PERFORMANCE-OBJECTIVE DESIGN OF A WIND-DIESEL HYBRID ENERGY SYSTEM FOR SCOTT BASE, ANTARCTICA

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Engineering in Mechanical Engineering at the University of Canterbury

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Abstract

New Zealand's Antarctic research station, Scott Base, is currently 100% reliant on aviation turbine fuel and existing diesel generator sets to produce the heat and electricity necessary to sustain staff activities. Decreasing fuel consumption at Scott Base has benefits economically, politically and environmentally. A method of reducing fuel consumption and increasing base independence that is receiving considerable attention from Antarctica New Zealand is the addition of wind power to the existing energy system. A performance-objective design of a wind-diesel hybrid energy system for Scott Base is proposed in order to determine the most effective hybrid system configuration with the lowest cost within a set of system constraints. A demand side management technique is also evaluated as a measure to further increase potential fuel savings. Modelling is completed using the simulation tool HOMER and results are presented for several different system configurations.

1. INTRODUCTION

> "It is evident that the fortunes of the world's human population, for better or for worse, are inextricably interrelated with the use that is made of energy resources." (Hubbert 1969)

Energy issues and the use of natural resources are topics that need more focus at every level of society. Mechanical engineers are typically called upon to solve technical problems that contain a human component. The following thesis, submitted in fulfilment of the requirements for a master's of engineering degree within the Mechanical Engineering Department at the University of Canterbury, explores energy issues related to Scott Base, New Zealand's Antarctic research station.

The INTRODUCTION chapter of this thesis presents the question that drives the research. A brief introduction of how the problem arose is followed by the possible solution that the thesis will then test. A description of how the remaining parts of the thesis are organized completes the first chapter.

1.1. The Problem

1.1.1. The Problem

Scott Base is an isolated research facility located in the harsh environment of Antarctica. The facility is completely reliant on fuel oil, AN8, to meet all of its heat and electricity loads. Antarctic New Zealand, the government body that manages all aspects of Scott Base's existence, has expressed the desire to operate in this fragile environment as sustainably as possible. This desire includes minimizing green house gas emissions and using renewable energy where possible. Recent discussions with Meridian Energy have raised the possibility of a wind turbine being installed at the base. A key question for the base which will be addressed through the research is how to design and operate the base energy system in order to meet the specified performance objectives: 1) Maximize generator, efficiency, 2) Minimize fuel consumption, and 3) Utilize the maximum available renewable energy.

The research paper seeks to answer two questions. **The first question is, with respect to current wind turbine technology, what wind-diesel hybrid energy system is appropriate for installation at Scott Base?** The solution to the first problem will be evaluated on predicted performance with particular attention paid toward potential fuel savings. **The second question is, if feedback from the proposed hybrid energy system is made available to influence certain Scott Base electric loads, can further fuel savings be realised?** The second question attempts to find a better way of utilizing wind power.

1.1.2. The Solution

Both research questions require identifying the best possible wind-diesel hybrid energy system configuration for Scott Base. The best possible configuration may include demand side management techniques and/or control strategies. The success of any demand side management techniques will rely heavily on the identification of Scott Base electric loads that are time flexible. The current energy architecture in place at Scott Base is very costly due to the dependence on AN8. The costs associated with burning AN8 are not only high financially, but environmentally as well. Utilising the large wind resource available at Antarctica's coastal areas via a wind turbine may lessen costs. While the construction of a wind-diesel hybrid energy system at Scott Base will have a positive impact for Antarctica and its inhabitants, it will also serve as a model for other remote locations.

The primary benefit is the improved environment of Scott Base via a decrease in AN8 consumption without a change in current activities. Long term cost savings as well as improved air quality will be realised by reducing the consumption of AN8. Beyond the fuel savings benefit, moving the base closer to sustainability is a major goal. If effective demand side management is utilized along with a renewable power source, it is possible to move Scott Base closer towards sustainability.

The energy research project performed for Scott Base will lay the groundwork for developing new methods which may become important for New Zealand's energy system in the future. The results of the proposed work, including ideas, concepts and products may have benefits for other remote locations around the world as well. New Zealand's electric energy system has not been engineered to deal effectively with energy or environmental constraints. The situation at Scott Base provides an excellent metaphor for the design of larger scale energy systems that must operate as efficiently as possible, produce little waste, keep fossil fuel use to a minimum, optimize utilization of renewable components, and function to meet performance objectives within system and supply constraints.

A traditional electrical power system is linear in nature as illustrated in the following figure.

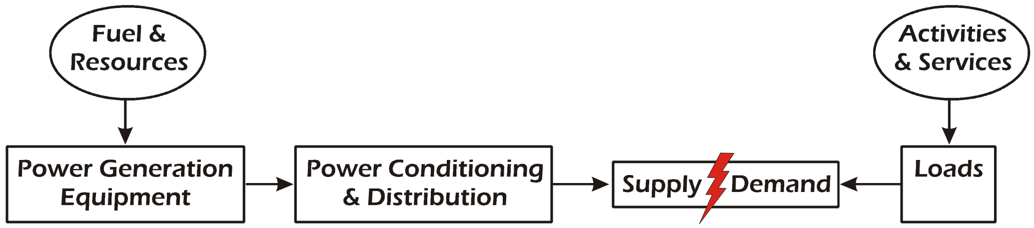


Figure 1: Traditional Electrical Power System Schematic

Natural resources fuel power generation equipment that produces an electricity supply to meet the current demand. Consumers, who create the demand, receive no information about the power system's status and therefore do not modify their behaviour even if it could be beneficial. A new approach to designing energy systems, called *Performance Objective Design*, recognizes that some supply availability objectives are "soft" like increased efficiency and minimized renewable utilization, and that other supply availability constraints are "hard" like maximum generation capacity. Performance Objective Design aims to find appropriate and effective solutions on both the supply and demand side that meet objectives within system constraints. A signal for consumers indicating current power system status is an example of constraints of the supply side influencing the objectives of the demand side. The modification to the traditional electrical power system is illustrated in the following figure.

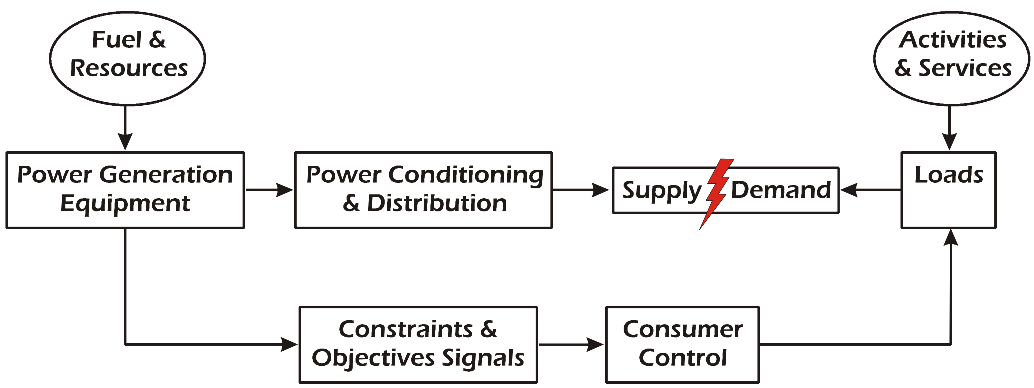


Figure 2: Performance Objective Design Power System Modification

Seeking to modify the traditional electrical power system to incorporate feedback for the consumer, performance objective design proposes an addition of signals and the associated control strategies. As oil prices continue to rise and environmental effects of fossil fuel use place greater risk on activities, it is an appropriate time to investigate performance-objective design for constrained energy systems.

1.2. Organization

1.2.1. Thesis Outline

Chapter two, BACKGROUND, is an overview of the key topics that are part of the research. Chapter two also includes the main points of the research's importance to the engineering field as well as relevance to the greater world. Chapter three, STATE OF THE ART, is a detailed study of the individual research topics that together make up the engineering project of designing a wind-diesel hybrid energy system for Scott Base. These include a literature review of the wind-diesel field of study and the current state of the art of diesel generators, wind turbines, energy storage technologies and demand side management techniques. Chapter three also identifies methodologies used to solve energy system problems such as those presented in this work. Chapter four, METHODOLOGY, details the process used to carry out the project's modelling. Describing the Scott Base system and the creation of a model that is able to simulate that system accurately is a major accomplishment of the research project. The validation of the model and analysis of resulting simulations is also part of Chapter four. Chapter five, RESULTS & DISCUSSION, presents the results of the wind-diesel hybrid energy system simulations. Discussions of each system's performance are the most important points that any reader should take away. Chapter six, CONCLUSIONS & FUTURE WORK, outlines the recommendations for Scott Base regarding the potential installation of a wind farm to complement the existing diesel generators. Chapter six also includes subjects for future study that may increase the benefits for Scott Base.

2. BACKGROUND

This chapter answers three key questions about the research. The first question, what is the topic, is covered in the *Topic* section. The second question, why is it important, is covered in the *Technical Importance* section. The third question, how does it fit into the broader view of engineering, is covered in the *Societal Relevance* section. The descriptions of each of the sub-topics make up the background of the thesis project.

2.1. Topic

2.1.1. Retrofitting Diesel-Based Energy Systems with Wind Power

The ability to generate electricity is a building block of modern societies. The utilization of wind turbines to produce electricity has been practiced for over one hundred years; similarly, diesel engines have been a method of producing electricity since the 1940s (Ackerman 2005) (Borbely 2001). However, the field of engineering concerned with the coupling of wind power and diesel generators has essentially just begun. The landmark book, Wind-Diesel Systems by Ray Hunter and George Elliot, published in 1994, identified the field's foundation principles and concepts as well as the major issues of the time (Hunter and Elliot 1994). The wind-diesel industry has grown leaps and bounds since 1994 and appears ready to make the next jump to large scale implementation (Baring-Gould et al. 2002). The following schematic represents the basic wind-diesel hybrid energy system.

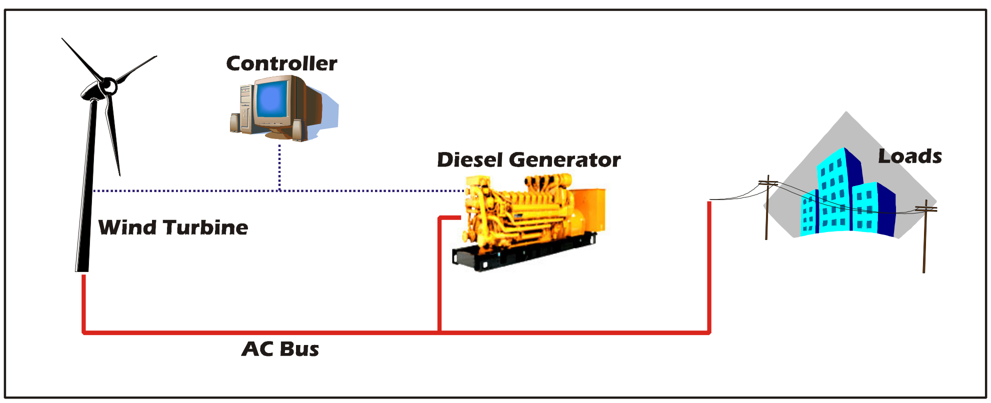


Figure 3: Wind-Diesel Hybrid Energy System Schematic

The technology behind each of the individual parts of a hybrid energy systems is mature. However, the relationships between the system components are not widely understood. Wind-diesel hybrid energy systems are becoming technically reliable options for isolated communities in first, second and third world countries. Beyond small communities, wind-diesel systems also have potential as distributed generation in large utility grids in developing countries (Ackerman 2005). Due to the large number of existing energy systems worldwide that are based on diesel engines, the market for retrofitting these systems with wind power is substantial (Ackerman 2005). According to the World Bank, over 2 billion people live in areas not connected to utility lines (Patel 1999). The market for retrofitting diesel based energy systems with wind power is very real and poised for huge growth.

2.1.2. Antarctica and Scott Base

Antarctica is the driest, coldest, windiest continent on earth. Temperatures can vary from 15 degrees Celsius in summer to -70 degrees Celsius in winter (McGonigal and Woodworth 2002). The extreme cold temperatures prevent the air from holding water vapour, making Antarctica the largest desert on earth. The rock and permanent ice cover approximately 14 million square kilometres. The addition of winter ice can almost double the size of the continent. Nearly 70% of the world's fresh water makes up the ice of Antarctica. If all that ice were to melt, the earth's oceans could all rise by as much as 80 meters (McGonigal and Woodworth 2002). Plain and simple, that's a tremendous amount of ice. The landscapes are harsh, dangerous, empty, nearly sterile and clearly not suitable for human life. The oceans surrounding the continent produce the largest waves on the planet and coastal winds can reach 300kmph. Yet, despite its isolation and barren landscapes, "the ice" has a mystical quality that scientists and visitors never fail to acknowledge.

The pull of "the ice" drew explorers in the mid 1800s. First the waters were conquered, then the shores, then the mountains, and finally the south pole. In December of 1911, a Norwegian expedition, led by Roald Amundsen, was the fist to reach the south pole with Sir Robert Scott's British expedition only a month behind. However, Scott's expedition ended in tragedy as none in the party survived the return trip. 44 years later, an expedition lead by New Zealander Sir Edmund Hilary and Englishman Vivian Fuchs began an expedition to both drive to the south pole and completely traverse the continent. An expedition base, named in Robert Scott's honor, was constructed for use during the expedition as well as for the upcoming International Geophysical Year (IGY) of 1957. The IGY became the inspiration and motivation for coordinated Antarctic research. Twelve countries took part, and 40 research bases were established (Martin 1996).

In the early 1900s, seven countries had made territorial claims on parts of Antarctica. Later there were disputes about territorial claims and apprehension about the possibility of using Antarctica as a military base. During the IGY, a treaty was created and signed by the twelve participating countries proclaiming Antarctica a giant scientific laboratory (Antarctica New Zealand 2006). Nowhere else in the world is such a treaty in effect. Today, the original seven countries, which include New Zealand, still lay claim to slices of the Antarctic pie. There are 82 research stations dotting the continent, 45 designed to be occupied year round, operated by 27 different nations (Poland et al. 2002). The following map shows the locations of the major year round research bases currently in use (Martin 1996).

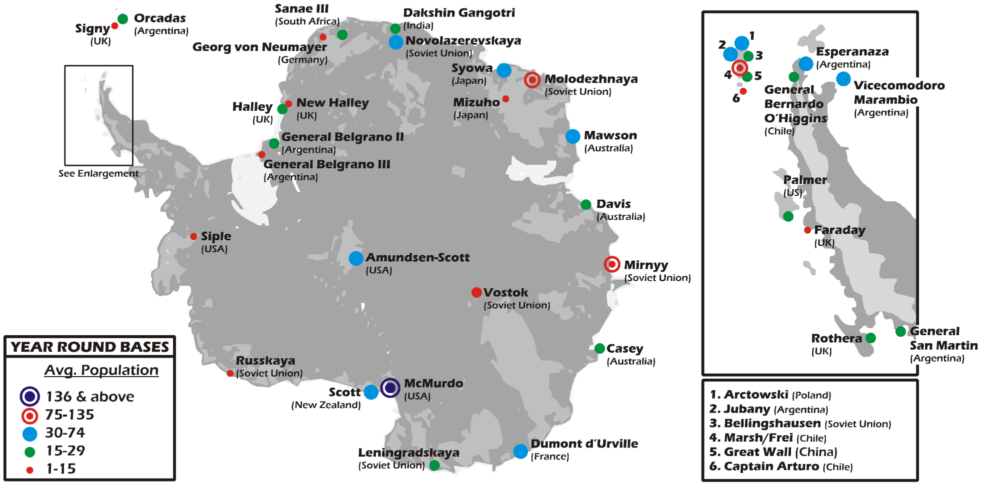


Figure 4: Antarctic Research Stations

After the official opening in 1957, Scott Base was extensively rebuilt in 1976 and looks much the same today. The base is located on Pram Point, which is at the end of the Hut Point Peninsula, on Ross Island, at the edge of the Ross Ice Shelf. Each year nearly 100 people spend the summer at Scott Base, while in the winter the populations drops to around 15. The figure below shows an aerial view of the base.

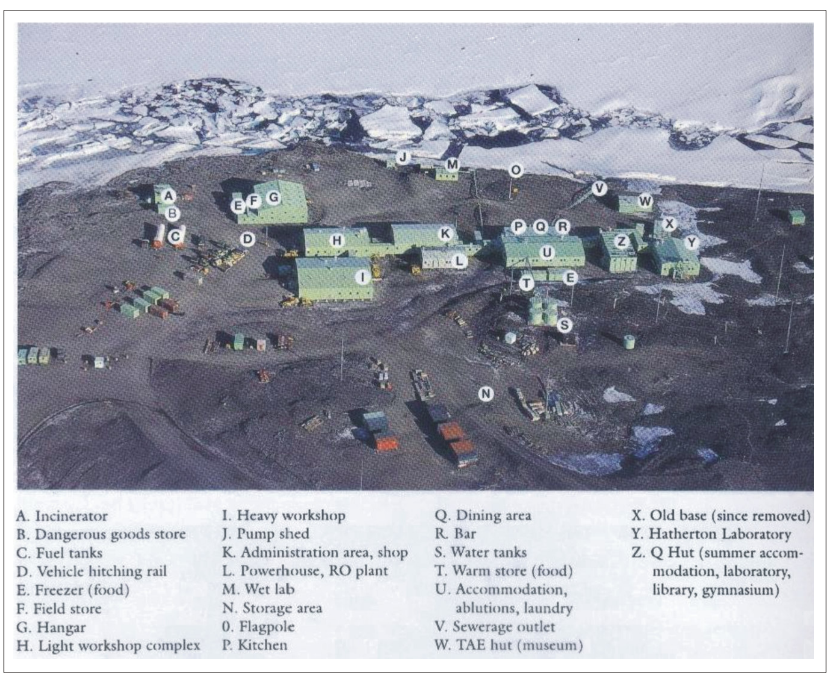


Figure 5: Scott Base Aerial Photo

The science currently underway at the bottom of the world is surprisingly vast and diverse. The cold temperatures, lack of organic material, and sparse precipitation make Antarctica ideal for preserving rocks and soils. Antarctica also has the cleanest air in the world. One major project, ANDRILL, involves drilling ice cores that can reveal climate data from thousands of years ago. Other major research topics that are ideally pursued on Antarctica are air quality monitoring and astronomical research. Over 4000 scientists spend each summer in this harsh land at one of the many bases. Research on Antarctica is very popular, worthwhile, and shows no sign of slowing. In fact, improvements to other bases such as McMurdo, the United States research base, will ensure that the number of scientists and visitors calling Antarctica home for long periods of time, will continue to rise. The fragile ecosystems of Antarctica are especially vulnerable to pollution such as oil spills. Decreasing the reliance of Antarctic bases on fossil fuel for electricity generation is an important step to ensure that research will continue on the ice for generations to come. One way to accomplish this goal is with the addition of wind power.

2.1.3. Wind Energy

Utilizing the power in wind to accomplish useful work has been an idea in practice for 3000 years. The first windmills were used to grind grain and used sails to capture the wind. The first horizontal axis windmill was built in about 1150 in England. The crusades likely spread the knowledge of how to build the machines all over Europe. Further improvement and innovation came each century. Windmills began to do other work such as pump water and in 1891, make electricity. Danish engineers improved on their designs until World War I & II when electricity generated from the wind fell by the wayside. Only when the major oil crisis of 1973 alerted governments to the uncertainty of their oil supplies did programs go into effect to promote more wind power research and installations (Ackerman 2005). Now, as many nations recognize the potential decline in the worldwide oil supply as well as the effects of burning that supply in earnest for the last 90 years, wind power is truly taking off. Indeed, wind energy has re-emerged as an important sustainable energy resource as indicated by the worldwide wind capacity doubling approximately every three years during the 1990s (Ackerman 2005). The main reason behind the recent surge in interest is profitability. New technology in power control electronics, improvements to turbine mechanical systems and available government subsidies are major contributors to wind power profits (Patel 1999). The following set of graphs indicates the trend in wind power installation around the world during the last ten years (Ackerman 2005).

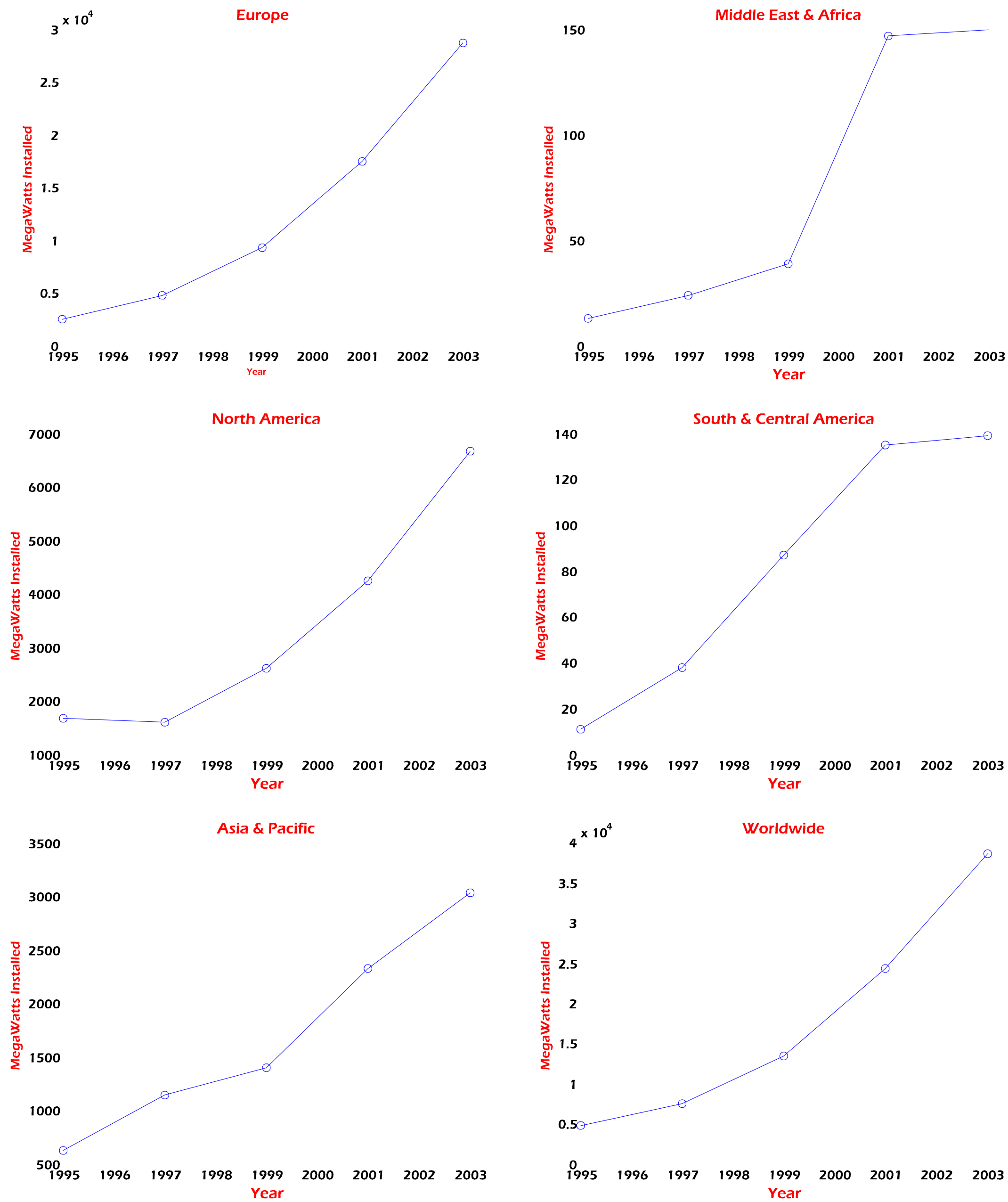
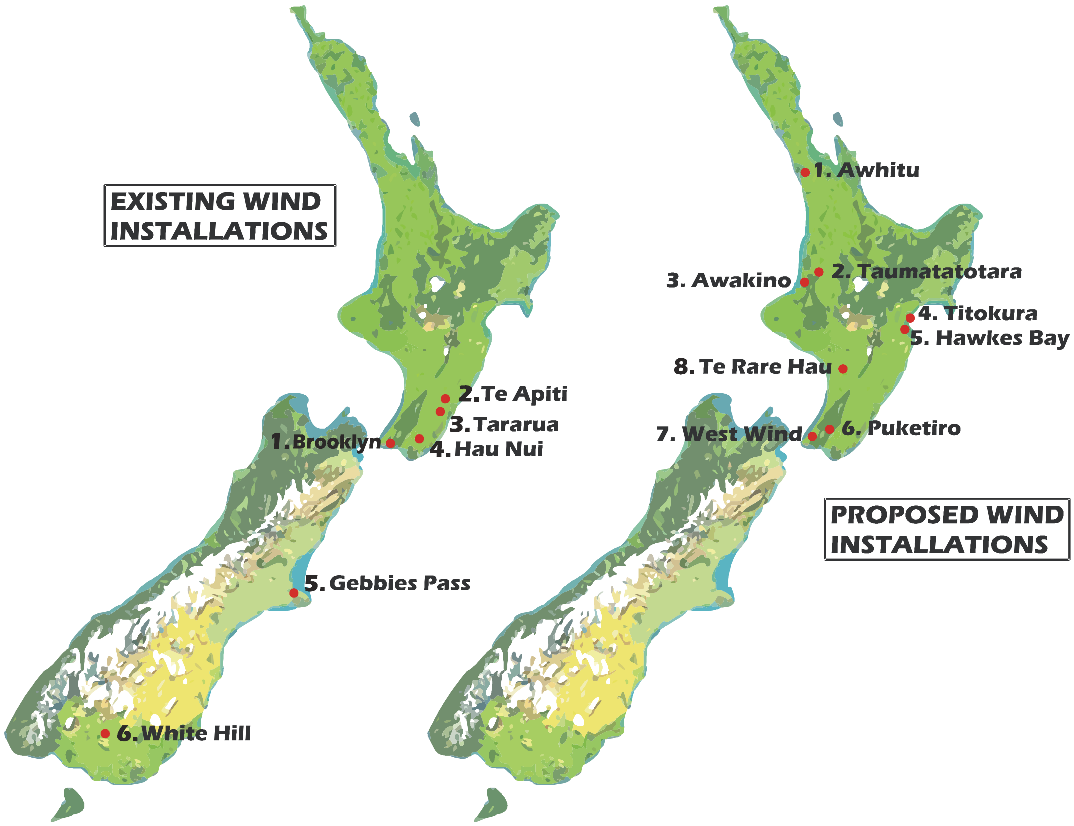


Figure 6: Wind Power Installed

The increase in popularity of wind power in the past 10 years has been remarkable. In New Zealand, as well as the rest of the world, there has been a large surge in wind power generation capacity as improved technology and government incentives make installations profitable. The incentives that are often offered by governments stem directly from measures taken to reduce reliance on fossil fuels and the pollution that comes along with them. The adoption of the Kyoto protocol has some countries looking for the best way to reduce carbon dioxide levels, and increasingly wind appears to be the answer. New Zealand has already begun its foray into large scale wind generation with the farms at Te Apiti (90MW) and Tararua (68MW). Meridian

Energy, who own and operate the Te Apiti wind farm have expressed interest in adding 700 MegaWatts to its portfolio in the next seven to eight years (Steeman 2005). TrustPower, who own and operate the Tararua wind farm, have plans to expand the farm with an additional 120 MegaWatts thus making it the largest in the southern hemisphere (Steeman 2005). Existing wind farms as well as other sites that are currently in the proposal phase are outlined in the map and table below.



Existing Wind Farms

1 **Brooklyn** Developer: ECNZ
State of affairs:
Installed as a research project by the ECNZ, since 1999 owned by Meridian Energy
Stats:
Number of turbines: 1
Project capacity: 225 kW

2 **Te Apiti** Developer: Meridian Energy
State of affairs:
Began generating in 2004.
Stats:
Number of turbines: 55 (on completion)
Project capacity: 90 MW (on completion)

3 **Tararua** Developer: Trust Power

State of affairs:

Tararua Stage III: Resource consent for another 40 turbines (3MW capacity each) was lodged on 23 Dec 2004 and approved on July 6, 2005.

Stats:

Number of turbines: 103

Project capacity: 68 MW

4 **Hau Nui** Developer: Genesis Energy

State of affairs:

Wind farmbuilt in 2 phases.

Stats:

Number of turbines: 15

Project capacity: 8,65 MW

5 **Gebbies Pass** Developer: Windflow Technology

State of affairs:

Single turbine in operation in the Port Hills near Christchurch

Stats:

Number of turbines: 1

Project capacity: 500 kw

6 **White Hill** Developer: Meridian Energy

State of affairs:

Resource consent granted on December 22, 2004. Construction to start in 2005.

Stats:

Number of turbines: up to 42

Project capacity: about 70 MW

Proposed Wind Farms

1 **Awhitu** Developer: Genesis Energy

State of affairs:

On 7 September 2005 The Environment Court set aside the decision of the Franklin District Council and granted resource consent.

Stats:

Number of turbines: 19

Project capacity: 19 MW

2 **Taumatatotara** Developer: Ventus

State of affairs:

Resource consent has been filed.

Stats:

Number of turbines: 28

Project capacity: 32.5 to 37.5 MW

3 **Awakino** Developer: Ventus

State of affairs:

Consent filed in April 2005. Deadline for submissions was July 8, 2005.

Stats:

Number of turbines: 32

Project capacity: 27.2 to 41.6 MW

4 **Titiokura** Developer: Unison/Hydro Tasmania
State of affairs:
Consent granted to Unison/Hydro Tasmania 48 MW Stage I project in Hastings District (19-8-05)
Stats:
Number of turbines: 38 to 42
Project capacity: 114 to 120 MW

5 **Hawkes Bay** Developer: Hawkes Bay Wind Farm
State of affairs:
Hawkes Bay wind farm could be New Zealand's largest. Deadline for submissions was July 20, 2005.
Stats:
Number of turbines: 75
Project capacity: 225 MW

6 **Puketiro** Developer: None chosen yet
State of affairs:
Wellington City Council has commissioned the wind farm. Public consultation will be sought starting June 27 and closes August 1, 2005.
Stats:
Number of turbines: 15
Project capacity: 26 MW

7 **West Wind** Developer: Meridian Energy
State of affairs:
Announced June 2, 2005.
Stats:
Number of turbines: 70
Project capacity: 210 MW

8 **Te Rere Hau** Developer: New Zealand Windfarms Ltd (subsidiary of Windflow)
State of affairs:
Project consented. Phase 1 to involve 6 turbines. 3 more stages proposed. Wind farm to be completed by end of 2007.
Stats:
Number of turbines: 104
Project capacity: 52 MW

Figure 7: New Zealand Existing & Proposed Wind Farms

The improvements in wind turbine technology and power electronics has not been lost on those operating on Antarctica. Currently power generation on the remote continent is done with diesel generator sets. The massive transport costs of bringing fuel to the ice make any local power generation techniques very attractive. One nation, Australia, has been researching the feasibility of introducing wind power generation to its research station since 1993. Today, Australia's Mawson station is currently provided with nearly 65% of its electricity by two Enercon E-33 wind turbines. The success of Mawson station's wind installation has asserted wind power as a reasonable alternative to diesel generators for Antarctic research stations. The wind resource near coastal locations, where most research stations are located, is immense. Katabatic winds, which occur when cold dense air over Antarctica's ice sheet flows downward to the coastal areas, interact with Southern Ocean weather to produce strong persistent winds (McGonigal and Woodworth 2002). After some preliminary trials of various designs and extensive data collection, Australia made the decision to install (3) 300kW Enercon turbines. The construction of the first two turbines began in the summer of 2002 and was completed in early 2004. The installation means that Mawson Station no longer receives a shipment of 700,000 litres of diesel fuel a year, but rather every five years (Australia Antarctic Division 2006; Pyper 2003). The cost of transport, risk of spillage, and reduction in carbon dioxide emissions have made Australia's Antarctic wind farm a huge success. The figure below shows one of the Enercon turbines at Mawson Station as well as a performance snapshot of the energy system.

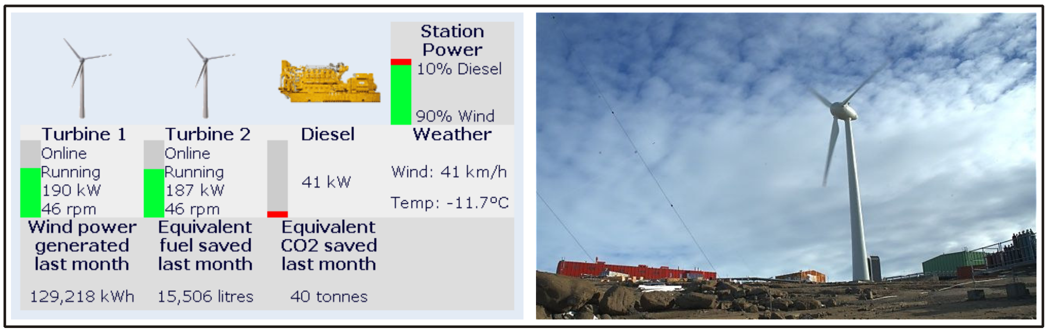


Figure 8: Mawson Station's Wind Power System

Although the Mawson Station wind farm is producing electricity to save on fuel consumption, wind turbines do not produce waste heat like diesel generator sets. In Antarctica, where supplying thermal loads is important for the safety of base personnel, the lack of any waste heat from electricity generating devices is a major disadvantage. Any wind turbine installation at Scott Base must balance the positive results of generating electricity with a wind turbine with essentially an increased thermal load. Wind-diesel hybrid energy systems may include storage devices, dump load strategies or demand side management to minimise these disadvantages.

2.1.4. <u>Demand Side Management</u>

The growth of wind power has not been the only strategy put into place to battle worldwide fossil fuel dependence. Hydro generation and to a lesser extent geothermal plants have produced an abundance of cheap energy for remote countries such as New Zealand and provide a comfortable lifestyle within a safe and prosperous nation. To a lesser effect, photovoltaics and biogas are available for alternative power generation. However, changes in the way a system's current energy architecture works can be approached on either of its two sides: the supply side, or the demand side. The addition of a wind turbine to supplement an existing diesel generator set is a supply side solution to reducing fuel use. Demand side management programs seek to affect the amount and timing of the customer's use of electricity. For example, by modifying energy patterns of use to decrease peak demand, the need to add more generation capacity could be avoided.

Demand side management has both economic and environmental benefits. By eliminating the need for costly new generation capacity, the utility can provide the same service at a lower cost (Nilsson 2005). Shifting energy use to off-peak hours, scheduling loads when solar irradiation is high, reducing energy requirements overall, and using more efficient appliances and equipment, are all examples of demand side management (DSM) (Al-Alawi and Islam 2004). There are two main categories of DSM. The first category is direct load control. Direct load control is when a consumer's facility is controlled directly by the utility operator. In this case, the consumer agrees to the possibility that energy supply may not be available at all times. In reward for participating, the consumer is given price benefits. The other category of DSM is load control by the consumer. Load control by the consumer is when information is sent from the utility to the consumer. In this case the burden of adjusting demand falls with the customer. In reward for making a choice to increase or decrease demand based on information from the utility, consumers receive price benefits. Types of load control by the consumer are real time pricing, time of use rates, smart metering, and web based communication systems (Saini 2004). The application of demand side management techniques at Scott Base could have the potential to effect the optimal hybrid system configuration with reduced capital, fuel and maintenance costs.

2.2. Technical Importance

2.2.1. Environmental Issues

Perhaps the most important reason to decrease Scott Base fuel use is the benefits to the Antarctic environment. All activities undertaken on Antarctica are governed by the Antarctic Treaty. Issues with a potential to effect the environment such as the handling, use, and clean-up of diesel fuel fall under the Protocol on Environmental Protection, and instrument of the Antarctic Treaty (Poland et al. 2002). The Protocol on Environmental Protection exists to commit all parties to comprehensive protection of the Antarctic environment and ensures that the protection of the Antarctic environment is paramount during the planning and conducting of all Antarctic activities (Poland et al. 2002).

The Council of Managers of National Antarctic Programs reports 82 national research facilities currently in operation on Antarctica. 27 countries are represented with 45 of the 82 being inhabited all year round. The total capacity of the 82 stations currently in use is approximately 4000 in summer and 1000 in winter (Poland et al. 2002). The extremely cold temperatures create a heating demand that must be met for the safety of those living on the ice. The majority of the population's heating needs are met by diesel generators. The supply of fuel to those generators is a major environmental risk to Antarctica as well as a huge proportion of the costs associated with maintaining scientific stations in such remote areas. Ships involved in the re-supply of fuel to Antarctic stations typically carry a stations entire annual fuel needs in a single shipment. A large maritime oil spill is a significant threat (Poland et al. 2002). The following table is an outline of the large maritime and terrestrial oil spills of the recent past (Cripps and Shears 1997; Deprez 1999; Kennicutt 1993; Poland et al. 2002; Simpson et al. 1995).

Recent Maritime Spills
On 28 January 1989, the Argentine supply ship Bahia Paraiso grounded on shoals in Arthur Harbour off Anvers Island, about 2 km from the United State's Palmer Station. An estimated 600,000 litres of diesel fuel spilled into the surrounding bays causing slicks within the first few days that covered 100 square kilometers of sea surface (Poland et al. 2002). On 3 December 1987, the supply ship Nella Dan ran aground at Macquarie Island releasing about 270 000 litres of oil, mostly light marine diesel, into the sea (Simpson et al. 1995). Russian tanker reported to have lost 850,000 litres on Grande Terre, Iles Kerguelen (Poland et al. 2002).
Recent Land Spills
90 cubic meter leak at Casey station (Cripps and Priddle 1991). 250 square meter spill at Williams Field on the Ross Ice Shelf (Cripps and Priddle 1991). Diesel fuel spill (1000 litres) from Faraday Research Station, Galindez Island, Antarctica in March 1992 (Cripps and Shears 1997).

Figure 9: Recent Antarctic Fuel Spills

Only 0.4% of the Antarctic continent is not covered in permanent ice. These areas are essential habitat for much of the wildlife and plants of Antarctica. However, the ice free areas are also attract research bases. The delivery and handling of fuel oil at Antarctic research stations puts at risk terrestrial flora and fauna in the vicinity such as Adelie penguins which are found nowhere else in the world (Poland et al. 2002).

Beyond decreasing the risk of fuel spill, the mitigation of carbon dioxide emissions is another key environmental benefit to decreasing Scott Base fuel use. Greenhouse gases, such as carbon dioxide, have been increasing in concentration in the earth's atmosphere in the last 50-100 years. The increased concentration traps more heat in the earth's atmosphere and contributes to global climate change. The stabilisation of greenhouse gas concentrations in the atmosphere at levels that would prevent major climate change is an objective of the Kyoto Protocol, of which New Zealand is a participant.

In 2002, Scott Base produced over 1100 tonnes of carbon dioxide supporting a maximum of approximately 90 inhabitants (Hume 2006). Holding that relationship as typical of Antarctic research stations, approximately 50,000 tonnes of carbon dioxide is produced each year. 50,000 tonnes of carbon dioxide is equivalent to driving a standard car 3 billion kilometres; or if each of the 4000 scientists who occupy Antarctica during the summer were to drive 75,000 kilometres each. Decreasing fuel consumption at Scott Base may effect total Antarctic carbon dioxide emissions only slightly, but becoming a model for other stations could have a significant effect for the future.

*2.2.2. **Remote Area Electricity Generation***

Another important reason for the research is the potential benefits for other remote areas. Up to 80% of the world's population is located in rural areas. In these rural areas, more than one billion people lack the essential energy services to meet basic needs and improve economic status (Notton et al. 2001). Regarding rural electrification, there are two general methods: grid extension and the use of diesel generators. Including wind power in an energy system based on a diesel generator can lower the lifecycle cost of providing power to rural areas (Ackerman 2005).

Entering an era when diesel fuel will be more expensive and not always available in remote areas presents a problem. The effects of rising oil prices and limited supply will affect those areas running diesel generators without centrally transmitted electricity much sooner than first world nations. One way in which to minimise the effects of rising oil price and falling supply is by supplementing the diesel power generation with a wind turbine. Small diesel generators pair relatively well with wind turbines to produce a reliable electricity supply. A wind turbine with a diesel generator back-up may just become the standard power station for remote areas in the future. Therefore, understanding the most effective way of design and control of a wind-diesel hybrid power generation system is of the utmost importance. The trend in electricity consumption in New Zealand and around the world, illustrated in the following graphs, further underlines the importance of building the knowledge base in the wind-diesel field of study (BP 2005).

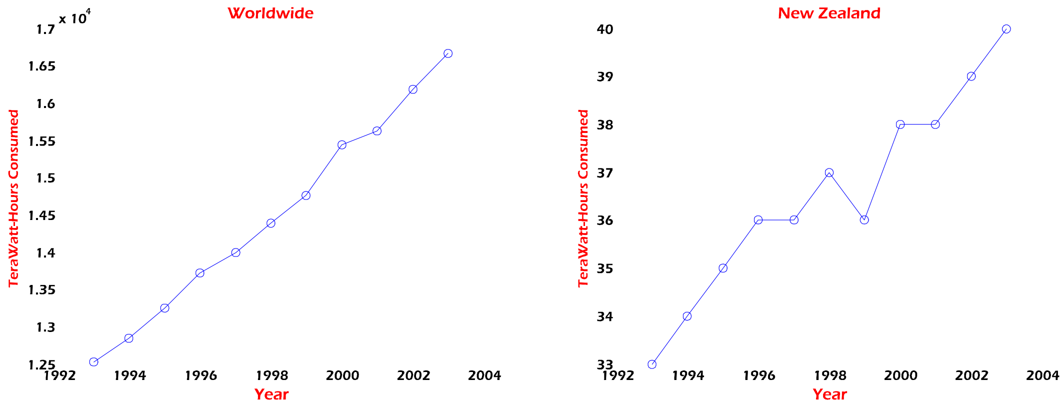


Figure 10: New Zealand & Worldwide Electricity Consumption

The rising demand for electricity places importance on perfecting the design of alternative generation techniques. Specifically for New Zealand, there are two large remote area communities currently utilising a diesel generator based power system. The communities located on Stewart Island and on the Chatham Islands are dependent on diesel fuel and could benefit significantly from added wind power. The high costs associated with transportation and purchase of diesel fuel makes the addition of wind power economically viable (Warman 1992).

2.2.3. Distributed Generation Compatibility

Directly related to remote area electrification is the concept of distributed generation. Borbely defines distributed generation (DG) as, "any small-scale electrical power generation technology that provides electric power at or near the load site; it is either interconnected to the distribution system, directly to the customer's facilities, or both" (Borbely 2001). DG is not a novel concept. Before central power stations and nationwide transmission grids were adopted due to economies of scale, all power generation was DG.

In New Zealand, DG has emerged as an attractive means of electricity generation. The improvement in technologies and the changing structure of the electricity industry have both contributed to a rising popularity (CAE 2003). The benefits of distributed generation for New Zealand are many. The addition of wind power into existing DG technologies will only further decrease reliance on fossil fuels. DG has the potential to reduce the supply-demand gap that is growing in New Zealand and could contribute up to 50% of the anticipated annual future electricity demand increases (CAE 2003).

While interest in DG for an industry or community is on the rise due to a reduction in overall energy costs, the most important aspect of adding wind power to DG systems is development of application specific engineering. The more DG systems that incorporate wind power are installed, the more engineering advances. In order to make any headway toward more localised power generation and higher renewable percentages, technologies such as wind-diesel hybrid energy systems must develop a solid background of successful installations and design experience.

2.2.4. New Zealand Policies and Regulations

After considering the benefits of the research to the Antarctic environment, DG compatability and remote areas worldwide, New Zealand policy issues need to be addressed. The high profile of Antarctica and the protection of its pristine environment are key to making Scott Base an example for other remote areas around New Zealand and the world to follow. Furthermore, decreasing the use of fossil fuels and increasing renewable energy generation are tasks that the New Zealand government is currently promoting. In the past five years the New Zealand government has introduced a number of specific energy and energy-related policies and strategies that contribute to their sustainable energy objectives (Hodgson 2004). These policies include the National Energy Efficiency and Conservation Strategy and the Climate Change Policy Package. The details of both are summarized in the New Zealand Government's *Sustainable Development Programme of Action for 2004*,

> New legislation in 2000 required the formation of a National Energy Efficiency and Conservation Strategy and made the Energy Efficiency and Conservation Authority (EECA) and independent statutory body. In 2001 the government produced the strategy, which sets targets for improving energy efficiency across five sectors: government, energy supply, industry , buildings and appliances, and transport.
>
> In 2002 the government introduced a comprehensive package of policies to address New Zealand's international obligations to tackle climate change. The policies are designed to enable New Zealand to meet its greenhouse gas reduction target under the Kyoto Protocol, which New Zealand ratified in December 2002, while promoting sustainable energy and protecting the nation's economic interests.

