWD system and the expected return on
investment from the fuel savings.
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