Hydrogen Storage of Energy for Small Power Supply Systems

By

Rory F. D. Monaghan

B.E. (Honors), Mechanical Engineering (2002)

National University of Ireland, Galway

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

At the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2005

Signature of Author.. ....
Department of Mechanical Engineering
May 12, 2005

Certified by..
Ernest G. Cravalho
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by..
Lallit Anand
Chairman, Department Committee on Graduate Students

Hydrogen Storage of Energy for Small Power Supply Systems

By

Rory F. D. Monaghan

Submitted to the Department of Mechanical Engineering
on May 12, 2005 in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Mechanical Engineering

Abstract

Power supply systems for cell phone base stations using hydrogen energy storage, fuel cells or hydrogen-burning generators, and a backup generator could offer an improvement over current power supply systems. Two categories of hydrogen-based power systems were analyzed: Wind-hydrogen systems and peak-shaving hydrogen systems. Modeling of base station requirements and alternative power supply system performance was carried out using MATLAB. Final results for potential alternative systems were compared to those for the current power systems. In the case of the wind-hydrogen systems, results were also compared to those of a wind-battery system.

Overall feasibility was judged primarily on the net present cost of the power supply systems. Other considerations included conformity to present regulations. Sensitivity analysis of the wind-hydrogen model was carried out to identify the controlling variables. Numerous parameters were varied over realistic ranges. Important parameters were found to include wind resource, electrolyzer size, distance from electricity grid, price of diesel fuel, and electrolyzer and fuel cell cost.

The model verified cell phone industry figures regarding the geographical conditions favorable to diesel genset use. Final results for wind-hydrogen systems suggest that for today's electrolyzer and fuel cell costs, wind-battery-diesel systems are the most suitable power system more than 8km from the existing electricity grid, with an annual average wind speed of 7m/s or more, and where diesel costs more than \$2.20/gallon. Thinking to the future, with 20% reduced electrolyzer and fuel cell costs, a wind-fuel cell-diesel system with a 15kW electrolyzer is the most suitable system at locations greater than 8km from the existing electricity grid with an annual average wind speed of 7m/s or more and total diesel costs greater than \$2/gallon. Within 8km the grid, in all cases, grid connection is most suitable. Outside this range, with diesel prices below \$2/gallon, a genset only system is most suitable in most cases.

Analysis of the peak-shaving hydrogen system suggests that it is not suitable for deployment under any realistic circumstances. Replenishment of hydrogen stores has a substantial power requirement.

Thesis Supervisor: Ernest G. Cravalho
Title: Professor of Mechanical Engineering

Acknowledgements

Huge thanks must first go to my research advisor, Professor Ernie Cravalho. Without his experience, knowledge and generosity, this work would never have been started, let alone finished. Professor John Brisson and Professor Joe Smith were constant sources of support and information for all things thermodynamic.

As this is a modeling work, the sources of my data were very important. The following people among others made vital contributions in the construction of the model and I thank them for it: Mr. Dean Halter and Mr. Larry Moulthrop at Proton Energy Systems, Mr. Michael Murphy at NEXTEL, Mr. Jack O'Brien at NSTAR Electric and Mr. Brian Hurley at Airtricity.

I must thank my labmates Alicia, Derya, Doris, Franklin, Fritz, Gunaranjun, Justin, Omar, Sofy and Teresa in the Fuel Cell & Cryogenic Engineering Lab at MIT for all of their help, jokes, happy hours and telephone answering services over the last two years. Were it not for them, the lads of Chez Jay, and all my friends in and around Boston, my experience here would have been very different.

To my parents, Anne and Paul, and to Fergal, I dedicate this work. Without them I never would have taken the engineering road, and certainly would never had ended up here. Thank you.

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Small Power Supply Systems

Small power supply systems can be defined as those which are be used to meet the electrical load requirements of installations in the kilowatt range. Examples of these installations are cellular base stations, military outposts and remote communities. The term “small power supply system” can apply to systems ranging from the electricity grid to an on-site diesel generator to battery-charging solar photovoltaic cells. This means that they can be either grid-connected or stand-alone.