2.3.Societal Relevance

2.3.1. Sustainability

The overall relevance of the research project is quite ambitious. Alternative power generation, renewable energy and sustainable design are hot topics of the day. Finding a solution to an energy problem at Scott Base that entails decreasing fossil fuel use is a metaphor for greater problems throughout the world. Parallels can be drawn between Scott Base's fuel supply and the oil supplies of the world. The relevance of small scale energy projects to the issues of the greater world should not be hard to visualise. If Scott Base can decrease its fuel use without compromising it's current lifestyle, why not the rest of the world?

Sustainability has become the buzz world of the new millennium. Politicians, the media, and those who consider themselves environmentally conscious use the term "sustainability" freely.

Therefore, any discussion of the topic requires a definition. Sustainability can be defined as meeting the needs of today without compromising those of tomorrow. Increasingly, sustainability, and its Earth friendly connotations, are becoming goals of businesses, industries, and nations. Yet despite all the talk, are we closer to sustainability today than we were 35 years ago?

In 1972 results from a study concerned with the sustainability of the Earth's resources was published. The ground breaking project took place from 1970-1972 at the Massachusetts Institute of Technology and the results were published in a book called Limits to Growth. The project was the first of its kind and could be said to have brought the idea of sustainability to the attention of the world. The major focus of the research centered around predicted resource depletion for a certain world scenario and the resulting growth limit. The results showed that the expansion of population and physical capital result in the inability to support further growth in industrial output. As industry declines, so does the outputs of other key economic sectors such as food and services. The end of growth might occur as a collapse, defined as an uncontrolled decline in human welfare and population, and will no doubt be accompanied by conflict over scarce resources such as fresh water as well as ecological devastation (Meadows et al. 2004).

In 1972, Limits to Growth predicted continued growth until 2015. However, the project's vast goals to influence societies towards advancing technology and modifying patterns of resource use to decrease their ecological footprint has not been realised. Thirty years on, in an update to the original study, the research team proposes that human's ecological footprint has risen above the earth's carrying capacity. Amazingly, the crossing of earth's carrying capacity happened in the late 1970s. For the last 25 years human's have been operating above the carrying capacity of the earth (Meadows et al. 2004). Clearly it is time to address this serious issue (if it is not too late).

In 2004, New Zealand's Minister of Energy, Pete Hodgson, described the current situation in his Sustainable Development Program of Action:

> Energy sustains our lives. We consume it constantly, at work and at home, 24 hours a day. Yet many of us give little if any thought to where our energy comes from, how well or badly we are using it, where it will come from in the future. We enjoy and prosper from the services energy provides. We pay attention mainly when the bills arrive, or when supply disruptions remind us how much energy matters.
>
> This must change. Two huge challenges will force the development of a radically different energy system this century. One is the coming peak in global oil production, which will probably occur within our lifetimes or our children's. The other is global climate change. Both of these render our current energy habits unsustainable. Both compel us to think about the decline of the fossil fuel era, and what comes next.

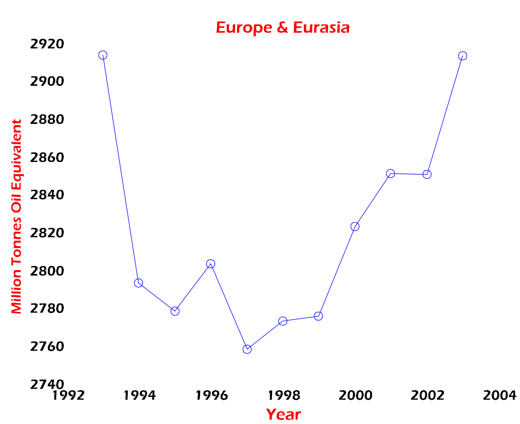
> The place to begin is not with supply, but with demand. We have been preoccupied with expanding supply to meet our growing energy needs, which have increased steadily with our population and our economy. But our energy needs are ours to control. By making smarter energy choices we can get more value from the energy we use, waste less and start building a cleaner, more dependable energy system.

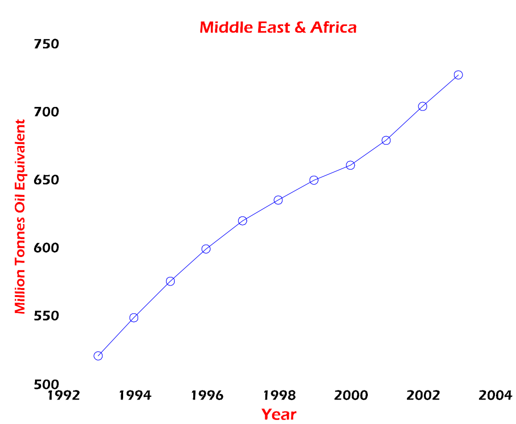
The use of renewable technologies plays a gigantic part in all scenarios of a sustainable future. Wind power's future prospects are high due to its ability to fit within the existing energy system. Grid connected wind farms, stand alone remote area turbines, as well as hybrid distributed generation systems all factor into a future that meets the needs of the current generation without compromising those of the next. When in place to decrease fuel consumption and not only to increase electricity supply, the addition of wind power to existing diesel generator based energy systems in remote areas as well as existing or proposed distributed generation pushes the world closer to sustainability.

2.3.2. Current Methods of Energy Production and the Future

Technical progress and development, from the most common perspective, has a direct relationship with the quantity of energy consumed (Ter-Gazarian 1994). Energy is a building block of modern society. Without an adequate and reliable supply of energy or a substantial change in energy consuming technologies and patterns of use, economic development and overall standard of living will decrease rapidly (Hinrichs and Kleinbach 2002).

In the last 50 years, global energy use has increased 500% (Hinrichs and Kleinbach 2002). Worldwide energy consumption was over 400 quadrillion BTU's in 2003; the equivalent of nearly 10 trillion tonnes of oil, or 73 trillion barrels. Of the total energy consumed in 2003, over one third comes from oil, one quarter each from coal and natural gas, with hydro and nuclear power contributing the majority of the remaining percentage. From 1993 to 2004, worldwide energy consumption increased 1.9% on average per year (BP 2005). The following graphs illustrate the trend in energy consumption around the globe (BP 2005).





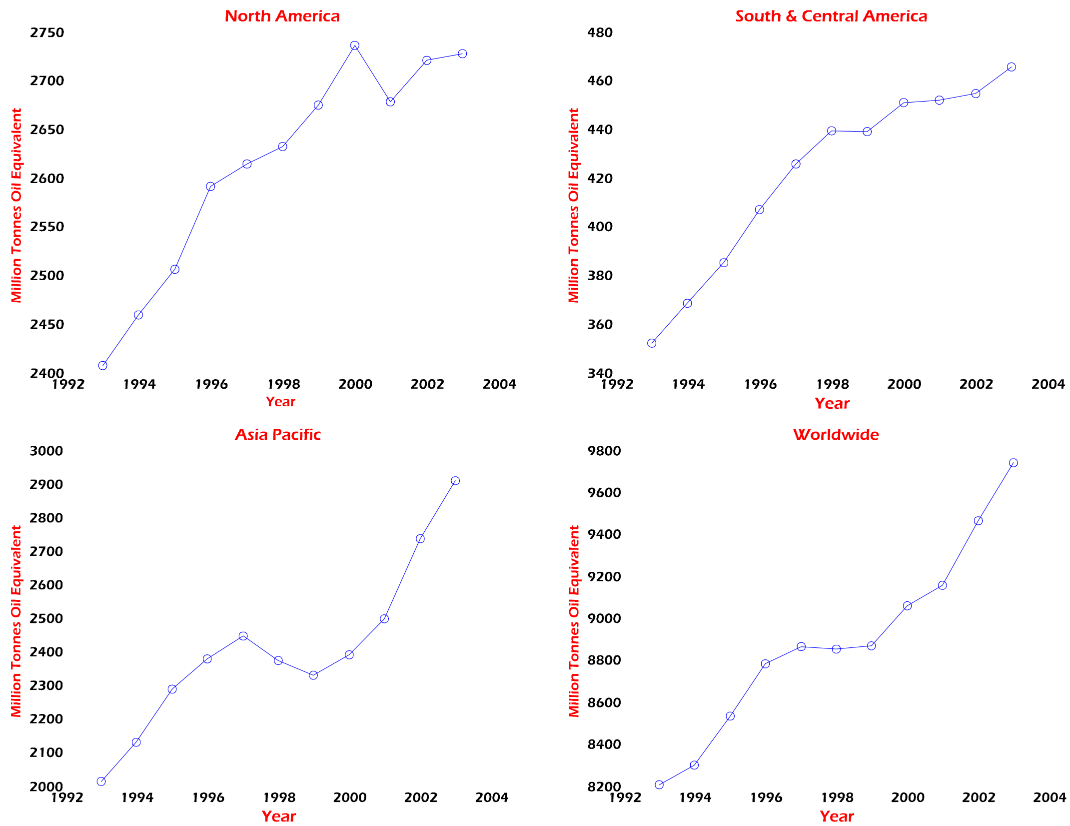


Figure 11: Worldwide Energy Consumption

The amount of energy consumed in New Zealand in 2003 was approximately 845 trillion Kilojoules; the equivalent of 18.4 million tonnes of oil, or 138 million barrels. In 2003, New Zealand's primary energy supply fell 4.0%, due to the decreasing yields of indigenous oil, gas, geothermal and hydro production (Hodgson 2004). Of the total energy consumed in New Zealand, 26% is used as electricity, nearly double the world average of 16%. Energy demand in New Zealand increases by 2.0% on average every year (Hodgson 2004) as illustrated by the following graph.

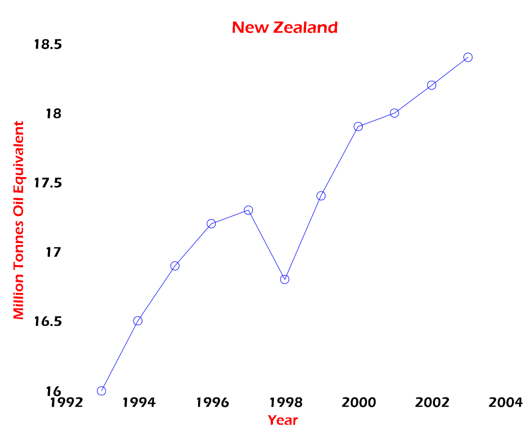


Figure 12: New Zealand Energy Consumption

Although the research project is meant to be used as a template for other remote area energy systems around the globe, the focus for Scott Base is on Aviation Turbine Fuel (AN8). Scott Base's current energy production is realised through the conversion of AN8 fuel oil in diesel generators. The energy system operates with a single input, AN8. The dependence on this fossil fuel ties Scott Base's future to that of global oil supplies and therefore the peak oil debate.

A peak in global oil production is inevitable. The peak oil debate is not about if it will happen but rather when it will happen. The answer to when global oil production will peak has enormous ramifications. The consequences of a declining world oil supply for remote locations as well as the rest of the world range from dire to utopia. From the collapse of world economies to the emergence of a sustainable energy supply, the speculations are hard to digest. There are two ramifications that are clear and hold specific importance for Scott Base: 1) oil will increase in price, and 2) the potential for oil shortages will increase. What this means for Scott Base is an urgency to decrease its fossil fuel dependence. How much time Scott Base and the rest of the world has is a heavily debated topic. Several experts in the field have ventured predictions concerning the timeframe of peak oil production.

> "The supply of oil in the ground is not infinite. Someday, annual world crude oil production has to reach a peak and start to decline. It is my opinion that the peak will occur in late 2005 or in the first few months of 2006". (Deffeyes 2005)

> "Using several different techniques to estimate the current reserves of conventional oil and the amount still left to be discovered, we conclude that the decline will begin before 2010." (Campbell and Laherrere 1998)

> "…when global oil demand will exceed the world's production will fall somewhere between 2000-2010, and may occur very suddenly due to unpredictable political events. This is within the lifetimes of most people now alive. The foreseeable energy crisis will affect everyone on earth." (Ivanhoe and Hubbert 1997)

> "Ultimately, we will know for sure when global oil production peaks only after the fact: one year we will notice that gasoline prices have been climbing at a rapid pace, and we will look back on the previous few years' petroleum production figures and note a downward slope. It is possible (as Colin Campbell has suggested) that the first global production peak has already happened – in the fall of 2000 – and that the next decade will be a "plateau" period, in which recurring economic recessions will result in lowered energy demand, which will in turn temporarily mask the underlying depletion trend." (Heinberg 2003)

2.4. Background Summary

2.4.1. <u>Summary</u>

New Zealand's Scott Base is a remote research station located on the harsh coastline of Antarctica. Eight inter-connected buildings comprise the core of the base with electricity and heat provided by diesel generators burning Aviation Turbine Fuel (AN8). The current power system is secure and reliable; however, the logistics of transporting nearly 400,000 litres of fuel each year to Scott Base is expensive and compromises the pristine environment of the area. New turbines that can withstand extremely cold temperatures and harness the abundant wind resource make wind power on Antarctica a legitimate candidate to increase sustainability and decrease fossil fuel dependence at Scott Base.

At Scott Base, all loads are met by the conversion of fuel oil through internal combustion generators. Many of the loads are required for staff wellbeing and for performance of tasks. Other loads may be optional or time-flexible, meaning they could be postponed or brought forward in time to match energy availability. The design and integration of a wind turbine into the existing energy system will add renewable energy to the supply side. However, the maximum utilization of available wind energy can only be achieved through integration with the demand side.

The importance of the project is not isolated to Scott Base. The current uncertainties about global oil supplies and the timeframe of peak oil production has revealed total fossil fuel dependence as pure ignorance. Apart from the protection of the Antarctic environment, the New Zealand government has put forward a number of policies to take steps toward a more sustainable New Zealand energy system. Extending these policies to Scott Base is important to raise awareness of the energy supply issues that New Zealand and the world will one day face. The benefits of wind-diesel technology are more than economic for Antarctic research stations. Furthermore, a station such as Scott Base is an ideal test bed for wind-diesel technology to mature while still remaining highly effective.

3. STATE OF THE ART

What is known about the thesis problem and the methods that have been used to solve similar problems in the past are the major topics of chapter three. The approach taken was to break the problem of decreasing Scott Base fuel consumption down into components and subsystems. Research into each of the sub-topics, 1) hybrid energy systems 2) diesel generators 3) wind turbines 4) energy storage technologies and 5) demand side management, and their potential roles on Antarctica, make up the state of the art of the thesis. Methods of solving energy systems problems are also outlined, with particular attention paid toward computer simulation programs.

3.1. What is known about decreasing Scott Base fuel consumption?

3.1.1. Hybrid Energy Systems

3.1.1.1. Configurations

A power system with electricity production from both a diesel generator and a wind turbine is more accurately described as a "hybrid power system" or "hybrid energy system". Hybrid power systems incorporate more than one piece of equipment for electricity production as well as storage, power conditioning components, and system controls. The classic hybrid system is based on a fossil fuel engine generator, energy storage in the form of batteries and a power converter (Baring-Gould et al. 2002). The configuration of the system can vary based on the system size. Small systems usually focus on a DC bus bar and include small renewable generation devices and enough storage for a few days. The production of AC power comes from a power converter or diesel generator. Large systems focus on the AC bus bar. These systems utilize larger equipment and storage in order to cover fluctuations in power production (Baring-Gould et al. 2002). Hybrid systems installed in remote communities follow these guidelines as well. In all cases, the overall efficiency and expected maintenance costs of the fossil fuel engine generator will depend on the number of starts and stops it experiences. A more detailed description is as follows:

Direct current based hybrid system for small remote communities:

For small remote communities that provide less than a few hundred kilowatt-hours per day, a battery bank is the main device of power supply. The batteries operate as a direct current bus and central connection point. Small wind turbines or photovoltaic convert available resources to electric power that is rectified to DC to charge the battery bank. A diesel generator is available to charge the battery bank when wind and solar power availability drops below demand. The

AC load demand is met by inverting the DC power supplied from the battery bank (Ackerman 2005).

Alternating current based hybrid system for small remote communities:

A new development for small remote communities has been the deployment of smart power electronics. Utilising an AC distribution grid and a smart inverter, the system's generation equipment can meet the AC load demand without first charging batteries. In this type of system, a wind turbine, photovoltaic array, a diesel generator, or a combination of the three, can meet the AC load with the incorporation of improved power electronics and control. The benefits are that more generation equipment can be added as needed and at greater distances without much modification to the overall system structure. Disadvantages include lower efficiencies if battery storage is necessary, high costs, and the use of technologies that would be difficult to service in remote areas (Ackerman 2005).

3.1.1.2. Sizing

Thomas Ackerman in *Wind Power in Power Systems*, defines the role of the wind-diesel hybrid energy system engineer and the essence of this research project.

> "A technically effective wind-diesel system supplies firm power, using wind power to reduce fuel consumption while maintaining acceptable power quality. In order to be economically viable, the investment in the extra equipment that is needed to incorporate wind power, including the wind turbines themselves, must be recouped by the value of the fuel savings and other benefits. As the ratio of the installed wind capacity to the system load increases, the required equipment needed to maintain a stable AC grid also increases, forcing an optimum amount of wind power in a given system. This optimum is defined by limits given by the level of technology used in the system, the complexity of the layout chosen and the power quality required by the user. For this reason the optimal design must be based on careful analysis, not simply the maximum amount of wind energy possible."

The role of the engineer in the design of hybrid power systems is in the sizing of the individual components and in particular the wind turbine, diesel generator if nonexistent and storage capacity. When considering the addition of a wind turbine to an existing energy system, two overlapping issues strongly influence system design. The first is the amount of wind penetration and the second is power quality.

Wind Penetration

When sizing hybrid system components, and in particular a wind turbine, wind power penetration is a major consideration dictating system design. Within this consideration are two slightly different definitions: instantaneous wind power penetration and average wind power penetration. Instantaneous wind power penetration is the ratio of the power output from the wind turbine to the primary electric load at any specific point in time. Instantaneous penetration is a technical measure that determines system layout and components. The average wind power penetration is the ratio of the wind energy output over the average primary electric load. Average penetration is generally used as an economic measure (Ackerman 2005). There are three categories of wind power penetration, all based on the average wind power penetration definition.

Low Penetration:

Low penetration systems can be those defined as having less than 20% average wind power penetration and less than 50% instantaneous penetration. There have been many low penetration systems installed worldwide ranging in size from very small to very large. In such systems, the additional wind turbine is treated the same as any other added generation device due to the relatively low amount of added generation capacity. Control is trivial and is left to the internal controls of the other generation equipment, specifically any diesel generators in the system. As diesel gensets are able to cover rapid changes in system load, they are also able to meet the requirements of a variable supply of wind power to the system (Baring-Gould et al. 2002).

Medium Penetration:

Medium penetration systems operate with average wind power penetrations between 20% and 50% and instantaneous penetration levels between 50% and 100%. Options exist to maintain high power quality when average wind penetration levels are under 50% and instantaneous penetration levels are under 100%. The closer the hybrid system comes to these limits, the harder it is for the diesel generator(s) to achieve an adequate power balance. Additional equipment and controls are often necessary due to the issue of power balance, thus power quality. Power reduction capabilities of the wind turbine controller, secondary loads to handle excess generated electricity, capacitor banks to correct power factor, or advanced power electronics all might be called for. The complexity increases costs and the amount of necessary supervision (Baring-Gould et al. 2002).

High Penetration:

High penetration systems are defined as systems with average wind power penetrations above 50% and instantaneous penetration levels between 100% and 400%. Although not yet considered a mature technology, these systems may very well be the future of wind-diesel systems. There are high penetration systems in operation today, most notably on Antarctica at Australia's Mawson station. These systems require equipment installed so that the diesel generator can be shut down completely. Advanced control systems, along with short term storage, load banks, and a variety of controllable secondary loads are used to ensure power quality in a functioning high penetration system (Baring-Gould et al. 2002).

Power Quality

The second major issue influencing hybrid power system design is power quality. The ideal characteristic of any power supply is a voltage with constant frequency and amplitude. However, any deviation between power generation and demand causes frequency deviations. Most power systems, including the existing Scott Base power system, deliver three phase power. The goal of three phase power systems is to deliver as symmetric three phase power as possible. In a perfectly symmetric system, the voltage of all three phases will have the same amplitude and between each phase will be a 120 degree phase shift (Ackerman 2005).

There are four possible negative effects of adding wind turbines in electrical supply systems and all have acceptable and unacceptable levels (Ackerman 2005). A description of each of the four potential negative effects toward power quality due to wind turbines is as follows,

1. Slow voltage variations
   Changes to the voltage amplitude based on how the energy system is meeting demand. The two cases that result in the largest deviation of voltage amplitude from desired levels are 1) maximum consumer load with zero wind power production and 2) minimum consumer load with maximum wind power production.
2. Flicker
   Rapid voltage changes can result in flicker and are most likely caused by changes in load or system switching operations. However, wind turbines can emit flicker due to their switching operations during start-up or during rapid power output (wind) changes.
3. Voltage Dip
   During start-up of a wind turbine, a sudden reduction in voltage can occur with recovery occurring after a few seconds.
4. Harmonics
   Some loads distort the voltage waveform to a level that causes overheating of certain electrical components and can result in electronic equipment malfunctioning. The distortion of the voltage waveform is known as a harmonic voltage. Electronic converters are one of the loads that contribute to harmonic voltages. (Ackerman 2005)

Reactive Power

Consider power as a vector. Active power, that consumed by all electrical appliances is the x-direction component of the power vector. Reactive power is the y-direction of the power vector. Reactive power depends on the phase shift between voltage and current. Reactive power equals the product of the active power and the sine of the phase shift divided by the cosine of the phase shift (Ackerman 2005). The important concept to understand is that in an electrical generation and transmission system reactive power must be balanced. In regards to everything that is connected to an electricity transmission grid, both electrical loads and generation equipment, certain devices consume reactive power and others produce reactive power. Power electronics are typically used to facilitate the reactive power balance.

Depending on the style of generator that a wind turbine employs, reactive power can be an issue requiring attention during the design of wind-diesel hybrid energy systems. An asynchronous generator consumes reactive power at uncontrollable levels. Shunt capacitors are typically used to fully or partly compensate for this consumption by producing reactive power and decreasing phase shift. This technique is called phase compensation. For synchronous generator and converters, it is possible to control reactive power consumption and therefore control voltage (Ackerman 2005).

Power Electronics

Power electronics make it possible for variable speed turbines, the current state of the art in turbine design, to control frequency and thus power quality. Without frequency control, wind generated power would not be useful as most energy systems have specific frequency and voltage requirements. Power electronics are devices that improve wind turbine performance. These typically include soft starters, capacitor banks and frequency controllers that include rectifiers and inverters (Ackerman 2005). A description of each of the major power electronic devices regarding wind turbines is as follows,

1. Soft Starter
   A device necessary for fixed speed wind turbines to limit disturbances to the grid during initial start-up.
2. Capacitor Bank (Shunt Capacitors)
   A device that supplies reactive power to the wind turbine's generator thus reducing the demand of reactive power by the turbine from the transmission grid.
3. Frequency Controller
   A device that utilises a rectifier, a device using electronic switches to convert alternating current to direct current, and an inverter, a device using electronic switches to convert direct current to alternating current while controlling voltage and frequency, to adjust a generator's frequency and voltage to specific requirements. (Ackerman 2005)

Acceptable Levels of Power Quality

There are three major power quality measurements to monitor in hybrid energy systems: 1) total harmonic distortion generated by the associated power electronics such as an inverter, 2) transient voltage sags caused by system disturbances or faults and 3) periodic voltage flicker (Patel). The amount of wind power capacity that can be installed is a function of the size of the electrical system and the power quality considerations. Regarding wind farms and utility size electrical grids, a rough rule of thumb to control power quality has been to keep the amount of wind power capacity in megawatts less than the grid line voltage in kilovolts. For smaller systems, 10%-20% of this capacity is recommended (Patel 1999). Typically, the higher the instantaneous wind penetration, the greater the potential for power fluctuations and the more electronic power conditioning devices necessary to ensure high-quality electric power (Ackerman 2005).

Determining the level of slow voltage variations in any hybrid energy system is accomplished via measurements at the main busbar. Based on instantaneous true root mean square values of busbar voltage, estimates on slow voltage variations are possible (Lundsager et al. 2001). Two cases present the greatest voltage amplitudes. The first case is when wind turbine power generation is at its lowest and consumer demand is at its highest. The second case is when wind power generation is at its highest and consumer demand is at its lowest (Tande 2002). The standard acceptable level of deviation in voltage amplitude is 10% (Lundsager et al. 2001). Typically, the case when wind power generation is high and consumer demand is low presents the greatest deviation from optimal voltage and can be represented by a maximum instantaneous wind penetration value. An energy system is not fully secure when its maximum instantaneous wind penetration is above the level predicted to produce (at certain times) voltage variations beyond the 10% standard. Each energy system is different and its maximum instantaneous wind penetration level is determined by the consumer load and power generation devices. Busbar measurements are required to predict specific power quality. However, in the case of Scott Base, an estimate can be made based on past studies of other remote area wind-diesel hybrid energy systems and the current prevailing knowledge of the experts in the field (Ackerman 2005).

3.1.1.3. Case Studies

An existing diesel generator based energy system, providing for a remote area community, is a good prospect for the addition of renewable generation technologies. The suitability of diesel generators for start-stop operation matches quite well with photovoltaics and wind turbines which provide and intermittent and variable flow of electricity. A remote area diesel power system is typically characterized by the following:

- A very small number of operating diesel gensets, often only one.
- The control of the system is quite simple, often just the governors and voltage regulators of the diesel generator(s).
- There are very little or no resources for maintenance or replacement of the genset(s).
- Fuel is expensive, and sometimes prone to delivery and storage problems. (Lundsager et al. 2001)

Recent reviews have identified approximately 100 documented wind-diesel installations worldwide (Ackerman 2005; Lundsager et al. 2001). The following two tables, adapted from those reviews, detail the most established wind-diesel hybrid energy system installations worldwide and research laboratories with wind-diesel systems under observation and study.

Site	Region	Report Period	Diesel (kW)	Wind Turbine (kW)	Wind Penetration (%)
Extreme Climate Locations					
Wales	Alaska, USA	1995-2003	411	2 x 65	70
St. Paul	Alaska, USA	1999	300	1 x 225	-
Mawson St.	Antarctica	2005	480	2 x 300	65
Island Installations					
Sal	Cape Verde	1994-2001	2820	2 x 300	14
Mindelo	Cape Verde	1994-2001	11200	3 x 300	14
Cape Clear	Ireland	1987-1990	72	2 x 30	70 (peak)
Rathlin Island	Ireland	1992-2001	260	3 x 33	70
Kythnos Island	Greece	1995-2001	2774	5 x 33 + 1 x 150	-
Lemnos Island	Greece	1995-2005	10400	8 x 55 + 7 x 100	-
Dachen Island	China	1989-2001	10440	3 x 55 + 2 x 20	15
Fuerteventura	Canary Is.	1992-2001	150	1 x 225	-
Foula	Shetland Is.	1990-2001	28	1 x 60	70
Froya Island	Norway	1992-1996	50	1 x 55	94
Other					
La Desirade	Guadeloupe	1993-2001	880	12 x 12	40 (peak)
Marsabit	Kenya	1988-2001	300	1 x 150	46
Alto Baguales	Chile	2001	13000	3 x 660	16
Denham	W. Australia	2000	1970	3 x 230	50

Figure 13: Wind-Diesel Hybrid Energy System Installations

Laboratory	Country	Report Period	Diesel (kW)	Wind Turbines (kW)	Notes
NREL	USA	1996	120	1 x 20 1 x 75 1 x 20 1 x 10 1 x 50	Multiple units, AC & DC buses, battery storage
CRES	Greece	1995	45	1 x 30	PC based control system
DEWI	Germany	1992	30	1 x 50 1 x 30	
RAL	UK	1991	85	1 x 45	Microcomputer controller, PC data logger and flywheel storage
EFI	Norway	1989	50	2 x 55	Microcomputer controller, data acquisition system and wind turbine simulator
RERL-UMass	USA	1989	15	1 x 15	PC based control system, data acquisition system and rotary converter
IREQ	Canada	1986	35	1 x 50 1 x 30	Rotary condenser
AWTS	Canada	1985	100	1 x 40 1 x 35 1 x 65 1 x 80 1 x 50	Rotary condenser
RISO	Denmark	1984	30	1 x 55	PC based control system, data acquisition system and rotary condenser

Figure 14: Wind-Diesel Hybrid Energy System Laboratories

Of those systems outlined above, few are appropriate for comparison with a potential Scott Base wind-diesel hybrid power system. However, the three installations that fall under the extreme climate locations subheading all contain valuable information when considering the design of a Scott Base hybrid system. Therefore, Wales, St. Paul, and Mawson Station are all detailed further with particular close attention paid to the Mawson Station installation due to its location on Antarctica.

Wales, Alaska

The Alaska Energy Authority (AEA), in association with the National Renewable Energy Laboratory (NREL) and Kotzebue Electric Association began a collaboration in 1995 to reduce the cost of rural power generation in remote Alaskan communities. The solution to the problem was to implement a high penetration wind-diesel hybrid energy system. The project was intended to show that the technology could work and be highly effective as well a pilot for other remote Alaskan communities.

Wales, Alaska is home to approximately 160 inhabitants, and has an average electric load of 70kW. The hybrid energy system designed for Wales included: three diesel generators with a combined power of 411kW, two 65kW Atlantic Orient Corporation 15/50 wind turbines and a 130Ah nickel cadmium battery bank. Power control electronics were built and supplied by NREL and contributed to a hybrid power system designed to minimise diesel fuel use while delivering quality power to the community. The system also uses excess wind power to heat hot water for home heating use.

The system is expected to have an average wind penetration of 70%. This high penetration will translate to a fuel savings of 45%. In an 18 day test period in August of 2002, a lower wind speed month, 41% of the consumer load was met with wind power. In addition, 10,000kWh of excess electricity was supplied to heat hot water for home heating use. This represents a heating fuel savings of approximately 450 litres (Ackerman 2005; Baring-Gould et al. 2002).

St. Paul, Alaska

St. Paul is an island in the Bering Sea. The island is home to an airport and industrial complex owned by the Tanadgusix Corporation (TDX). TDX with the help of Northern Power Systems, installed a high penetration wind-diesel hybrid energy system to reduce the overall energy costs of the complex. The main components of the system include: two 150kW diesel generators, one 225kW Vestas V27 wind turbine, a 27,000 litre insulated hot water tank, a synchronous condenser and a microprocessor based control system.

The average electric load is 85kW. When wind power exceeds the electric demand, the excess power is diverted to heating hot water. The heating of the complex is a major consumer of diesel fuel and the sizing of the wind turbine above and beyond the average complex electric load was intentional in order to save on heating costs. The wind-diesel hybrid energy system installed on St. Paul cost approximately $1,200,000 (USD). Since installation in 1999, the system has saved $200,000 (USD) per year in electric utility charges and $50,000 (USD) in diesel heating fuel (Ackerman 2005; Baring-Gould et al. 2002).

Mawson Station, Antarctica

Australia operates four Antarctic research stations. Mawson Station is one of the three that are spread out along 1800 nautical miles of Antarctica's eastern coast. The Australian research stations follow patterns much like Scott Base; low populations during the winter months swelling to over 100 during the summer. All supplies are brought by ship in the ice free summer months (Brown et al.). The energy systems of all the bases are designed to provide reliable, safe and efficient electrical and thermal energy necessary to provide suitable comfort conditions and power those services associated with an array of scientific programs (Brown et al.).

Before the addition of the wind farm, the Mawson Station power house contained four 480kW Caterpillar 3306 diesel generators. Typically, two or three of these generators were operating at all times. The following annual averages were derived from data collected at Mawson Station over a four year period in the mid 1990s.

- Fuel Use (Generators) = 630,000 litres
- Fuel Use (Boilers) = 135,500 litres
- Electrical Energy Production = 2267.5 MWh (Brown et al.)

The main drivers behind the addition of wind turbines to the Mawson Station energy system were much the same as other remote area locations. Primary is the cost of shipping the fuel nearly 5500 kms from Australia to Antarctica. Secondary reasons are reduced CO2 emissions and the reduced risk of fuel spillage (Brown et al.). Wind energy resources on Antarctica are substantial. Data collected at Mawson station from 1990-1994 is summarized below.

- Maximum wind speed = 39.1 m/s
- Maximum wind gust = 68.9 m/s
- Mean wind speed = 11.15 m/s
- Standard deviation = 6.95 m/s (Brown et al.)

The wind turbine requirements mirrored those of most extreme cold weather sites. The most desirable turbines were those incorporating direct drive technology, which replaces the need for a gear box, and a blade pitching mechanism to control speed and therefore power output. Modified Enercon E-30 wind turbines were selected as the most appropriate machines for the Mawson Station hybrid energy system project. Further wind turbine modifications included extra insulation and a lower than usual hub height. Two turbines were erected, each with a 60m3 concrete foundation. The E-30s have a cut-in wind speed of 2.5m/s, cut-out speed of between 28-34 m/s, and a nominal speed of 12m/s. The hub heights are at 33 m and the blade diameter is 30 m. The capital cost is reported at approximately $6 Million (Australian Antarctic Division 2006). The turbines are rated at 300kW (Magill 2003)

The wind farm installation at Mawson Station was the first large scale wind power project with the goal of reducing diesel fuel consumption on Antarctica. On average, the turbines have been able to supply 65% of the station's needs and have reduced shipments of 700,000 litres of diesel fuel from once a year to once every four to five years. Furthermore, CO2 emissions have been reduced by a third, approximately 600 tonnes per year (Pyper 2003).

3.1.2. ***Antarctic Diesel Generators***

In the world of off-grid electrification, combustion engines are king. Of the world's 3000 GW of installed electric generating capacity, stationary reciprocating engines account for 146 GW. The advantages of combustion engine power generation include low installed cost, high shaft efficiency, suitable for start-stop operation, and high exhaust heat for other uses. Also, engines and parts are readily available, as well as sales and technical support (Borbely 2001). The following schematic illustrates the features of a diesel-electric plant.

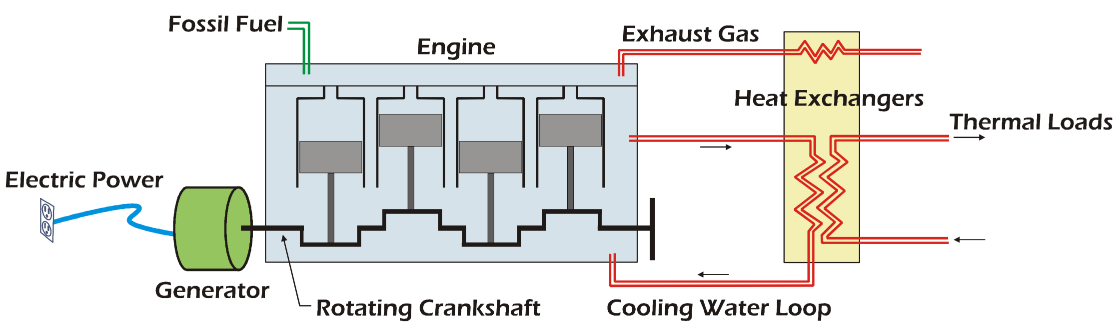


Figure 15: Diesel-Electric Plant Schematic

The Caterpillar 3406 diesel generator sets operating on Scott Base are considered a mature prime moving technology (Borbely 2001). These internal combustion engines convert heat from combustion into work via the rotation of a shaft. In this case, the shaft is directly coupled to a generator and produces electricity. The CAT gensets are four stroke compression-ignited engines. The four cycles (intake, compression, power, and exhaust) are completed in every two rotations of the crankshaft producing a power stroke every other turn of the shaft. Diesel engines do not have sparkplugs nor the associated coils and distributors that contribute to the dependability issues for spark ignited engines, rather they rely on the fuel to ignite itself. The ignition of the fuel is due to an increase in pressure and temperature within the piston chamber.

Engines that are directly coupled to generators to produce electricity are generally run at speeds defined by the frequency of the electricity grid being supplied. The relationship is defined by the following equation.

$$\text{Shaft Rotation Rate (rpm)} = \frac{\text{1 Revolution}}{(\text{Poles/2})\,\text{Cycles}} * \frac{(\text{frequency})\,\text{Cycles}}{\text{seconds}} * \frac{\text{60 seconds}}{\text{minute}} \qquad (1)$$

In the case of Scott Base, the gensets operate to provide a frequency of 50Hz. Reorganizing equation (1), the frequency is equal to the product of the RPM and the number of poles on the generator divided by 120. Scott Base gensets run at 1500 revolutions per minute (Borbely 2001; Hume 2006). Other system components that are typical of diesel generators and the system installed at Scott Base include: air filtration, lubrication system, cooling system and an excess heat recovery system.

The excess heat recovery system at Scott Base is a major component of the powerhouse. Approximately one third of the energy content of the fuel in a diesel genset is exhausted or radiated from the engine (Borbely 2001). The recovery of this energy in order to heat water that is pumped throughout Scott Base to increase the level of base comfort is not only useful, but absolutely crucial. The powerhouse contains two oil fired boilers for back-up in case additional heat is necessary, however, the majority of the thermal energy used at Scott Base is recovered from the gensets. This is accomplished through marine manifolds that facilitate thermal recovery through heat exchangers.

3.1.3. Wind Turbine Technology

3.1.3.1. An Overview

A wind turbine is made up of a number of components. The main components being the tower, blades, rotor, gearing, generator, speed sensors and control devices. Modern wind turbines also include power electronics to condition the electricity generated as well as a computer based control system. The following figure details the configuration of components in a typical wind turbine.

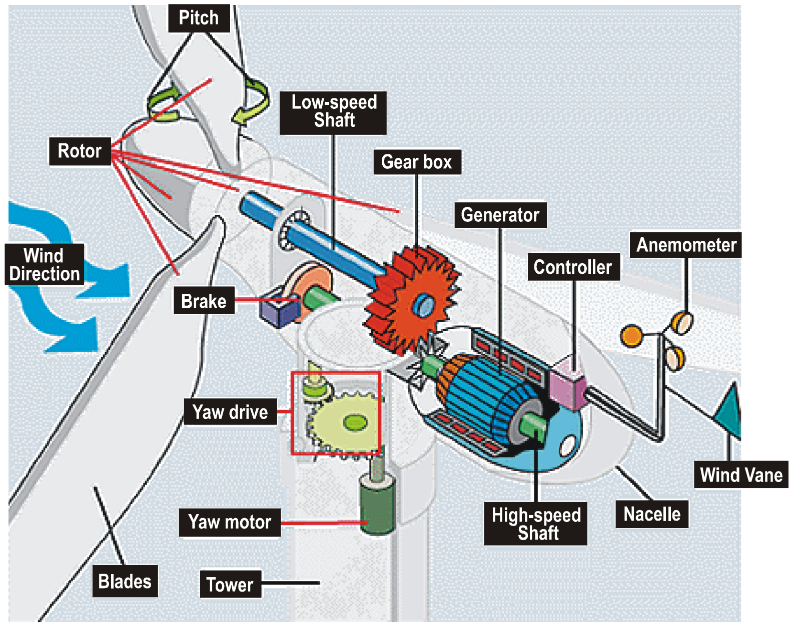


Figure 16: Typical Wind Turbine Schematic

Modern wind turbines function on aerodynamic lift. Airfoils catch the wind and produce a drag force and a lift force. The lift force is perpendicular to the wind direction. Using the leverage of the rotor, the lift force causes the torque that spins the blades (Ackerman 2005).

Modern turbines that utilize aerodynamic lift can be subdivided into two categories, vertical axis and horizontal axis turbines. Vertical axis turbines, for example Darrieus turbines, use two symmetrical airfoils attached to the top and near the base of a vertical shaft. The airfoils are curved away from the shaft to create an oval like shape and as they spin they turn a rotor at ground level. Benefits to a vertical axis turbine are that they operate independently of the wind direction and the main machinery can be placed at ground level. Research and development of vertical axis turbines has nearly stopped worldwide since the late 1980s.

Horizontal axis turbines currently dominate installations worldwide. The horizontal axis turbine is comprised of a tower, blades and nacelle. The nacelle contains the generator, rotor and gearbox if required. The nacelle sits atop the tower and the blades are fixed to the rotor in a propeller like fashion. Horizontal axis turbines come in many varieties. Two and three bladed turbines typically are for electricity generation while turbines with twenty or more blades are for mechanical work such as pumping. Three bladed horizontal axis turbines currently dominate the market for electricity generation utilizing the wind. The different designs of wind turbines for electricity generation follow a design philosophy that seeks to manage loads mechanically and/or electrically. The physics of extracting power from the wind explain the various designs available and their corresponding advantages and disadvantages (Ackerman 2005; Patel 1999).

3.1.3.2. The Physics Part 1

Step One

The basis of extracting power from wind begins with the relationship that kinetic energy (KE) in air is one half the product of the mass (m) and velocity (V) of that air.

$$KE = \frac{1}{2} * m * V^2 \quad (2)$$

To find the power (P) available in the air stream, the mass within the kinetic energy equation must be substituted with the mass flow rate of the air.

$$P = \frac{1}{2} * (\text{Mass Flow Rate}) * V^2 \quad (3)$$

Where:

P = mechanical power in moving air (watts)
V = velocity of air (meters / second)

The mass flow rate is equal to the product of the air's density, the area swept by the rotor blades and the air's velocity.

$$\text{Mass Flow Rate} = \rho * A * V \quad (4)$$

Where:

$$\rho = \frac{p}{R * T} \quad (5)$$

With*:*

p = air pressure (kilograms / meters cubed)
R = gas constant
T = temperature (absolute scale)
A = area swept by rotor blades (meters squared)
ρ = air density (kilograms / meters cubed)

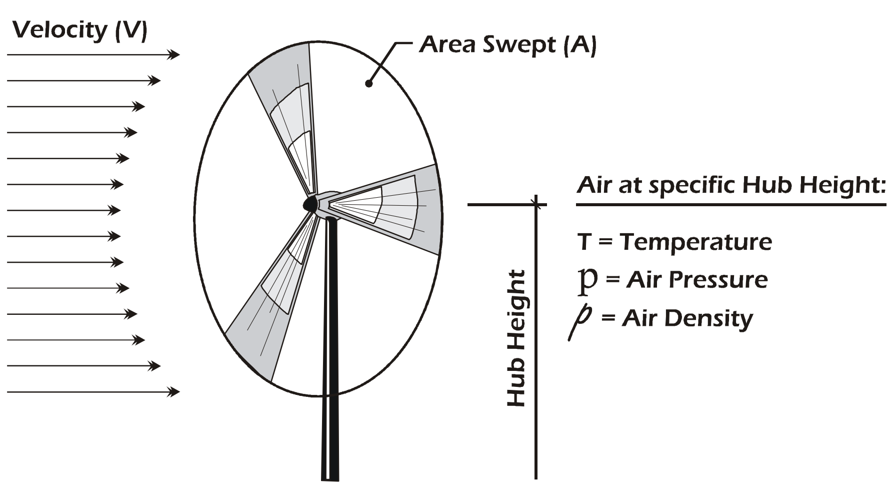


Figure 17: Wind Power Variables

Therefore, the power equation is achieved by substituting equation (5) into equation (4) and then equation (4) into equation (3).

$$P = \frac{1}{2} * \rho * A * V^3 \qquad (6)$$

Step Two

In order to find the power extracted by the rotor blades of a wind turbine, the difference between the upstream wind power and the downstream wind power is calculated. The mass flow rate for the average wind speed is required.

$$\text{Mass Flow Rate}_R = \rho * A * \frac{V_U + V_D}{2} \qquad (7)$$

Where:

V_U = upstream velocity of air (meters / second)
V_D = downstream velocity of air (meters / second)

Substituting equation (7) into equation (3) with velocity as the difference of the square of the upstream air velocity and the square of the downstream air velocity results in the following rotor power equation.

$$P_R = \frac{1}{2} * \left(\rho * A * \frac{V_U + V_D}{2} \right) * (V_U^2 - V_D^2) \qquad (8)$$

Equation (8) can be rewritten as,

$$P_R = \frac{1}{2} * \rho * A * V^3 * \frac{\left[1 + \frac{V_D}{V_U}\right] * \left[1 - \left(\frac{V_D}{V_U}\right)^2\right]}{2} \qquad (9)$$

In order to simplify the power equation above, a variable is introduced to represent the fraction of the upstream wind power that is captured by the rotor blades. This variable is called the power coefficient and is as follows,

$$C_P = \frac{\left[1 + \frac{V_D}{V_U}\right] * \left[1 - \left(\frac{V_D}{V_U}\right)^2\right]}{2} \qquad (10)$$

The power coefficient has a maximum value of .59 when the downstream air velocity is one third that of the upstream air velocity. In practical designs, power coefficient values do not exceed .5 (Patel 1999).