For the purpose of this research, the load requirement of a cellular telephone base station is modeled as the demand that needs to be met by a small power supply system. The reasons for this choice are: It is relatively easy to gain access to base stations through cell phone service providers; Base stations numbers are increasing sharply as providers compete for market-share; Providers are currently looking for cheaper, more reliable power supply systems for their base stations; Regulations curtailing the use of certain power supply technologies are driving research.

Over the next few years, it is expected that an increasing number of base stations will be built in remote areas. This is due to the belief that the most desirable potential base station sites have already been developed and to gain a greater market share, providers must use less accessible, more remote sites [1].

1.2 Cellular Telephone Base Stations

Base stations, or cell phone towers, serve as the communications links between individual cell phones and the telephone network. They are perhaps the most visible part of the cellular telecommunications infrastructure. Figure 1.1 illustrates the essentials of the cellular communication network.

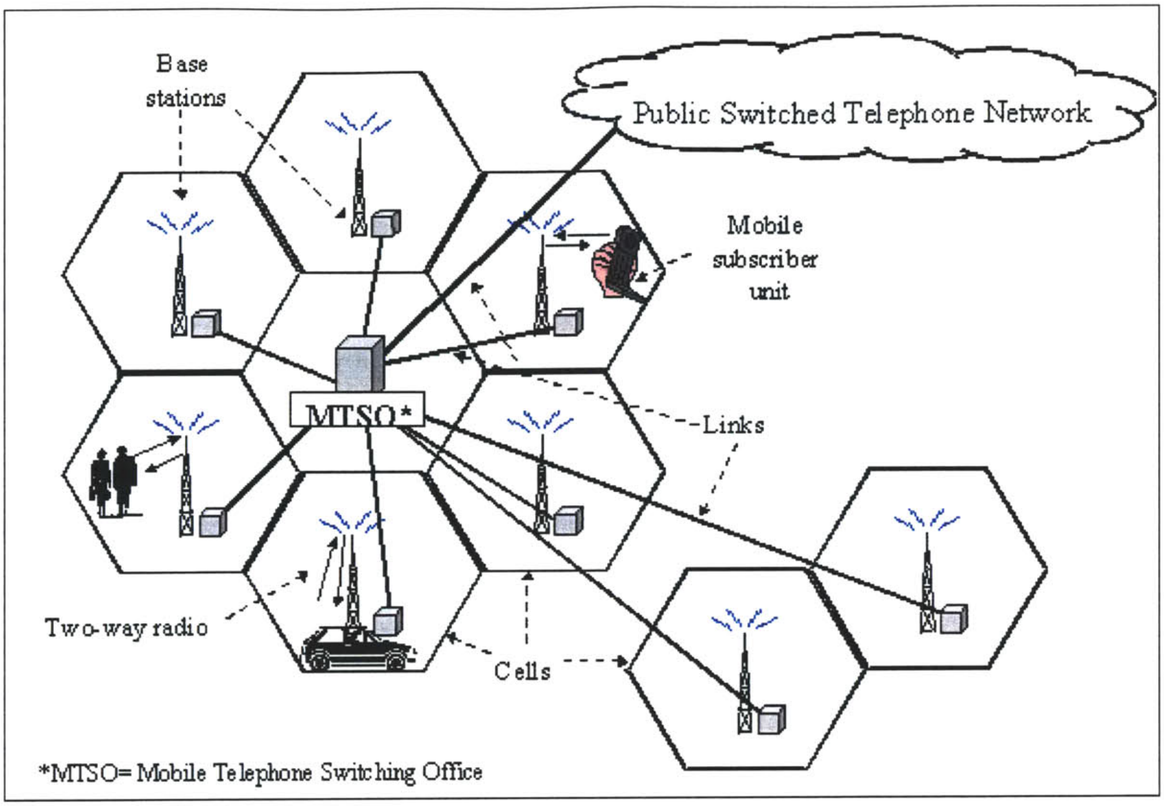


Figure 1.1 Schematic of the Cellular Telephone Network*

Cellular base stations serve the following purposes: To receive signals from individual cell phones; To transmit these signals, via a hard connection, to a Mobile Telephone Switching Office (MTSO), where they are routed to the Public Switched Telephone Network (the telephone network at large); To receive signals from the MTSO, and transmit them to cell phones; To allow communication between two cell phones in the same cell (geographical area served by the base station).

Depending on prevailing conditions, cellular base stations serve areas (cells) ranging in radius from 1 km to 50 km [2]. In rural areas, with fewer customers, cells tend to be larger than those in urban areas. This is because only a limited number of channels are available for use for any one base station. In effect, similarly sized base stations serve similarly sized populations. Figure 1.2 shows examples of base stations in various settings. All are grid-connected.

---

* International Telecommunication Union, *About Mobile Technology*, 2001

Figure 1.2 NEXTEL Base Stations at (a) Cross St., Cambridge, MA, (b) Monadnock Mountain, NH, (c) Green St., Cambridge, MA

Typical cell phone base stations draw in the region of 10 kW of electrical power. This will be discussed further in the modeling chapter. For now, it is necessary to know that the load requirement for a base station is made up of an intermittent AC requirement for environmental control and a DC requirement for telecommunications equipment.

1.3 Current Power Supply Systems for Base Stations

1.3.1 Primary Power Supply

The vast majority of base stations in the United States receive their primary electrical power from the electricity grid. In many urban and suburban areas, base stations are sited at or very near the grid. Electricity utility companies charge per foot of grid extension. That is, if a customer far from the grid wants to be connected, the utility company charges the customer to extend the existing grid to him/her. A typical grid extension rate is \$8.49/foot or \$27,836/km [3].

It is economical for cell phone companies to connect to the electricity grid for power system costs of up to \$300,000. At that point, it becomes more economical to provide stand-alone power rather than to extend the grid to the base station with the associated grid extension cost. Roughly speaking, this crossover occurs around the 10km mark. For more remote base stations, diesel powered generator sets (diesel gen-sets) are typically used as primary power. Propane and natural gas generators are also used, although they are not as widespread. These generators must be refueled every 2-3 weeks [1].

1.3.2 Short-term Backup Power Supply

Virtually all base stations have short-term backup in case of grid failure in the form of battery banks. Valve Regulated Lead Acid batteries (VRLAs) are the battery of choice for most backup applications. These banks are sized to provide backup power to the telecom equipment for 2-4 hours, typically storing 15-30 kWh of energy. As the banks provide DC, they do not power the A/C units. Figure 1.3 shows a typical VRLA battery bank as employed in a base station.

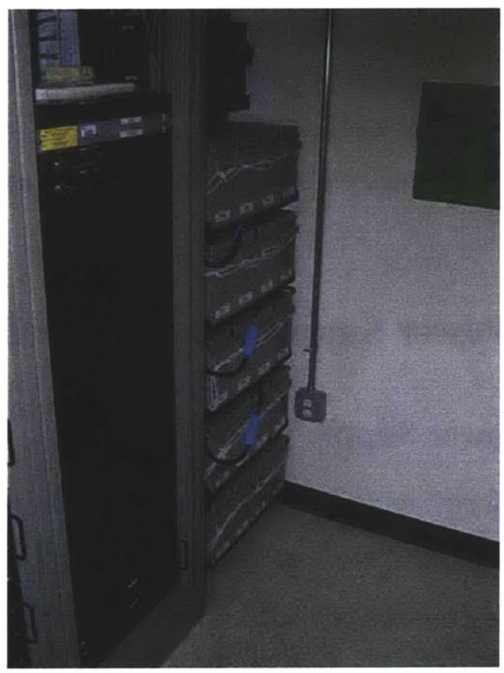


Figure 1.3 VRLA Battery bank in NEXTEL base station, Green St., Cambridge, MA

1.3.3 Long-term Backup Power Supply

Where space and regulations permit, diesel generators are used for longer term backup (up to 2-3 days). At more rural base stations, generators can be kept onsite, while in urban areas generators must be towed to base stations from depots in the event of grid failure. Noise and pollution regulations in some areas forbid the use of generators under any circumstances, so grid failures lasting for more than 2-3 hours result in the loss of service from the base station. Figure 1.4 shows fixed and mobile gensets.