Substituting equation (10) into equation (9) results in the following rotor power equation,

$$P_R = \frac{1}{2} * \rho * A * V^3 * C_P \qquad (11)$$

This power equation is the basis of all wind farm power predictions.

3.1.3.3. The Mechanics Part 1

Control

Customarily there are a range of wind speeds over which a given wind turbine can operate. The cut-in wind speed is when the turbine begins to generate power. At any speeds below the cut-in speed, generating power is counter productive. The cut-out wind speed is when the turbine has reached its safety limits and stops generating power. The nominal speed is that wind speed that is ideal for the given wind turbine to produce its maximum rated power. In order to design wind turbines to operate as close to nominal speeds as possible, for as long as possible, as well as stopping power generation above cut-out speeds, speed control has been introduced (Patel 1999).

The maximum amount of power a wind turbine can produce occurs at its nominal speed. Therefore, at speeds above nominal speed, it is desirable to modify the properties of the turbine in order to achieve conditions closer to those occurring at nominal speed. Wind turbine speed controls also operate to maximize the time that a wind turbine can generate power. By manipulating the blades and their orientation during wind speeds above the nominal speed and especially the cut-out speed, power generation is optimized. The most popular speed control technique for large wind turbines is pitch control which changes the pitch of the blade to regulate rotor speed. Pitch control is achieved by rotating the blade where it attaches to the spinner. Another popular method of speed control is yaw control. Yaw control represents the orientation of the rotor. During wind speeds between the cut-in speed and the nominal speed, the yaw control device orients the rotor in the direction of the wind. The controlling device might be a tail vain or an electric motor. During speeds between the nominal speed and cut-out speed, the yaw control may orient the rotor slightly out of the wind speed direction thus operating closer to the nominal speed. However, yaw control is mainly for speeds above the cut-out speed, when the rotor is oriented out of the wind direction to slow or stall the turbine blades. The final method of speed control is tilt control which tilts the whole plane in which the blades spin up or down slightly. In this way, blade speeds can be decreased during high winds (Ackerman 2005; Patel 1999).

3.1.3.4. The Physics Part 2

Another reason why speed control is important is that as wind speed changes so does the power coefficient of the turbine. Therefore, it is important to be able to maximize the power coefficient at every wind speed. This is accomplished using the tip speed ratio.

$$\text{Tip Speed Ratio} = \frac{\text{Linear Speed of the Blade at the Tip}}{\text{Upstream Wind Velocity}}$$

or

$$TSR = \frac{\omega * r}{V_U} \quad (12)$$

Where:

ω = rotor angular speed (meters / second)

r = rotor radius (meters)

The power coefficient varies along with the tip speed ratio and therefore, so does the power extracted by the rotors. Realising the maximum amount of power generation is only possible by maintaining the tip speed ratio constant at its optimal level. Modern two and three blade horizontal axis turbines have optimal tip speed ratios in the 4-6 range (Masters 2004).

3.1.3.5. The Mechanics Part 2

Maximum power operation

Two methods are used to achieve close to maximum power operation. The first is called the constant tip speed ratio scheme and involves continuously measuring the wind speed and rotor angular speed. With these two measurements the current tip speed ratio is calculated and compared to the known optimal values stored in a computer linked to the turbine. Speed control techniques are used to match the current tip speed ratio to that of the optimal known ratio as often as possible. The other method of maximizing power operation is a peak power tracking scheme. In this method, the rotor speed is increased or decreased in small increments while power is continuously measured. If the speed is increased and the power increases, then the speed is further increased. If the speed is increased and the power decreases, then the speed is decreased. If the speed is decreased and the power decreases, then the speed is increased. If the speed is decreased and the power increases, then the speed is further decreased. In this way, the speed is maintained at its optimal power generating level (Ackerman 2005).

Generators

Converting the mechanical power delivered by the turbine rotor to electrical power is done using a generator. Various generator concepts have been developed and are summarised in the following table.

Asynchronous (Induction) Generators

- squirrel cage induction generator (SCIG)
- wound rotor induction generator (WRIG)
- doubly-fed induction generator (DFIG)
- OptiSlip induction generator (Vestas) (OSIG)

Synchronous Generator

- wound rotor generator (WRSG)
- permanent magnet generator (PMSG)

Other Generator Concepts

- high voltage generator (HVG)
- salient pole synchronous generator (direct drive)

Figure 18: Wind Turbine Generator Concepts

Asynchronous or induction generators are the most commonly used generators in wind turbines today. Their simplicity and robustness are reasons behind the wide use of the asynchronous generator. However, because an asynchronous generator does not contain permanent magnets, the stator requires reactive power to excite. That means that a wind turbine with an asynchronous generator can only establish a magnetic field in order to generate electricity when receiving its exciting current from another source such as a transmission gird or power electronic system. For stand alone applications, an asynchronous generator requires equipment to self-excite. This is typically done using shunt capacitors (Ackerman 2005; Patel 1999).

A synchronous generator is mechanically more complicated and therefore more expensive than an asynchronous generator. A synchronous generator works at a constant speed at a fixed frequency. This characteristic is ideal for a constant speed system but at a significant disadvantage in a variable speed system. As variable speed turbines are currently in favour, synchronous generator applications are limited. One advantage that a synchronous generator has over an asynchronous generator is that it requires no reactive power to create a magnetic field (Ackerman 2005).

Within the other generator concepts outlined, the salient pole synchronous generator, otherwise known as a direct drive generator, is worth explaining for its' potential benefits in Antarctic applications. In most wind turbines there is a gearbox located between the rotor and the generator. In a wind turbine using a direct drive generator no gearbox is necessary. The generator incorporates a direct drive which operates at very low speeds, typically 10-25 rpm. A converter is needed to condition the varying generator frequency to that of the grid frequency. The advantages are the elimination of a costly and heavy gearbox with its associated risk of failure. In Antarctic installations, freezing temperatures would effect the operation of the gearbox quite significantly if lubrication was effected. The disadvantages are that the generator must operate at relatively low speeds and an additional full scale power conversion system is required to operate as a grid connected generator (Ackerman 2005). The figure below illustrates Enercon's system configuration utilising a direct drive generator and therefore no gearbox.

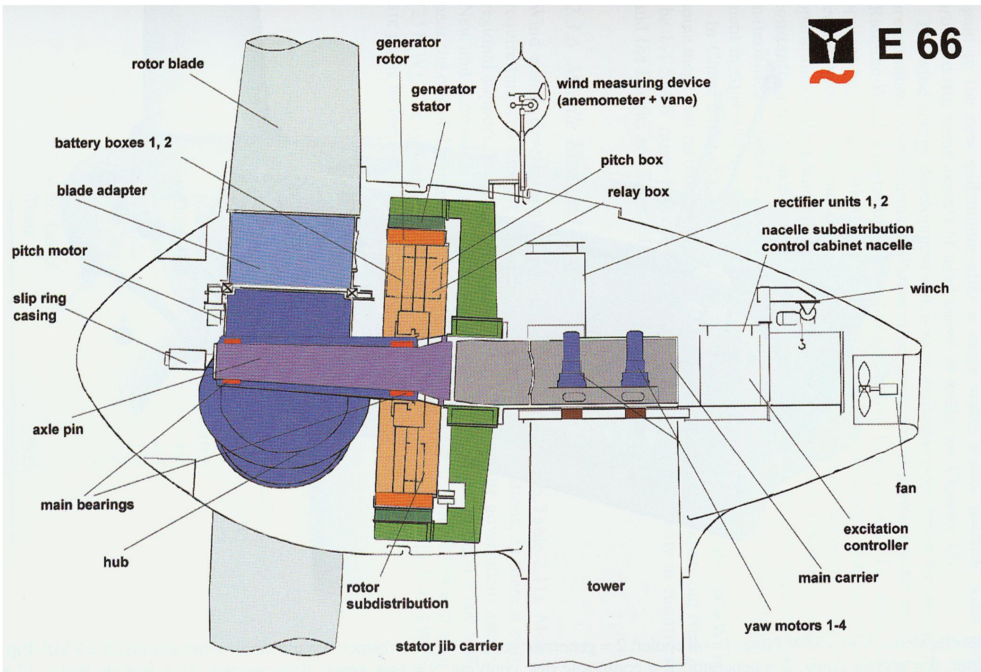


Figure 19: Enercon Wind Turbine Schematic

3.1.3.6. Current State of the Art

Today, for the purposes of electricity generation, there are hundreds of wind turbines available in a wide range of sizes. As size typically correlates with rated power, the trend has been to build bigger and bigger turbines with higher and higher rated power. However, there is still plenty of opportunity for smaller turbines where size, cost or visual impact may need to be minimized. As the trend of turbine design goes bigger and bigger, it is therefore possible to assemble the state of the art in wind turbine design by detailing the world's largest turbines. The following table outlines the two biggest turbines in each of the world's ten leading turbine manufacturer's portfolios (Ackerman 2005; Lundsager et al. 2001).

Manufacturer	Wind Turbine	Configuration	Control Features	Comments
NEG Micon (Denmark)	NM 2000/72	A	Active Stall	Two Speed
	NM 1500C/64	A	Stall	Two Speed
Vestas (Denmark)	V80 -2MW	C	Pitch & Variable Speed	905rpm-1915rpm
	V66 -1.65MW	B	Pitch & OptiSlip	1500rpm-1650rpm
Gamesa (Spain)	G52 -850kW	C	Pitch & Variable Speed	900rpm-1650rpm
	G47 -660kW	C	Pitch & Variable Speed	1200rpm-1626rpm
Enercon (Germany)	E66 -1.8MW	D	Pitch & Variable Speed	10-22rpm Gearless
	E58 -1MW	D	Pitch & Variable Speed	10-24rpm Gearless
Enron Wind (USA)	1.5s -1.5MW	C	Pitch & Variable Speed	989rpm-1798rpm
	900s -900kW	C	Pitch & Variable Speed	1000rpm-2000rpm
Bonus (Denmark)	2MW	A	Active Stall	Two Speed
	1.3MW	A	Active Stall	Two Speed
Nordex (Germany)	N80 -2500kW	C	Pitch & Variable Speed	700rpm-1303rpm
	N60 -1300kW	A	Stall	Two Speed
Dewind (Germany)	D4 -600kW	C	Pitch & Variable Speed	680rpm-1327rpm
	D6 -1.25MW	C	Pitch & Variable Speed	700rpm-1350rpm

***Two largest (i.e. newest) wind turbines from each of the top 10 manufacturers worldwide**

A)	Fixed speed wind turbine with an asynchronous generator with a cage rotor, soft starter and battery bank for reactive power compensation.
B)	Variable speed wind turbine with a doubly fed asynchronous generator using OptiSlip setup.
C)	Variable speed wind turbine with a doubly fed asynchronous generator connected to the grid through a frequency converter.
D)	Gearless variable speed wind turbine using a multipole wound synchronous generator, where the stator is connected to the grid through a frequency converter and the rotor through a rectifier.

3.1.3.7.Installation

Wind Speed Distributions

Wind speed is the most important variable when appraising potential wind farm sites. At any site, wind speeds will vary by the second, hour, day and season. To determine potential wind farm power production, a probability distribution function is used to represent the site's overall "windiness". The Weibull probability distribution best describes the variations in wind speed at a specific site (patel). Advantages to the Weibull distribution are 1) general ease of use due to only two parameters *c* and *k,* 2) it is a good representation based on observed distributions and 3) adjustments based on height can be made easily when the parameters *c* and *k* are known

(Justus). Two parameters define the Weibull distribution, the shape parameter *k* and the scale parameter *c*. The probability of a wind speed (v) at any given time at a specific site is represented by the following:

$$f(V) = \left(\frac{k}{c}\right) * \left(\frac{V}{c}\right)^{(k-1)} * e^{-\left(\frac{V}{c}\right)^{k}} \tag{13}$$

The shape parameter *k* modifies the look of the distribution function. A shape parameter of *k*=1 translates to a distribution where the majority of the wind speeds are around zero. A shape parameter of *k*=2 translates to a distribution where the wind blows consistently around a peak speed with periods when the speeds are much harder than the peak. A shape parameter of *k*=3 translates to a distribution that looks like a bell curve; therefore, the wind is blowing around a specific speeds fairly consistently (Masters 2004). How the shape parameter effects the overall Weibull distribution is illustrated in the following figure.

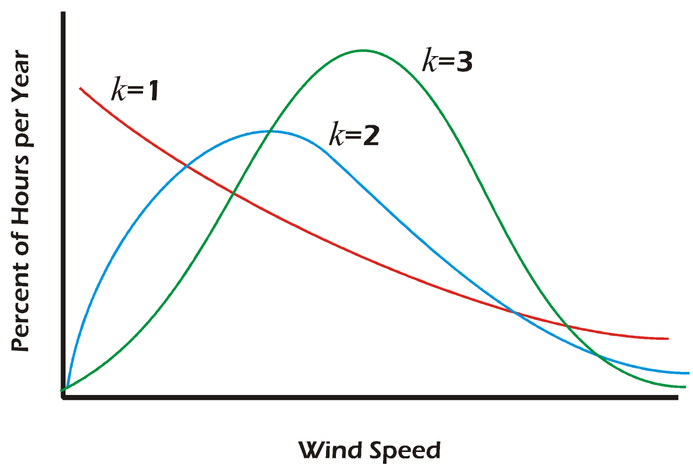


Figure 20: Weibull Distribution Shape Parameters

The shape parameter of *k*=2 has a specific name, the Rayleigh distribution. The Rayleigh distribution is desirable for wind farm sites and is commonly used for approximations (Masters 2004). The impact of the scale parameter c is on the peak of the distribution curve. For a set shape factor, changing the scale parameter c shifts the peak toward lower or higher wind speeds. At higher scale factors the distribution peak is shifted toward higher wind speeds (Masters 2004).

Wind Farms

With a wind speed distribution, knowledge of the physics detailed in the previous sections and a selected turbine, the energy potential of any specific wind farm site can be determined. More than one wind turbine on a site is often desirable. Turbines located too close to one another can have detrimental effects on one another due to the disturbance of the downwind airflow via any upstream turbines. At some distance this effect is negligible. Standard practice today places turbines 5-9 blade diameter widths apart in the predominant wind direction and 3-5 blade diameter widths apart in the direction perpendicular to the predominant wind direction (Masters 2004).

Other issues to investigate when analyzing potential wind farm sites are foundations, roading, and transmission. Turbine foundations are a significant work in structure engineering and require soil analysis. The soil characteristics along with the potential forces exerted by the turbine on its foundation determine its size and depth. For construction and maintenance purposes, roading is usually required for any wind farm installation. The transmission of the electricity produced via any wind turbine generators at a wind farm is also an obvious issue that must be considered. Larger wind farms may bury the transmission cable and feed all turbines supplies to a central control station. Smaller installations may run transmission lines above ground. The proximity of the electrical grid being supplied and thus the electrical loads being served is another factor to be considered when estimating the effectiveness of any wind farm installation.

Noise and visual aesthetics are potential objectionable phenomena that any wind turbine installation will have to address (Masters 2004). Noise and visual aesthetics can affect the neighbours of any potential site. Each installation is different regarding these two issues due to land terrain, proximity of neighbours, turbine size and predominant wind speeds. The objections to wind farms due to noise and visual aesthetics can be countered by the displacement of conventional fossil fuel based electricity generation and the realised benefits; most notably, improved air quality and a decrease in the dependence on a finite resource.

3.1.4. Antarctic Energy Storage Technologies

The history of energy storage starts with the stock piling of wood followed by the damning of streams and rivers. Now, the most common form of energy storage might be the oil tank or gas cylinder (Jensen 1980). Large-scale energy storage is a limiting factor in the installation of renewable technologies. With an intermittent electricity generation device such as a wind turbine, energy storage is highly desirable. Secondary energy storage is defined as an installation designed to accept energy generated by a power system, store that energy in some form for a period of time and return as much as possible back to the power system in a form required by the consumer (Ter-Gazarian 1994).

When evaluating energy storage systems, energy density and storage time are the parameters that carry the most influence (Jensen 1980). The various secondary energy storage methods fall into three categories: mechanical storage, electromagnetic storage and electrochemical storage. Characteristics of the major secondary energy storage systems are detailed in the following two tables (Jensen 1980).

SECONDARY ENERGY STORAGE				
	Storage Type	**Storage Medium**	**Storage Vessel**	**Power Transformation**
Mechanical				
	Pumped Hydro	Water at Elevation	Upper & Lower Reservoir	Motor/Generator driven Pump Turbine
	Flywheel	Rotating Mass	Rotating Mass	Motor/Generator
	Compressed Air	Air	Pressurized Container	Motor/Generator & Compressor Turbine
Chemical				
	Synthetic Fuels	Methanol, Ethanol, Ect.	Fuel Containers	Thermal Power Plant
	Batteries	Electrode / Electrolyte	Battery Casing	Inverter/Rectifier
	Fuel Cells	Synthetic Fuel (Hydrogen)	Fuel Cell Casing	Electrolyser & Inverter/Rectifier
Electrical				
	Superconducting Coil	Electromagnetic Field	Superconductive Coil	Inverter/Rectifier
	Capacitors	Electrostatic Field	Capacitor	Inverter/Rectifier

Figure 21: Secondary Energy Storage Systems

Storage Type	Pumped Hydro	Flywheel	Compressed Air	Hydrogen	Batteries	Superconducting Coil	Capacitors
Approx. Efficiency (%)	80	85	50	50	80	90	80
Reasonable Energy Capacity (Joules)	10^13	10^9	10^12	10^12	Not Constrained	10^13	Not Constrained
Energy Density (Joules/m^3)	10^6 for 100m head	10^8	10^5	10^9	10^8	-	-
Construction Lead Time (Years)	8	3	3	3	2	12	2
Life Time (Years)	50	20	25	25	10	30	10
Number of Cycles	no limit in expected lifetime	no limit in expected lifetime	no limit in expected lifetime	no limit in expected lifetime	500	10^6	10^7

Figure 22: Secondary Energy Storage Parameters

The suitability of the secondary energy systems outlined above for use on Antarctica varies widely. Flywheels and batteries are the most mature technologies currently in use on Antarctica although batteries are not ideally suited to the cold environment. Each of the secondary energy storage systems is outlined below with a focus on the potential for Antarctic installation.

Pumped Hydro

The only storage technique with well developed and reliable technology in general use is pumped hydro (Ter-Gazarian 1994). Pumped hydro storage is when a utility pumps water from a reservoir at a low level to one at a high level. When energy is required, the water is released through the pumps, now acting as turbines, to generate electricity. Pumped hydro storage has an efficiency of approximately 80% due to friction, turbulence, viscous drag and losses of the turbine and generator (Ter-Gazarian 1994). Pumped hydro storage is inappropriate for installation on Antarctica due to the freezing temperatures that prevail.

Flywheels

Flywheels store kinetic energy in a rotating mass. A typical flywheel has a high speed rotor attached to a central shaft encased in an air tight shell. The shaft is connected to an electromechanical energy converter. This electric machine can work as a motor during charging and a generator during discharging. The storage capacity is limited by the stress and friction occurring at the very high speeds of the rotor (Patel 1999). Therefore, flywheels of different material construction yield different specific storage.

Flywheels have certain benefits over batteries that are magnified when working in Antarctica. Flywheels have a high storage capacity per weight and volume, which is important when considering shipping costs to Antarctica. Furthermore, flywheels typically need to be kept at very cold temperatures while batteries operate poorly in cold temperatures. Flywheels have efficiencies of approximately 85% (Ter-Gazarian 1994). The long cycle life of a flywheel ensures it does not need to be replaced as often as a battery bank (Patel 1999). Anything that decreases the amount of heavy equipment (replacement batteries) to be shipped to Scott Base and removed at the end of its useful life is a benefit.

Compressed Air

Compressed air storage is categorized as electromechanical storage. In this storage system, an air compressor is run by the electricity from a wind turbine or other generation device. Air is compressed into a storage tank or large cavern. The energy storage is the potential for that compressed air to do useful work such as generate electricity via an expansion turbine. Compressed air storage systems have an overall efficiency of approximately 50% due to heat losses, leakage, and losses of the compressor and expansion turbine (Patel 1999).

Larger compressed air systems, in reality the only ones that make sense, require a level of cooling in the compression stage to prevent the degradation of the cavern. As the compressed air is expanded into the turbine which drives a generator, heating is also required. Both the heating and cooling necessary incur losses. Furthermore, as a stored gas's temperature falls, so does its potential energy (Ter-Gazarian 1994). Again, the freezing temperatures that prevail on Antarctica make compressed air storage systems inappropriate.

Synthetic Fuels

Using the creation of synthetic fuels as a storage technique is only appropriate for certain applications. The energy storage is realised by producing synthetic fuels, such as methanol and ethanol, and then utilizing those fuels in later applications such as transportation, thermal power production and fuel cell systems. The production of a synthetic fuel can occur with an input of any raw material containing carbon and hydrogen. In reality this means coal, biomass or natural gas. The two most popular synthetic fuels are methanol and ethanol. The performance characteristics of methanol and ethanol are quite similar utilized in transportation (internal combustion engines) and thermal power plants. However, ethanol can be produced from a much smaller range of biomass materials than methanol and is vastly inferior for fuel cell system utilization (Larminie and Dicks 2003).

There are specific safety hazards inherent in using the production of methanol and ethanol as storage systems. Methanol is a poison, made worse by the fact that it can easily mix with water and does not have a taste. Methanol is highly flammable and burns without a visible flame. Methanol vapour is particularly dangerous and great care should be taken to ensure it is not taken into the lungs. Ethanol is much safer than methanol because it is not nearly as poisonous (Larminie and Dicks 2003).

The use of synthetic fuels as a storage device on Antarctica is limited. The materials necessary for production of fuels such as methanol or ethanol is quite substantial. There are logistical issues involved with the procurement and storage of the raw inputs for the fuel production such as coal, biomass or natural gas. Safety of the fuels produced is another issue that would take great care to resolve. A major reason for any modification of the existing Scott Base energy system is to decrease the consumption of aviation turbine fuel to reduce costs and fuel spill risks. Introducing another fuel with a similar terrestrial fuel spill risk as an alternative is not ideal. Overall, the production of a fuel as a storage device would seem highly suspect when designing an energy system with a primary goal of decreasing Scott Base fuel consumption.

Batteries

Batteries are the most widely used device for energy storage (Patel 1999). A battery converts electrical energy to chemical energy while in charge mode. This reaction is reversible. Therefore, in discharge mode, the chemical energy is converted back to electrical energy and heat. A typical battery being used in a hybrid energy system that includes a wind turbine operates at an efficiency of approximately 70-80% (Patel 1999). Five of the most common types of batteries are detailed in the following table.

Electrochemistry	Avg. Cell Voltage	Temp. Range (*C)	Energy Density (Wh/litre)	Cycle Life	Calender Life (years)	Cost ($/kWh)
Lead-Acid	2	(-10 to 50)	70-75	500-1000	(5-8)	200-500
Nickel-Cadmium	1.2	(-20 to 50)	70-100	1000-2000	(10-15)	1500
Nickel-Metal Hydride	1.2	(-10 to 50)	140-200	1000-2000	(8-10)	2500
Lithium-Ion	3.4	(10 to 45)	200-250	500-1000	-	3000
Lithium-Polymer	3	(50 to 70)	150-300	500-1000	-	>3000

Figure 23: Battery Specifications

The Lead-Acid battery is the most common and least cost technology available. Lead-Acid batteries come in different versions including shallow-cycle and deep-cycle; the latter being used for most energy storage applications. Nickel Cadmium batteries have a longer deep cycle life, are more temperature tolerant, and are half the weight of Lead-Acid batteries. However, cadmium has come under environmental regulatory scrutiny and Nickel-Metal Hydride batteries have replaced them. Lithium-Ion batteries have three times the energy density than Lead-Acid batteries but are not as mature a technology. Lithium-Ion batteries use elaborate charging circuitry and need protection against overcharging (Patel 1999).

If allowable under environmental protection laws, Nickel Cadmium batteries are the most suitable battery for the Antarctic environment. One brand of Nickel Cadmium battery, the Sunica Plus, states an extreme tolerance of -50 degrees Celsius. Despite this limit, in order to achieve a level of performance that would warrant the purchase, shipping and maintenance of a large battery bank, a heated space is necessary. To ensure at least a 90% capacity, the batteries would need to be in a temperature controlled space between 0 and 20 degrees Celsius (Saft 2004). Not a requirement to be taken lightly in Antarctica where both heat and floor space are at a premium.

Fuel Cells

A fuel cell is an electrochemical device. Unlike a battery, a fuel cell generates electricity by chemical reaction without changing the electrodes or electrolyte materials within the cell. With an input of hydrogen, a fuel cell produces electricity, water and heat (Larminie and Dicks 2003). Therefore, a fuel cell acts more like a diesel generator, consuming hydrogen ‘fuel’ instead of diesel fuel, than a storage device. Indeed, the hydrogen is the real storage medium in a fuel cell system. Hydrogen does not exist on its own in our environment. However, it can be derived from water with an input of energy. There are a number of different types of fuel cell systems as outlined in the following table (Patel 1999).

Fuel Cell Type	Electrolyte	Temp (*C)	Efficiency (%)	Operation Field
AFC	Alkaline	80	60	Space & Military
PEMFC	Polymer	80-110	60	Transportation
PAFC	Phosphoric Acid	200	40	Combined Heat & Power Plants
MCFC	Molten Carbonate	650	48-56	Power Production & Cogeneration
SOFC	Solid Oxide Ceramic	1000	55-65	Power Production & Cogeneration

Figure 24: Fuel Cell Systems

The benefits of electricity generated by a fuel cell versus a battery on Antarctica are mostly environmental. The replacement of toxic batteries with a fuel cell that outputs just water and heat is desirable; but it is not that simple. The creation and storage of the hydrogen necessary to power the fuel must be accounted for. The cost and uncertainties of fuel cell systems, such as lifespan and efficiency of the total system, have prevented their widespread application. The same issues exist for Antarctic installation. Another consideration is the temperature range at which fuel cell systems operate. As can be seen from the table above, phosphoric acid fuel cells, molten carbonate fuel cells and solid oxide fuel cells, which are typically used for power production, operate at high temperatures. A high operating temperature is not a desirable characteristic for equipment in use on Antarctica.

Superconducting Coil

Energy stored in the magnetic field of a coil is electromagnetic storage and has been a recently developed technology. Superconducting coils have key benefits that may see them become a preferred storage system in the future. Those benefits are efficiencies near 95%, very long lifetimes (up to 30 years), no moving parts and the ability to handle very short charge and discharge times. Despite these benefits, superconducting coils are still a developing technology and therefore remain extremely expensive. The high cost is a reflection of the need to keep the coils at extremely cold temperatures. Liquid nitrogen is typically used to refrigerate the coils to below 100 degrees Kelvin (Patel 1999). Barriers to an Antarctic installation of a superconducting coil are cost and size. The systems in use today are the size of small shipping containers. Temperatures in Antarctica are very low; however, superconducting coils would still require cryogentic plant which adds to the capital and shipping costs of this type of storage technique.

Capacitors

Capacitors are simple electronic devices that are made up of two plates sandwiching a dielectric. The capacitance depends on the permittivity of the dielectric and the area of the plates. The amount of energy a capacitor can store is directly related to its capacitance (Ribeiro et al. 2001). Due to their low energy densities, capacitor's have many applications for short term storage such as in power converters and consumer electronics (Ter-Gazarian 1994). However, there are large capacitors (super-capacitors) capable of use in large scale power applications.

Super-capacitors are a new technology, maturing in the last 5 years. There are limitations on voltage and discharge rates. Currently, large scale implementation of these devices has not occurred due to the current voltage ratings (Ribeiro et al. 2001). Antarctic installation of capacitors or super-capacitors is realistic after the technology matures into a useful device. However, a secondary energy storage system based on capacitors has a storage time of fractions of a second. Therefore, the benefit is an increase in power quality.

3.1.5. Demand Side Management

Demand side management (DSM) implies actions that influence the quantity and timing of energy consumed by users. It can also include actions targeting a reduction of peak demand to lower overall costs. Peak demand management does not necessarily decrease total energy consumption but can be expected to reduce the need for investments in networks and power plants (Turner 1997). The history of DSM has spanned roughly 35 years and formed 3 distinct phases (Sioshansi 1995). During those phases, new programs and types of control were developed, each coining new names and phrases. Currently, the many names are used interchangeably and thus contribute to a disorganized field of study.

Prior to 1973, electric utilities were generally left alone to provide electricity however they saw fit. In 1973, due to the Arab oil embargo and ensuing "energy crisis", DSM was essentially born. The quadrupling of oil prices, from $2.50US to $10US a barrel, woke up the world to energy supply issues (Sioshansi 1995). Availability and security of oil was suddenly in question and DSM was born. Phase One took place from 1973 until 1980. The methods developed during this first phase focused around education and conservation. In 1981 and unexpected downturn in energy prices reduced the urgency and cost effectiveness of DSM programs. The decline of energy prices greatly reduced the interest in DSM programmes and the urgency that had been present in the field (Sioshansi 1995). Between 1981 and 1989 Phase Two developed. New strategies to influence consumer energy use focused on loans, rebates and market transformations. Incentivized DSM , the last phase, occurred from 1989 until around 1996. During this period, policies that enabled utilities to actually make more money under certain

circumstances by selling less kilowatt hours kept interest in DSM very high. Schemes developed raised peak time prices while allowing utilities either direct load control of consumer's demand or indirect control via real time information provided (Nadel and Geller 1996; Saini 2004; Sioshansi 1995; Smith 1994; Turner 1997). The following table categorizes the major DSM techniques practiced in Belgium, Denmark, France, Japan, Norway, Republic of Korea, The Netherlands, Spain, Sweden and the United States
from 1973 to 1996.

Category 1	**Conservation & Efficiency**
Education:	Energy Audits and information concerning best practices and equipment
Loans & Rebates:	Loans to upgrade buildings. Rebates to purchase more efficient HVAC equipment, refrigerators and lighting.
Market Transformation:	Building code implementation and appliance manufacture standards.
Category 2	**Load Control**
Direct Load Control:	Direct control of consumer load by utility. Typically hot water heaters, pool pumps and air conditioners in the residential sector. Typically called "Ripple Control"
Indirect Load Control:	Utility provides information to consumer who modifies load. Businesses identify loads that can be interruptible. Those loads are timed in accordance to the utilities need for a decrease in load at peak times. Interruptible schemes, time of use rates and real time pricing are all examples of indirect load control.

Figure 25: Demand Side Management Techniques

The deregulation, liberalization, and unbundling of the energy sector that has occurred in many countries around the world since 1996, including the United States and New Zealand, has hindered many DSM programmes. Electric utilities cutting DSM programmes have created a market for energy service companies (ESCOs) to provide cost saving services to electricity consumers while sharing profits with the utilities themselves. ESCOs offer services such as energy auditing or energy system monitoring (Turner 1997). "Electricity saved is worth more than electricity generated" is a phrase that is now accepted throughout the industry (Saini 2004).

In this newly competitive electric industry, DSM programs still exist. Building on knowledge from the past, utilities have implemented a wide range of energy savings programmes since deregulation. Starting in 1994, the International Energy Agency (IEA) has compiled a database of DSM programmes from 14 of its 26 member countries. New Zealand and the United States are both member countries of IEA. The IEA database provides a source of 229 programmes from around the world that make up the current state of the art. The following is a brief summary of 229 DSM programmes from around the world that have been implemented in the past 10 years. The programmes are diverse and are not all directly related to electricity consumption. However, the programs are characterised by a greater understanding of the full life cycle of consumer products and how best to utilize increasingly expensive resources (Nilsson 2005). Therefore, all programmes ultimately effect resource consumption and the way people use electricity.

- The primary objective for almost all the programmes (94%) is energy efficiency. Some 57% are targeted towards residential customers, 32% towards commercial customers, 25% towards industrial customers, and only 7% towards agricultural customers. (Laar, 2004)
- Electricity consumption is affected by 90% of the programmes. Utility companies implemented around 84% of the programmes, central governments 7%, and energy service companies 3%. (Laar, 2004)
- 52% use rebates and cash rewards as incentive to participate. Others use financing, loans and leasing, tariff reduction, direct installation, and bulk purchasing to promote the programmes. 25% are classified as 'market transformation' programmes; with the majority of these being high efficiency lighting and home appliance oriented.

The energy savings potential of a Scott Base demand side management program is subject of ongoing investigation. In the past, kitchen appliance upgrades and lighting upgrades have reduced electricity demand. Currently only one type of DSM technique is in use on the base. The "mouse round" is a daily activity where a base occupant turns off any unnecessary equipment that may have inadvertently been left on at the end of the workday (Hume 2006). Opportunities exist for load control schemes, either direct or indirect, as well as further equipment upgrades.

3.2. Other methods to solve energy systems problems

3.2.1. <u>Systems Approach</u>

The complexity of real-world problems, those that include a social or human component, can not be handled by applying the traditional scientific method alone. A systems approach is geared for solving complex problems involving systems (Khisty and Modammadi 2001). Systems are composed of components, attributes and relationships. A system component has inputs, a process and outputs. An attribute is the properties of a system component. The links between components and attributes are the relationships (Blanchard and Fabrycky 1990; Khisty and Modammadi 2001).

The systems engineering process is based on a top-down approach to design. Keys to the systems approach are starting with the requirements about the external behaviour of any part of the system and meeting those requirements at every stage of the process. The systems approach to solving complex engineering problems is suggested as the best for designing products, systems and structures that will be cost effective and competitive (Blanchard and Fabrycky 1990; Khisty and Modammadi 2001). The following figure illustrates the top-down systems approach to solving complex engineering problems.

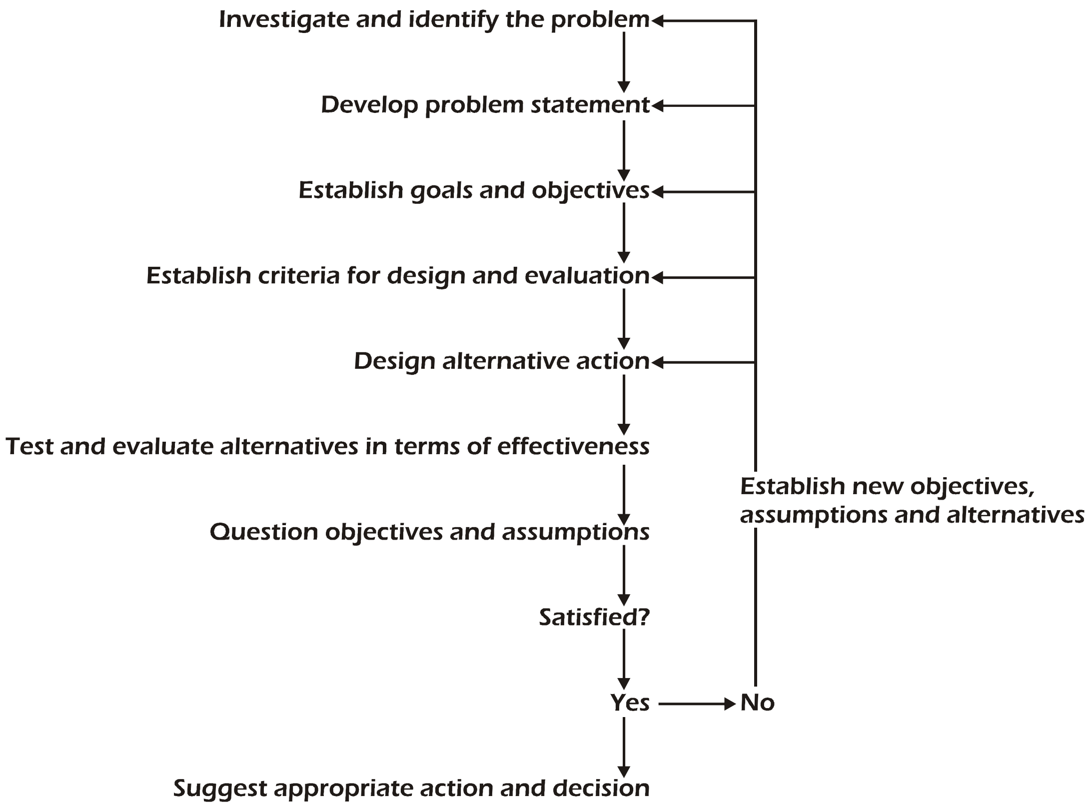


Figure 26: Systems Engineering Approach

The first step of the systems engineering process is the identification of a “need”, “want”, or “desire” for a new entity(s), or for an improved or new capability. Within this first step, the establishment of a baseline against which a design can be evaluated is also essential (Blanchard and Fabrycky 1990). After a baseline has been established, the specific functions that the system must perform can be specified. System metrics may be necessary in order to compare the performance of different system configurations. For example, cost, reliability, and effectiveness may need to be quantified for the sake of comparison. The most important measures of the system are called *technical performance measures* (TPMs). Some popular TPMs are: Functional Capability, Reliability, Maintainability, Usability and Safety, Supportability and Serviceability, Disposability and Affordability (Blanchard and Fabrycky 1990).

There are three ways a system engineer can meet the established need, want, or desire:

1. Choose an item that is commercially available. This method assures a relatively high level of maintenance and support capability.
2. Modify an existing commercially available item.
3. Design, develop, and produce a new item. (Blanchard and Fabrycky 1990)

Limiting factors are those that curtail meeting the system requirements and objectives. An important goal of any systems engineering process is the identification of those limiting factors. Locating strategic factors, those that can be altered to make progress possible, within the limiting factors is essential in determining the optimal solution (Blanchard and Fabrycky 1990).

The Scott Base energy system fits the definition of a complex engineering problem with a human component. The "desire" of Antarctic New Zealand to improve upon the capabilities of the existing energy system is the first step in a systems approach to solving the problem. A benchmark for evaluation purposes is the existing energy system's recent performance. What is left for the engineer is to present a solution to meet Antarctic New Zealand's desire using one of the three methods listed above.

3.2.2. Control System Theory

A control system is a type of system with self regulating properties. Control systems have existed since the beginning of life on earth or perhaps even earlier. A control system is made up of subsystems and processes assembled to control behaviour or performance. For example, as the light that reaches the human eye decreases, the diameter of the pupil is increased to catch more of that light (Nise 1995). Control system theory plays an important part in the design of mechanical systems. Stability within a mechanical system is paramount and therefore, controlling performance characteristics such as exponential growth, which leads to catastrophic instability, is essential. The figure below is a simplified control system schematic showing the components and the key role feedback plays to facilitate changes within the system.

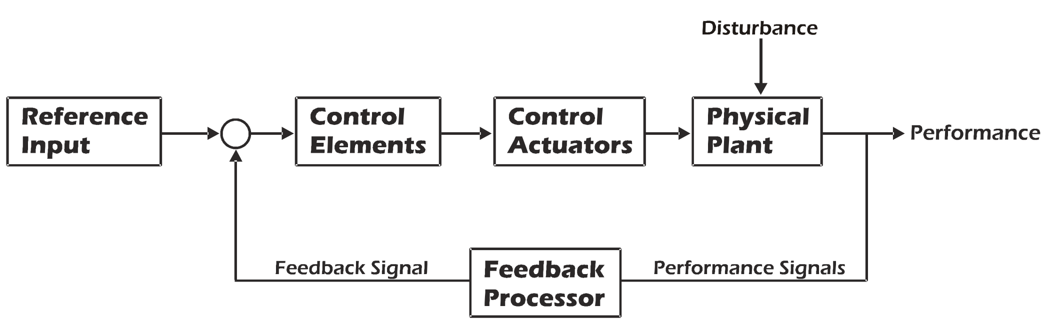


Figure 27: Simplified Control System Schematic

Open and Closed-Loop Systems

The figure above is characterised as a closed-loop system. A closed-loop system is able to compensate for external or temporal disturbances by measuring the output response as reported by the feedback signal. Without a feedback signal there is no capability for measurement or correction and any oscillation in system performance may continue unchecked until system malfunction. A lack of feedback signal is a distinguishing characteristic of an open-loop system (Nise 1995; Ogata 1997). Consider an electric kettle. This simple mechanical system provides boiling water with inputs of non-boiling water and electricity. After start-up, electricity supplies the kettle element which heats the water. With no measurement of the water temperature (feedback of system performance), the element would continue to heat until the electricity supply was discontinued or the element malfunctioned. In this case, the kettle is operating akin to an open-loop system. However, most electric kettles contain a thermocouple to measure the water temperature. When the water temperature reaches boiling point, the kettle automatically discontinues the electricity supply. This simple control device introduces performance feedback to the system and prevents kettle malfunction and/or complete utilisation of kettle resources. With the addition of the thermocouple and associated on/off control switch, the kettle operates akin to a closed-loop system.

3.2.2.1.Emerging Applications of Control System Theory

As illustrated previously in Figure 1, traditional electric power systems operate in a linear fashion. Natural resources fuel power generation equipment that produces an electricity supply to meet the current demand. This system, where energy is produced in order to be available at every moment of every day, operates as an open-loop system. Consumers, who create the demand, receive no information about the power system's status and therefore do not modify their behaviour even if it could be beneficial. Without feedback, a closed loop electric power system is impossible and thus stability impossible. In order to achieve at least a minimal amount of stability, appropriate feedback could be introduced in order for the energy system to operate akin to a closed loop system.

Dr. Susan Krumdieck of the University of Canterbury studies the use of finite resources supporting our present standard of living. By applying the concepts of systems engineering and systems control theory, Dr. Krumdieck has identified a hypothetical model for sustainability applied to regional energy/environment/socioeconomic systems (Krumdieck and Wood 1989). Implementing the missing components of a sustainable system that Dr. Krumdieck's hypothetical model indicates as absent in current electrical energy systems is a challenge. Performance objective design is a method of designing and selecting optimal technologies and can be utilised to find appropriate solutions to constrained energy system problems (Dantas et al. 2005; Krumdieck et al. 2004).

Today there are control systems throughout the process industry regulating levels in tanks, concentration of materials and size of fabrication. Widespread application within the guidance, navigation and control of missiles, spacecraft, planes and ships have also utilized the digital computer as part of control systems (Nise 1995). There are also thousands of control systems in use this very moment throughout our modern society in the home, office and built environment; and to see millions of control systems each charged with maintaining individual stability yet self organizing to produce entire system stability we can look at our mother earth (Capra 1996). By applying the fundamental ideas of systems engineering and control theory to the design of energy systems for isolated communities, it may be possible to bring those isolated community systems closer to stability and thus sustainability.

*3.2.3. **Hybrid Power System Simulation***

The study of electrical energy systems is accomplished through simulation of actual phenomena with models that reflect the elements in the physical system. When dealing with energy systems, the range of time to be simulated is an important aspect to consider (Barret et al. 1997). The ability of the model to behave exactly as the physical system between certain constraints is defined as its robustness. The robustness of a model defines its field of validity. A model only gives precise results within its field of validity and only within this field does the relationship between data and outputs mean anything (Barret et al. 1997).

The key issue in the design of wind-diesel systems with high wind energy penetration is the potential fuel savings. As wind power penetration rises, so does the expense of added equipment to ensure high power quality. However, as more equipment is added to a wind-diesel system, complexity increases and it becomes difficult to predict fuel savings. Therefore, long term logistic computer simulation models are necessary. These models simulate system behaviour over a period of time at specific time steps (Ackerman 2005; Lundsager et al. 2001). The following table contains a short description of the more popular simulation programs currently in use today.

Model	Description
HOMER	NREL's HOMER is an optimization tool used to determine energy system configurations given specified resources and load data. Simulation is compiled in hourly steps and is fast and comprehensive. HOMER is considered the state of the art in this category. (Lundsager, 2001 & Ackerman, 2005) Publicly available and used widely.
Hybrid2	The University of Massachusetts and NREL's Hybrid2 operates much like the HOMER software with a much higher degree of detail. Hybrid2 is a time series model used to predict technical and economic system performance. The user interface is not as straightforward as HOMER. Publicly available and used widely.
WINSYS	Riso's WINSYS model is a spreadsheet based application that uses probabilistic representations of resources and demands. WINSYS allows for long term economic factors to be incorporated in system's analysis. Therefore, WINSYS focuses on full life cycle assessment. WINSYS is not commercially available.
IPSYS	Riso's IPSYS is the follow-up to WINSYS. The IPSYS simulation package is able to predict system performance and economic analysis as well as active and reactive power flows and grid voltage levels. This level of detail is only possible with time steps down to a few seconds. The modelling of flexible supervisory system controllers is another benefit of the IPSYS software. IPSYS is not commercially available.
WDL Tools	Engineering Design Tools for Wind Diesel Systems has created a package of a number of European logistic models as well as one modular electromechanical model. This package is called WDL Tools. The package includes: VINDEC (Norway), SOMES (Netherlands), WDILOG (Denmark), RALMOD (UK), TKKMOD (Finland) and the modular model JODYMOD. WDL Tools is not publicly available.
INSEL	Doppelintegral GbR's (Germany) INSEL is a modular simulation environment that is used for planning, monitoring and visualising energy systems. INSEL offers nearly unlimited flexibility in system configurations. INSEL is available but not as popular as HOMER.
PROLOAD	PROLOAD was developed in conjunction with an electric utility and uses Monte Carlo techniques to determine probabilistic load flows. PROLOAD is not publicly available.
RETScreen	CEDRL's RETScreen is a spreadsheet based analysis and evaluation tool used to determine the economics of hybrid energy system projects. RETScreen is publicly available but not as popular as HOMER.
RPM-Sim	NREL's RPM-Sim is a software based in the VisSim analysis software environment. RPM-Sim can be used to analyze the dynamic performance of wind/photovoltaic/diesel systems with and without storage. RPM-Sim is not publicly available.

Figure 28: Hybrid System Simulation Models

3.3.State of the Art Summary

3.3.1. __Summary__

The field of wind-diesel hybrid energy systems is emerging as a field with market potential in first, second and third world countries. Remote and island communities have so far been ideal locations for prototype and pilot systems. The technology behind the main components of the wind-diesel hybrid energy system, the wind turbine and diesel generator, has been evolving for many decades. The state of the art diesel generator sets that operate on Antarctica produce reliable and high quality electricity to meet 100% of the Scott Base electric demand. The range of wind turbines now spans from a few hundred watts to five megawatts. The three bladed, horizontal axis, variable speed turbine appears to be the most popular turbine configuration in use today. Hybrid energy systems can often perform better if an energy storage component is designed within the system. For Antarctic hybrid energy systems, batteries, flywheels and superconducting coil all have potential although each is designed for different uses. However, demand side management has the potential to replace the need for storage by shifting electricity demand away from peak times or to times when energy supply is abundant.

Solving problems associated with energy systems is often difficult due to the complexity of the energy systems and their individual components. A systems engineering approach can be utilized when dealing with complex problems with a human component. This top down approach presents a framework to solve problems such as designing a hybrid energy system for Scott Base while ensuring that predetermined requirements will be met throughout the process. Control theory is a method typically used for the regulation of dynamic systems. With the application of control theory, a system design can be engineered from an open loop system to a closed loop system. Fossil fuel based energy systems operate in a way similar to an open loop system. Modifying an existing energy system to one that operates in a similar way to a closed loop system is a major goal of the research project.

The most common method of solving hybrid energy system problems is utilizing a hybrid system simulation tool. A hybrid system simulation tool is a computer model that is able to replicate a physical system and make performance predictions based on resource inputs. Several programs are widely used with HOMER being the most popular for determining optimal system configurations.

4. Methodology

The energy systems research conducted for Scott Base is specific to the base's energy architecture. However, the methodology used to investigate the addition of a wind turbine to the existing diesel generator based energy system is applicable to other remote area communities. The methodology outlined can help an engineer design a transition from fossil fuel based energy systems to hybrid energy systems. Although the data and results are specific to Scott Base, the basis for the project stems from the far-reaching question, can the additional of wind power to existing diesel generator based energy systems be effective in meeting load demands while reducing fossil fuel consumption.

The following chapter is organized into five parts. Section 4.1, *Systems Analysis*, is a study of the existing Scott Base energy system and its individual parts. Section 4.2, *Experimental Design*, outlines the performance objective design methodology that is implemented over the following sections. Section 4.3, *Model Construction*, explains the creation of the model used to represent the real Scott Base system. Section 4.4, *Model Verification and Validation*, describes how the model operates in its intended manner and details how the model is an accurate representation of the real system. Section 4.5, *Model Analysis*, outlines the application of alternate inputs to the model and their effects on the model outputs.

4.1. System Analysis: understanding the Scott Base system

4.1.1. Scott Base Description

Scott Base was officially opened on January 20th, 1957 for use during the International Geophysical Year and Commonwealth Transantarctic Expedition. The base was extensively rebuilt in 1976 and looks much the same today. The base is located on Pram Point, which is at the end of the Hut Point Peninsula, on Ross Island, at the edge of the Ross Ice Shelf (McGonigal and Woodworth 2002). The base is currently comprised of eight main buildings, each made of sheet steel encased polyurethane foam and connected by all weather corridors. These buildings have a combined floor area of 2340 square meters of which 570 square meters is used as accommodation. The base is maintained at 18 - 20 degrees Celsius indoors (Antarctic New Zealand 1995). The figure below is a simplified blueprint of the base and its ten stages.

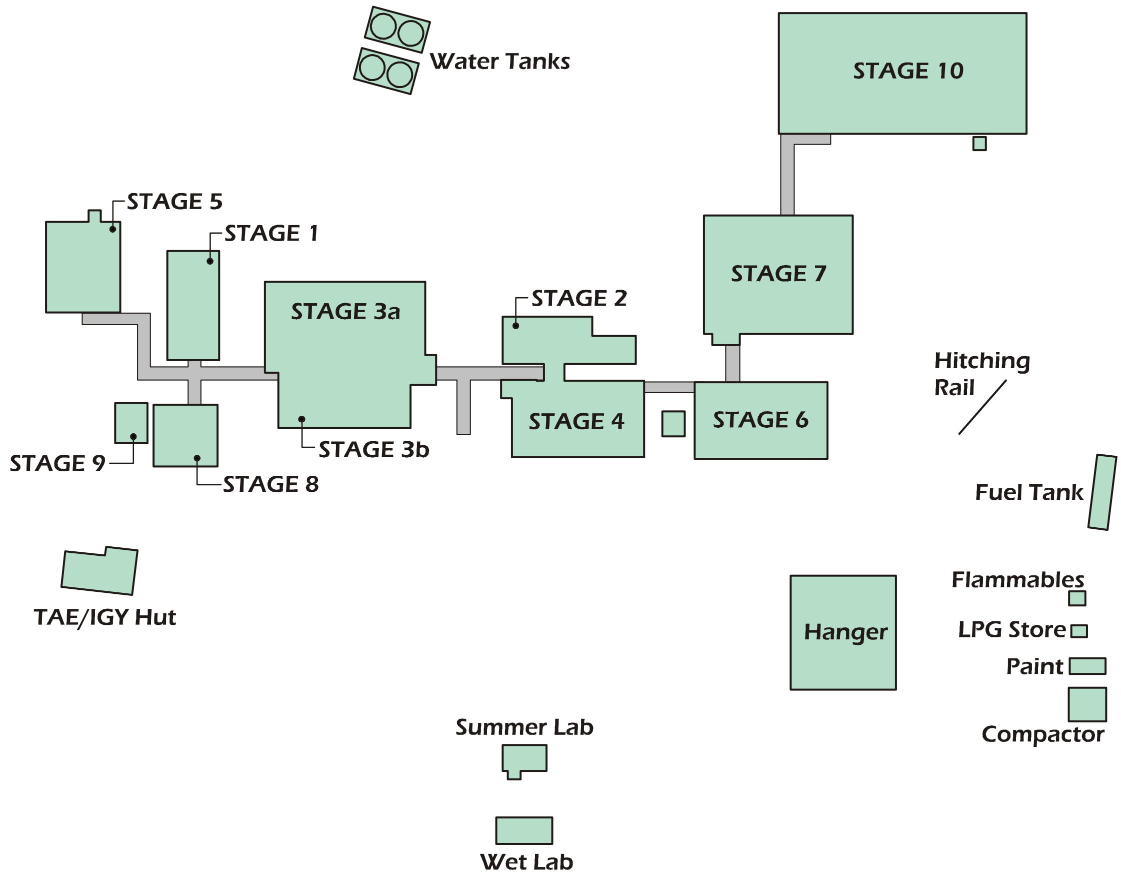


Figure 29: Scott Base Layout

Each of Scott Base's ten stages represents an area and corresponding electrical and thermal load. For each stage there is a switchboard that contains the breakers for each of the electricity supplies in that stage. The following is a list of the Scott Base stages.

Stage 1: Q Hut
Stage 2: Power House
Stage 3a: Accommodations & Bathrooms
Stage 3b: Kitchen, Dining Area & Bar
Stage 4: Administration
Stage 5: Hatherton Laboratory
Stage 6: Workshop
Stage 7: Garage
Stage 8: TAE Hut
Stage 9: Wastewater Treatment
Stage 10: Hillary Field Centre
(Lawson 2006)

Other buildings on site, which are not connected to the main base which support the station include water tanks, stores, fuel tanks and the summer and wet lab.

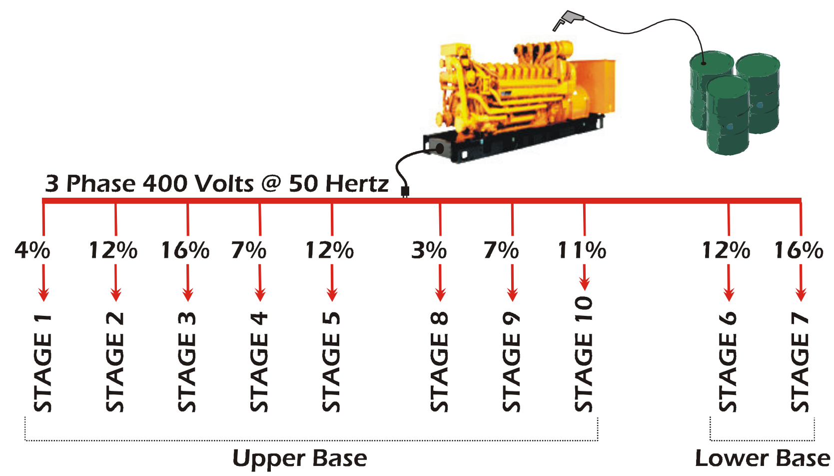
4.1.2. Existing Scott Base Energy System

4.1.2.1. Overview

Scott base operates on one energy input, Aviation Turbine Fuel (AN8). The combustion of AN8 in Caterpillar generators produces electrical energy, thermal energy and exhaust. Three Caterpillar generators are in operation at Scott Base. All three generator sets are Caterpillar 3406 DI-T Series B electric generators with a maximum rating of 225kW electrical and 110kW thermal (Hume 2006). CAT1 and CAT2 are located in the power house and produce 100% of the base's electrical and thermal needs. CAT3 is available as a backup and is located a short distance away from the main eight interconnected buildings. CAT1 and CAT2 alternate supplying the base's electrical and thermal demands. One of the two generators may run anywhere from one day to twenty days with the other CAT taking over production after a very specific routine is completed by the power house engineer. This routine entails switching the base's electrical load from one CAT to the other without interrupting electricity distribution (Antarctic New Zealand 1995). The existing energy system is essentially two subsystems, electrical power supply and hot water supply. On average, of the fuel energy burnt in the generators, 38% is converted to electrical energy with approximately 32% thermal energy recovery (Hume 2006). Two 98 kilowatt oil fired boilers are also available in the power house for additional thermal load support. If the waste heat captured from the active CAT generator set is insufficient to meet the Scott Base thermal demand, one of the oil fired boilers is utilized.

4.1.2.2. Electrical Energy Supply

Electrical power is provided to the base by one of the two generator sets in stage two, known as the duty set. The other generator set is on stand-by and can start automatically in the event of a duty set failure. The alternators coupled to the generators produce 3 phase 400 volts at 50 hertz. In order to maintain 50 hertz, the generator sets run at 1500 revolutions per minute (Antarctic New Zealand 1995). Below is an illustration of the electricity supply to the ten stages of Scott Base with approximate percentage of demand as well as a table listing electrical power statistics for the past three years (Hume 2006).



	2002	2003	2004
Average Electrical Power	155 kW	150 kW	137 kW
Minimum Electrical Power	106 kW	110 kW	102 kW
Maximum Electrical Power	183 kW	183 kW	172 kW

Figure 30: Scott Base Electrical Demand

4.1.2.3. Thermal Energy Supply

The thermal energy from the generators as well as the reverse osmosis desalination plant located in stage 2 heat water moving at 8.5 litres per second in the base's heating loop. The heating loop is a 90 millimetre diameter steel pipe with 5 millimetre thick walls. The generators are fitted with marine manifolds and water heat exchangers in place of radiators in order to facilitate a high level of heat recovery. After leaving the powerhouse, the heating loop splits into two loops. One loop heats the upper base, consisting of stages 1,3,4,5,8 & 9, while the other loop heats the lower base consisting of stages 6 & 7. The illustration below is a representation of the thermal loop that delivers heat and domestic hot water to the ten stages of Scott Base (Antarctic New Zealand 1995; Hume 2006).

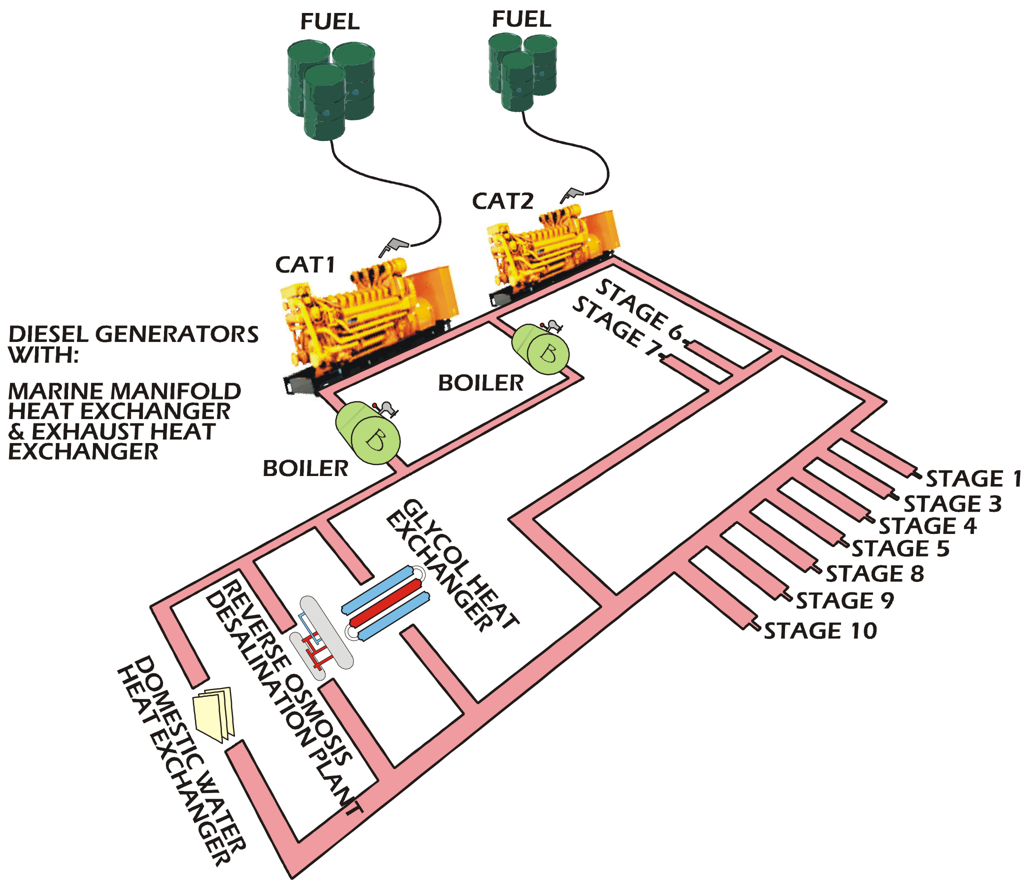


Figure 31: Scott Base Thermal Loop

4.1.2.4. Stages & Associated Loads Description

Ten electrical switchboards are scattered throughout the base. In Scott Base technical documentation, the various electrical loads that each switchboard supports are referred to as *stages*. Each stage is typically associated with the operations necessary for life and scientific study to exist on Antarctica for that specific area. Each stage contributes to the overall Scott Base electrical load. The following is the daily load profile for Scott Base acquired from data collection in December of 2004 (Hume 2006).

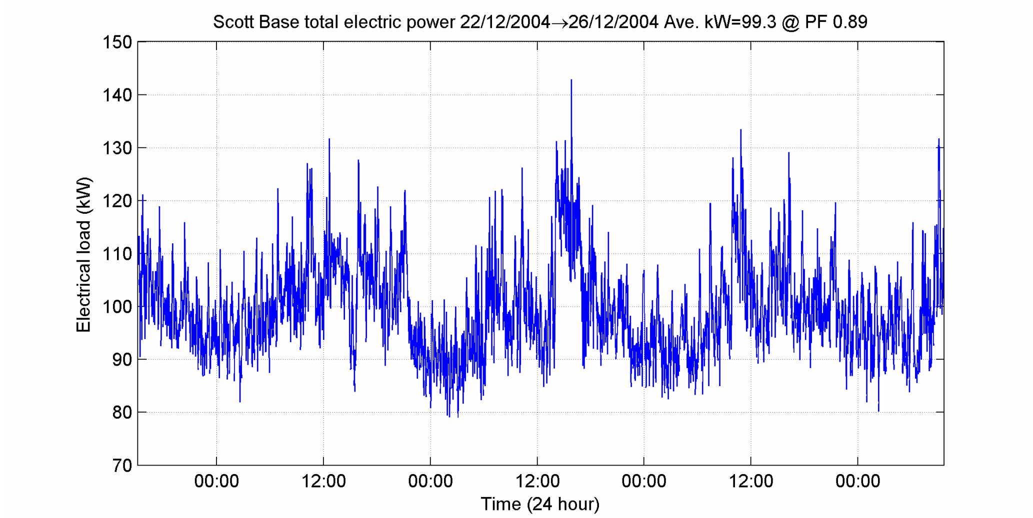


Figure 32: Scott Base Load Profile

The electrical information for each stage is referenced from an energy audit performed in December and January of 2004/2005. This audit was completed by technicians from the Electric Power Engineering Centre within the Electrical Engineering Department at the University of Canterbury. The results of the audit, which are recounted in the following stage descriptions, were reported to Antarctic New Zealand in a document authored by Dave Hume (Hume 2006).

Stage 1: Q Hut

The additions to Scott Base that began in 1976 with the Q hut and the Summer Laboratory are typical of all the new buildings. The polyurethane insulated steel buildings have a heat loss of approximately 7 watts per meter squared of area, extremely low for the conditions. The buildings are completely air tight with double or triple glazing that does not open. Therefore, it is necessary that each building have its own air conditioning unit for ventilation.

Stage one is heated with the base heating loop through an air handler that consists of a mixing valve, pump, and a system of ducts. An old boiler previously used for heating is available in stage one for back-up. Lighting is present.

Base Loads: 2.5kW air handler
Cyclic Loads: 2.5kW fan heater

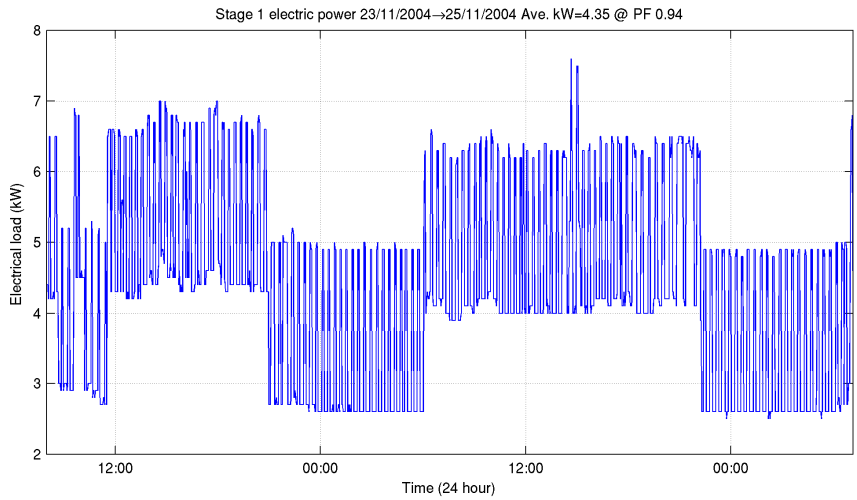


Figure 33: Stage 1 Load Profile, Q Hut

Stage 2: Power House

Stage two is the heart of Scott Base. The three diesel generator sets present at Scott Base, two of which operate in Stage 2 (or the powerhouse), are Caterpillar 3406 DI-T Series B engines. They were initially installed during the 1986/1987 summer season and gave 180 kilowatts at 50 hertz on prime duty. Since that time, each of the generator sets has been re-rated for 225 kilowatts at 50 hertz on prime duty. 225 kilowatts is the maximum published output of a Caterpillar 3406 DI-T Series B engine and Caterpillar has suggested lowering the rating to improve service life as well as for safety reasons. The generator sets were re-rated to meet the increased Scott Base demand.

The building also houses a reverse osmosis desalination plant, two oil fired boilers for heating back-up, compressed air system, lubricating oil system and ventilation systems. Sea water is pumped from a melt hole to the power house where it is treated by the reverse osmosis desalination plant. There are two stages to the process. Water through only the first stage is not suitable for drinking. (Scott Base Manual) All of the above consist of various piping, pumps, and valves. Stage two also contains the main electrical controls of the base. Lighting is present.

Base Loads:	3.8kW heat circulation pump
	2.3kW exhaust and inlet fans
	2kW pump motor
	2kW seawater return heating wires
Cyclic Loads:	2kW each to 3 fan heaters
	4-8kW saltwater pump house (wetlab)
	12kW reverse osmosis desalination plant including pump

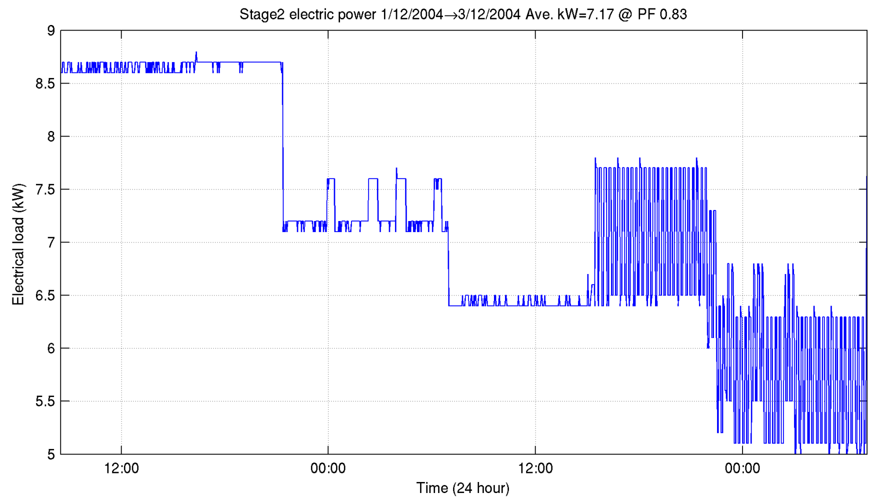


Figure 34: Stage 2 Load Profile, Power House

Stage 3a/3b: Staff Accommodation & Bathroom / Kitchen, Dining Area & Bar

The first part of stage three (3a) contains radiators supplied by the base heating loop. An air handler system is also present distributing air with three fans via a ducting system throughout the building. The second part of stage three (3b) is the kitchen and eating area. This stage has the most electrical appliances in operation on the base. Along with the typical air handler system, this part of stage three contains the kitchen equipment.

Base Loads:	3kW Fridge/Freezer unit
	1kW wetlab trace wiring
	5kW air handlers
Cyclic Loads:	2kW waste water pump
	3kW lighting
	1kW misc. personal equipment

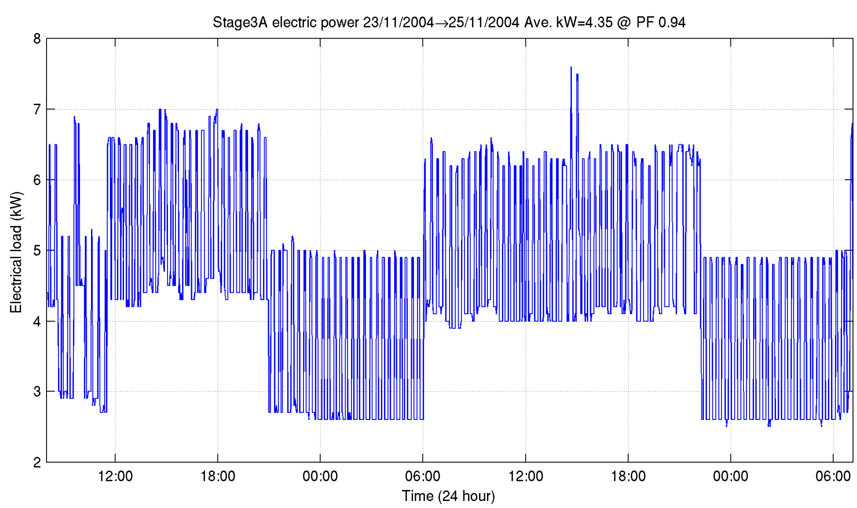


Figure 35: Stage 3 (A) Load Profile, Staff Accommodation & Bathroom

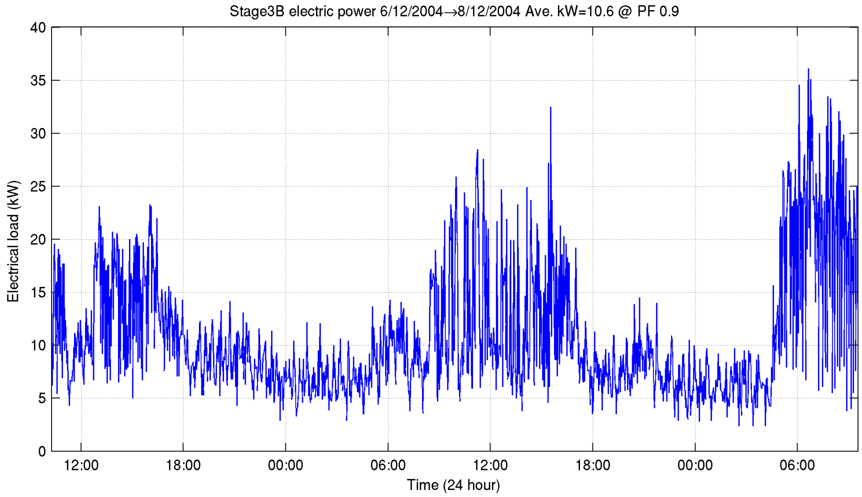


Figure 36: Stage 3 (B) Load Profile, Kitchen, Dining Area & Bar

Stage 4: Administration (Command Centre)

Stage four, administration or the command centre, contains the typical air handler system as well as a humidifier. Numerous pieces of office equipment also contribute to the electric load.

Base Loads:	5kW communication lab
Cyclic Loads:	2kW lighting
	2kW office equipment

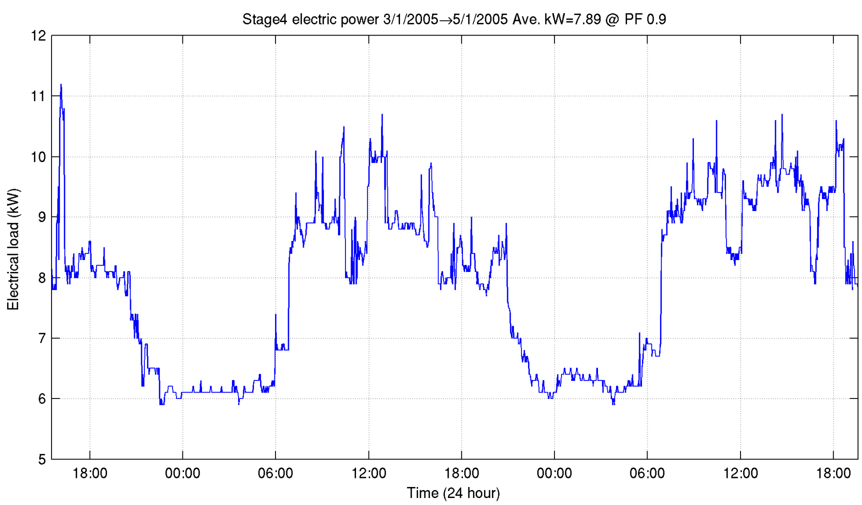


Figure 37: Stage 4 Load Profile, Administration

Stage 5: Hatherton Laboratory (Geomagnetic Laboratory)

Stage five is a busy scientific laboratory that contains the equipment to connect with satellites in order to communicate with those outside of Antarctica. The relatively large supply of electricity supplies a range of scientific equipment as well as the typical air handler system and lighting.

Base Loads:	1.2kW Uninterruptible supplies
	1.5kW air handlers
Cyclic Loads:	2kW lighting
	4kW Satellite earth station (occasional 15kW pulses)

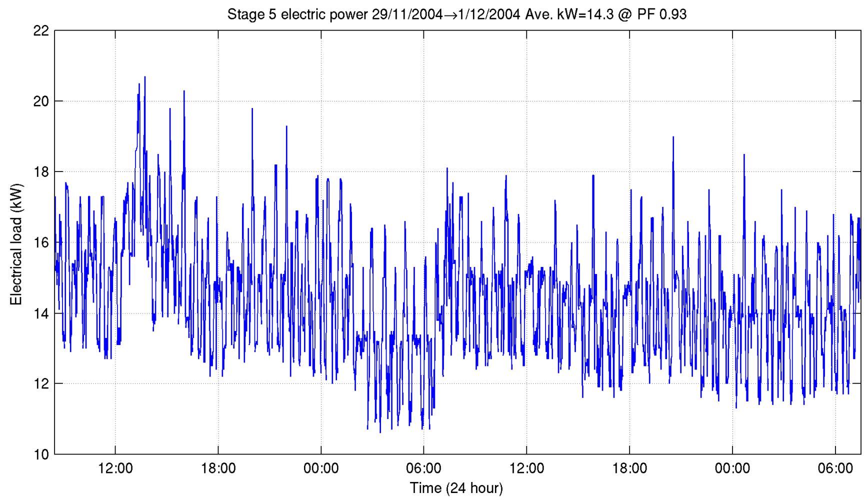


Figure 38: Stage 5 Load Profile, Hatherton Laboratory

Stage 6: Backup Generator Room, Workshop & East Hitching Rail

Stage 6 contains CAT3 and therefore a lot of the same equipment as the powerhouse. This includes air handlers, compressed air and oil lubrication systems. The other main supply is that of the east hitching rail. The east hitching rail is a piece of equipment that base vehicles can plug into in order to insure that the oil in the engine block will not freeze. This method of heating vehicle engines in the winter months at Scott Base is a major percentage of the total base electrical load.

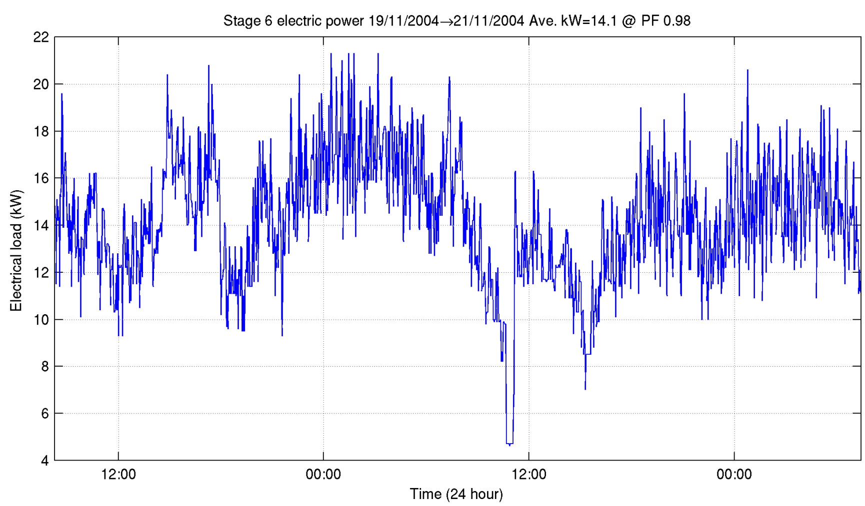


Figure 39: Stage 6 Load Profile, Backup Generator Room, Workshop & East Hitching Rail

Stage 7: Garage, Cold Stores & West Hitching Rail

Similar to stage 6, the majority of the stage 7 electrical load is a vehicle hitching rail. The stage 7 load is quite large due to two hitching rails. One rail is within the garage and the other, the west hitching rail, is outside the garage. Other equipment found in workshops and vehicle maintenance areas such as an air handler, vehicle exhaust system, compressed air, oil lubrication, cold area heaters and the necessary lighting contribute to the stage 7 load.

Base Loads:	1.5 Air Handlers
Cyclic Loads:	9kW Garage Hitching Rail
	7kW West Hitching Rail
	2.5kW Lighting

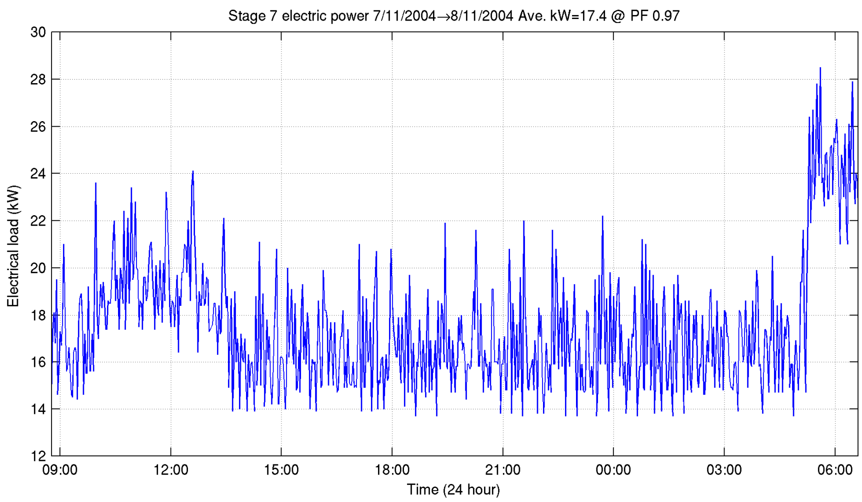


Figure 40: Stage 7 Load Profile, Garage, Cold Stores & West Hitching Rail

<u>Stage 8: Bathrooms, Laundry Room, Sauna & TAE Hut</u>

Stage 8 is a light load and highly variable. Consisting of lighting, washing machines, dryers, the sauna and a supply to the TAE hut, stage 8 has peaks of loading significantly above the average load.

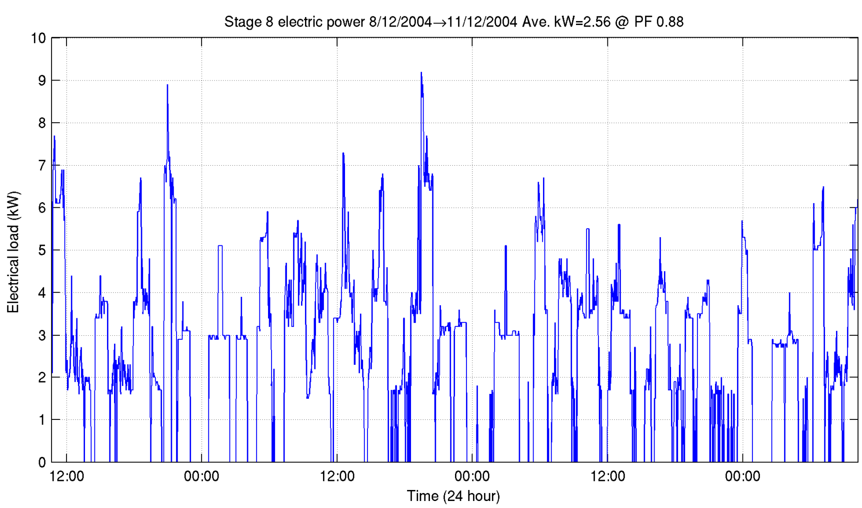


Figure 41: Stage 8 Load Profile, Bathrooms, Laundry Room, Sauna & TAE Hut

<u>Stage 9: Wastewater Treatment Plant</u>

Stage 9 is unique in that it is not associated with a specific area of the base. The stage 9 load is comprised of the wastewater treatment plant in operation for the entire Scott Base. The load consists of various pumps and heat traces.

Base Loads: 7.5kW Plant

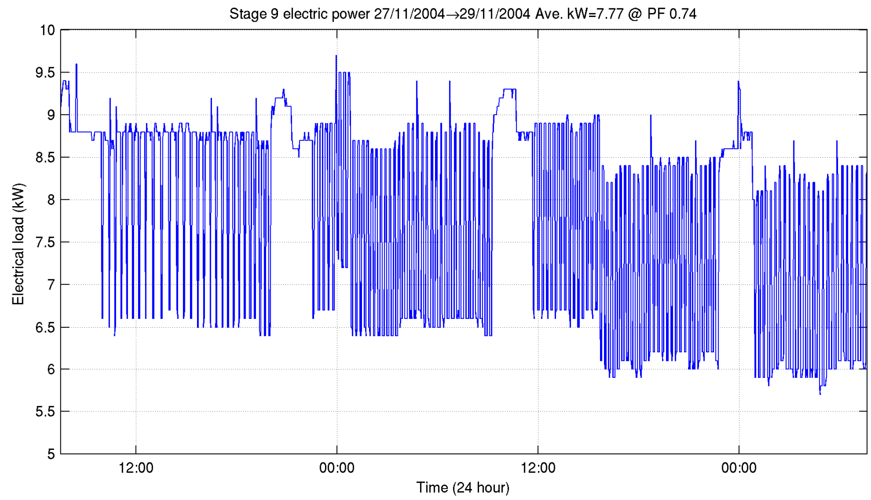


Figure 42: Stage 9 Load Profile, Wastewater Treatment Plant

<u>Stage 10: Hillary Field Centre</u>

The Hillary Field Centre is the newest of the Scott Base facilities. The Field Centre became operational in October of 2005. The heated building is designed to provide facilities for field party preparation, waste handling, storage, a drying room, offices, a fitness centre and briefing and training rooms. Electrical and thermal data for Stage 10 is currently unavailable.

<u>Other Buildings (not interconnected)</u>

Scott Base contains and incinerator that burns non treated waste materials and food scraps. Of the building not interconnected to the main base, the hanger is the only one in which electrical data is available. The hanger does not contain much equipment. However, its large space requires heating which is a substantial load. A field freezer is also supplied from stage 10.

Base Loads: 6kW Thermostatically controlled electric heating
3kW Field Freezer
Cyclic Loads: Lighting

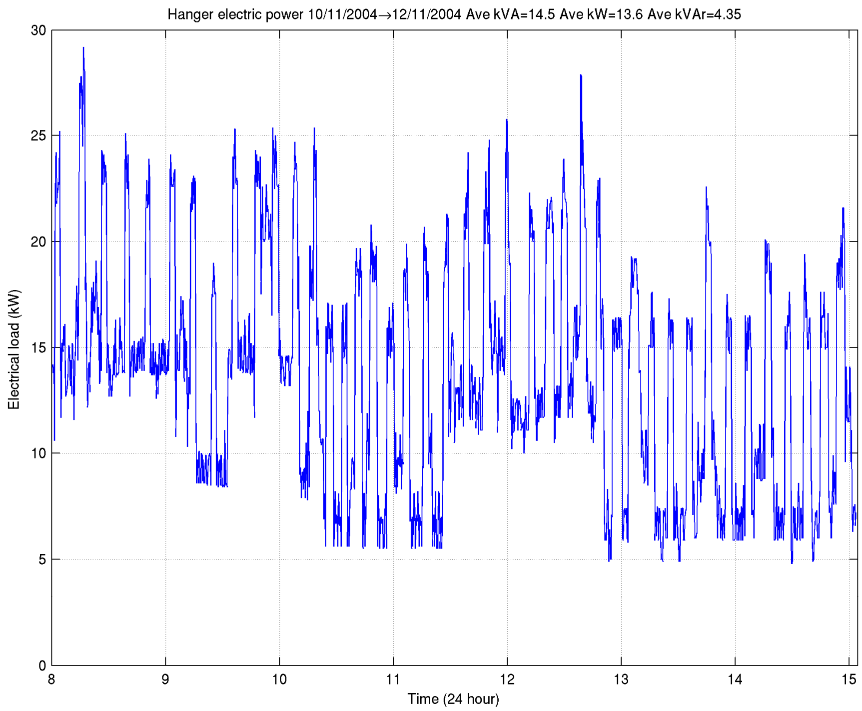


Figure 43: Stage Ten Load Profile

4.1.2.5. Characteristic Fluctuations

In 2004, the electrical and thermal loads were met with the consumption of 377,825 litres of AN8 fuel (Hume 2006). Scott Base electrical and thermal loads fluctuate with outside temperature, season, time of day, and number of base inhabitants. The following is a general outline of the variations in the Scott Base electric load.

During the summer months of December through February, base population can near 90 staff members. The large number of loads associated with science and personal equipment coupled with a full base lighting load creates the electricity demand. The average electrical demand in the summer months is approximately 127 kilowatts. During the winter months of June through August, base population is very low around 15 staff members. The lighting load is lower than summer and science and personal equipment use is much lower with so few inhabitants. However, the outside temperature can reach such extremes that it is necessary to heat Scott Base vehicle engines. Three hitching rails are located around the base and this electric load in winter is quite large. The average electrical demand in the winter months is approximately 145 kilowatts (Hume 2006).

4.1.3. Potential Demand Side Management Techniques in the Existing Energy System

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 fuel oil through internal combustion generators. Many of the loads are required for staff wellbeing and for performance of tasks. Other loads may be optional or may be time-flexible, that is they may be postponed or brought forward in time to match energy availability. Time-flexible loads are the focus of potential demand side management techniques at Scott Base. Specifically, load shifting to take advantage of surplus wind power is investigated. To a certain extent, all loads at Scott Base could be categorised as time-flexible. However, for every load there is a level of inconvenience reached when the demand is not immediately met. For example, the level of inconvenience is quite high for a load such as lighting or heating. After evaluating the individual stages of Scott Base, a number of loads are identified for possible demand side management technique implementation. Those loads and their profile characteristics are listed below.

R.O. Desalination Plant Stage 2	The reverse osmosis desalination plant operates autonomously to provide Scott Base with fresh water. A major electrical load of the plant is the pump. Coordinating the desalination plant pump to surplus wind power seems appropriate. However, Scott Base personnel believe that only in the winter months when base population is at its lowest is any interruption in the desalination plant possible. Furthermore, a delay of only a few hours in a week is advised. The short period of time-flexibility in only the winter months rules out existing desalination plant for demand side management.
Satellite Earth Station Stage 5	The satellite earth station, due to its spikes of electrical demand, is a prime candidate for a load shifting program. The 4 kilowatt base electrical demand of the earth station spikes to approximately 15 kilowatts when transmitting data via satellite. Shifting those spikes to times of wind power abundance at first seems reasonable. However, satellite communication and data transmission is an essential part of Scott Base and any delays are not appreciated. A fibre cable link to the United State's McMurdo Station is also in place to keep Scott Base and McMurdo connected to New Zealand and the world. Interruptions to the satellite earth station should be avoided.
Hitching Rails Stage 6&7	The three hitching rails of Scott Base account for approximately 30% of the overall base demand. Decreasing this electrical demand has the potential for large fuel savings. The load profile is is not perfect for load shifting as it is not characterized by spikes in demand. However, due to the size of the load, any potential savings, no matter how small the percentage, may result in big savings. One drawback to further modelling the hitching rails is that they are not utilized all year. During the summer months the hitching rails are disconnected.
Sauna Stage 8	The sauna in stage 8 is currently operated as a dump load. Excess thermal load is made available to the sauna when the generator meets the electrical and thermal demand with surplus thermal energy. As the sauna is a luxury and is already managed in accordance to the demand side of the energy system equation it is not appropriate for further modelling. In fact, as the sauna acts as a dump load, ideally it should be kept at the absolute minimum.
Laundry Facilities Stage 8	The laundry facilities meet all the criteria to attempt a load shifting program. The load profile jumps from zero to as much as 9 kilowatts and back to zero over just a few hours. The load is in operation all year round with more activity during the summer when base population is at its highest. The level of inconvenience is relatively low as the load is not essential to safety or scientific work progress.

Figure 44: Scott Base Loads with DSM Possibilities

Further analysis of the identified loads outlined above points to one Scott Base load as a good candidate for demand side management modelling. The laundry facilities are in operation all year round, are time-flexible and have a low level of inconvenience associated with load interruption. The laundry facilities are not the only Scott Base load that could realise fuel savings with the incorporation of load shifting; however, they are an ideal load for modelling purposes and for fuel savings predictions. It is the laundry facilities pattern of use that makes it an ideal load. As can be seen in the load profile of Stage 8, the electrical demand of the laundry facilities is characterised by jumps from zero to approximately 3 kilowatts. This level of demand is sustained for a period of time until the demand drops sharply back to zero. This profile is characteristic of a batch process. The load is repetitive and the appliances of the laundry facilities are automatic once started. As the methodology for fuel savings outlined here is appropriate for not only Scott Base, but many other remote locations around the world relying on a diesel generator based energy system, the laundry facility load is analogous to any time-flexible load with a low level of inconvenience associated with a delay in the service provided.