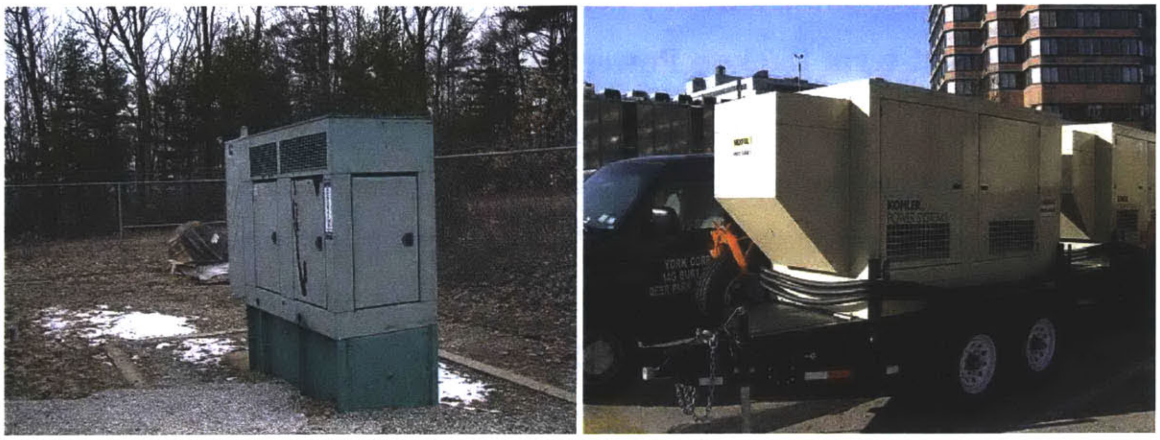


Figure 1.4 Kohler gensets used by NEXTEL (a) Fixed genset, Monadnock Region, NH, (b) Mobile genset depot, W 42nd St., New York, NY

1.4 Drawbacks of Current Power Supply Systems

1.4.1 Primary Power Supply

As stated above, the main source of primary power for base stations is the electricity grid. For very remote areas, gensets are used. Connection to the electricity grid can be expensive, particularly when an extension must be built. Extension costs are in the region of $28,000/km, as previously stated.

The use of a genset as a primary power source presents a different set of problems. Although generators are relatively cheap to purchase at $800-$2,000/kW, they are expensive to maintain, $1.20-$2.00/hour of operation [4]. This maintenance cost reflects the fact that for continuous operation, internal combustion engines endure serious wear. Filters must also be changed at regular intervals. Even with this maintenance, generators are usually replaced after 12,000-15,000 hours [5]. Fueling of gensets for primary power represents a large expense. As well as the cost of diesel fuel, the cost and inconvenience of refueling remote, sometimes snowbound, base stations every 2-3 weeks are significant. Regulations governing the use of diesel generators are restrictive. Some areas, particularly those of scenic or natural significance, do not allow gensets to operate at all. In other places, limits of hours of operation apply, usually 200 hours (8 days) per year [6].

1.4.2 Short-term Backup Power Supply

Valve Regulated Lead Acid Batteries, or VRLAs, are the standard short-term backup to grid power for base stations. In recent years, experience has led many cell phone service providers, including NEXTEL, to re-evaluate their use and seek alternatives [1] & [7]. The main reasons for this are:

- Shorter than expected lifetime. Batteries rated for 10 years of use can last as little as 3 years.
- Heavy transportation weight. Replacing batteries, especially in remote areas, is difficult due to their size and weight.
- Difficulties associated with disposal. Batteries must be disposed of according to strict regulations due to their toxic contents. This can be an expensive process.
- Explosive potential due to venting of hydrogen gas in enclosed spaces. VRLAs release miniscule amounts of hydrogen during normal operation. Over time, in poorly ventilated spaces, dangerous amounts of hydrogen gas can build up. Incidents have been reported of explosions at battery banks due to this phenomenon [8].