4.2. Experimental Design: the plan of attack

Performance objective design seeks to find the best solutions to systems problems while considering system requirements and constraints. The research paper seeks to answer two questions. **The first question is, with respect to current wind turbine technology, what wind-diesel hybrid energy system is appropriate for installation at Scott Base?** The solution to the first problem will be evaluated on predicted performance with particular attention paid toward potential fuel savings. **The second question is, if feedback from the proposed hybrid energy system is made available to influence certain Scott Base electric loads, can further fuel savings be realised?** After determining system constraints and requirements, potential solutions to these problems can be evaluated. To this end, the energy needs of Scott Base must be investigated. A detailed description of the energy requirements at Scott Base is outlined in the following *System Analysis* section. However, the results of that analysis are detailed in the following three subsections, System *Requirements, System Constraints* and *System Objectives*.

4.2.1. System Requirements

A requirement is something wanted or needed. In the field of systems engineering, a design requirement is a factor that must be included or maintained. In the following section, *System Analysis*, the existing Scott Base energy system is outlined and the specific energy requirements are detailed. In summary, Scott Base requires, on average, a 137 kilowatt electrical supply and a 125 kilowatt thermal supply. At times the electrical supply must be able to reach 172 kilowatts while the thermal supply must reach 186 kilowatts. The load identified for any potential demand side management technique is the laundry facility load. Other system requirements are included to ensure staff safety (Reliable in Environment) and to meet Antarctic New Zealand desires (Utilise Wind Power).

4.2.1.1. Essential Loads Met 100%

All potential model designs must deliver an electrical and thermal energy supply to meet 2004 Scott Base requirements. All Scott Base loads must be supplied 100%. One exception is that the identified demand side management load, laundry facilities, must be supplied, but within certain time limits.

4.2.1.2. Reliable in Environment

Any equipment proposed must be suitable and reliable in the Antarctic environment.

4.2.1.3. Utilise Wind Power

Antarctic New Zealand is committed to lowering the carbon footprint of Scott Base. Along with support from Meridian Energy, Antarctic New Zealand is currently exploring the possibility of wind power to reduce AN8 fuel consumption at the base. Therefore, any proposed energy system design must lower the carbon footprint (reduce fuel use). To that end, wind turbines are the preferred renewable energy provider.

4.2.2. System Constraints

A constraint is a factor which restricts an action or process. In the field of systems engineering, a design constraint acts as a barrier that restricts and is to be avoided. The environmental constraints inherent to a scientific research station on Antarctic have been touched on in Chapter 2, *Background*, within the sections *Antarctica and Scott Base* as well as *Technical Importance*. In review, the extreme cold temperatures and isolation of the area cause a wide range of engineering issues with few acceptable solutions. The technical constraints of any wind-diesel hybrid energy system have been outlined throughout Chapter 3, *State of the Art*, in regards to wind turbine technology, diesel generators and energy storage. In order to access system performance, it is necessary to define specific quantifiable variables to represent each system constraint. For the case of a potential wind-diesel hybrid energy system at Scott Base, the following constraints will be managed:

4.2.2.1. Fuel Use

The overall goal of the research project is to propose an energy system that reduces AN8 fuel consumption at Scott Base. Therefore, total predicted fuel use will not be greater than that of the current diesel based system currently utilised at Scott Base. The variable used to represent the fuel use of each potential system during system analysis will be Total Predicted Fuel Consumption. The constraint level for Total Predicted Fuel Consumption is 379,000 litres per year.

4.2.2.2. Diesel Generator Operation

A Minimum Diesel Load must be implemented in order to maintain reasonable generator efficiency and to prevent a premature operational failure. The Minimum Diesel Load is set to 30% of generator rated power and thus 67.5 kilowatts.

4.2.2.3. Power Quality

A level of power quality must be maintained for the safety of the base staff and equipment. Outages are unacceptable; likewise, limits on slow voltage variations, voltage dips and flicker are necessary. These characteristics need to be maintained within acceptable levels. Instantaneous Wind Penetration as well as Average Wind Penetration are quantifiable variables with a direct correlation to power quality. As outlined previously in the *Sizing* section of Chapter 3, the greater the values of Average Wind Penetration and Instantaneous Wind Penetration, the more power conditioning equipment necessary to meet the power quality requirements. Due to the minimum diesel loading situation, the definition of the wind penetration constraints are modified. The equations for these constraining variables are as follows:

$$\text{Average Wind Penetration} = \frac{\text{Total Useful Wind Energy Generated (kWhrs)}}{\text{Total Electrical Load Served (kWhrs)}} \quad (14)$$

$$\text{Instantaneous Wind Penetration} = \frac{\text{Wind Power Output (kW)}}{\text{Electrical Load (kW)}} \quad (15)$$

The constraint level for Average Wind Penetration is 50%.

The constraint level for the maximum allowable Instantaneous Wind Penetration is 100%.

4.2.3. System Objectives

A system objective is an individual factor that helps achieve the overall goal. In this case, the overall goal of the project is proposing an energy system that reduces fuel consumption at Scott Base. Therefore, system objectives are the identified factors which make that goal achievable.

4.2.3.1. Fuel Consumption

The addition of wind power to the existing Scott Base energy system will reduce the amount of fuel consumed by the base generator sets in order to meet electrical and thermal loads. The more wind power capacity is added, the lower the predicted fuel consumption. Fuel use at Scott Base represents more than an economic cost. The risk of fuel spills, carbon dioxide emissions and base reliance on an insecure supply chain make total fuel consumption that much more important. The benefits of reducing base fuel consumption have been explained throughout Chapters 1 and 2. The primary objective of the design is the maximum amount of fuel savings while still remaining within the limits of the power quality constraint.

4.2.3.2. Cost

Although environmental concerns and public perception are factors in Antarctic New Zealand's desire to reduce fuel consumption at Scott Base, cost is the primary reason. At over one million dollars a year, fuel costs for the base are significant. Any proposed energy system design must be cost effective. Based on predicted fuel savings per year, a time-frame can be calculated for when the proposed energy system will pay itself off. The cost objective is to keep the pay-back period as short as possible.

The cost of installation for each proposed system is estimated based on proposed wind capacity and data gathered from the Mawson Station wind project. Mawson Station is the only Antarctic research station that has undergone and completed the installation of a medium scale wind-diesel hybrid energy system. The figure for project cost includes the turbines, foundations and infrastructure, additional plant and equipment, transport, project management, powerhouse control, installation and commissioning as well as turbine spares. The cost of installing two Enercon E-30s (300 kilowatts each) was approximately 7 million NZD (Magill 2006). Therefore, in the case of Scott Base, project costs are estimated at $11,600 NZD per kilowatt installed.

4.2.4. Energy System Design Process

Various wind-diesel hybrid energy systems are proposed. The configurations of those systems are not arbitrary, but are derived from a design process. The design process seeks to identify the best possible wind-diesel system configurations that meet the system requirements while operating within the system constraints. The evaluation of each proposed system is based on the system objectives and is outlined in the *Model Analysis* section.

4.2.4.1. Energy System Configurations

The creation of each proposed wind-diesel hybrid energy system is based on two identified wind turbines suitable for Antarctic installation. Utilising the two identified turbines, all possible wind-diesel hybrid energy system configurations are modelled without mixing the two turbines. For example, systems with one and two type 'A' turbines as well as systems with one and two type 'B' turbines are modelled. However, a system with type 'A' and type 'B' turbines is not modelled. The reason for not mixing sizes is one of practicality. During construction and maintenance, two different machines are undesirable. Five possible configurations are created for evaluation at Scott Base.

4.2.4.2. Simulation Structure

For each system configuration there are multiple simulation structures possible. The simulation structures represent how the architecture of the energy system is built. Different protocols on how power supply meets demand can result in different levels of fuel savings and other variables. The primary analysis is based on a standard simulation structure for each model. A demand side management structure is also modelled. Other simulation structures, such as using secondary energy storage in the form of batteries or directly supplying the thermal load with wind generated electricity, are noted and discussed.

Standard Structure

At any point in time, Scott Base demands a supply of power for electrical loads as well as thermal loads. If a wind turbine is operating within the system, its power supply, if any, is utilized to meet the electrical load. Any remaining electrical load that is not supplied by wind generated power is supplied by electricity produced by the diesel generator sets. In generating power to meet any left over Scott Base electrical loads, the diesel generator sets also produce thermal energy. This recovered heat is applied to the Scott Base thermal load. Often the recovered thermal energy from the diesel generator is not sufficient to meet the base thermal load and power from the boiler(s) is necessary to supply the remaining thermal load. This is the typical way in which wind-diesel hybrid energy systems are structured and is illustrated in the following figure.

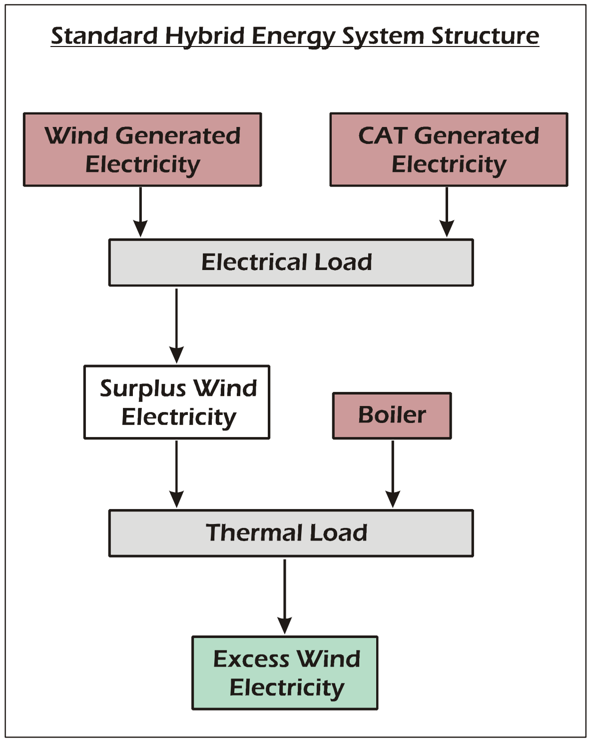


Figure 45: Standard Wind-Diesel Hybrid Energy Structure

Demand Side Management Structure

The final simulation structure includes a novel demand side management technique. The Scott Base laundry facilities load has been identified as suitable for modification as it is nonessential and time-flexible. The new demand side management technique moves the laundry facility load forward in time to when wind generated electricity may be abundant. By pausing the laundry facility load for a number of hours, wind generated electricity may be able to supply a greater percentage of the electrical load. A limit to how long the laundry load can be shifted is established. In this way the laundry service is always provided, however, that service is provided within a set of time limits. This technique is introduced to better coordinate any potential wind turbines with the electrical demand of Scott Base.

The incorporation of time flexibility into the laundry facility load creates the demand side management technique of load shifting. At each hour in the hybrid system simulation an algorithm is run to determine any possible extra fuel savings via the load shift. At each hour if there is enough excess electricity to meet the laundry load, it is supplied. If there does not exist enough excess electricity to meet the laundry load, it is postponed and not supplied by the generator sets. The following hour sees either a new laundry load or one that incorporates the demand of the previous hour according to the previous hour's supply. This logic continues unless the laundry facility load remains unmet for a continuous number of hours that correspond to the identified time period. If the time period is reached the complete laundry facility load is supplied with power from the generator sets. In this manner, the service that the laundry facility provides is made available not at all times but over an identified period of time. The schematic representation of this technique is illustrated within the *Demand Side Management Representation* section.

Wind Generated Electricity Direct to Thermal Load Structure

As the Scott Base thermal load is a significant part of the overall base load, it is possible that supplying it directly with wind generated electricity may prove beneficial. For this simulation structure, an electric hot water heater is introduced to convert the wind generated electricity to thermal supply. In this case, the Scott Base electrical load is supplied 100% by the generator sets. The base thermal load is supplied via a proposed electric hot water heater operating with wind generated electricity. Any base thermal load remaining is supplied by recovered heat from the generator sets and the boiler(s). The following schematic represents the simulation structure with wind power supplying the Scott Base thermal load directly.

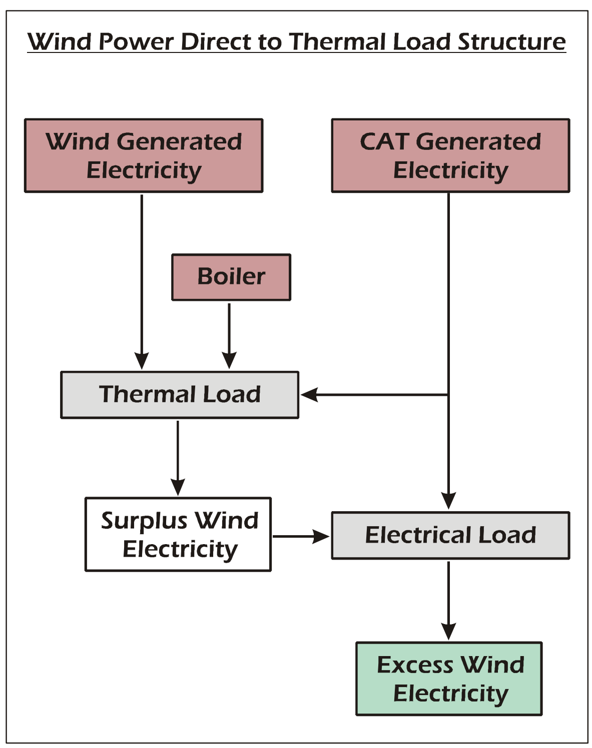


Figure 46: Wind Power Direct to Thermal Load Simulation Structure

0% Minimum Diesel Load Structure

A 30% minimum diesel load as a system constraint limits the amount of potential fuel savings at Scott Base to roughly two-thirds of its current consumption. In order to evaluate just how much a minimum diesel load constraint effects overall predicted fuel consumption for each model, an alternative 0% minimum diesel load structure is proposed. In this case, the wind-diesel hybrid system would operate exactly as the standard structure indicates. A 0% minimum diesel load constraint represents the hybrid system that allows the generators to be completely shut down and rely solely on the wind turbine for power supply.

4.3. Model Construction: the Scott Base energy system as a computer model

4.3.1. Hybrid Optimization Model Energy Resource, H.O.M.E.R.

Evaluating energy systems can be a time intensive process. Energy auditing begins by understanding the operations of the energy system and collecting historical data. A walk through of the facilities is necessary to gather information about current equipment and patterns of use. Levels of detail are different for every study; however, lighting, HVAC systems, electric motors, water heaters and waste heat sources are some of the more important features to identify and record (Turner 1997).

The most common method of evaluating the potential of adding renewable generation devices to an existing energy system is to simulate an entire year. For example, collected load data of a community along with solar radiance data of the area allows a modeller to predict how a photovoltaic installation might perform. The full year simulation is broken up into time-steps. At each time-step photovoltaic production based on the solar radiance resource is compared to the community load data. The summation of the data for each time-step makes up the predicted overall performance of such a system. Evaluating potential hybrid energy systems, with multiple components with a variety of possible sizes, is labour intensive even with the utilization of a computer model.

The Hybrid Optimization Model Energy Resource, otherwise known as HOMER, is a computer model tailored for the simulation of hybrid power systems. HOMER was developed by the National Renewable Energy Laboratory in Golden, Colorado. HOMER is a broad-based optimization tool that is best used to determine basic system design (National Renewable Energy Laboratory 2005). With inputs such as community loads and wind speed data, multiple system components can be evaluated in order to determine the most appropriate system configuration. HOMER uses an hourly time-step and is considered the state of the art to determine optimal system configurations in the field of hybrid system simulation (Baring-Gould et al. 2002; Lundsager et al. 2001).

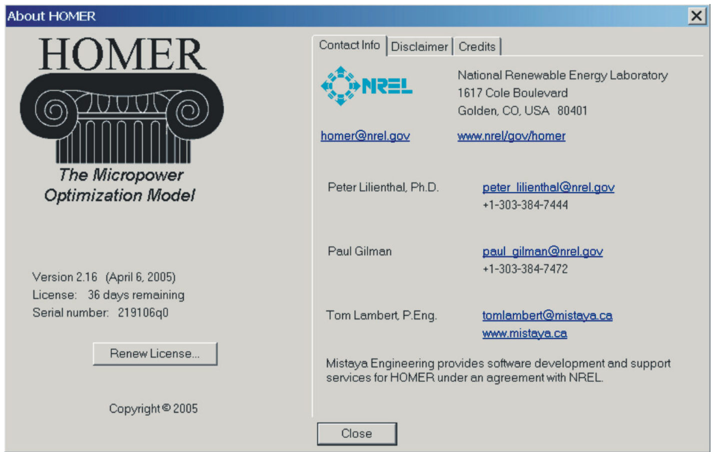


Figure 47: HOMER Preliminary Information

4.3.2. <u>Model Structure</u>

4.3.2.1. Step One: Components

The first step to building an accurate model of the Scott Base energy system using HOMER is building a power system schematic. Initially, the 3 Caterpillar 3406 generator sets are the only components to input to the model. This is completed by specifying all relevant generator data points such as power curve, fuel efficiency, scheduling and minimum loading requirements. The figure below shows HOMER's graphic user interface.

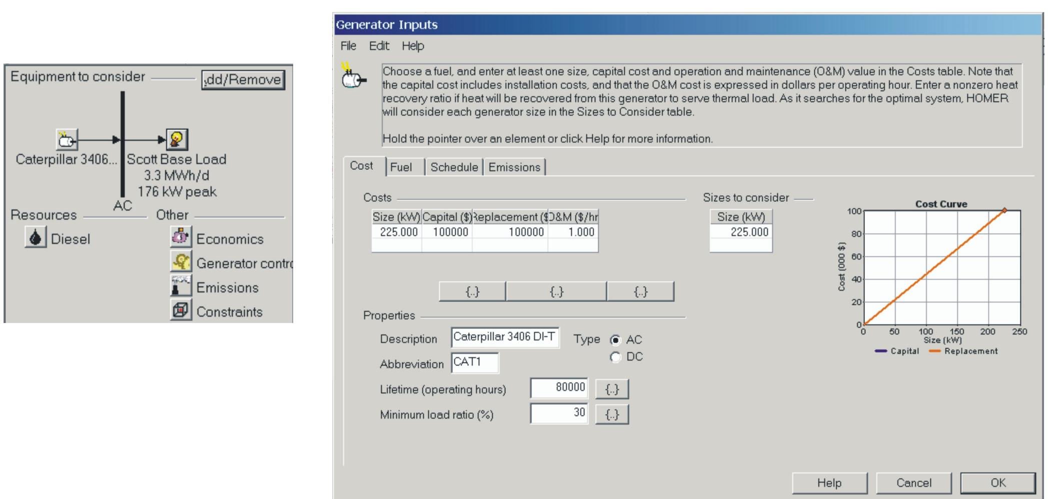


Figure 48: HOMER Generator Inputs

When building the hybrid wind-diesel model, the addition of more components to the system becomes necessary. Specifying wind turbines is done in a similar fashion to that of the generator sets. Characteristics of the turbine, such as power curve, hub height, cut-in and cut-out speeds, are detailed in the graphic user interface as illustrated below.

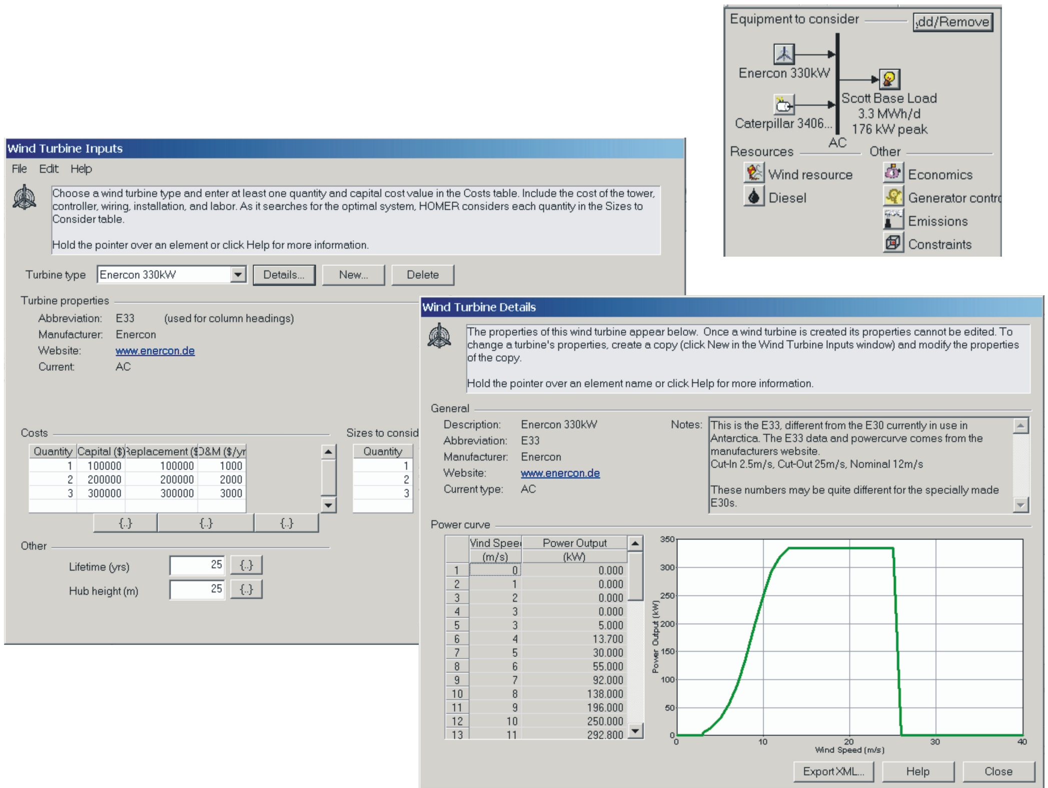


Figure 49: HOMER Wind Turbine Inputs

Further components are added as necessary to build the generating subsystem to be simulated. For wind-diesel hybrid systems, storage devices and inverters are typically considered.

4.3.2.2. Step Two

The second step to building an accurate model in HOMER is adding appropriate resource data. The resource details are those resources that each of the components listed in the power system schematic step require to operate. Resource data takes the form of fuel supply for diesel generators, wind speed distribution for wind turbines and solar radiance data for photovoltaics. As HOMER uses an hourly time-step, the resource data must also be hourly.

AN8 fuel data and hourly wind speeds for a full year are input via a graphic user interface as shown below.

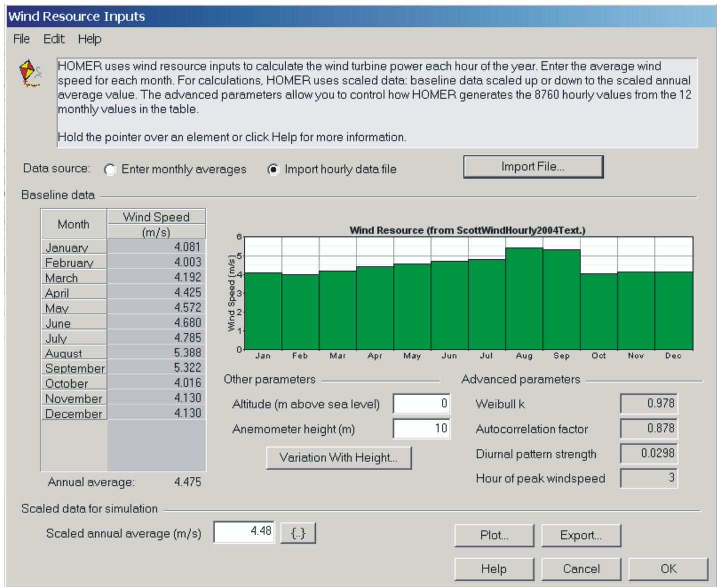


Figure 50: HOMER Wind Resource Inputs

4.3.2.3. Step Three

The final step to building an accurate energy system model is adding load data. Two primary loads, a deferrable load, a thermal load, and even a hydrogen load can be defined. It is necessary that one of the electrical loads (primary or deferrable) is defined or that the system is defined as being connected to a grid. As opposed to the resource data, the load details can be at any time-step.

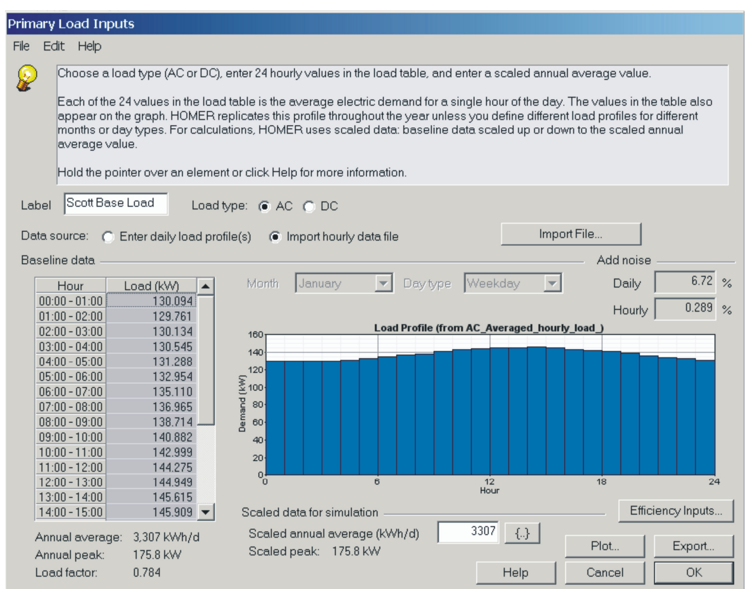


Figure 51: HOMER Load Data Inputs

4.3.3. Model Functionality

After providing HOMER with the appropriate inputs, a simulation is possible. HOMER simulates a complete year for all possible system configurations and generates results as a list of feasible configurations. These feasible configurations can then be evaluated on their technical and economic merit (National Renewable Energy Laboratory 2005). HOMER simulates an energy system with energy balance calculations for every hour of a full year. For each of the 8,760 hours in the year, HOMER compares the energy that the system can supply, based on the available resources, with the electrical and thermal demand. Furthermore, through specifications made concerning equipment operation and constraints, HOMER decides each hour how to operate the diesel generators and charge any batteries if required (National Renewable Energy Laboratory 2005). An example of how HOMER presents results for each of the feasible configurations is as follows.

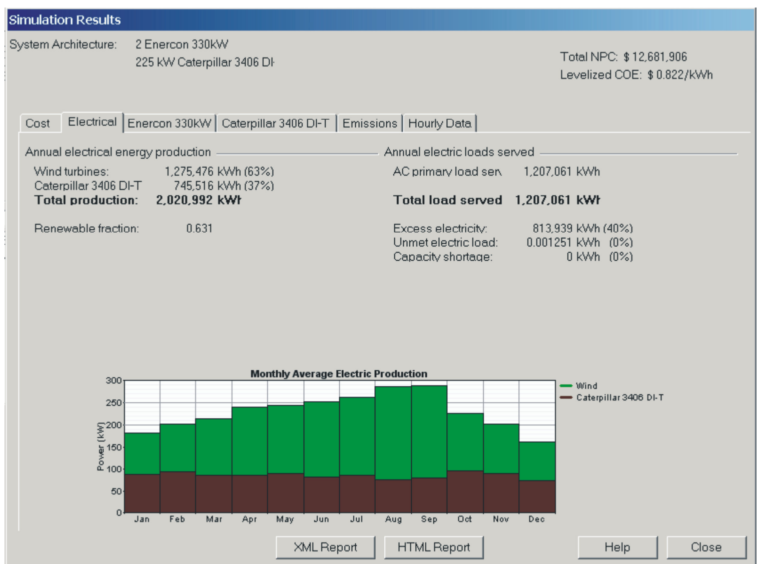


Figure 52: HOMER Simulation Results

Although higher resolution, such as a 2 minute time step, would yield greater accuracy, HOMER's hourly simulation is appropriate for the Scott Base analysis for two reasons. The first reason is that the wind data obtained for Scott Base from NIWA is hourly data; the second reason is that for the purposes of this analysis, an hourly simulation is adequate to draw overall conclusions about each potential power system's performance.

4.3.4. Demand Side Management Representation

Although within the Load category their exists an input for deferrable load, it is inappropriate for representing the demand side management technique of a load shift. Therefore, a modification to the model Scott Base energy system is necessary to represent this demand side management technique.

Before the modification to the HOMER model can be understood, an explanation of exactly what the demand side management technique entails is required. In the case of Scott Base, a specific load has been identified as appropriate for load shifting. This load is the laundry facilities. The possibility of a load shift must be evaluated at the same time-step as that of the HOMER model. Therefore, for each hour of a year the laundry facility load must be compared to the wind turbine(s) electrical production. To compare the laundry facility load with the wind turbine(s) electrical production at each time-step, a Matlab algorithm is created and used as an add-on to the HOMER model. The Matlab algorithm is structured as follows.

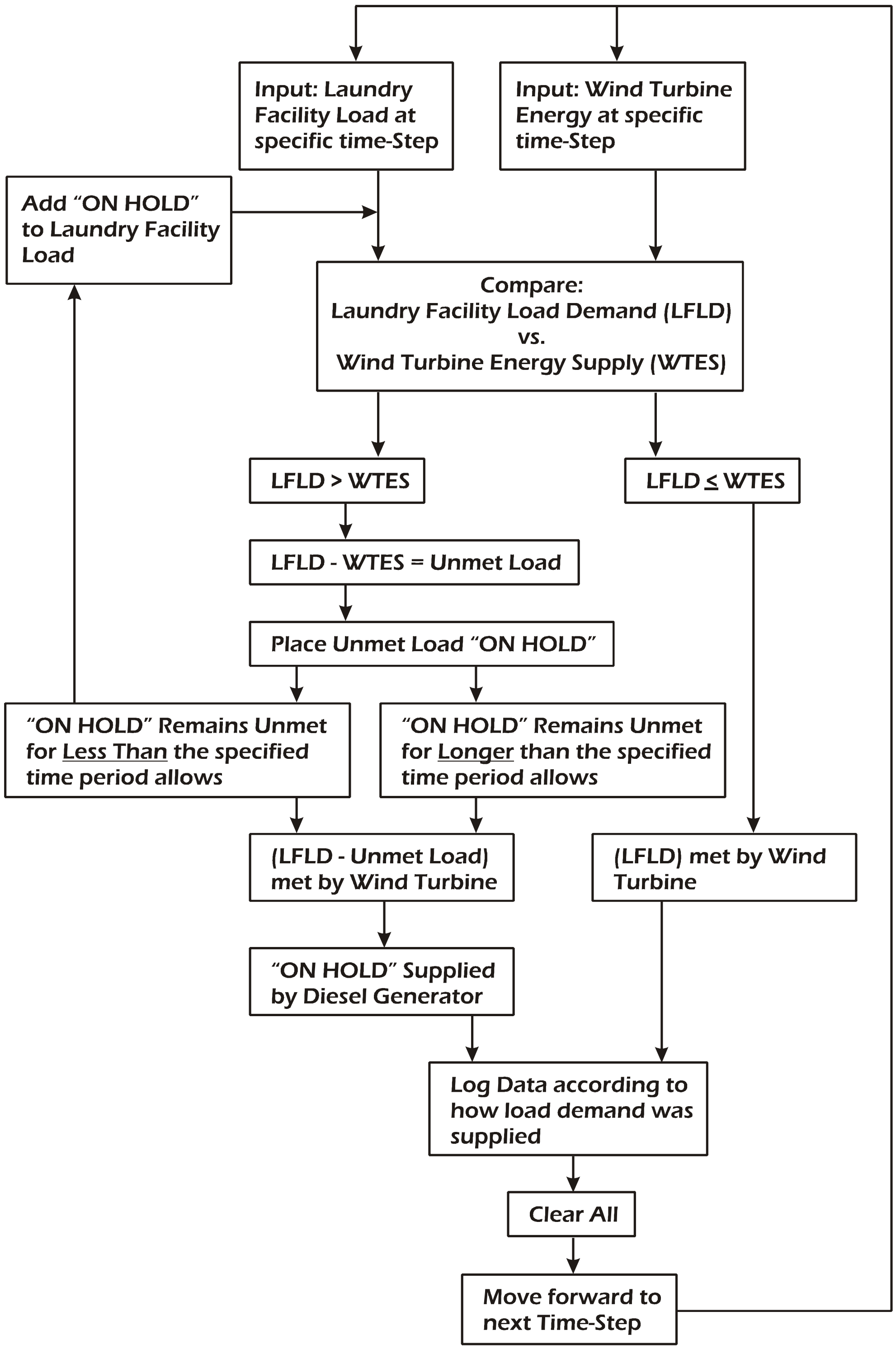


Figure 53: Load Shift Code Schematic

According to the schematic above, at each time-step the laundry facility load is compared to that of the wind turbine(s) electrical production. If the wind power available is equal or more than that of the load, the demand is met immediately by the available wind power. If the wind power available is less than that of the load, the demand is not met and is placed "on hold" until the next time-step. At the following time-step, the load to be compared to the available wind power is the sum of the original load at that time-step and the load currently "on hold". This comparative process continues for every time-step. A specific time-period is designated as the length of time the load can be kept "on hold". If there remains an unmet load "on hold" for the designated time-period, the "on hold" load is cleared by a supply of electrical power from the diesel generator. Through this process, for a specific maximum "on hold" time-period, it is possible to determine how much of the laundry facility load can be met with the available wind power and how much must be met with diesel power. See Appendix A for the complete Matlab code and comments.

4.3.5. Model Inputs

The following section describes the various inputs utilized in the HOMER model. The specifics for all the equipment considered for each power system schematic is listed and the resources of fuel supply and wind speed data are explained. Particular attention is paid to the Scott Base electrical load and how it was derived from data collected at the base in January of 2005.

4.3.5.1. Components

Diesel Generators

The following table outlines the characteristics of the 3 diesel generator sets currently in operation on Scott Base.

Caterpillar 3406 B-DIT Diesel Generator Set						
			Sample of General Performance Data			
					Fuel Rate	
Engine Power	225	KW	Power	% Load	L/hour	L/KWhour
Speed	1500	RPM	225	100	64.9	0.29
Hertz	50	Hertz	180	80	52	0.29
			135	60	40.2	0.30
			90	40	29.2	0.32

Figure 54: Diesel Generator Specifications

Wind Turbines

The design of a hybrid wind-diesel energy system is not a linear process. The ideal design process is to evaluate site characteristics, estimated future load and determine the optimal wind turbine for a given set of performance criteria. The reality is that there exists a limited availability of wind turbines in a size range appropriate for Scott Base that can withstand the extreme weather conditions.

As wind turbine technology continues to improve, the machines are growing larger. Currently in construction stages, 5MW turbines are destined for the coasts of Germany. These machines will have 414 ft. diameters and stand over 600 ft. at their highest point (Parfit 2005). The trend to go bigger and bigger stems from making the price per kilowatt to go lower and lower. To compete with existing electric generation facilities, and ultimately continue receiving investment for research and development, price per kilowatt remains the driving factor. With only the bottom line as a design guideline, most smaller wind turbines will fall out of favour and eventually become unavailable.

When considering the addition of a wind turbine to a remote area energy system, medium scale turbines are the scale at which to look. However, the choices remaining in this category (as turbines grow larger) are not many. Most of the research and development in wind turbine design in recent years has skipped the medium scale. Choices become even more limited when siting turbines in extreme climates. Fortunately, there are still medium scale wind turbine choices appropriate for extreme conditions like those of Antarctica. The following two tables outline the specifications of the two medium scale wind turbines appropriate for extreme climates. With the identified turbines, an evaluation of each potential hybrid energy system incorporating the current available technology suited for extreme climates is possible.

North Wind NW 100/19 Wind Turbine

Nominal Rated Power	100	KW	Drive Train:	Variable Speed Direct Drive
Nominal Wind Speed	15	m/s	Generator:	Salient Pole Synchronous
Cut-In Speed	4	m/s	Speed Range:	45-69 RPM
Cut-Out Speed	25	m/s		Active Yaw Control
Diameter	19.1	m/s	Braking:	Mechanical & Electrodynamic
Swept Area	284	m2		
Hub Height	25,32	m	Cost:	**$550,000**

Figure 55: North Wind NW100 Specifications (Northern 2004)

Enercon E-33 Wind Turbine

Nominal Rated Power	330	KW	Drive Train:	Enercon Direct Drive
Nominal Wind Speed	12	m/s	Generator:	Synchronous Annular
Cut-In Speed	2.5	m/s	Speed Range:	18-45 RPM
Cut-Out Speed	28-34	m/s		Active Yaw Control
Diameter	33.4	m/s	Braking:	Rotor brake & lock with 3 inde
Swept Area	876	m2		-pendent blade pitching systems
Hub Height	34-50	m	cost:	**$900,000**

Figure 56: Enercon E-33 Specifications (Enercon 2004)

4.3.5.2. Resources

Fuel:

AN8 is an aviation turbine fuel used not only to power electrical generators but also to fuel the aircraft in operation on Antarctica. AN8 is nearly identical to Jet A-1 fuel, the aircraft industry standard used worldwide by all commercial airlines (Chevron 2000). The key difference in AN8 being a fuel system icing inhibitor in its makeup. The estimated cost of AN8 for Scott Base in 2006 is $2.65 per litre. Approximately $1.50 of the total cost per litre is due to the shipping costs (Rigarlsford 2006). Scott Base purchases fuel from nearby McMurdo Station, the United States Antarctic research station. McMurdo Station has a large store of fuel due to its relatively gigantic size. The transport of fuel from McMurdo Station to Scott Base is accomplished using trucks.

Wind Speed Data:

Accurate wind speed data is paramount to the accuracy of any wind-diesel hybrid energy system model. Meridian Energy, a New Zealand power company has logged wind speed data at Scott Base since March of 2005. An anemometer, mast and data logger were purchased by Meridian Energy from the National Institute of Water and Atmospheric Research (NIWA) who have experience in Antarctic climate monitoring. NIWA operates the Scott Base weather station located 16 meters above sea level on the hill behind the base. The weather station has been operational for 35 years (National Institute of Water and Atmospheric Research 2006). Scott Base operational staff erected the mast with the anemometer at a height of 20 meters. High quality data has been collected since March of 2005 with the exact purpose of determining the wind power potential. A comparison with historical McMurdo Research Station weather data has shown the Meridian Energy wind data collected at Scott Base to be an accurate representation of the wind resource of the area (Cornelius 2006).

The data utilised in the HOMER simulations was collected between March 2005 and March 2006. The wind resource during this period has an overall mean wind speed of 7.54 meters per second or 27.1 kilometers per hour. The highest mean wind speed over an hourly span was 29.4 meters per second or 106 kilometers per hour. The following figure shows the wind speed distribution for the weather station at Scott Base.

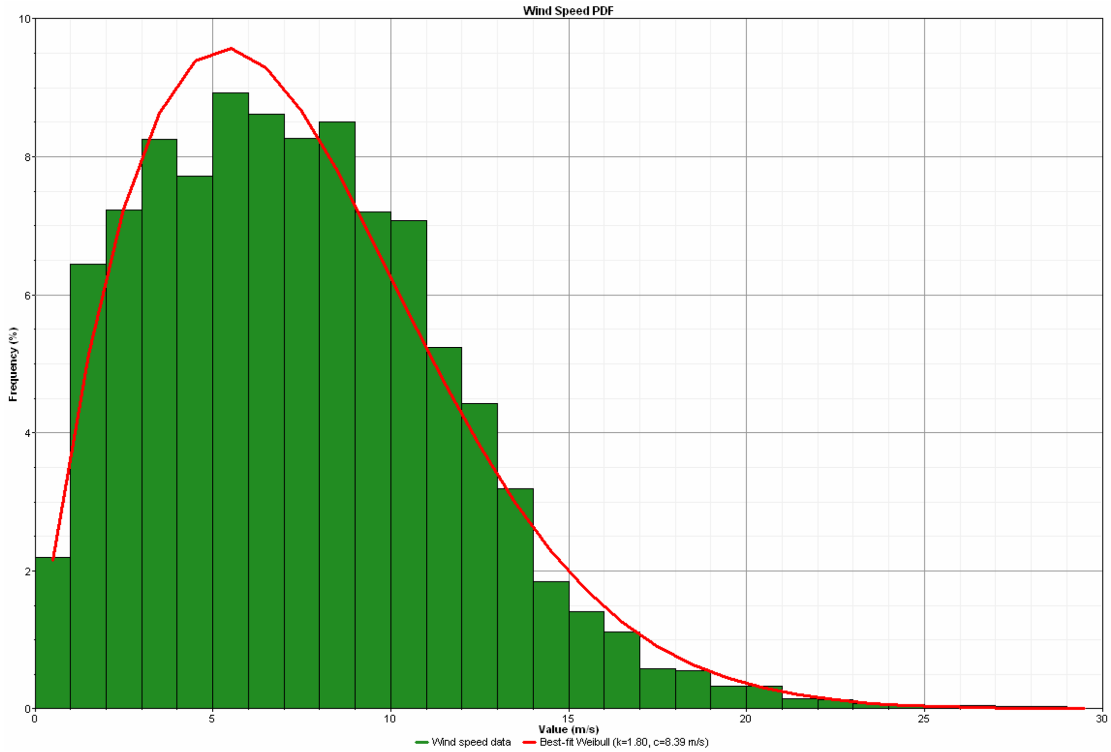


Figure 57: Scott Base Wind Resource Distribution

4.3.5.3. Loads

Electrical Load

The electrical load input for the HOMER model is not Scott Base's exact hourly load. The load input used was created with a Matlab algorithm to represent a Scott Base hourly load as close as possible to reality. This was achieved using daily load data as well as the two minute data collected from the base in December of 2004 and January of 2005. The two minute Scott Base load data is available for only a three day span. The daily load information is available for a full year, but are only daily averages. HOMER requires hourly load data. In order to create a set of hourly load data to accurately represent Scott Base, it is necessary to use the two minute data available over the three day span as a representation as to how the base operates all year round. The following is the graph of the two minute data for all of Scott Base over the three day span.

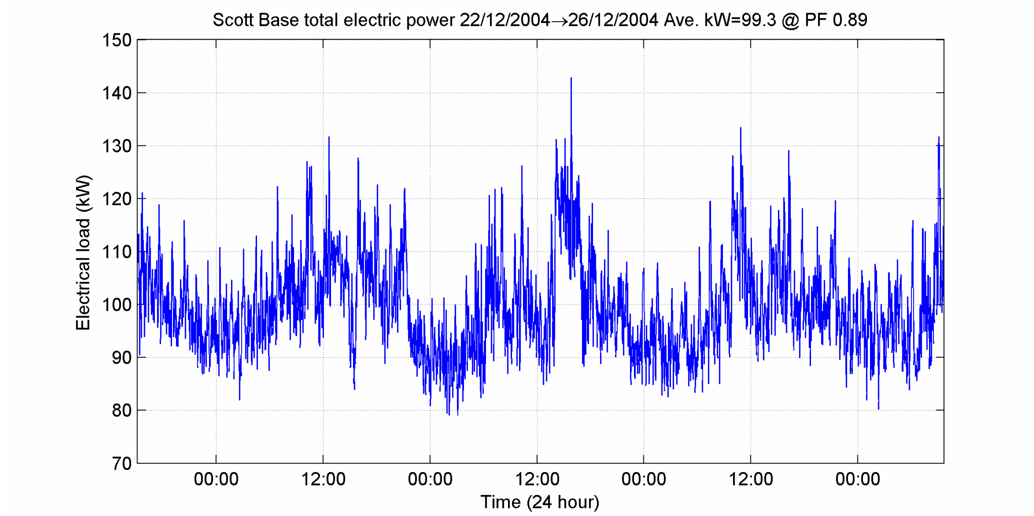


Figure 58: Scott Base Load Profile

The two minute load data has a sinusoidal shape that oscillates around the daily electrical load average. The sinusoidal load shape contains a lot of noise that is made up of spikes and dips above and below the sinusoid. These spikes and dips are repetitive and predictable. There exists a small envelope around the sinusoid with peaks of 5 kilowatts every 16 minutes and another bigger envelope with peaks of 15 kilowatts every hour (Hume 2006).

Therefore, in order to extrapolate a full year's worth of data from a three day span and daily averages, the equation of an equivalent sinusoid must be used. The following equation is an accurate representation of the Scott Base load curve.

$$\text{New Electrical Load} = 8 * \text{Cos}\left[\left(\frac{\pi}{12} * \text{Time}\right) - \pi - 0.5\right] - \text{Average Daily Electric Load} \quad (16)$$

As is illustrated in the following figure, the extrapolated load curve represents the original two minute data well. Furthermore, by basing the sinusoid around the daily averages, the overall load totals for the newly created load data is ensured to be the same as that which was collected.