1.4.3 Long-term Backup Power Supply

When considering gensets as a long-term backup option, maintenance costs, lifetime and refueling are not as important issues as they are for primary power use. However, they still face the problem of tight regulations in certain areas.

Chapter 2 Alternative Power Supply Systems

2.1 Overview of Alternatives

For any alternative power supply system to be considered as a replacement, it must meet the following criteria:

- It must be able to meet the base station load at least as effectively and reliably as the current power supply systems.
- It must be at least as cost effective as the current power supply systems.
- Due to difficulties discussed above, an alternative to Valve Regulated Lead Acid (VRLA) batteries would be preferred.
- It must adhere to regulations governing the duration of use of generators.

In this work it is proposed that power supply systems using hydrogen storage of energy are realistic alternatives to current systems under the right conditions. It is hoped that by the end of this work we will have an idea of what these conditions are.

There are two basic divisions of power systems using hydrogen storage:

1. Power System with Hydrogen Storage of Renewable Energy (Renewable-Hydrogen System)
2. Power System with Hydrogen Storage of Off-Peak Electrical Energy (Peak-Shaving Hydrogen System)

The basic function of hydrogen storage is to convert excess cheap or abundant primary electrical energy into chemical energy via water electrolysis. When the primary energy is expensive or scarce, this chemical energy is then converted back to electricity in a fuel cell or a combustion engine generator. Of courses, losses during the conversion processes mean that we lose a significant portion of the original energy.

2.2 Renewable-Hydrogen System

2.2.1 Choosing Among Renewable Energy Resources

Many renewable energy resources are characterized by their intermittent nature. Therefore if they are to be used effectively as a primary power supply to a user, some form of energy storage is needed. In this work, hydrogen is proposed as the means of renewable energy storage. Table 2.1 shows various renewable energy resources and the advantages and disadvantages of their use for powering a base station. It should be noted that not all of these resources are necessarily intermittent.

Renewable Resource	For	Against
Wind	Commercialized, Distributed, Infrastructure	Intermittent, Expensive
Solar PV	Commercialized, Predictable, Reliable	Low energy density, Expensive
Solar Stirling Engine	More compact than PV	Not commercialized
Geothermal		Not commercialized for this application
Microscale Hydroelectric		Geographically specific

Table 2.1 Advantages and Disadvantages of various Renewable Energy Resources

From a practical standpoint, wind and solar PV are the only technologies which could be considered for this application. A solar Stirling engine consists of the following: a reflecting dish mounted on a solar-tracking base; a Stirling engine mounted on an arm at the focal point of the reflecting dish; and an electrolyzer with hydrogen compression and storage. During sunny periods, solar radiation is reflected off the dish and onto the hot end of the Stirling engine, which supplies electricity to the user. When there is excess solar energy, the Stirling engine produces more electricity than is required. This excess electricity is used in water electrolysis and hydrogen compression and storage. At night, hydrogen is supplied to the same Stirling engine and electricity is produced this way. Although this technology has been explored [9], it has in many cases been abandoned and is at best a very long way from commercialization.

A geothermal project to provide power for a base station suffers from the fact that geothermal wells are very expensive to drill and so are usually built on a MW scale to benefit from economies of scale. Electricity generation from geothermal energy is also very geographically specific. Microscale hydroelectricity is also not suitable for this application because of its geographically specific nature.

Solar PV cells have been and are currently being used to power telecommunication sites around the US and the world. However, due to the low energy density of solar PV cells, they are typically only installed on much smaller stations than those being considered here, around 50-500W in size. Also, due to the low electricity-to-electricity efficiency of using hydrogen as an energy storage medium, a very large solar array (on the order of 1,000m^2) would be needed in order to generate enough hydrogen to power the base station during the night. For these reasons, a solar PV-hydrogen system was is not considered as an alternative.