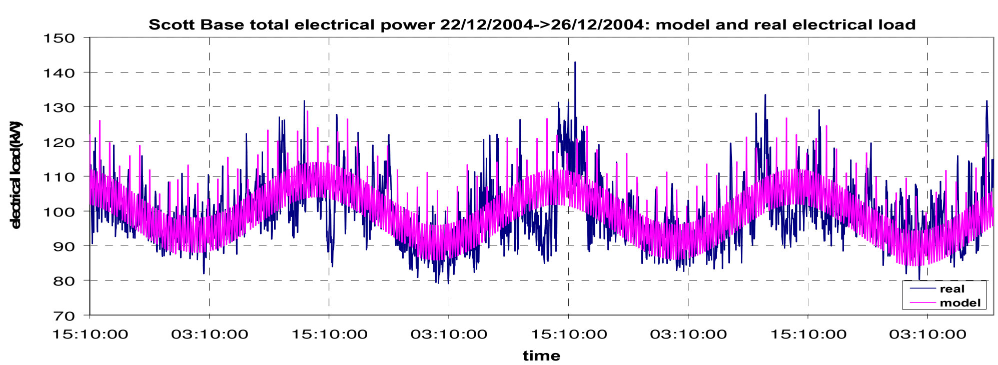


Figure 59: Extrapolated Load Model vs. Collected Data

Thermal Load

The thermal load input for the Scott Base HOMER simulation is based on temperature data and boiler fuel consumption for 2004. A relationship exists at Scott Base between the outside temperature and the thermal load at Scott Base. When outside temperatures are at their lowest, the thermal load is at its highest (Hume 2006). The relationship is illustrated in the figure below.

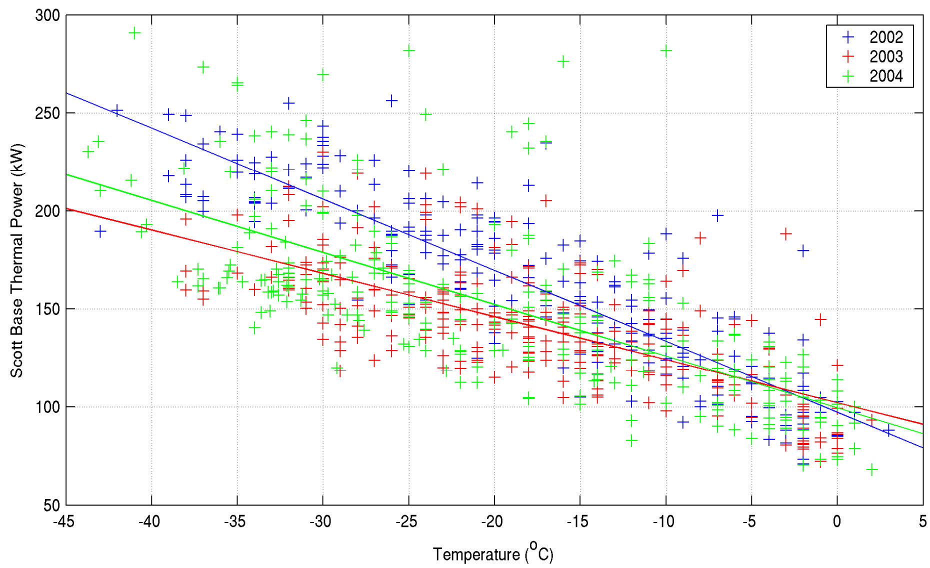


Figure 60: Scott Base Thermal Load vs. Temperature

No data exists concerning the overall Scott Base thermal load. An accurate representation of the thermal load as demanded/supplied during 2004 can be created by regarding the amount of fuel consumed by the base boilers in 2004 along with the waste heat production by the diesel generators for the same time period. The figure above allows a diurnal load pattern to be developed based on temperature data. By applying the temperature based load pattern to an overall average demand derived from generator waste heat calculations and boiler fuel consumption data, an accurate thermal load for Scott Base can be realised.

In order to create an accurate thermal load for Scott Base, appropriate temperature data is necessary. In this case, temperature data is acquired via the NIWA weather station located 16 meters above sea level behind the base (National Institute of Water and Atmospheric Research 2006). Average monthly temperatures for Scott Base are outlined in the table below.

Scott Base Average Monthly Temperatures 2005 (Celsius)					
January	February	March	April	May	June
-3.6	-11	-20.8	-26.3	-21.9	-27.6
July	August	September	October	November	December
-28.4	-31	-27.9	-19.1	-10.9	-3

Figure 61: Scott Base Average Monthly Temperatures

Calculated from data acquired by the Scott Base energy audit, the monthly thermal load as a percentage of the overall yearly thermal load is as follows:

Scott Base Thermal Load Pattern (% of total yearly load)					
January	February	March	April	May	June
6%	7%	8.5%	9.4%	8.7%	9.6%
July	August	September	October	November	December
9.8%	10%	9.6%	8.3%	7.1%	6%

Figure 62: Scott Base Monthly Thermal Loads as a Percentage of the Total

In 2004, Scott Base had an average electrical load of 137 kilowatts. The marine manifold heat exchangers on the diesel generator sets were able to collect, on average, 33% of that electrical load as waste heat (Hume 2006). Therefore, the fuel consumed by the diesel generators supplied an average of 45.2 kilowatts to the thermal load.

The total boiler fuel consumption for 2004 was 47,534 litres. The majority of time that the base boilers were necessary occurred in the winter months when temperatures are at their lowest. It is not possible to calculate the average fuel consumed by the boiler per day and add the corresponding boiler thermal output to that of the waste heat output from the diesel generators to arrive at an accurate representation of the Scott Base thermal load. The large variations based on the season mean that often in winter months waste heat from the generators is not enough to meet the thermal load and the base boilers are required; while in summer, often the boilers are unnecessary as the waste heat from the generators can meet the thermal demand. By applying the monthly load pattern established previously to the overall boiler fuel consumption, an accurate representation can be achieved. An iterative process is undertaken by applying a theoretical base thermal load average to the load pattern established by the monthly percentages. The following figure illustrates the last iteration and thus a theoretical Scott Base thermal load.

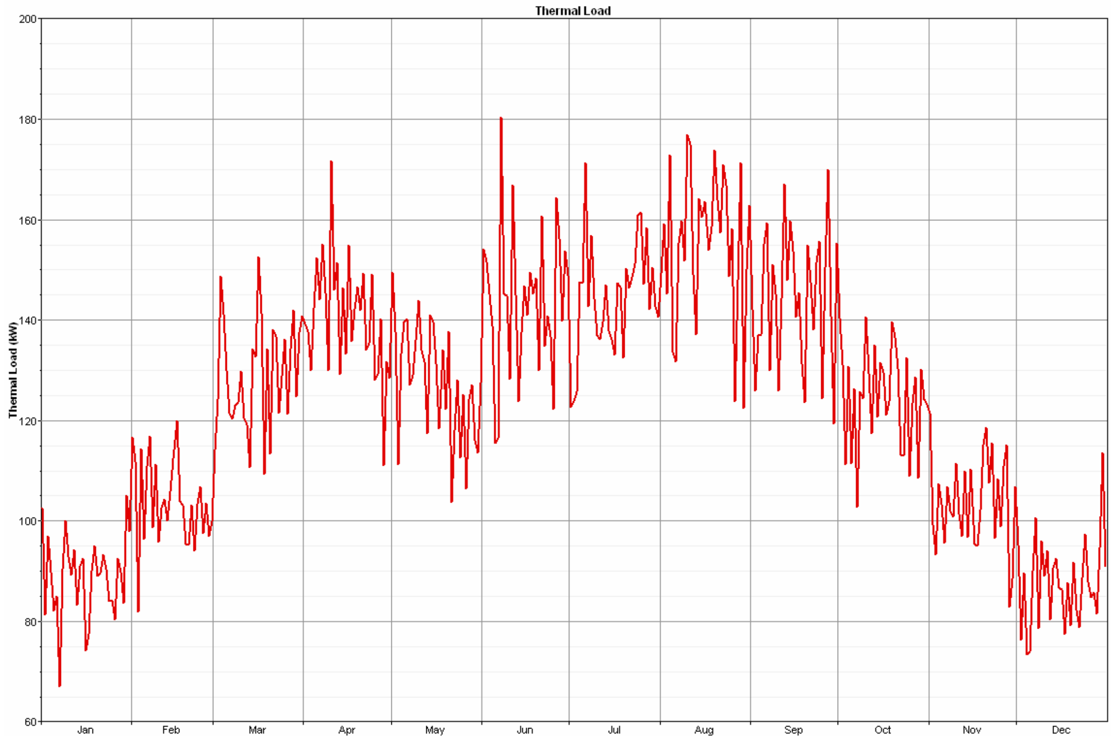


Figure 63: Simulated Scott Base Thermal Load

The theoretical thermal load above, created for use in the HOMER simulations, has an overall average of 124.6 kilowatts. Noise is introduced to modify the load slightly to more accurately reflect a fluctuating thermal demand. A 9% daily variation and 2% hourly variation are allowed and the resulting peak thermal demand is 185.7 kilowatts.

4.4.Model Validation: representing Scott Base accurately

4.4.1. Existing Energy System Model Response Benchmark

Before proceeding with the model and predicting the performance of wind-diesel hybrid energy systems for Scott Base, it is necessary to validate the HOMER model. Model validation answers the question, "can the model describe known facts and situations sufficiently well?" For the case of Scott Base, validation answers the question, "do the results of the HOMER simulation for the model of the existing Scott Base energy system match the physical data collected?"

The existing Scott Base energy system is modelled in the HOMER environment to represent the 2004 energy system. The components of the power schematic are based on the specifications for the Caterpillar 3406 B-DIT diesel generator sets and their schedule. The load data input to the simulation is extrapolated from the daily load averages collected for 2004. The fuel resource is based on specifications for aviation turbine fuel. In this way the HOMER model seeks to represent the 2004 Scott Base energy system as closely as possible. The HOMER simulation yields the following results as compared to collected data.

Scott Base 2004 Collected Data		
Total Electrical Load	1218263	kWh
Total Fuel Consumed by Generators	330291	litres
Total Fuel Consumed by Boilers	47534	litres
Total Fuel Consumed	**377825**	**litres**

HOMER 2004 Model Simulation Results		
Total Electrical Load	1207061	kWh
Total Fuel Consumed by Generators	346629	litres
Total Fuel Consumed by Boilers	45963	litres
Total Fuel Consumed	**392592**	**litres**

Figure 64: Scott Base Collected Data vs. Simulation Results

It is no surprise that the total electrical load of both systems is nearly equal. The HOMER model load input is based on the daily load averages for 2004 and should therefore be a very close approximation. The discrepancies between the total fuel consumed by the generators, in this case a 3.9% difference, can be attributed to a number of different reasons. The primary reason is most likely the efficiency of the diesel generators converting the AN8 fuel to electricity and the corresponding thermal energy recovery. The description of the diesel generators within the HOMER model are based on specifications for the Caterpillar generators and not from data collected at Scott Base. In this case, it is possible that the diesel generators at Scott Base run along a power curve slightly different than that specified by Caterpillar. Other reasons for the difference in predicted fuel consumption and the historical data could be discrepancies in the fuel properties themselves. Everything has been done to create a model as accurate as possible, however, all models make simplifications that can lead to slight differences between simulation results and collected data. For the purpose of evaluating potential wind-diesel hybrid energy systems at Scott Base, fuel consumption estimates of plus or minus 4% are within the accuracy of the model.

Validating the HOMER model also serves another purpose. The results of the HOMER 2004 model simulation sets a benchmark to compare any potential wind-diesel hybrid energy systems. Therefore, all potential hybrid energy systems will be evaluated against the benchmark model, not the 2004 collected data.

4.4.2. Hybrid Energy System Model Response

After validating the HOMER model of the existing Scott Base energy system and establishing a benchmark, the wind-diesel hybrid energy system models must be validated. Validation of the hybrid models seeks to answer the question, "is using HOMER to simulate potential wind-diesel hybrid energy systems an accurate method of predicting future performance?" This method is validated by referencing literature that describes the use of HOMER for hybrid system performance prediction.

- Klaas van Alphen creates the optimal renewable energy system design for the Maldive Islands. The Maldives are highly vulnerable to the impacts of climate change and depend heavily on petroleum imports for electricity generation. Sustainable energy is being promoted by the government. Alphen uses the system design tool HOMER to evaluate different renewable energy system alternatives. The results show that fully renewable systems are not financially viable in the Maldives. However, renewable systems supplying up to 10% of the overall electricity demand could be cost effective (Alphen et al. 2006).

- S. Rehman evaluates the potential for a wind-diesel hybrid energy system for a village in the north eastern part of Saudi Arabia. The hybrid system design tool HOMER is used to perform a feasibility study. Results show that only when average wind speeds are below 6 meters per second is a wind-diesel hybrid energy system not feasible. If carbon taxes are introduced, wind-diesel systems can be considered at lower wind speeds (Rehman et al. 2005).

- S.M. Shaahid uses HOMER in the evaluation of the implementation of photovoltaic hybrid systems on the Dhahran coast of Saudi Arabia. HOMER software is used to carry out the techno-economic viability. The investigation emphasizes excess electricity generation, fuel savings and reduction in carbon emissions(Shaahid and Elhadidy 2006).

- Mattias Henryson and Martin Svensson use HOMER to evaluate possibilities for meeting energy demands of a Swedish Antarctic research station. Results indicate that wind power for the station, located in Wasa, Antarctica, has the highest potential to be a primary energy source. The research was carried out for use by the Swedish Antarctic Research Program and the results are presented in a thesis (Henryson and Svensson 2004).

4.5. Model Analysis: applying alternate inputs to the model and studying their effects on the model outputs

4.5.1. Method for Analysis

Five system configurations, each with a different level of wind power capacity, are modelled using the standard simulation structure as well as the demand side management simulation structure. The methodology for evaluation of each proposed system is intended to identify the optimal system configuration and structure for Scott Base. Performance-objective design aims to determine the optimal wind-diesel hybrid energy design for a complex system with a human component. The characteristics of the optimal design are established in the previous section, *Experiment Design*, and represent the requirements, constraints and objectives of the energy system.

The performance-objective design system requirements are addressed in the design stage of the modelling process. No wind-diesel hybrid energy system is proposed that does not meet the system requirements. System constraints, however, may or may not be approached or surpassed by each energy system. Each proposed system is evaluated regarding the system constraints; if those constraints are surpassed, the proposed energy system is deemed not suitable for Scott Base. All proposed wind-diesel hybrid energy systems that meet system requirements and constraints are compared. The comparison and resulting ranking is based on the predicted performance of each model according to the system objectives. How close a proposed design comes to system objectives is quantified using a systems engineering technique of establishing criteria in order to evaluate each alternative. There are two types of criteria, a *measure of effectiveness* and a *measure of cost*. A measure of effectiveness is a measurement of how well an alternative action satisfies the objective. These are balanced by the measures of cost. A measure of cost is the consequence or lost opportunity due to the alternative (Khisty and Modammadi 2001).

4.5.1.1. System Requirements

- **Essential Loads Met 100%**

  All potential model designs deliver an electrical and thermal energy supply to meet 2004 Scott Base requirements. Standard, with secondary energy storage and wind power direct to thermal load all supply the Scott Base electrical and thermal loads 100% without exception. The novel demand side management technique supplies all essential base loads as demanded. However, the laundry facilities load is identified as time-flexible and is coordinated with available wind power. The laundry facility load is always supplied, but only within certain time limits.
- **Reliable in Environment**

  All models propose only components suitable for Antarctic installation.
- **Utilise Wind Power**

  All models propose a certain level of wind power capacity corresponding to a specific number of extreme cold climate wind turbines.

4.5.1.2. System Constraints

- **Fuel Use**

  Total predicted fuel use will not be greater than that of the current diesel based system currently utilised at Scott Base, 379,000 litres per year.
- **Power Quality**

  A level of power quality must be maintained for the safety of the base staff and equipment. Outages are unacceptable; likewise, limits on slow voltage variations, voltage dips and flicker are necessary. These characteristics must be maintained within acceptable levels. Average Wind Penetration and Maximum Instantaneous Wind Penetration are quantifiable variables with a direct correlation to power quality. As outlined previously, the greater the value of Average Wind Penetration and Maximum Instantaneous Wind Penetration, the more power conditioning equipment necessary to meet the power quality requirements. The constraint level for Average Wind Penetration is 50%. The constraint level for Maximum Instantaneous Wind Penetration is 100%. However, Maximum Instantaneous Wind Penetration values above 100% are permissible, but only for very short periods of time. Therefore, the Maximum Instantaneous Wind Penetration constraint is below 100% for 95% of the simulated year. Time spent above the Instantaneous Wind Penetration limit of 100% represents surplus energy being generated by the wind-diesel hybrid energy system.

- **Diesel Generator Operation**

  The Minimum Diesel Load is 30% of generator rated power (225kW) and thus 67.5 kilowatts.

4.5.1.3. System Objectives

- **Measure of Effectiveness**

  The measure of effectiveness for any proposed wind-diesel hybrid energy system for Scott Base is predicted annual fuel savings in litres. Representing not only an economic value, total fuel consumption savings also has a direct relationship with risk of fuel spills, carbon dioxide emissions and the reliance on a fossil fuel with an insecure supply chain.

- **Measure of Cost**

  The consequences of selecting one alternative instead of another is quantified by a measure of cost. In the case of wind-diesel hybrid energy systems for Scott Base, this measure of cost is represented by the proposed average economic cost savings of each system configuration. The economic cost savings of a proposed system configuration is equal to the difference between the average annual cost of that system and the existing Scott Base system. This average annual cost savings includes predicted fuel costs and capital costs of any new equipment necessary averaged over the predicted Antarctic lifecycle of the equipment (30 years). Therefore, the measure of cost for each proposed system is represented as follows:

  Averaged Annual Economic Cost Savings:

  A.A.E.C.S. = ($ Base Case) - ($ Fuel Use) + ($ Equipment Capital Costs / 30)

Economic data used to determine each system's measure of cost, such as the cost of AN8 fuel, has been gathered through a literature review of relevant Antarctic projects and personal communication with Scott Base staff. Kevin Rigarlsford, a maintenance engineer for Antarctic New Zealand, states the overall cost of supplying Scott Base with AN8 fuel at $2.65NZD per liter. This price includes the shipping costs, approximately $1.50NZD per liter (Rigarlsford 2006). The measure of cost for each proposed system does not take into account inflation or potential increases in materials and fuel costs.

An important characteristic of each proposed hybrid energy system that average annual economic cost does not take into account is system complexity. In an environment such as Scott Base, minor mechanical problems can become major issues due to base isolation and the infrequency of equipment supply. Therefore, the addition of generation equipment to the existing Scott Base energy system should be of a relatively simple design. The economic cost of a complex system is not just the capital cost of the extra equipment necessary. In order to compare the different proposed wind-diesel energy systems, a ranking is used to describe the level of complexity. This complexity ranking is from 1 to 5 with 5 being extremely complex and 1 being relatively simple.

4.6.Methodology Summary

4.6.1. Summary

Using models to represent a potential wind-diesel hybrid energy system is a major part of the research project. The correct method of modelling has five steps. The first step is *systems analysis*. The Scott Base energy system is analyzed through its individual stage loads. Ten stages make up the electrical and thermal energy demand of Scott Base. The second step is *experimental design* which outlines what is to be done and why. The third step is, *model construction*. The HOMER (Hybrid Optimization Model Energy Resource) simulation tool is utilized to model each of the proposed energy systems. After models are constructed, annual Scott Base fuel consumption is simulated for the existing energy system as well as the proposed wind-diesel hybrid energy systems. A technique is also developed to incorporate load shifting into the HOMER simulation process. The third step is *validation* of the model. This is accomplished by comparing modelled results with data collected in the field for the existing energy system. For the hybrid energy systems, a literature review highlighting the use of HOMER for hybrid system feasibility and sizing was conducted. The final step in the modelling process is *model analysis*. A systems engineering approach is utilized to analyse each of the proposed energy system configurations. A set of measures of effectiveness and a measure of cost are determined for each configuration to establish how well the objective is satisfied. Although this study focuses solely on Scott Base, the methodology is appropriate for all remote locations with a diesel based energy system and a desire to reduce fuel consumption.

5. Results and Discussion

Each proposed hybrid energy system model represents a configuration of equipment for use at Scott Base to meet its energy demand. The first model simulated using HOMER, the hybrid system evaluation tool, is the representation of Scott Base's existing energy system consisting of two main diesel generators and one back-up. The following models of proposed hybrid energy systems contain one or more wind turbines along with the existing generators. Each model is simulated over a time period of one year and utilizes the same sets of input data. The results of each simulation are predicted amounts over the course of one year.

The following chapter reports the results of each of the proposed hybrid system simulations as well as the existing Scott Base energy system for use as a benchmark. The proposed systems are evaluated based on the systems engineering method of analysis outlined in the *Model Analysis* section of Chapter 4; an overall measure of effectiveness will be weighed against a measure of cost. A discussion of how each proposed system effectively meets the performance objectives is included for each simulation structure. This discussion within each subsection is important as it represents the culmination of all efforts made to determine the answer to each of the two questions that make up the thesis problem statement:

1. With respect to current wind turbine technology, what wind-diesel hybrid energy system is appropriate for installation at Scott Base?

2. If feedback from the proposed hybrid energy system is made available to influence certain Scott Base electric loads, can further fuel savings be realised?

5.1. Existing Scott Base Energy System

The first set of results are those of the existing Scott Base energy system. The diesel only system supplies 100% of the Scott Base electrical and thermal load with Caterpillar generator sets and boilers. The following data sets the base case values for all other proposed systems to be evaluated against.

Model #1	**Existing Scott Base Energy System Model**	
Components:	Caterpillar 3406 B-DIT Diesel Generator Set	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
Load Input:	Extrapolated Scott Base Overall Load Temperature Based Thermal Load	(see Appendix B)

Model #1: **Existing Base Case**		Standard Structure
Total Predicted Fuel Consumption:	**392592**	Litres
Generator Fuel Consumption:	346629	L
Boiler Fuel Consumption:	45963	L
Average Wind Penetration:	**-**	%
Max. Instantaneous Wind Penetration:	**-**	%
Time Below 100% Max Inst. Wind Pen.	-	%
Caterpillar Generators & Boiler Production		
Total Electrical Power Generated:	1207061	kWh
Average Electrical Power Generated:	137.8	kW
Maximum Electrical Power Generated:	83.9	kW
Average Electrical Efficiency:	35.9	%
Minimum Generator Load:	37.3	%
Total Thermal Production:	1094769	kWh
Generator Thermal Production:	710021	kWh
Boiler Thermal Production:	384748	kWh

Total Fuel Consumption = 392,592 L

- **Measures of Effectiveness = 0 L (Total Fuel Savings per Year)**

Annual Economic Cost = $1,040,368

- **Measure of Cost = $0 (Total Cost Savings per Year)**

5.2.Standard Results

5.2.1. Model Simulation Data

Simulated over the course of one full year, the following results represent the predicted performance of the five proposed wind-diesel hybrid energy system models. Using the standard simulation structure, any wind generated electricity is supplied to the Scott Base electrical load with the generator sets supplying any unmet demand. A 30% minimum diesel load is enforced to ensure the generator set's life-spans are not adversely effected by low loading. After supplying the electrical load, excess wind energy is applied to the base thermal load with the remaining thermal demand being supplied by recovered heat from the generator sets and the base boilers. In each model the Scott Base electrical and thermal demand are met 100% with a combination of the diesel generators, boilers and wind turbines. Any remaining wind generated electricity in excess of the electrical and thermal demand is considered surplus.

Model #2	**Hybrid Energy System Model with One Northwind 100kW Wind Turbine**	
Components:	Caterpillar 3406 B-DIT Diesel Generator Set	(see *Components* section of Chapter 4)
	North Wind NW 100/19 Wind Turbine	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Extrapolated Scott Base Overall Load	(see Appendix B)
	Temperature Based Thermal Load	

Model #2: One Northwind Turbine			Standard Structure
Total Predicted Fuel Consumption:	**331151**	Litres	
Generator Fuel Consumption:	274731	L	
Boiler Fuel Consumption:	56420	L	
Average Wind Penetration:	**23.8**	%	
Max. Instantaneous Wind Penetration:	**58.1**	%	**Meets System**
Time Below 100% Max Inst. Wind Pen.	**100**	%	**Constraints**
Caterpillar Generators & Boiler Production			
Total Electrical Power Generated:	919703	kWh	
Average Electrical Power Generated:	105	kW	
Maximum Electrical Power Generated:	67.5	kW	
Average Electrical Efficiency:	34.5	%	
Minimum Generator Load:	30	%	
Total Thermal Production:	1047221	kWh	
Generator Thermal Production:	574947	kWh	
Boiler Thermal Production:	472274	kWh	
(1) Northwind 100 Wind Tubine Production			
Total Power Generated:	337573	kWh	
Surplus Wind Generation:	50218	kWh	
Average Power Generated:	38.5	kW	
Maximum Power Generated:	102	kW	
Surplus Applied to Thermal Load:	47412	kW	
Hours in Operation:	6963	hours	

Total Fuel Consumption = 331,151 L

- **Measures of Effectiveness = 61,441 L (Total Fuel Savings per Year)**

Annual Economic Cost = $895,883

- **Measure of Cost = $144,485 (Total Cost Savings per Year)**

See Appendix D for graphical representation of electrical and thermal load supply simulation.

Model #3	Hybrid Energy System Model with Two Northwind 100kW Wind Turbines

Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	North Wind NW 100/19 Wind Turbine	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Extrapolated Scott Base Overall Load	(see Appendix B)
	Temperature Based Thermal Load	

Model #3: Two Northwind Turbines			Standard Structure
Total Predicted Fuel Consumption:	**295556**	Litres	
Generator Fuel Consumption:	255028	L	
Boiler Fuel Consumption:	40528	L	
Average Wind Penetration:	**30.3**	%	
Max. Instantaneous Wind Penetration:	**116.3**	%	**Meets System Constraints**
Time Below 100% Max Inst. Wind Pen.	**99.3**	%	
Caterpillar Generators & Boiler Production			
Total Electrical Power Generated:	841083	kWh	
Average Electrical Power Generated:	96.1	kW	
Maximum Electrical Power Generated:	67.5	kW	
Average Electrical Efficiency:	34	%	
Minimum Generator Load:	30	%	
Total Thermal Production:	877101	kWh	
Generator Thermal Production:	537854	kWh	
Boiler Thermal Production:	339247	kWh	
(2) Northwind 100 Wind Tubines Production			
Total Power Generated:	675147	kWh	
Surplus Wind Generation:	309172	kWh	
Average Power Generated:	77.1	kW	
Maximum Power Generated:	204	kW	
Surplus Applied to Thermal Load:	217533	kW	
Hours in Operation:	6963	hours	

Total Fuel Consumption = 295,556 L

- **Measures of Effectiveness = 97,036 L (Total Fuel Savings per Year)**

Annual Economic Cost = $819,889

- **Measure of Cost = $220,479 (Total Cost Savings per Year)**

See Appendix D for graphical representation of electrical and thermal load supply simulation.

Model #4	Hybrid Energy System Model w/ Three Northwind 100kW Wind Turbines	
Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	North Wind NW 100/19 Wind Turbine	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Extrapolated Scott Base Overall Load	(see Appendix B)
	Temperature Based Thermal Load	

Model #4: Three Northwind Turbines			Standard Structure
Total Predicted Fuel Consumption:	**270064**	Litres	
Generator Fuel Consumption:	237216	L	
Boiler Fuel Consumption:	32848	L	
Average Wind Penetration:	**35.4**	%	
Max. Instantaneous Wind Penetration:	**174.4**	%	**Does Not Meet**
Time Below 100% Max Inst. Wind Pen.	**85.0**	%	**System Constraints**
Caterpillar Generators & Boiler Production			
Total Electrical Power Generated:	779319	kWh	
Average Electrical Power Generated:	94	kW	
Maximum Electrical Power Generated:	67.5	kW	
Average Electrical Efficiency:	33.9	%	
Minimum Generator Load:	30	%	
Total Thermal Production:	776242	kWh	
Generator Thermal Production:	501283	kWh	
Boiler Thermal Production:	274959	kWh	
(3) Northwind 100 Wind Tubines Production			
Total Power Generated:	1012720	kWh	
Surplus Wind Generation:	584982	kWh	
Average Power Generated:	115.6	kW	
Maximum Power Generated:	306	kW	
Wind Power Applied to Thermal Load:	318392	kW	
Hours in Operation:	6963	hours	

Total Fuel Consumption = 270,064 L

- **Measures of Effectiveness = 122,528 L (Total Fuel Savings per Year)**

Annual Economic Cost = $770,700

- **Measure of Cost = $269,668 (Total Cost Savings per Year)**

See Appendix D for graphical representation of electrical and thermal load supply simulation.

Model #5	Hybrid Energy System Model with One Enercon 330kW Wind Turbine	
Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	Enercon E-33 Wind Turbine	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Extrapolated Scott Base Overall Load	(see Appendix B)
	Temperature Based Thermal Load	

Model #5: One Enercon Turbine			Standard Structure
Total Predicted Fuel Consumption:	**219907**	Litres	
Generator Fuel Consumption:	191750	L	
Boiler Fuel Consumption:	28157	L	
Average Wind Penetration:	**47.8**	%	
Max. Instantaneous Wind Penetration:	**194.4**	%	**Does Not Meet**
Time Below 100% Max Inst. Wind Pen.	**67.0**	%	**System Constraints**
Caterpillar Generators & Boiler Production			
Total Electrical Power Generated:	629489	kWh	
Average Electrical Power Generated:	93.6	kW	
Maximum Electrical Power Generated:	67.5	kW	
Average Electrical Efficiency:	33.9	%	
Minimum Generator Load:	30	%	
Total Thermal Production:	641057	kWh	
Generator Thermal Production:	405364	kWh	
Boiler Thermal Production:	235693	kWh	
(1) Enercon E-33 Wind Tubine Production			
Total Power Generated:	1395693	kWh	
Surplus Wind Generation:	818125	kWh	
Average Power Generated:	159.3	kW	
Maximum Power Generated:	335	kW	
Wind Power Applied to Thermal Load:	453578	kW	
Hours in Operation:	7576	hours	

Total Fuel Consumption = 219,907 L

- **Measures of Effectiveness = 172,685 L (Total Fuel Savings per Year)**

Annual Economic Cost = $612,754

- **Measure of Cost = $427,614 (Total Cost Savings per Year)**

See Appendix D for graphical representation of electrical and thermal load supply simulation.

Model #6	Hybrid Energy System Model with Two Enercon 330kW Wind Turbines

Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	Enercon E-33 Wind Turbine	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Extrapolated Scott Base Overall Load	(see Appendix B)
	Temperature Based Thermal Load	

Model #6: Two Enercon Turbines			Standard Structure
Total Predicted Fuel Consumption:	**154766**	Litres	
Generator Fuel Consumption:	133924	L	
Boiler Fuel Consumption:	20842	L	
Average Wind Penetration:	**63.3**	%	
Max. Instantaneous Wind Penetration:	**388.8**	%	**Does Not Meet**
Time Below 100% Max Inst. Wind Pen.	**49.4**	%	**System Constraints**
Caterpillar Generators & Boiler Production			
Total Electrical Power Generated:	442764	kWh	
Average Electrical Power Generated:	97.5	kW	
Maximum Electrical Power Generated:	67.5	kW	
Average Electrical Efficiency:	34.1	%	
Minimum Generator Load:	30	%	
Total Thermal Production:	456570	kWh	
Generator Thermal Production:	282104	kWh	
Boiler Thermal Production:	174466	kWh	
(2) Enercon E-33 Wind Tubines Production			
Total Power Generated:	2791386	kWh	
Surplus Wind Generation:	2027093	kWh	
Average Power Generated:	319	kW	
Maximum Power Generated:	670	kW	
Wind Power Applied to Thermal Load:	638064	kW	
Hours in Operation:	7576	hours	

Total Fuel Consumption = 154,766 L

- **Measures of Effectiveness = 237,826 L (Total Fuel Savings per Year)**

Annual Economic Cost = $470,130

- **Measure of Cost = $570,238 (Total Cost Savings per Year)**

See Appendix D for graphical representation of electrical and thermal load supply simulation.

5.2.2. Discussion

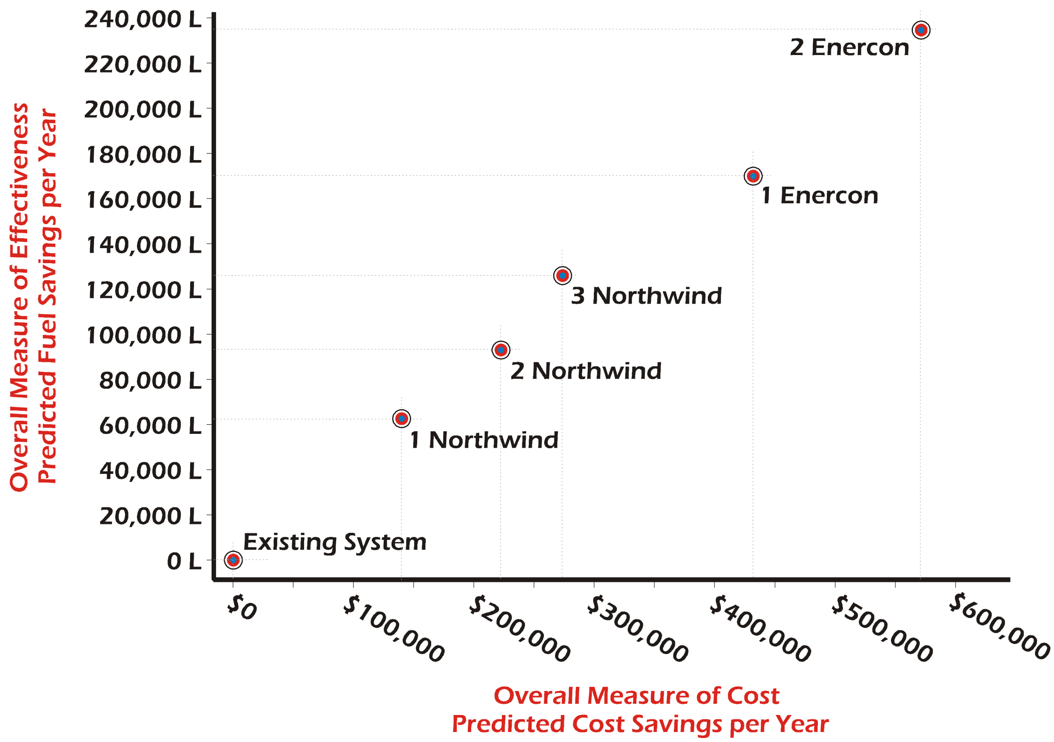


Figure 65: Standard Simulation Results Matrix

As can be seen in the graph above, as proposed wind power capacity increases from a single 100kW turbine to (2) 330kW turbines, predicted annual fuel savings and annual economic savings increases. In accordance with the performance objective design methodology, determining the optimal hybrid energy system for Scott Base is not only based on the predicted fuel and economic savings (system objectives), but also system requirements and constraints. All proposed models meet the system requirements of utilising wind power, being reliable in the Antarctic environment and meeting all essential loads. However, only two proposed models performs within the boundaries of the identified system constraints.

System constraints represent limits on fuel consumption, power quality assurances and generator reliability. All proposed models are within fuel consumption limits and maintain a minimum diesel load of 30%. Only models #2 and #3, the wind-diesel hybrid energy systems consisting of one and two Northwind 100kW wind turbines, operates within the power quality constraints as quantified by the average wind penetration and instantaneous wind penetration. Only Model #6 is predicted to operate above the average wind penetration constraint of 50%. However, only models #2 and #3 are predicted to operate below the instantaneous wind penetration constraint of 100% for at least 95% of the simulation.

Predicted fuel use for all models follows an expected pattern with only one exception, as wind power capacity increases, predicted generator and boiler fuel use decreases. The exception is for Model #2 where predicted boiler fuel use increases with the addition of a 100kW turbine. This highlights the potential problem of adding wind power to an energy system partly dependent on recovered waste heat to supply a thermal load. However, Model #3, with 200 kW of wind power capacity, predicts a decrease in boiler fuel use. Therefore, unless Scott Base is comfortable with an increased dependence on the boilers, more than 100 kW of installed wind capacity is necessary.

5.3.Demand Side Management Results

5.3.1. __Model Simulation Data__

The demand side management simulation structure is evaluated to determine potential fuel savings if a novel laundry facilities load shifting technique were implemented at Scott Base. This novel technique is a theoretical automation of the laundry facilities at the base. As described previously, the laundry service would be time-flexible; thus if wind generated electricity was not available then the laundry service is delayed. This load management might be possible with a signal device for users to obey or automatically with a ripple control style switch. By coordinating available wind power with the laundry load, surplus wind power, which may have otherwise been unused, may be applied to a time flexible service such as the base laundry. Results are illustrated with a graph of additional fuel savings predicted versus allowed time delay.

Model #2(DSM)	Hybrid Energy System Model with One Northwind 100kW Wind Turbine and Laundry Facility Load Shifting

Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	Northwind 100 Wind Turbine	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Overall Load LESS Laundry Load	(see Appendix B)
	Laundry Facility Load	(see Appendix B)
	Temperature Based Thermal Load	

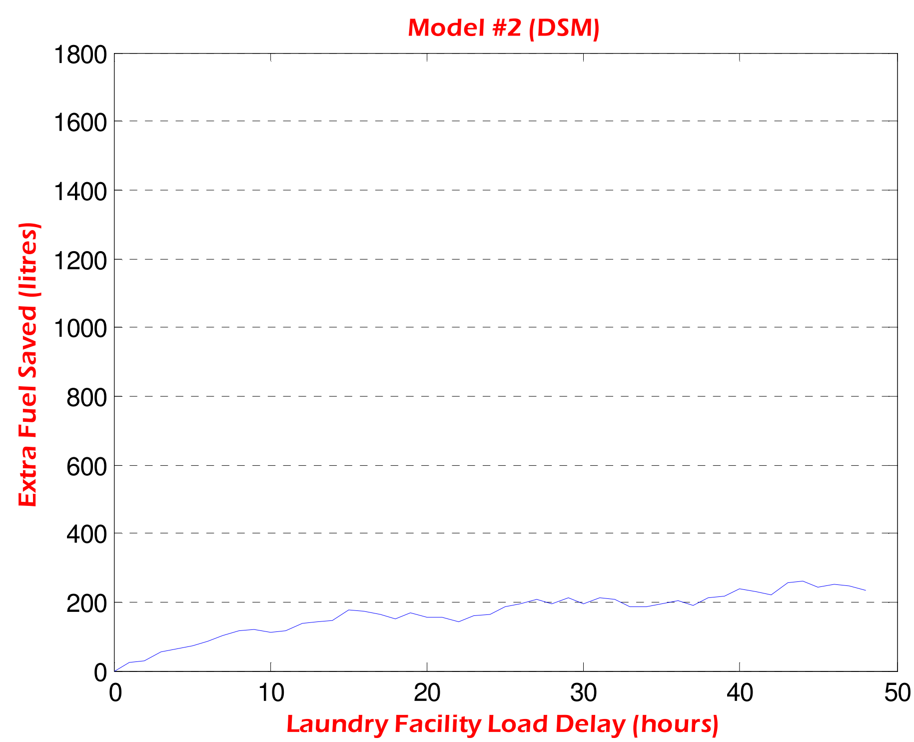


Figure 66: Model #2 Demand Side Management Results

Model #3(DSM)	**Hybrid Energy System Model with Two Northwind 100kW Wind Turbines and Laundry Facility Load Shifting**

Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	Northwind 100 Wind Turbines	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Overall Load LESS Laundry Load	(see Appendix B)
	Laundry Facility Load	(see Appendix B)
	Temperature Based Thermal Load	

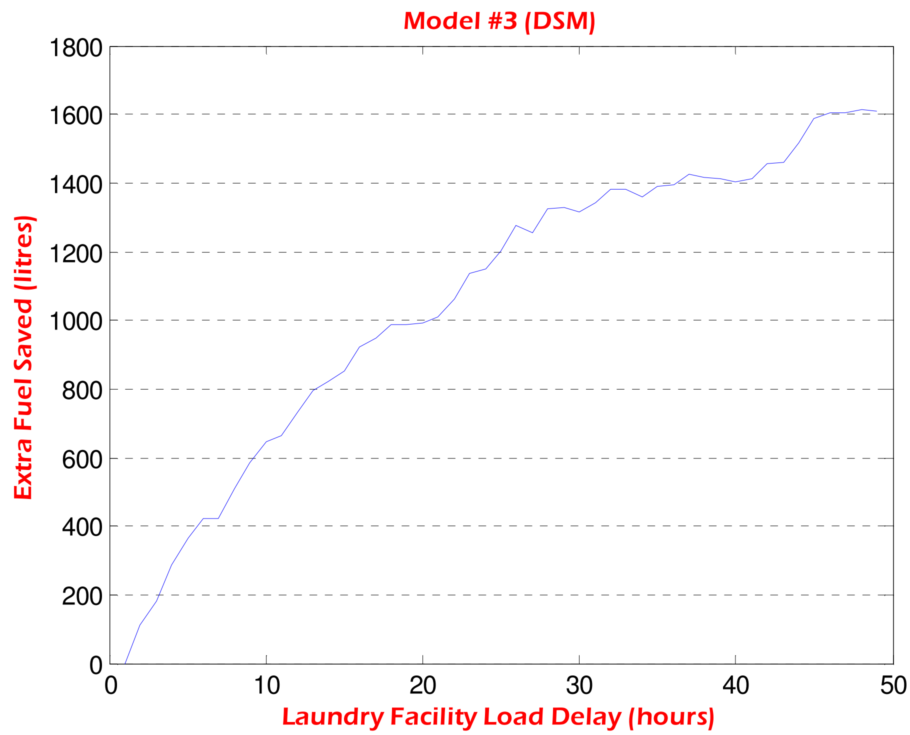


Figure 67: Model #3 Demand Side Management Results

Model #4(DSM)	Hybrid Energy System Model with Three Northwind 100kW Wind Turbines and Laundry Facility Load Shifting

Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	Northwind 100 Wind Turbines	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Overall Load LESS Laundry Load	(see Appendix B)
	Laundry Facility Load	(see Appendix B)
	Temperature Based Thermal Load	

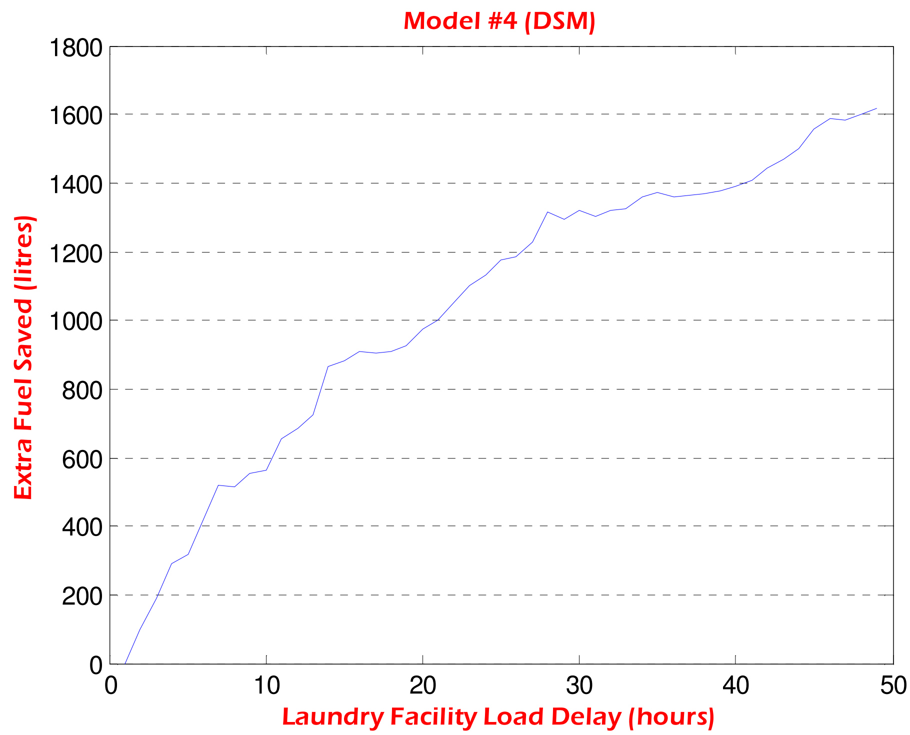


Figure 68: Model #4 Demand Side Management Results

Model #5(DSM)	**Hybrid Energy System Model with One Enercon 330kW Wind Turbine and Laundry Facility Load Shifting**

Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	Enercon E-33 Wind Turbine	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Overall Load LESS Laundry Load	(see Appendix B)
	Laundry Facility Load	(see Appendix B)
	Temperature Based Thermal Load	

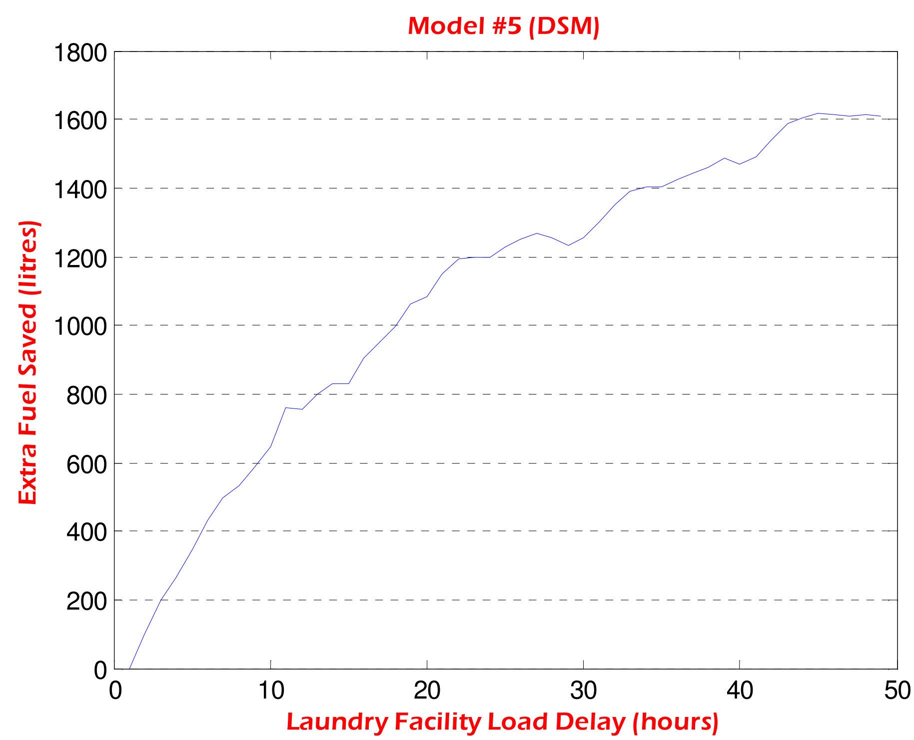


Figure 69: Model #5 Demand Side Management Results

Model #6(DSM)	Hybrid Energy System Model with Two Enercon 330kW Wind Turbines and Laundry Facility Load Shifting

Components:	Caterpillar 3406 Diesel Generator Set	(see *Components* section of Chapter 4)
	Enercon E-33 Wind Turbines	(see *Components* section of Chapter 4)
Data Inputs:	AN8 Fuel	(see *Resources* section of Chapter 4)
	Scott Base Wind Data	
Load Input:	Overall Load LESS Laundry Load	(see Appendix B)
	Laundry Facility Load	(see Appendix B)
	Temperature Based Thermal Load	

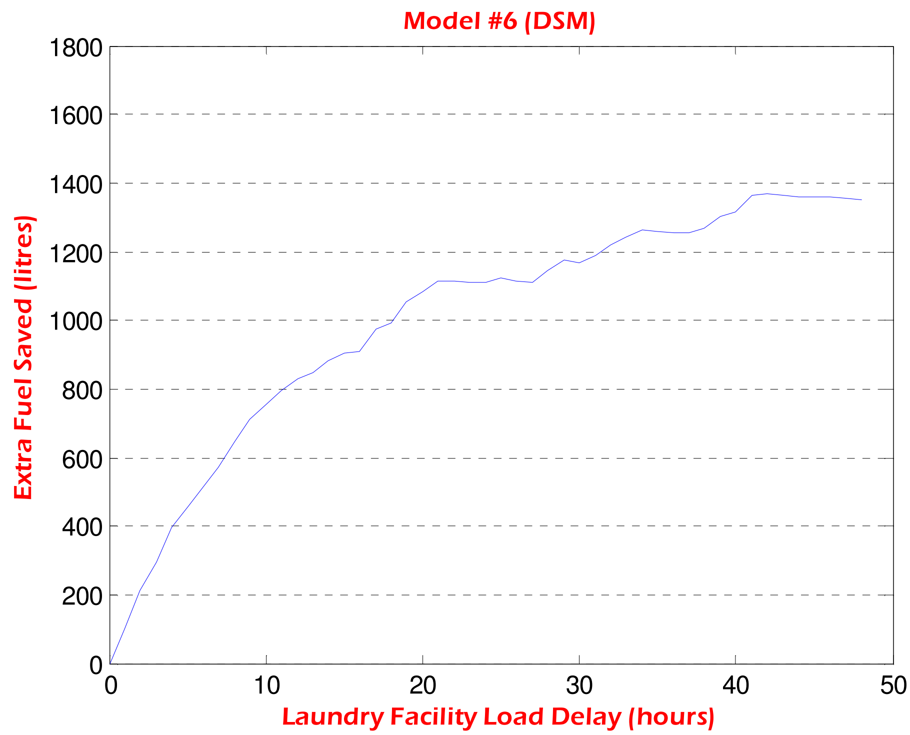


Figure 70: Model #6 Demand Side Management Results

5.3.2. Discussion

Each model proposed in the previous section represents a wind-diesel hybrid energy system for Scott Base utilising a novel demand side management technique of coordinating the laundry facilities load with that of the wind turbine electricity generation. Each model specification is followed by a graph of the predicted extra fuel savings versus load delay. Full simulation results, showing predicted fuel consumption, wind penetrations and extra power saved for each level of load delay, can be found in Appendix C. Each proposed model is evaluated for load delay periods from zero hours to 48 hours. In all cases, if the laundry facility load is not met by wind generated electricity in the specified period of time, it is met with the generators. In this way, the laundry service is always provided within the specified time period.

Model #2 incorporating the novel demand side management technique is predicted to save an additional 50 litres of AN8 fuel per year allowing a 5 hour laundry facility load delay. Increasing the allowable load delay increases the predicted extra fuel savings. Other models with higher wind power capacities, such as Model #5 with 330kW, are predicted to save a greater amount of fuel than Model #2 but do not meet the constraints of the performance objective design methodology. As with the standard simulation structure, only models #2 and #3 are predicted to operate within the system constraints.

5.4. Alternative Simulation Structure Discussion

5.4.1. Wind Generated Electricity Direct to Thermal Load

Alternate structures exist for each model to meet the Scott Base load demands. One such alternative is supplying the base thermal load primarily with wind generated electricity. In this structure wind generated electricity supplies the base thermal load first. After the thermal load is supplied any excess wind generated electricity supplies the base electrical load. This structure seeks to minimise the dependence on the base boilers to meet the thermal load if recovered heat from the generators decreases due to added wind power. The issue is highlighted for Model #2 with a standard simulation structure. In this case, with the addition of one Northwind 100kW wind turbine, predicted boiler fuel use increases compared to the existing system. As illustrated in the following tables, predicted boiler fuel consumption is greatly reduced as wind capacity is increased for this simulation structure.

Model #2:	One Northwind Turbine	Wind Generated Electricity Direct to Thermal Load
Predicted Fuel Savings per Year:	**25845**	**Litres**
Total Predicted Fuel Consumption:	366747	L
Generator Fuel Consumption:	345936	L
Boiler Fuel Consumption:	20811	L

Model #3:	Two Northwind Turbines	Wind Generated Electricity Direct to Thermal Load
Predicted Fuel Savings per Year:	**57540**	**Litres**
Total Predicted Fuel Consumption:	335052	L
Generator Fuel Consumption:	318897	L
Boiler Fuel Consumption:	16155	L

Model #4:	Three Northwind Turbines	Wind Generated Electricity Direct to Thermal Load
Predicted Fuel Savings per Year:	**84331**	**Litres**
Total Predicted Fuel Consumption:	308261	L
Generator Fuel Consumption:	294064	L
Boiler Fuel Consumption:	14197	L

Model #5:	One Enercon Turbine	Wind Generated Electricity Direct to Thermal Load
Predicted Fuel Savings per Year:	**105633**	**Litres**
Total Predicted Fuel Consumption:	286959	L
Generator Fuel Consumption:	276142	L
Boiler Fuel Consumption:	10817	L

Model #6:	Two Enercon Turbines	Wind Generated Electricity Direct to Thermal Load
Predicted Fuel Savings per Year:	**130556**	**Litres**
Total Predicted Fuel Consumption:	262036	L
Generator Fuel Consumption:	253702	L
Boiler Fuel Consumption:	8334	L

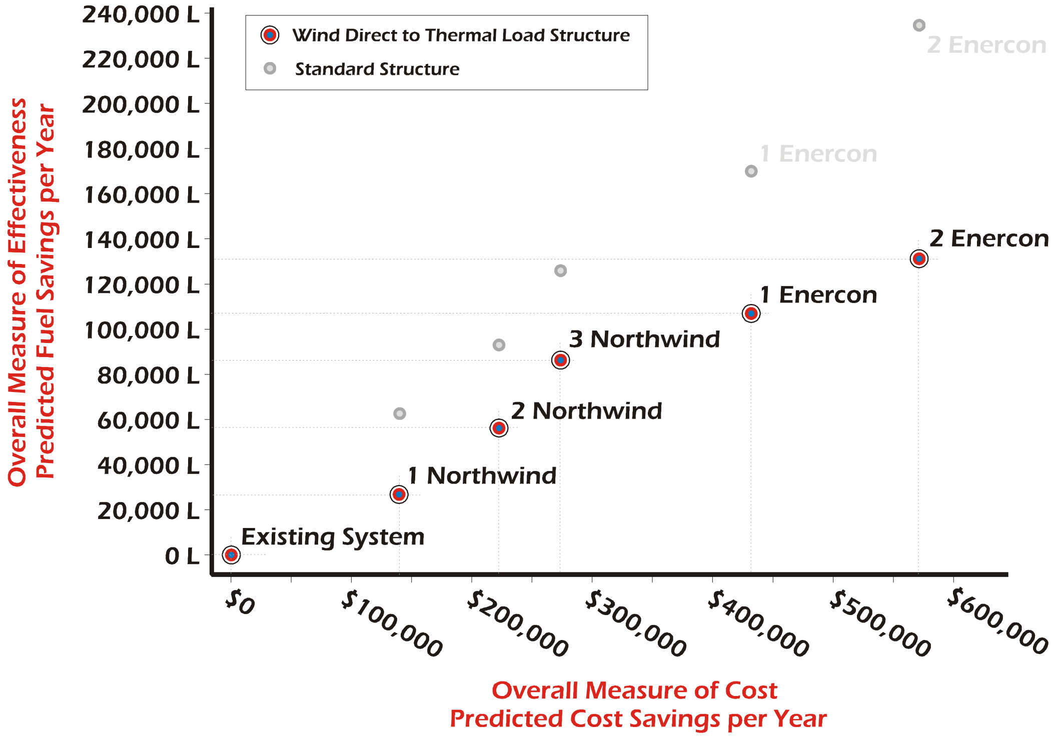


Figure 71: Wind Direct to Thermal Load Results Matrix

Although the dependence on base boilers is significantly lowered, predicted generator fuel consumption is only mildly reduced (relative to the standard simulation structure). The resulting overall predicted fuel savings for each model is less than that predicted for the standard simulation structure. This is illustrated in the figure above with each model utilising a wind generated electricity direct to thermal load structure saving less than its standard structure equivalent.

5.4.2. 0% Minimum Diesel Load

A simulation structure with a 0% minimum diesel load is evaluated to highlight how adjusting this system constraint could lead to even further fuel savings. A wind-diesel hybrid energy system with a 0% minimum diesel load puts the security of the energy supply in the hands of advanced power electronics and a control system. In Antarctica, any interruption in power supply causes safety concerns to base personnel. Therefore, completely shutting down all generators and supplying all base loads with wind power is an option that should be considered with great care. However, the simulation results are recorded for future use when Antarctica New Zealand may consider upgrading the existing generator sets with smaller or load-load equipment.

Model #2:	**One Northwind Turbine**	0% Minimum Diesel Load
Predicted Fuel Savings per Year:	**65500**	**Litres**
Total Predicted Fuel Consumption:	327092	Litres
Generator Fuel Consumption:	262222	L
Boiler Fuel Consumption:	64870	L

Model #3:	**Two Northwind Turbines**	0% Minimum Diesel Load
Predicted Fuel Savings per Year:	**123772**	**Litres**
Total Predicted Fuel Consumption:	268820	Litres
Generator Fuel Consumption:	201262	L
Boiler Fuel Consumption:	67558	L

Model #4:	**Three Northwind Turbines**	0% Minimum Diesel Load
Predicted Fuel Savings per Year:	**164983**	**Litres**
Total Predicted Fuel Consumption:	227609	Litres
Generator Fuel Consumption:	174812	L
Boiler Fuel Consumption:	52797	L

Model #5:	**One Enercon Turbine**	0% Minimum Diesel Load
Predicted Fuel Savings per Year:	**206355**	**Litres**
Total Predicted Fuel Consumption:	186237	Litres
Generator Fuel Consumption:	144014	L
Boiler Fuel Consumption:	42223	L

Model #6:	**Two Enercon Turbines**	0% Minimum Diesel Load
Predicted Fuel Savings per Year:	**254124**	**Litres**
Total Predicted Fuel Consumption:	138468	Litres
Generator Fuel Consumption:	107075	L
Boiler Fuel Consumption:	31393	L

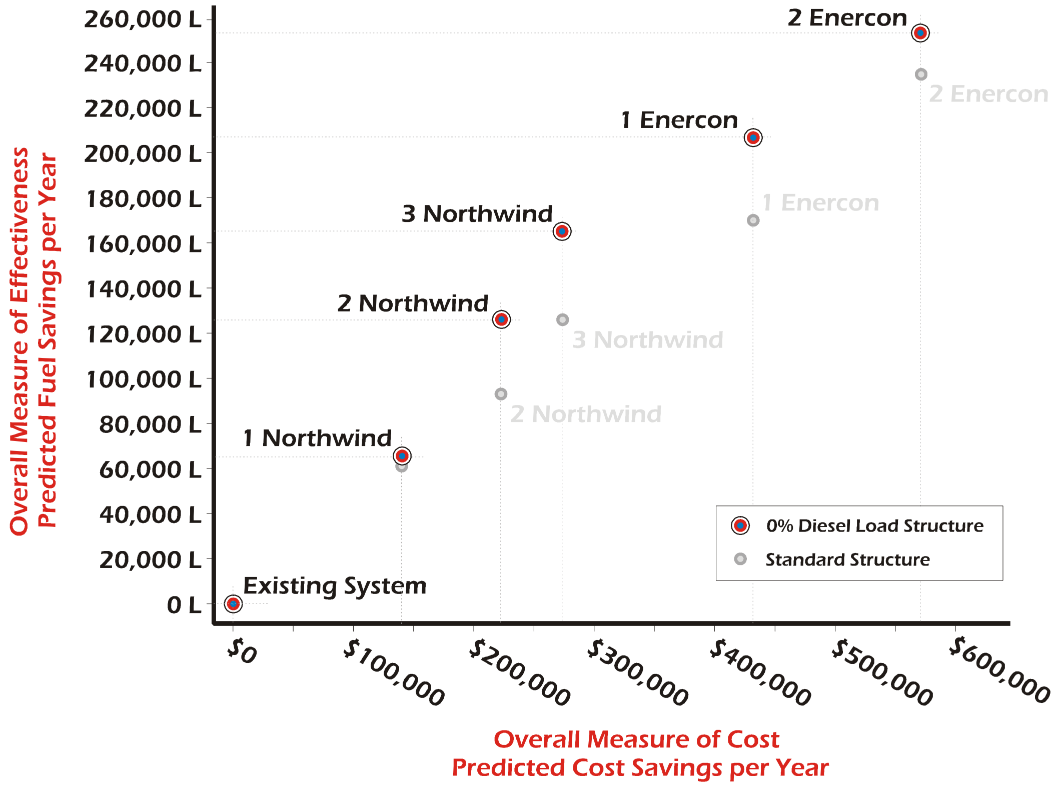


Figure 72: 0% Minimum Diesel Load Results Matrix

As expected, reducing the minimum diesel load from 30% to 0% has a positive effect on the potential amount of fuel saved at Scott Base. A greater penetration is achieved in all models corresponding to further fuel savings. Model #4 and #5 show the most improvement and illustrate the range of capacity at the base when reducing the minimum diesel load has the greatest effect. For example, a wind capacity of 100kW such as that of Model #2, shows very little improvement from a reduction in minimum diesel load. This indicates that, in the case of Model #2, rarely does wind generated power displace standard generator set power below 30%. However, models with a greater wind capacity, such as Model #5 with 330kW, often produce enough power to displace standard generator power below the 30% minimum load. Therefore, reducing the minimum diesel load results in greater fuel savings in these cases.

5.5.Further Cost Analysis

5.5.1. <u>Payback Periods</u>

The overall measure of cost for each of the simulated models accounts for only fuel and capital costs. The predicted overall measure of cost for each model is based on annual fuel use of the generators and boilers as well as an average capital cost for the proposed wind turbine(s) over a thirty year span. Therefore, a proposed wind-diesel hybrid energy system for Scott Base that consists of the existing diesel generators and one Enercon E-33 wind turbine results in an overall measure of cost of $612,754. While the overall measure of cost is a convenient way to compare models to one another, it does not accurately reflect the actual cost of installing one or multiple wind turbines on Antarctica.

An accurate estimate of costs for a project of this magnitude is difficult to make as so many factors contribute to making a wind turbine installation on Antarctica so different from other wind farms. However, the wind farm project recently completed at Mawson Station, Australia's Antarctic research base, allows for a general estimate to be made. Through personal communication with Peter Magill, a research and development engineer at the Australian Antarctic Division and project manager of the Mawson Station wind installation, an outline of project costs is possible. The following breakdown of costs is derived from the experience of Mawson Station in erecting two Enercon E-30 300kW wind turbines to create an Antarctic wind-diesel hybrid energy system (Magill 2006).

- Project Management: 10%
- Turbine Capital Costs: 25%
- Turbine Foundations and Infrastructure: 20%
- Plant and Equipment: 20%
- Transport: 10%
- Powerhouse Control: 8%
- Installation and Commissioning: 5%
- Turbine Spare Parts: 2%

Utilising the breakdown of costs listed above, an estimate for each proposed model's payback period can be made. Estimates in the following table reflect information gathered from turbine manufacturers, Antarctic New Zealand technicians and Mawson Station engineers. The fuel cost for the 2006 season at Scott Base is $2.65 per litre (Magill 2006).

		Predicted Fuel Use (L)	Predicted Fuel Savings (L)	Wind Turbine Cost ($)	Total Project Cost ($)	Estimated Payback Period	
Model #1	Existing Scott Base	392592	-	0	0	**0.0**	Years
Model #2	One Northwind 100kW Wind Turbine	331151	61441	550000	2200000	**13.5**	Years
Model #3	Two Northwind 100kW Wind Turbines	295556	97036	1100000	4400000	**17.1**	Years
Model #4	Three Northwind 100kW Wind Turbines	270064	122528	1650000	6600000	**20.3**	Years
Model #5	One Enercon 330kW Wind Turbine	219907	172685	900000	3600000	**7.9**	Years
Model #6	Two Enercon 330kW Wind Turbines	154766	237826	1800000	7200000	**11.4**	Years

Figure 73: Cost Analysis for Models #1 through #6

5.6.Sensitivity Analysis

5.6.1. Wind Speed Sensitivity

A potential source of error in the simulation of every wind-diesel hybrid system model is the validity of the wind speed data. Although the wind speed data was acquired via instrumentation specifically installed to accurately forecast the Scott Base wind resource, uncertainties still exist. Each application is different, but ideal wind data is gathered at the same height as the proposed wind turbine hub. In most cases however, data is gathered at a lower height than proposed hub height and scaled up. The scaling factor depends on topography and any objects creating a turbulent flow. Misjudging the scaling factor can add a degree of inaccuracy to the data. Other errors can arise from placement of the turbines in different areas from where the data was collected. Frequently decisions on turbine placements are made after wind data has been collected. The greatest potential error regarding wind speed data is its predictability from one year to the next. For this research, wind data gathered over one calendar year is used to predict energy outputs decades into the future. There are no certainties that a windy site one year will not become less windy the next. Therefore, tracking the potential range of error through the simulation is important. The following table outlines the change in predicted fuel consumption for each model if the annual mean wind speed at Scott Base was found to have a 10% or 30% disparity from that of the NIWA weather station data.

Wind Speed Error Analysis				
Model #2	One Northwind Turbine			
	10% Mean Wind Speed Reduction	=	2.7%	Increase in Fuel Consumption
	30% Mean Wind Speed Reduction	=	8.9%	Increase in Fuel Consumption
Model #3	Two Northwind Turbines			
	10% Mean Wind Speed Reduction	=	4.0%	Increase in Fuel Consumption
	30% Mean Wind Speed Reduction	=	14.0%	Increase in Fuel Consumption
Model #4	Three Northwind Turbines			
	10% Mean Wind Speed Reduction	=	5.4%	Increase in Fuel Consumption
	30% Mean Wind Speed Reduction	=	18.5%	Increase in Fuel Consumption
Model #5	One Enercon Turbine			
	10% Mean Wind Speed Reduction	=	9.5%	Increase in Fuel Consumption
	30% Mean Wind Speed Reduction	=	32.2%	Increase in Fuel Consumption
Model #6	Two Enercon Turbines			
	10% Mean Wind Speed Reduction	=	13.4%	Increase in Fuel Consumption
	30% Mean Wind Speed Reduction	=	50.2%	Increase in Fuel Consumption

Figure 74: Wind Speed Error Analysis

The possible change in total fuel consumption based on inaccurate wind speed data becomes quite significant as proposed wind capacity increases. Meaning, the more kilowatts of wind power that are proposed, the greater the potential error in predicted fuel consumption. For example, in Model #6, with a proposed wind capacity of 660kW, a 10% change in the mean wind speed results in a 13.4% change in the total fuel consumption.

5.6.2. <u>Load Sensitivity</u>

As with wind data inaccuracies, disparities between actual Scott Base load characteristics and those represented within the HOMER models can cause significant changes to resulting fuel consumption predictions. Tracking disparities through each simulation is important to understand just how much a change in the load characteristics effect the final results.

Regarding the electrical load, potential inaccuracies exist due to the method of representation within the HOMER models. The representation of the Scott Base electrical demand is based on the daily averages as collected in 2004. The daily load patterns for each stage are based on a three day period monitored in December of the same year. Extrapolating a full year of load data for each stage from a three day period in summer may lead to discrepancies. Furthermore, with a system as busy and dynamic as that of Scott Base, with personnel changes frequent and equipment replacement often, load data has a very short shelf life. The following table tracks changes to the electrical load and the resulting fuel consumption predictions.

Electrical Load Error Analysis				
Model #2	One Northwind Turbine			
	10% Reduction in kWhrs/day average	=	6.2%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	17.6%	Decrease in Fuel Consumption
Model #3	Two Northwind Turbines			
	10% Reduction in kWhrs/day average	=	5.5%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	16.9%	Decrease in Fuel Consumption
Model #4	Three Northwind Turbines			
	10% Reduction in kWhrs/day average	=	9.3%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	27.2%	Decrease in Fuel Consumption
Model #5	One Enercon Turbine			
	10% Reduction in kWhrs/day average	=	11.8%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	28.5%	Decrease in Fuel Consumption
Model #6	Two Enercon Turbines			
	10% Reduction in kWhrs/day average	=	7.7%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	22.9%	Decrease in Fuel Consumption

Figure 75: Electrical Load Error Anaylsis

Thermal load data carries the same uncertainties as the electrical load data. Based on temperature data gathered at the base, the thermal load is subject to yearly changes in weather patterns. Again, the dynamic nature of Scott Base also introduces uncertainties as to how well the thermal load can be predicted from one year to the next. The following table tracks discrepancies to the representation of the base thermal load in the HOMER models and their resulting fuel consumption predictions.

Thermal Load Error Analysis				
Model #2	One Northwind Turbine			
	10% Reduction in kWhrs/day average	=	3.9%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	11.1%	Decrease in Fuel Consumption
Model #3	Two Northwind Turbines			
	10% Reduction in kWhrs/day average	=	3.4%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	9.3%	Decrease in Fuel Consumption
Model #4	Three Northwind Turbines			
	10% Reduction in kWhrs/day average	=	3.0%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	8.4%	Decrease in Fuel Consumption
Model #5	One Enercon Turbine			
	10% Reduction in kWhrs/day average	=	3.1%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	8.7%	Decrease in Fuel Consumption
Model #6	Two Enercon Turbines			
	10% Reduction in kWhrs/day average	=	3.3%	Decrease in Fuel Consumption
	30% Reduction in kWhrs/day average	=	9.2%	Decrease in Fuel Consumption

Figure 76: Thermal Load Error Analysis

5.7. Results and Discussion Summary

5.7.1. Summary

Models of the existing energy system at Scott Base as well as six proposed wind-diesel hybrid energy systems were simulated for a typical year. The existing energy system, Model #1, was simulated and predicted a base fuel consumption of 392,592 litres. This result is very close to data collected over the 2004 year. The proposed wind-diesel hybrid energy system models predict a range of fuel consumption from 331,151 litres (Model #2) to 154,766 litres (Model #6) corresponding to fuel savings of 61,441 litres and 237,826 litres per year. Selecting the optimal system for Scott Base is based on the performance objective methodology and results in only Model #2 and Model #3 meeting all requirements and constraints. The following figure outlines, in basic terms, the findings of the standard simulations.

	Fuel Savings per Year	Cost Savings per Year	Generator Reliance	Boiler Reliance	Power Quality	Pay Back Period
One Northwind 100kW	Moderate	Moderately High	Slightly Decreased	Slightly Increased	Acceptable	13.5yr
Two Northwind 100kW	Moderately High	High	Moderately Decreased	Slightly Decreased	Acceptable	17.yr
Three Northwind 100kW	High	High	Moderately Decreased	Moderately Decreased	Unacceptable	20.3yr
One Enercon 330kW	Very High	Extremely High	Significantly Decreased	Significantly Decreased	Unacceptable	7.9yr
Two Enercon 330kW	Extremely High	Extremely High	Significantly Decreased	Significantly Decreased	Unacceptable	11.4yr

Figure 77: General Summary of Standard Simulation Results

Further simulations are carried out to evaluate the different structures that are possible for each wind-diesel hybrid system to supply the base demand. A novel demand side management technique is developed by coordinating available wind power to the Scott Base laundry facility load. Results show that extra fuel savings are possible using this technique although relatively small. The level of savings increases with an increase in allowable time delay. For Model #2, utilising a standard simulation structure, reliance on base boilers to meet the thermal load is increased due to the lack of recovered heat from the generator sets. In order to address this consequence of adding wind power to a diesel based system, a structure is proposed that supplies the Scott Base thermal load directly with wind generated electricity. Results show that boiler fuel use is greatly reduced from predictions based on the standard simulation structure. However, overall fuel consumption predictions are higher for a wind power direct to thermal load versus that of the standard structure. A final set of simulations evaluated the effects of the minimum diesel load constraint. By altering the constraint to a 0% minimum diesel load, thus allowing the generator sets to be completely shut down, significant fuel savings are predicted above and beyond those of the standard models.

An analysis for pay back period was performed for each of the five proposed wind-diesel hybrid energy systems. With a fuel cost of $2.65 per litre of AN8, the pay back periods ranged from just under six years to fourteen and a half years. All the results presented in Chapter 5 are subject to change if inputs used in the modelling of the proposed wind-diesel hybrid energy systems change. Discrepancies in electrical and thermal load representation can lead to inaccurate fuel consumption predictions. Within a dynamic system such as Scott Base, making predictions years into the future based on one single year in the past can be dangerous. A sensitivity analysis is provided to illustrate how slight discrepancies in the major model inputs can effect overall results.

6. Conclusions

6.1. What Was Done

Scott Base is an isolated research facility located in the harsh environment of Antarctica. The facility is completely reliant on fuel oil, AN8, to meet all of its heat and electricity loads. Antarctica New Zealand, the government body that manages all aspects of Scott Base's existence, has expressed the desire to operate in this fragile environment as sustainably as possible. This desire includes minimizing green house gas emissions and using renewable energy where possible. To this end, the research project intended to answer two questions. Question 1 was what wind-diesel hybrid energy system is the most appropriate for Scott Base? Question 2 was by modifying the structure of the wind-diesel hybrid energy system to incorporate a novel demand side management technique, could further fuel savings be realised?

6.1.1. __Modelling__

In order to answer the research questions, an accurate model of the existing Scott Base energy system was developed. After this benchmark model was validated, other potential wind-diesel models could be developed. Modelling was undertaken utilising the hybrid modelling information tool, HOMER. With detailed component specifications and load data based on real data collected at the base in 2004, accurate representations of a number of proposed systems were created. The wind resource at the base was obtained from Meridian Energy via a purpose built wind monitoring station. The wind resource was found to be very good with a mean wind speed of 7.54 m/s. Different system structures exist for each proposed model. Several structures were evaluated for each model, such as the standard simulation structure and demand side management simulation structure, to determine the optimal solution for Scott Base.

6.1.2. __Method of Analysis__

A technique called performance objective design was used to create and analyze each proposed wind-diesel hybrid energy system for Scott Base. The design process identifies the best possible wind-diesel system configurations that meet the system requirements while operating within the system constraints. The evaluation of each proposed system is based on the system objectives.

System requirements are included to ensure staff safety and to meet Antarctica New Zealand desires. Requirements include meeting essential loads 100%, utilising wind power and being reliable in the Antarctic environment. System constraints address fuel use, power quality and generator reliability and therefore personnel safety. These constraints include a total base fuel consumption below that of the existing energy system, wind penetrations below identified limits to ensure power quality and a 30% minimum diesel load.

Each proposed hybrid energy system is simulated utilising a standard structure and results are collected for performance objective design evaluation. Only models that meet the identified system requirements and operate within identified system constraints are deemed suitable. How well each suitable model meets system objectives determines the optimal solution for Scott Base. In this case, system objectives are to minimise AN8 fuel consumption and keep costs as low as possible.

After evaluating each model using a standard structure, other structures are applied to determine the effect on predicted fuel consumption. The novel demand side management technique is analyzed to determine if coordinating available wind power with the Scott Base laundry facilities load results in significant fuel savings to warrant further research.

6.2.Findings

The findings of the study were overall very positive with significant fuel savings predictions made for the majority of models.

6.2.1. <u>Results</u>

6.2.1.1.Standard Simulation Results

Model #1	Benchmark	**Standard System Structure**				
Total:	**392592** L	Litres of Fuel Consumed			Predicted Fuel Savings Per Year (L)	Pay Back Period (Yrs.)
		Total	Generator	Boiler		
Model #2	One Northwind 100kW Wind Turbine	**331151**	274731	56420	**61441**	**13.5**
Model #3	Two Northwind 100kW Wind Turbines	**295556**	255028	40528	**97036**	**17.1**
Model #4	Three Northwind 100kW Wind Turbines	**270064**	237216	32848	**122528**	**20.3**
Model #5	One Enercon 330kW Wind Turbine	**219907**	191750	28157	**172685**	**7.9**
Model #6	Two Enercon 330kW Wind Turbines	**154766**	133924	20842	**237826**	**11.4**

Figure 78: Standard Results Summary Table

As can be seen in the table above, a wide range of fuel savings are predicted for the models proposed. A wind-diesel hybrid energy model consisting of one Northwind 100kW turbine and the existing generator sets at Scott Base is predicted to save over 61,000 litres of diesel per year (a savings of over $160,00 NZD). A hybrid system with two Enercon 330kW turbines and the existing Scott Base generator sets is predicted to save over 120,000 litres per year (a savings of nearly $325,000 NZD). However not all models proposed meet the system constraints outlined by the performance objective design methodology. In fact, only Model #2 and Model #3 operates within the wind penetration levels established to ensure power quality and thus personnel safety.

6.2.1.2.Demand Side Management Simulation Results

All values in litres of AN8 fuel		Allowable Laundry Facility Load Delay			
		3 hours	6 hours	12 hours	24 hours
Model #2	One Northwind 100kW Wind Turbine	54	85	139	166
Model #3	Two Northwind 100kW Wind Turbines	286	424	793	1204
Model #4	Three Northwind 100kW Wind Turbines	292	520	727	1177
Model #5	One Enercon 330kW Wind Turbine	266	499	800	1227
Model #6	Two Enercon 330kW Wind Turbines	295	514	831	1110

Figure 79: Demand Side Management Results Summary Table

The table above indicates the level of additional fuel savings predicted using the novel demand side management technique. Coordinating available wind power with a time flexible base load such as the laundry facilities results in additional fuel savings, though relatively small. Predicted additional fuel savings begin to reach levels that might warrant further research and possible installation only at time delay periods beyond 6 hours. However, the positive results in all cases indicate that more significant fuel savings may be possible if available wind power was to be coordinated with a larger base load.

6.2.1.3.Other Simulation Results

Two other simulation structures were evaluated to represent other techniques of supplying the Scott Base energy demand with a wind-diesel hybrid energy system. Directly supplying the base thermal load with wind generated electricity results in significant fuel savings predictions although not nearly as much as the standard structure. This method of supply should only be considered if an increase in Scott Base boiler reliance is undesirable. Finally, the minimum diesel load was decreased from 30% to 0% to indicate how this system constraint effects overall predicted fuel consumption. As expected predicted levels of fuel consumption are below that of the standard structure. Model #2 shows the least amount of improvement as wind power penetrations only occasionally facilitate generator load levels below 30%.

6.2.2. __Applications__

Over the course of the research project Antarctica New Zealand has shown a variable level of interest; at first non-existent, then mildly interested and onto extremely interested. Several meeting have occurred in the last few months (fall, 2006) to discuss Antarctica New Zealand intentions, the merits of the research project and its potential application at Scott Base. It is of the author's opinion that wind power at Scott Base is not just a desire of Antarctica New Zealand but a realisable goal. With the support of Meridian Energy, wind power at Scott Base seems inevitable.

Shipping schedules and Antarctic logistics dictate a very specific construction process at Scott Base. The erection of a wind turbine would take place in the summer months only after procurement of a crane of adequate boom height. As the Scott Base supply ship only sails once a year, typically any major projects are supplied the year previous to construction. Therefore, the start of any major project, such as the installation of a 100kW wind turbine, is always at least a year away and that is saying nothing about foundations (see *Future Work*). Never-the-less, a detailed report was submitted to Antarctica New Zealand on 1 July 2006 outlining all simulation results. The report was a resource for the Antarctica New Zealand board of directors during discussions on the potential for wind power at Scott Base and whether it will be pursued.

6.3. Future Work

6.3.1. Power Quality

6.3.1.1. Method of Calculation

The issue of power quality is well known and studied in large utility systems. On smaller scales, such as remote area power supplies, methods to predict power quality are not so straight forward. Measurements taken after installation are typically used to assess power quality. Each hybrid system in operation consists of different size wind turbines and diesel generator sets supplying loads with unique characteristics and patterns. Despite the differences, the effects of wind turbines on diesel only systems can be estimated with historical data. A method to determine the specific limit of wind penetration in order to maintain voltage variations within the 10% standard could be useful for the design of future wind-diesel hybrid systems.

6.3.1.2. Method of Power Quality Control

Modifying the instantaneous wind penetration constraint to a higher value within the performance objective design methodology could result in a greater number of hybrid systems being considered. Methods to increase the constraint and thus maintain power quality at greater wind capacities could be desirable. Secondary energy storage acts as a buffer between the wind turbine and the grid and has a smoothing effect on the supply of power. Adding a flywheel or batteries to the Scott Base system could result in a very high level of power quality even at the highest wind capacities. The addition of extra dump loads to the base system could have the effect of lowering predicted instantaneous wind penetrations. In this way more models could be considered as suitable for installation at Scott Base.

6.3.2. Demand Side Management

As reported in Chapter 5, the novel demand side management technique evaluated for Scott Base resulted in additional fuel savings. Levels of additional savings were relatively low for most models. Although the coordination of available wind power with the Scott Base laundry facility load did not result in significant savings, the technique did produce positive results across the board. It is of the author's opinion that the primary reason for the low values was the relative size of the time flexible load chosen. The laundry facility load is 1.2% of the overall Scott Base electrical load. If a larger base load were identified as time flexible and the same methods of coordination were implemented, the potential additional fuel savings could be enough to warrant further research and indeed installation of a device that could automate the load shift.

6.3.3. Antarctic Foundations

After the decision to install a wind turbine at Scott Base is made, the biggest technical hurdle to jump will be the tower foundations. Relatively straight forward in normal climate conditions, concrete foundation construction will be very difficult on Antarctica. Two major problems exist. The first problem is the need of fresh water. Scott Base currently makes fresh water with its desalination plant. Therefore, any freshwater necessary to mix concrete will cost in electricity and thus AN8 fuel. The second problem is curing the concrete which requires specific temperature conditions. These conditions do not exist at Scott Base and therefore would require some type of heating device. An alternate solution might be shipping pre-poured pieces of a foundation and securing them together on site. This method would be transport fuel intensive. Future work solving this problem might propose a foundation with a small amount of concrete secured with long steel pins driven into rock and held fast with ice.

6.3.4. Generator Set Replacement

Information gathered from meetings with Antarctica New Zealand points to a potential research project being developed with the purpose of selecting new generator sets. The operational life span of the current generator sets is set to expire in 2011. If a wind turbine installation is going to be pursued, identifying the most appropriate size generator will be important to minimise fuel consumption while still providing adequate power system security. With any improvements in Scott Base energy utilisation, smaller generators may be adequate to meet demand. Irregardless of any Scott Base efficiency improvements, selecting generator sets with a lower minimum diesel load would be beneficial in any wind-diesel hybrid system.

References

Ackerman, T. (2005). Wind Power in Power Systems, John Wiley & Sons, Ltd., Stockholm.

Al-Alawi, A., and Islam, S. M. (2004). "Demandside Management for Remote Area Power Supply Systems Incorporating Solar Irradiance Model." Renewable Energy, 29, 2027-2036.

Alphen, K. v., Sark, W. G. J. H. M. v., and Hekkert, M. P. (2006). "Renewable energy technologies in the Maldives-determining the potential." Renewable and Sustainable Energy Reviews, April(Available online).

Antarctic New Zealand. (1995). "Scott Base Operations Manual." Christchurch.

Antarctica New Zealand. (2006). http://www.antarcticanz.govt.nz/

Australian Antarctic Division. (2006). http://www.aad.gov.au/

Baring-Gould, E. I., Flowers, L., Lundsager, P., Mott, L., Shirazi, M., and Zimmermann, J. "Worldwide Status of Wind-Diesel Applications." DOE/AWEA/CanWEA wind-diesel conference.

Barret, J.-P., Bornard, P., and Meyer, B. (1997). Power System Simulation, Chapman & Hall, London.

Blanchard, B. S., and Fabrycky, W. J. (1990). Systems engineering and analysis, Prentice Hall, Englewood Cliffs., N.J.

Borbely, A.-M., Kreider, Jan F. (2001). Distributed Generation: The Power Paradigm for the New Millennium, CRC Press LLC, Boca Raton, Florida.

BP. (2005). "Statistical Review of World Energy 2004." 54.

Brown, C., Guichard, A., and Lyons, D. “Wind-Energy in Polar Regions: Casey Station Antarctica.”

CAE. (2003). "CAE Comments: Distributed Generation: a study of opportunities." Centre for Advanced Engineering, Christchurch.

Campbell, C. J., and Laherrere, J. (1998). "The End of Cheap Oil?" Scientific American [online].

Capra, F. (1996). The Web of Life, Anchor Books, New York.

Chevron. (2000). "Aviation Fuels Technical Review." Chevron Products Company, San Ramon, CA.

Cornelius, S. (2006). J. Frye, ed., The role of Meridian Energy and NIWA with Antarctic New Zealand concerning wind speed data collection.

Cripps, G. C., and Priddle, J. (1991). "Review: Hydrocarbons in the Antarctic marine environment." Antarctic Science, 3(3), 233-250.

Cripps, G. C., and Shears, J. (1997). "The Fate in the Marine Environment of a Minor Diesel Fuel Spill from an Antarctic Research Station." Environmental Monitoring and Assessment, 46(3), 221 - 232.

Dantas, A., Krumdieck, S., Hamm, A., Minges, S., and Saunders, M. (2005). "Performance-Objective Design for Energy Constrained Transportation System." Journal of Eastern Asia Society for Transportation Studies, 6, 3276-3292.

Deffeyes, K. S. (2005). Beyond Oil: The View from Hubbert's Peak, Hill and Wang, New York.

Deprez, P. P. A., M.; Locher, H. (1999). "Identification and assessment of contaminated sites at Casey Station, Wilkes Land, Antarctica." Polar Record, 35(195), 299-316.

Enercon. (2004). "Enercon E-33 Technical Data." Enercon, Bremen, Germany.

Heinberg, R. (2003). The party's over : oil, war, and the fate of industrial societies, New Society, Gabriola Island, B.C.

Henryson, M., and Svensson, M. (2004). "Renewable Power for the Swedish Antarctic Station Wasa," Stockholm University, Stockholm.

Herring, H. "Why Energy Efficiency is not Enough." Advances in Energy Studies (International Workshop): Exploring Supplies, Constraints, and Strategies, 349-359.

Hinrichs, R. A., and Kleinbach, M. H. (2002). Energy : Its Use and the Environment, Brooks/Cole Publishing.

Hodgson, P. (2004). "Sustainable Energy: Creating a Sustainable Energy System." New Zealand Government.
Hubbert, M. K. (1969). "Resources and Man." National Academy of Sciences and National Research Council.
Hume, D. (2006). "Scott Base Energy Audit." University of Canterbury: Electic Power Engineering Centre, Christchurch.
Hunter, R., and Elliot, G. (1994). Wind-Diesel Systems : A Guide to the Technology and its Implementation, Cambridge University Press, Cambridge.
Ivanhoe, L. F., and Hubbert, M. K. (1997). Hubbert Center Newsletter [online], http://hubbert.mines.edu.
Jensen, J. (1980). Energy Storage, Newnes-Buterworths, London.
Kennicutt, M. S., ST. (1993). "Hydrocarbon Contamination on the Antarctic Peninsula: III. The Bahia Paraiso--Two Years After the Spill." Marine Pollution Bulletin, 25(9-12), 303-306.
Khisty, C. J., and Modammadi, J. (2001). Fundamentals of Systems Engineering with Economics, Probability, and Statistics, Prentice Hall, Upper Saddle River, NJ.
Krumdieck, S., and Wood, B. D. "A theory of regional energy and environment systems behavior." 14th National Passive Solar Conference, Denver, CO, 227-232.
Krumdieck, S., Hamm, A., Dantas, A., and Minges, S. "Performance-Objective Design for A Renewable Energy Transportation Circuit of Christchurch, New Zealand." World Renewable Energy Congress VIII, Denver, CO.
Larminie, J., and Dicks, A. (2003). Fuel Cell Systems Explained, Wiley, West Sussex.
Lawson, W. (2006). J. A. Frye, ed., Scott Base Building Plans.
Lundsager, P. (1991). "RISO: WDILOG - A Logistic Wind-Diesel Simulation Model Description and Users Guide." Riso National Laboratory, Denmark.
Lundsager, P., Bindner, H., Clausen, N.-E., Frandsen, S., Hansen, L. H., and Hansen, J. C. (2001). "Isolated Systems with Wind Power." RISO, Roskilde.
Magill, P. (2003). "Project Profile: Mawson Wind Farm." EcoGeneration Magazine.
Magill, P. (2006). J. Frye, ed., Christchurch, Project costs and summary of the Mawson Station wind turbine installation.
Martin, S. (1996). A History of Antarctica, State Library of New South Wales Press, Sydney.
Masters, G. M. (2004). Renewable and Efficient Electric Power Systems, John Wiley & Sons Inc., West Sussex.
McGonigal, D., and Woodworth, L. (2002). Antarctica: the blue continent, Random House New Zealand, Auckland.
Meadows, D., Randers, J., and Meadows, D. (2004). Limits to Growth: the 30 year update, Chelsea Green Publishing Company, White River Junction.
Nadel, S., and Geller, H. (1996). "Utility DSM: What have we learned? Where are we going?" Energy Policy, 24(4), 289-302.
National Institute of Water and Atmospheric Research. (2006). http://www.niwa.co.nz/
National Renewable Energy Laboratory. (2005). "Getting Started Guide for HOMER Version 2.1." National Renewable Energy Laboratory, Golden, Colorado.
Nilsson, H. (2005). "State of DSM and EE in the World." International Energy Agency Demand-Side Management Programme.
Nise, N. S. (1995). Control Systems Engineering, Addison-Wesley Publishing Company, Menlo Park, CA.
Northern. (2004). "The North Wind NW100/19: Product Overview." Northern Power Systems, San Francisco, California.
Notton, C. G., Cristofari, P. P., and Muselli, M. (2001). "Wind Hybrid Electrical Supply System: Behaviour Simulation and Sizing Optimization." Wind Energy, 4, 43-59.
Ogata, K. (1997). Modern Control Engineering, Prentice-Hall, Upper Saddle River, NJ.
Parfit, M. (2005). "Future Power: where will the world get its next energy fix." National Geographic.
Patel, M. R. (1999). Wind and Solar Power Systems, CRC Press, Boca Raton.

Poland, J. S., Riddle, M. J., and Zeeb, B. A. (2002). "Contaminants in the Arctic and the Antarctic: a comparison of sources, impacts, and remedeation options." Polar Record, 39(211), 369-383.

Pyper, W. (2003). "Extreme Power." ECOS Magazine, 8-9.

Rehman, S., El-Amin, I. M., Ahmad, F., Shaahid, S. M., Al-Shehri, A. M., Bakhashwain, J. M., and Shash, A. (2005). "Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant." Renewable and Sustainable Energy Reviews, July(Available online).

Ribeiro, P. R., Johnson, B. K., Crow, M. L., Arsoy, A., and Liu, Y. (2001). "Energy Storage Systems for Advanced Power Applications." Proceeding of the IEEE, 89(12), 1744-1756.

Rigarlsford, K. (2006). J. A. Frye, ed., Christchurch, Scott Base Fuel Costs.

Saft, I. B. G. (2004). "Sunica.plus Ni-Cd batteries: Extended capability for challenging photovoltaic conditions." Performance Document, A. A. Limited, ed.

Saini, S. (2004). "Conservation V. Generation: The Significance of Demand-Side Management (DSM), its Tools and Techniques." Refocus, May/June(1471), 52.

Shaahid, S. M., and Elhadidy, M. A. (2006). "Technical and economic assessment of grid-independent hybrid photovoltaic-diesel-battery power systems for commercial loads in desert environments." Renewable and Sustainable Energy Reviews, April(Available online).

Simpson, R. D., Smith, S. D. A., and Pople, A. R. (1995). "The Effects of a Spillage of Diesel Fuel on a Rocky Shore in the Sub-Antarctic Region (Macquarie Island)." Marine Pollution Bulletin, 31(4), 367-371.

Sioshansi, F. P. (1995). "Demand-side management: The third wave." Energy Policy, 23(2), 111-114.

Smith, H. L. (1994). "DA/DSM Directions." IEEE Computer Applications in Power, October, 23-25.

Spinks, A. H. (1992). "Alternative Energy sources for Power Generation in Antarctica." Central Laboratories Report 92-28113.

Steeman, M. (2005). "Energy players push wind power." The Press, Christchurch, 6.

Tande, J. O. G. (2002). "Applying Power Quality Characteristics of Wind Turbines for Assessing Impact on Voltage Quality." Wind Energy, 5(1), 37-52.

Ter-Gazarian, A. (1994). Energy Storage for Power Systems, Peter Peregrinus Ltd., London.

Turner, W. C. (1997). Energy Management Handbook, The Fairmont Press, Inc., Lilburn, Georgia.

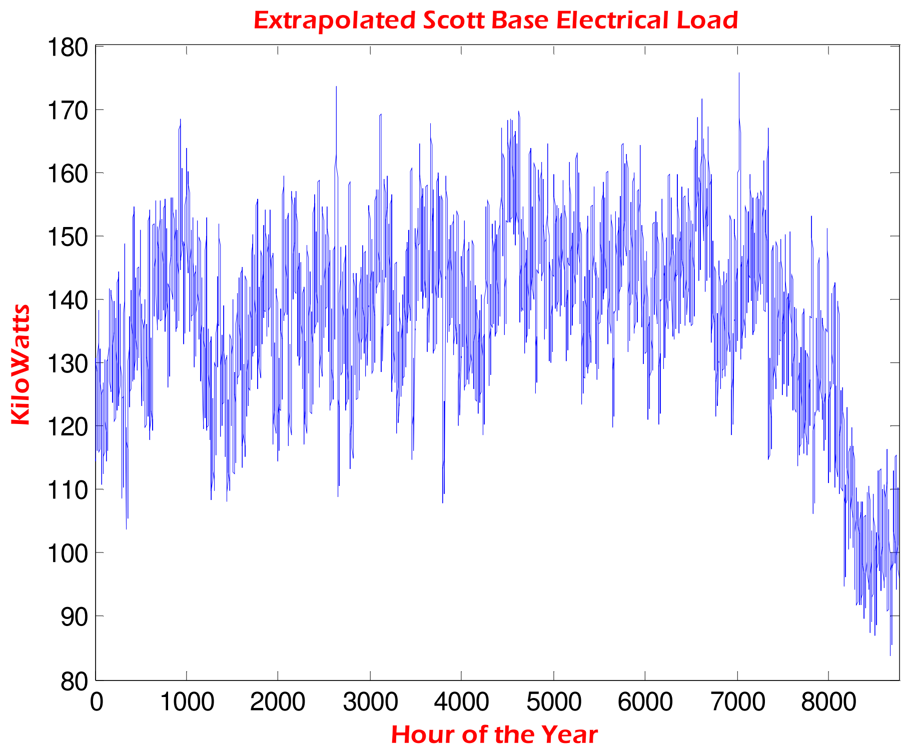
Warman, J. D. (1992). "Wind Power For Remote Area Power Supplies," University of Canterbury, Christchurch.

Appendix A

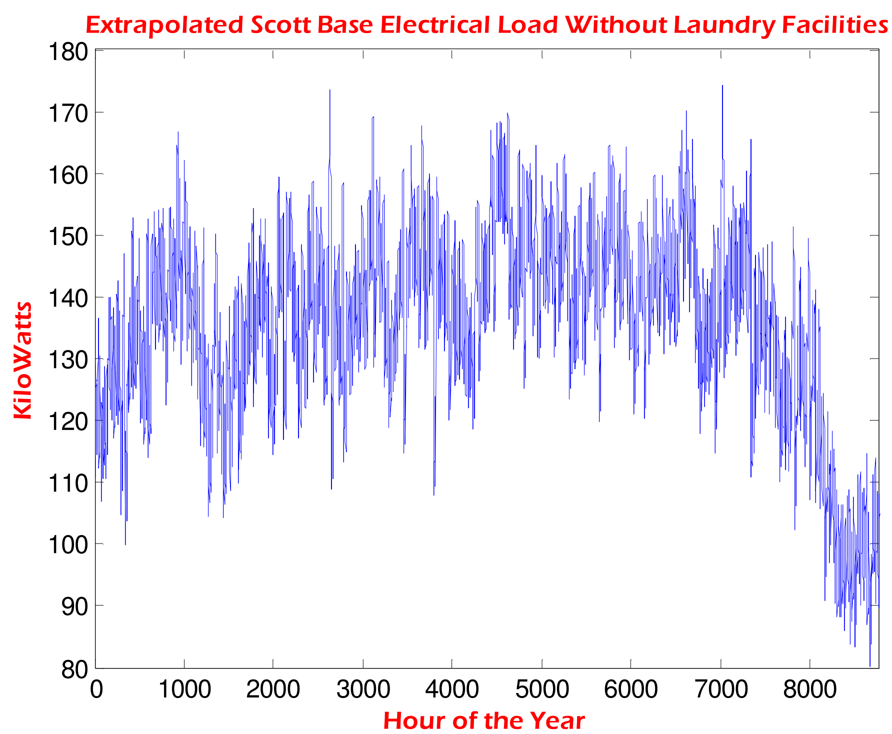
```
%Demand Side Management Code

close all
clear all
clc

%Load hourly laundry load data

deferable_load = 'Laundry8760x1.txt';
l=load(deferable_load);

%Load excess electricity data
%from HOMER simulation

excess_electricity =
'(1)Northwind8760x1.txt';
%excess_electricity =
'(2)Northwind8760x1.txt';
%excess_electricity =
'(3)Northwind8760x1.txt';
%excess_electricity = '(1)Enercon8760x1.txt';
%excess_electricity = '(2)Enercon8760x1.txt';
e=load(excess_electricity);

time=(0:71);

%Loop to run Matlab calcs for three days

for j=1:72
    time_length=time(j)+.1;

loadmet=zeros(8760,1);
h=zeros(8760,1);
t=zeros(8760,1);

hold=0;
extra=0;
thresh=0;

%Loop to run calcs for every hour of one
year

for i=1:8760;

    if e(i)>l(i);
        loadmet(i)=l(i);
        extra=e(i)-l(i);

        if extra>hold;
            sf(i)=hold;
            thresh=100;
        else sf(i)=extra;
            hold=hold-extra;
            thresh=thresh+1;
        end

    else loadmet(i)=e(i);
        hold=hold+l(i)-e(i);
        thresh=thresh+1;
        sf(i)=0;
    end

    if thresh>time_length;
        hold=0;
        thresh=0;
    end

    h(i)=hold;
    t(i)=thresh;
end

%Final output data vectors
%(data point for each hour of three days)

kwh_saved(j)=sum(sf');

end

%Final output totals

total_load_met=sum(loadmet)
kwh_saved'
```

Appendix B

Extrapolated Scott Base Load



Extrapolated Scott Base Electrical Load Without Laundry Facilities



Appendix C

Demand Side Management Full Simulation Results

Model #2: One Northwind Turbine

Maximum Time Flexibility	Total Predicted Fuel Consumption (litres)	Average Wind Penetration (%)	Instantaneous Wind Penetration (%)	Extra Power Saved via Load Shift (kWh)
0 Hours	331151	23.8	58	0.0
1 Hours	331128	23.8	58	75.8
2 Hours	331120	23.8	58	100.4
3 Hours	331097	23.8	58	179.1
4 Hours	331087	23.8	58	209.7
5 Hours	331077	23.8	58	243.0
6 Hours	331066	23.8	58	280.9
7 Hours	331050	23.8	58	332.1
8 Hours	331036	23.8	58	380.4
9 Hours	331031	23.8	58	396.2
10 Hours	331038	23.8	58	372.0
11 Hours	331034	23.8	58	387.0
12 Hours	331012	23.8	58	459.1
13 Hours	331010	23.8	58	464.0
14 Hours	331003	23.8	58	487.6
15 Hours	330975	23.9	58	580.9
16 Hours	330976	23.9	58	576.9
17 Hours	330986	23.9	58	545.4
18 Hours	331001	23.8	58	493.8
19 Hours	330981	23.9	58	560.3
20 Hours	330997	23.8	58	509.3
21 Hours	330997	23.8	58	507.7
22 Hours	331008	23.8	58	470.6
23 Hours	330990	23.9	58	532.4
24 Hours	330985	23.9	58	548.3
25 Hours	330964	23.9	58	616.4
26 Hours	330954	23.9	58	650.4
27 Hours	330941	23.9	58	693.5
28 Hours	330956	23.9	58	642.5
29 Hours	330938	23.9	58	701.8
30 Hours	330955	23.9	58	645.7

31 Hours	330938	23.9	58	703.3
32 Hours	330942	23.9	58	688.7
33 Hours	330964	23.9	58	615.8
34 Hours	330963	23.9	58	621.2
35 Hours	330957	23.9	58	638.3
36 Hours	330946	23.9	58	675.7
37 Hours	330959	23.9	58	632.5
38 Hours	330940	23.9	58	696.3
39 Hours	330933	23.9	58	717.9
40 Hours	330914	23.9	58	782.6
41 Hours	330921	23.9	58	758.7
42 Hours	330928	23.9	58	735.9
43 Hours	330893	23.9	58	850.0
44 Hours	330891	23.9	58	858.5
45 Hours	330906	23.9	58	806.8
46 Hours	330900	23.9	58	829.7
47 Hours	330903	23.9	58	817.1
48 Hours	330918	23.9	58	768.0

Model #3: Two Northwind Turbines

Maximum Time Flexibility	Total Predicted Fuel Consumption (litres)	Average Wind Penetration (%)	Instantaneous Wind Penetration (%)	Extra Power Saved via Load Shift (kWh)
0 Hours	295556	30.3	116	0.0
1 Hours	295443	30.4	116	374.0
2 Hours	295377	30.4	116	593.5
3 Hours	295270	30.4	116	944.5
4 Hours	295193	30.4	116	1200.9
5 Hours	295134	30.4	116	1393.2
6 Hours	295133	30.4	116	1399.0
7 Hours	295045	30.5	116	1686.7
8 Hours	294971	30.5	116	1932.5
9 Hours	294908	30.5	116	2140.0
10 Hours	294892	30.5	116	2192.7
11 Hours	294824	30.5	116	2417.7
12 Hours	294763	30.5	116	2617.8
13 Hours	294737	30.5	116	2704.4
14 Hours	294706	30.6	116	2805.4
15 Hours	294633	30.6	116	3047.4
16 Hours	294608	30.6	116	3129.4

17 Hours	294569	30.6	116	3257.9
18 Hours	294570	30.6	116	3256.7
19 Hours	294564	30.6	116	3275.4
20 Hours	294546	30.6	116	3335.6
21 Hours	294493	30.6	116	3511.0
22 Hours	294421	30.6	116	3748.4
23 Hours	294407	30.6	116	3795.1
24 Hours	294353	30.6	116	3972.0
25 Hours	294281	30.7	116	4211.0
26 Hours	294300	30.7	116	4145.6
27 Hours	294231	30.7	116	4375.2
28 Hours	294229	30.7	116	4382.6
29 Hours	294238	30.7	116	4350.3
30 Hours	294213	30.7	116	4434.9
31 Hours	294174	30.7	116	4562.2
32 Hours	294174	30.7	116	4563.8
33 Hours	294196	30.7	116	4490.2
34 Hours	294167	30.7	116	4584.4
35 Hours	294162	30.7	116	4602.6
36 Hours	294130	30.7	116	4706.2
37 Hours	294141	30.7	116	4671.9
38 Hours	294145	30.7	116	4659.3
39 Hours	294155	30.7	116	4626.3
40 Hours	294144	30.7	116	4660.6
41 Hours	294099	30.7	116	4810.5
42 Hours	294098	30.7	116	4814.6
43 Hours	294039	30.7	116	5007.7
44 Hours	293967	30.8	116	5245.4
45 Hours	293953	30.8	116	5290.5
46 Hours	293949	30.8	116	5304.2
47 Hours	293942	30.8	116	5327.7
48 Hours	293949	30.8	116	5305.5

Model #4: Three Northwind Turbines

Maximum Time Flexibility	Total Predicted Fuel Consumption (litres)	Average Wind Penetration (%)	Instantaneous Wind Penetration (%)	Extra Power Saved via Load Shift (kWh)
0 Hours	270064	35.4	174	0.0
1 Hours	269967	35.5	174	320.1
2 Hours	269872	35.5	174	633.6

3 Hours	269772	35.5	174	964.6
4 Hours	269746	35.5	174	1052.2
5 Hours	269645	35.6	174	1385.3
6 Hours	269544	35.6	174	1716.5
7 Hours	269551	35.6	174	1693.3
8 Hours	269511	35.6	174	1825.3
9 Hours	269501	35.6	174	1859.1
10 Hours	269410	35.6	174	2159.2
11 Hours	269380	35.6	174	2259.6
12 Hours	269337	35.6	174	2399.4
13 Hours	269201	35.7	174	2850.4
14 Hours	269182	35.7	174	2910.6
15 Hours	269157	35.7	174	2994.6
16 Hours	269158	35.7	174	2991.2
17 Hours	269157	35.7	174	2995.5
18 Hours	269137	35.7	174	3059.5
19 Hours	269089	35.7	174	3220.0
20 Hours	269065	35.7	174	3298.8
21 Hours	269010	35.7	174	3478.9
22 Hours	268962	35.7	174	3636.9
23 Hours	268931	35.7	174	3739.5
24 Hours	268887	35.8	174	3884.8
25 Hours	268881	35.8	174	3906.9
26 Hours	268837	35.8	174	4051.3
27 Hours	268749	35.8	174	4339.5
28 Hours	268771	35.8	174	4269.7
29 Hours	268743	35.8	174	4361.7
30 Hours	268764	35.8	174	4292.5
31 Hours	268742	35.8	174	4363.4
32 Hours	268738	35.8	174	4376.0
33 Hours	268705	35.8	174	4486.3
34 Hours	268692	35.8	174	4528.6
35 Hours	268706	35.8	174	4484.3
36 Hours	268702	35.8	174	4497.0
37 Hours	268696	35.8	174	4514.8
38 Hours	268689	35.8	174	4539.8
39 Hours	268672	35.8	174	4595.5
40 Hours	268655	35.8	174	4650.5
41 Hours	268621	35.8	174	4764.7
42 Hours	268596	35.8	174	4846.9
43 Hours	268566	35.8	174	4944.5
44 Hours	268509	35.9	174	5134.5
45 Hours	268477	35.9	174	5238.7
46 Hours	268483	35.9	174	5220.3
47 Hours	268463	35.9	174	5284.6
48 Hours	268445	35.9	174	5344.3

Model #5: One Enercon Turbine

Maximum Time Flexibility	Total Predicted Fuel Consumption (litres)	Average Wind Penetration (%)	Instantaneous Wind Penetration (%)	Extra Power Saved via Load Shift (kWh)
0 Hours	219907	47.8	194	0.0
1 Hours	219811	47.9	194	319.2
2 Hours	219709	47.9	194	654.0
3 Hours	219641	47.9	194	877.8
4 Hours	219557	47.9	194	1156.3
5 Hours	219474	48.0	194	1430.6
6 Hours	219408	48.0	194	1647.4
7 Hours	219373	48.0	194	1762.5
8 Hours	219323	48.0	194	1928.7
9 Hours	219263	48.0	194	2125.6
10 Hours	219145	48.1	194	2515.9
11 Hours	219150	48.1	194	2498.5
12 Hours	219107	48.1	194	2640.3
13 Hours	219077	48.1	194	2738.9
14 Hours	219078	48.1	194	2736.8
15 Hours	219003	48.1	194	2984.9
16 Hours	218955	48.1	194	3142.0
17 Hours	218912	48.1	194	3283.8
18 Hours	218845	48.1	194	3506.3
19 Hours	218821	48.1	194	3585.5
20 Hours	218757	48.2	194	3795.8
21 Hours	218714	48.2	194	3938.9
22 Hours	218707	48.2	194	3960.6
23 Hours	218710	48.2	194	3951.3
24 Hours	218680	48.2	194	4050.3
25 Hours	218656	48.2	194	4130.4
26 Hours	218637	48.2	194	4191.1
27 Hours	218653	48.2	194	4140.5
28 Hours	218673	48.2	194	4072.8
29 Hours	218654	48.2	194	4137.0
30 Hours	218603	48.2	194	4304.8
31 Hours	218555	48.2	194	4461.8
32 Hours	218516	48.2	194	4591.2
33 Hours	218505	48.2	194	4627.4
34 Hours	218503	48.2	194	4636.0
35 Hours	218482	48.2	194	4704.4

36 Hours	218466	48.2	194	4758.2
37 Hours	218447	48.2	194	4818.2
38 Hours	218423	48.3	194	4900.0
39 Hours	218437	48.3	194	4851.4
40 Hours	218414	48.3	194	4928.1
41 Hours	218367	48.3	194	5083.3
42 Hours	218321	48.3	194	5236.3
43 Hours	218302	48.3	194	5298.1
44 Hours	218288	48.3	194	5345.1
45 Hours	218295	48.3	194	5320.2
46 Hours	218296	48.3	194	5318.4
47 Hours	218292	48.3	194	5331.9
48 Hours	218300	48.3	194	5306.0

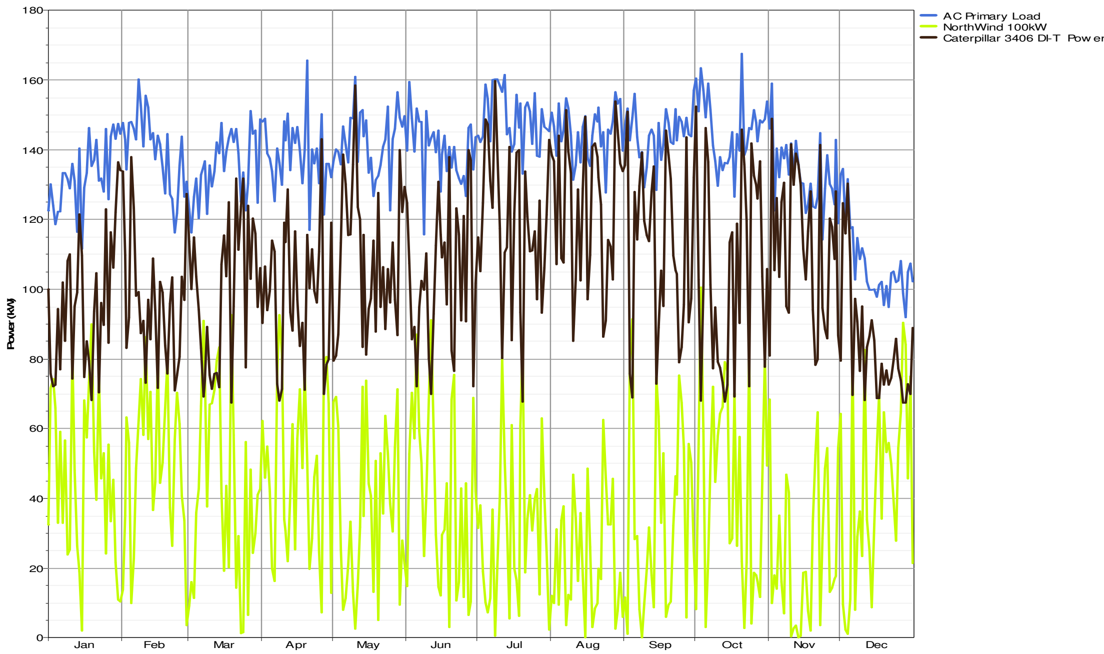
Model #6: Two Enercon Turbines

Maximum Time Flexibility	Total Predicted Fuel Consumption (litres)	Average Wind Penetration (%)	Instantaneous Wind Penetration (%)	Extra Power Saved via Load Shift (kWh)
0 Hours	154766	63.3	389	0.0
1 Hours	154661	63.3	389	345.5
2 Hours	154553	63.4	389	703.3
3 Hours	154470	63.4	389	975.1
4 Hours	154370	63.4	389	1305.0
5 Hours	154307	63.4	389	1513.4
6 Hours	154251	63.5	389	1697.7
7 Hours	154195	63.5	389	1884.8
8 Hours	154122	63.5	389	2125.7
9 Hours	154053	63.5	389	2351.1
10 Hours	154009	63.5	389	2499.0
11 Hours	153971	63.5	389	2624.1
12 Hours	153935	63.5	389	2743.4
13 Hours	153917	63.6	389	2800.0
14 Hours	153883	63.6	389	2912.2
15 Hours	153862	63.6	389	2982.7
16 Hours	153857	63.6	389	2999.0
17 Hours	153792	63.6	389	3214.3
18 Hours	153773	63.6	389	3277.3
19 Hours	153713	63.6	389	3476.1
20 Hours	153680	63.6	389	3582.3
21 Hours	153651	63.6	389	3678.8

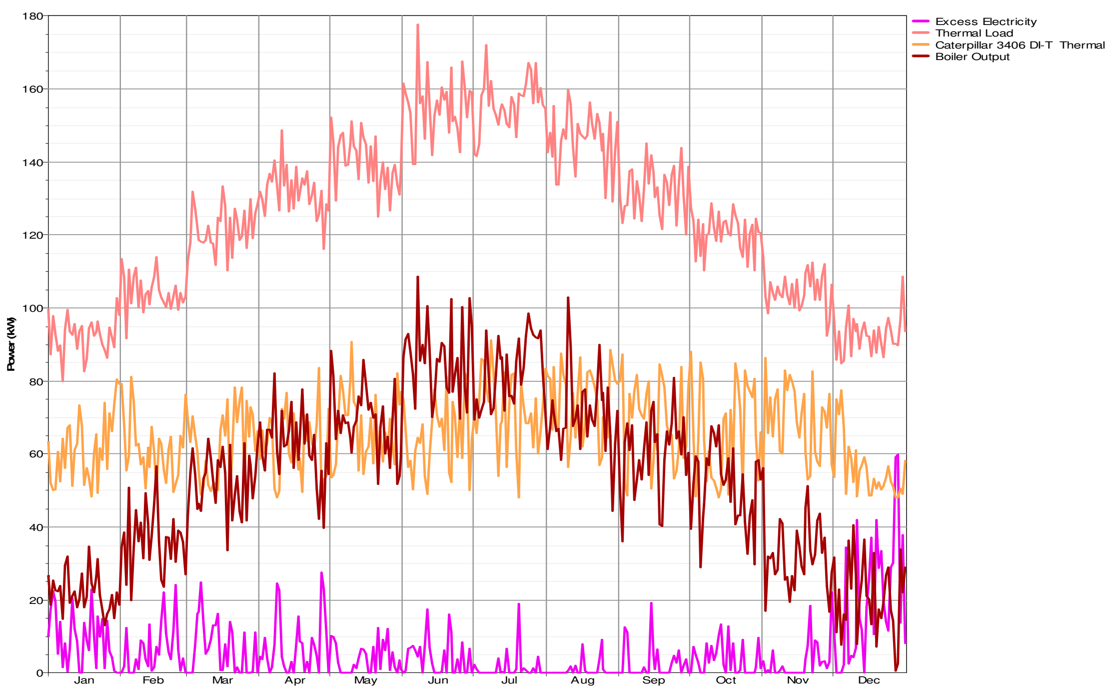
22 Hours	153653	63.6	389	3673.2
23 Hours	153656	63.6	389	3662.8
24 Hours	153656	63.6	389	3663.4
25 Hours	153643	63.6	389	3705.8
26 Hours	153653	63.6	389	3672.8
27 Hours	153654	63.6	389	3669.1
28 Hours	153621	63.6	389	3777.0
29 Hours	153589	63.6	389	3883.3
30 Hours	153598	63.6	389	3855.1
31 Hours	153578	63.6	389	3920.6
32 Hours	153548	63.7	389	4018.4
33 Hours	153524	63.7	389	4097.0
34 Hours	153502	63.7	389	4171.2
35 Hours	153508	63.7	389	4149.7
36 Hours	153513	63.7	389	4134.0
37 Hours	153513	63.7	389	4134.7
38 Hours	153497	63.7	389	4188.6
39 Hours	153461	63.7	389	4307.9
40 Hours	153451	63.7	389	4339.1
41 Hours	153400	63.7	389	4508.7
42 Hours	153397	63.7	389	4518.3
43 Hours	153400	63.7	389	4507.0
44 Hours	153403	63.7	389	4496.4
45 Hours	153405	63.7	389	4492.7
46 Hours	153408	63.7	389	4482.4
47 Hours	153410	63.7	389	4473.8
48 Hours	153413	63.7	389	4464.6

Appendix D

Model #2: One Northwind 100kW Wind Turbine
Simulation Results (Graphical Representation)

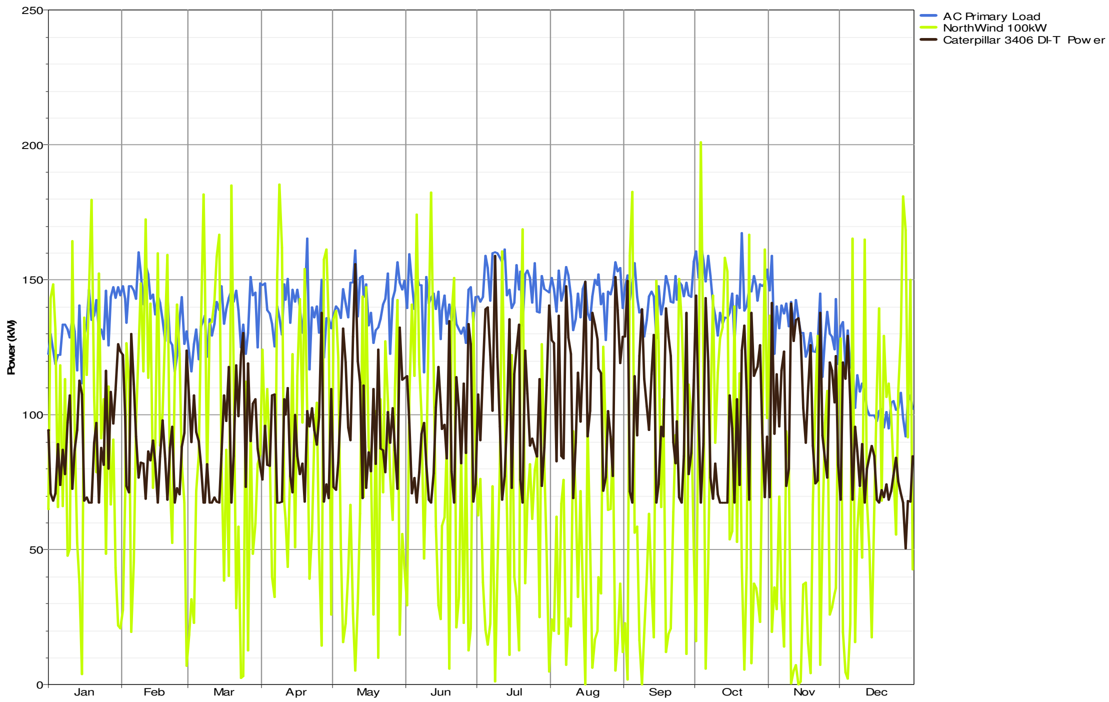


Electrical Load Simulation

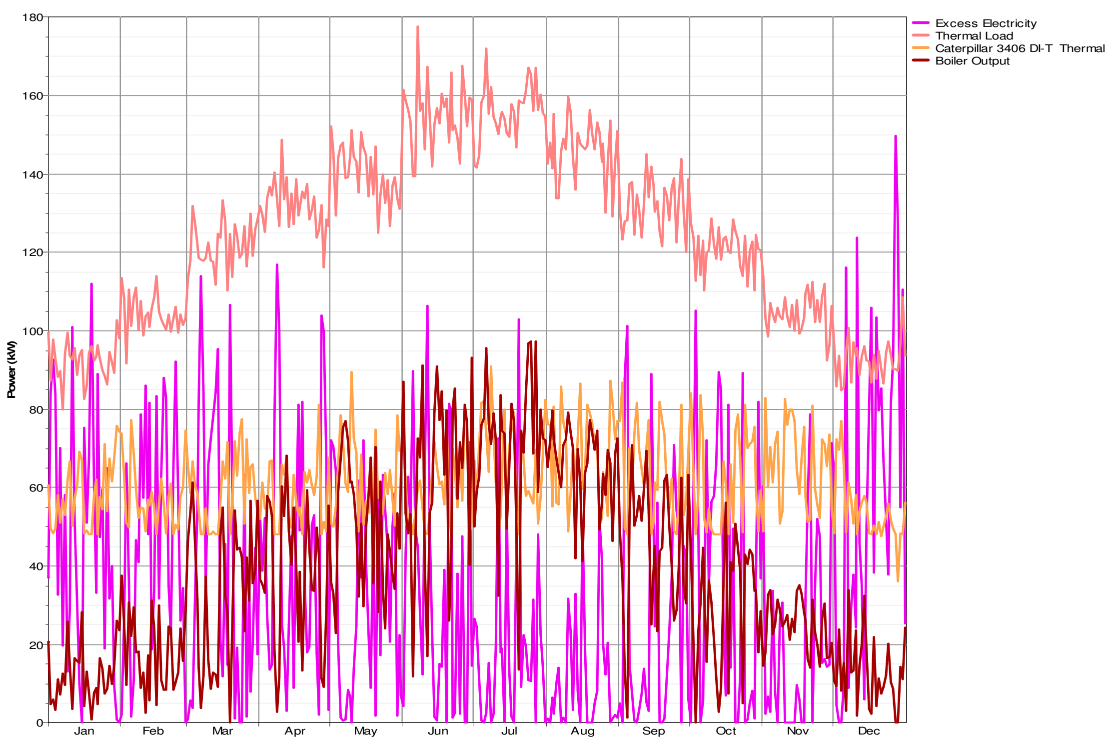


Thermal Load Simulation

Model #3: Two Northwind 100kW Wind Turbines
Simulation Results (Graphical Representation)

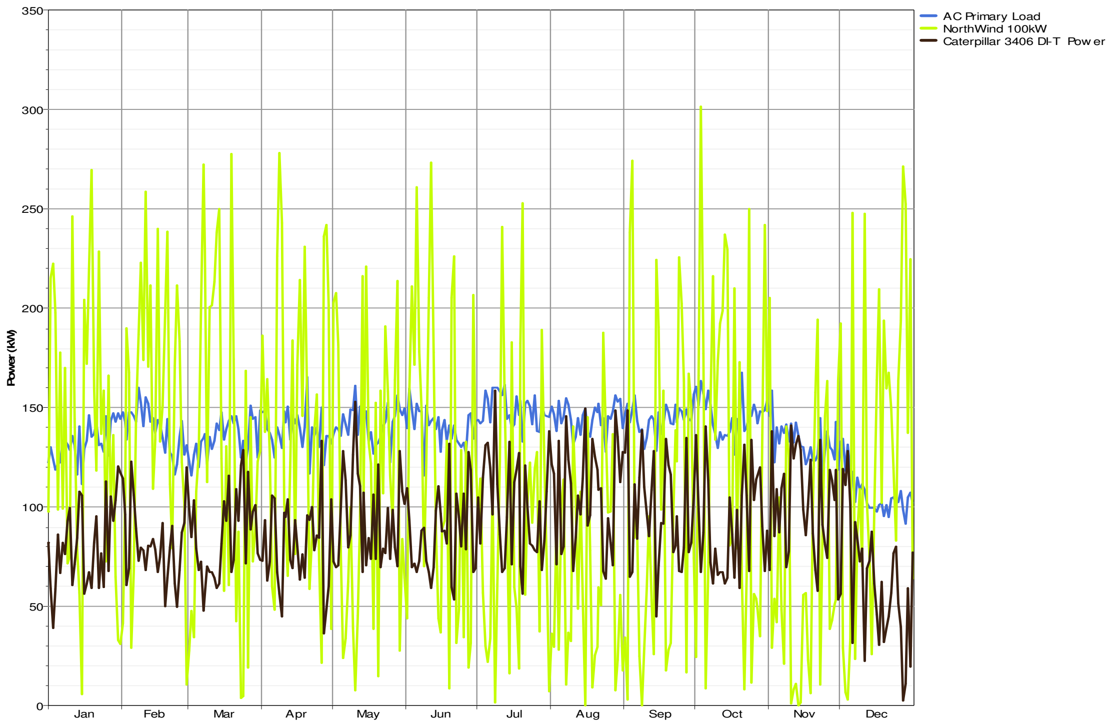


Electrical Load Simulation



Thermal Load Simulation

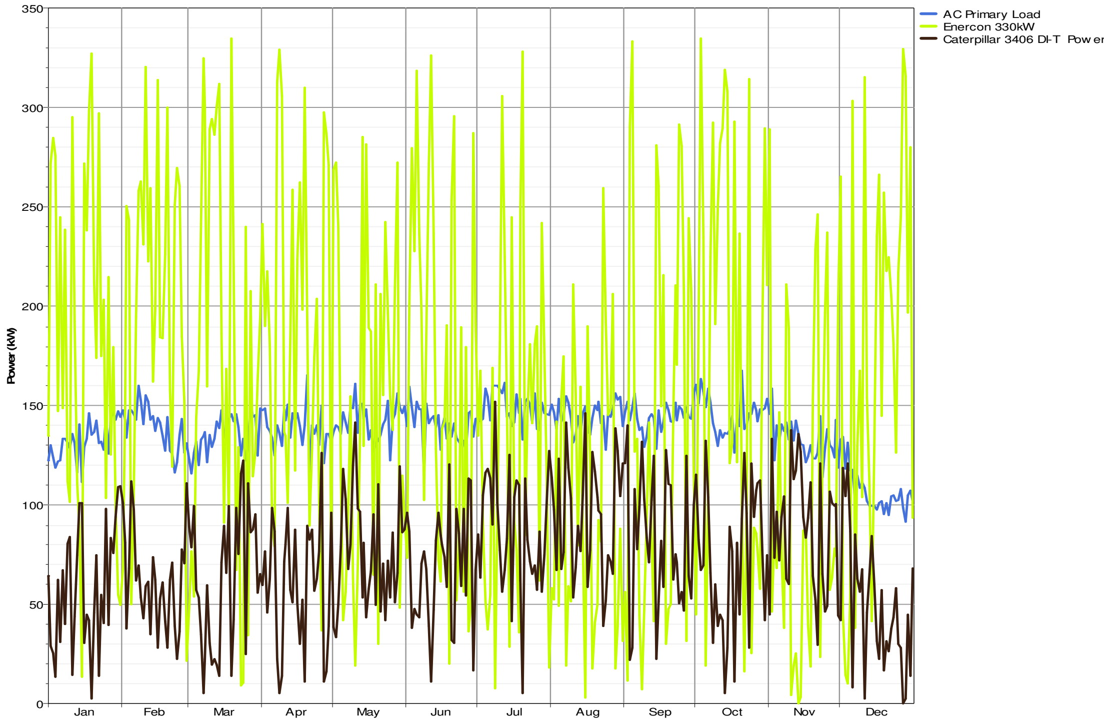
Mo**del #4: Three Northwind 100kW Wind Turbines**
Simulation Results (Graphical Representation)



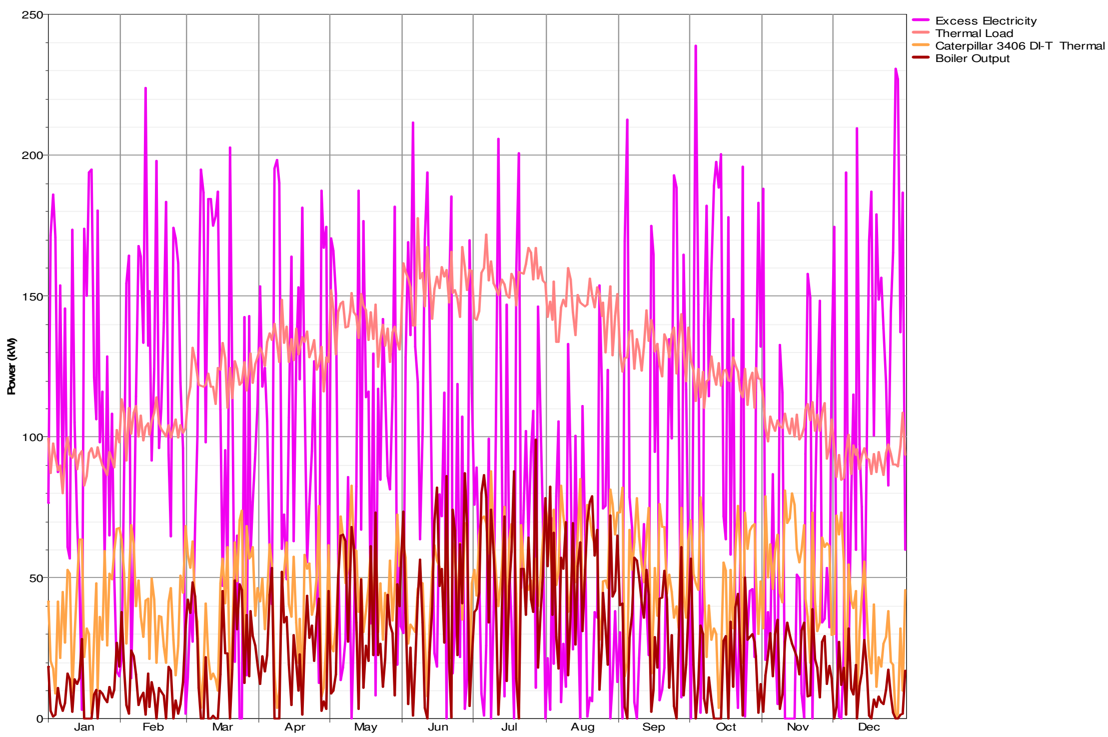
Electrical Load Simulation

Thermal Load Simulation

Model #5: One Enercon 330kW Wind Turbine
Simulation Results (Graphical Representation)



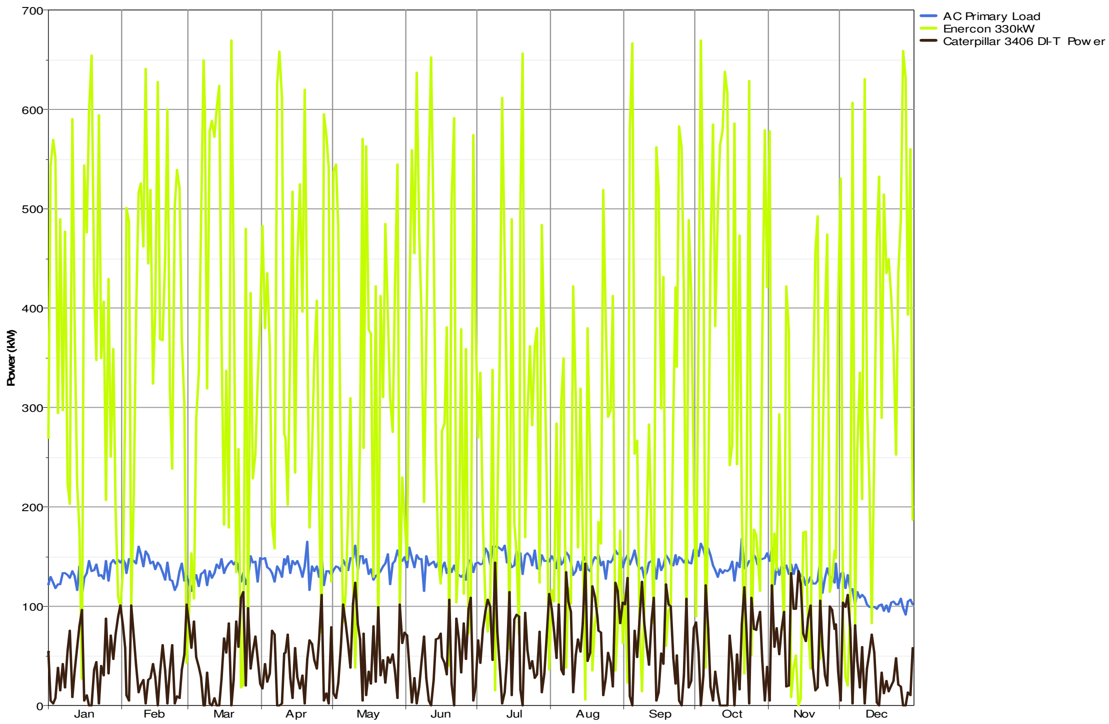
Electrical Load Simulation



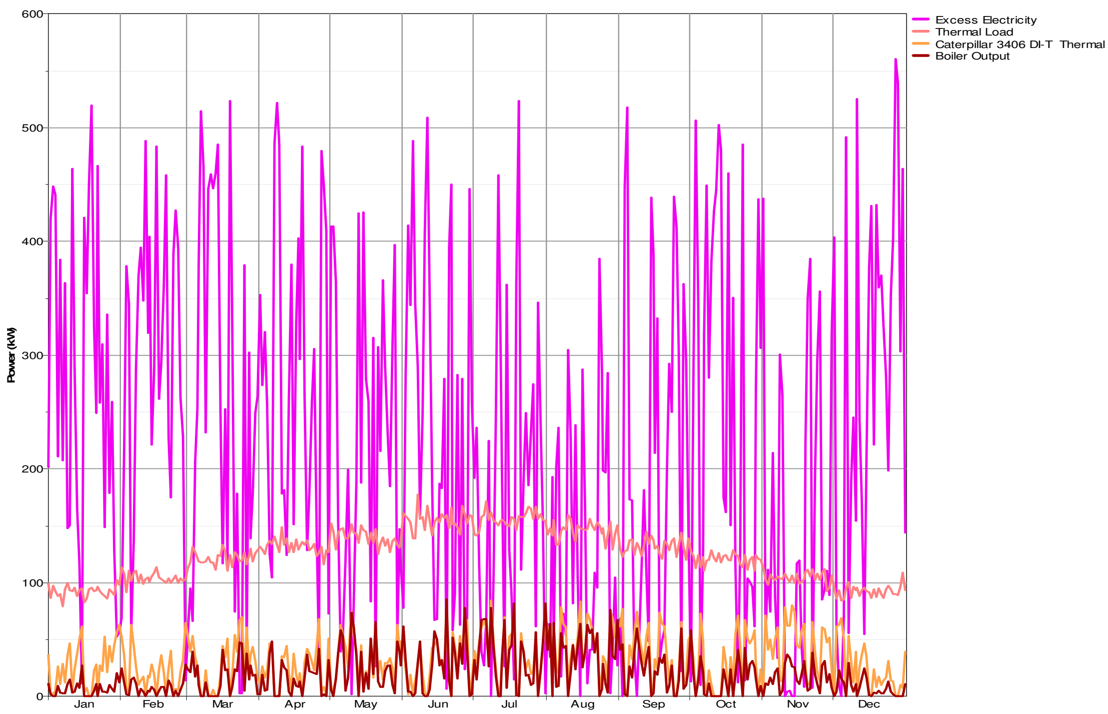
Thermal Load Simulation

Model #6: Two Enercon 330kW Wind Turbines

Simulation Results (Graphical Representation)



Electrical Load Simulation



Thermal Load Simulation