Wind energy is left as the only possibly feasible renewable energy source under consideration. Wind energy is a well developed technology, it has a small footprint, and wind is a well distributed resource. In addition, there is a possible infrastructural benefit of wind energy, by being able to mount the base station transmitters and receivers on the tower of the wind turbine. Wind turbines are currently in use in very small numbers around the world to power small base stations. Again these projects are typically smaller than the base station under consideration here, usually 500W-2kW.

A schematic of a wind-hydrogen power system is shown in Figure 2.1. It shows the relevant energy and mass flows, in the form of electricity (both DC and AC) and flows of hydrogen, oxygen, air and water. The precise requirements of the base station will be discussed in the modeling chapter. The next section will discuss the individual components in depth.

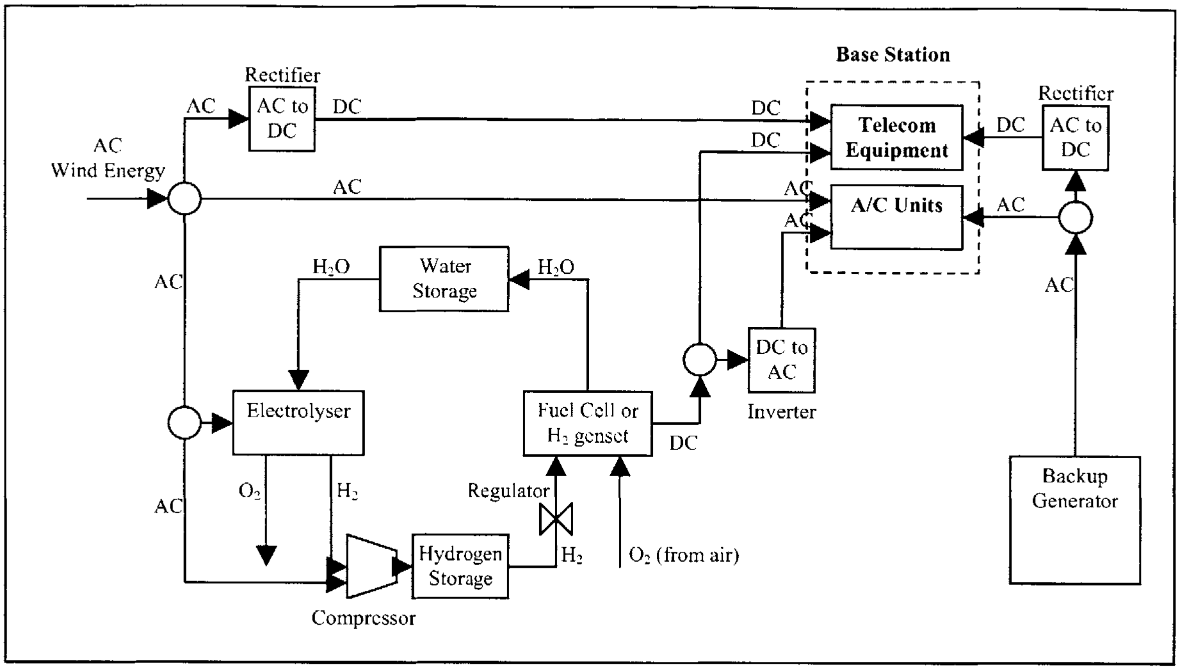


Figure 2.1 Components, Energy and Mass Flows of proposed Wind-Hydrogen Power Supply System

2.2.2 Components of a Wind-Hydrogen System

Where possible, actual commercial product data was used, rather than performance and costing data from the literature. Table 2.2 shows the various components under consideration for the system, the source of information and the specifications used in the modeling of the system. Each component and its role will now be discussed in detail.

Component	Specifications for model
Wind Turbine [10]	AOC 15/50 50kW rated turbine
Electrolyzer [11]	HOGEN H 6Nm^3/hr (37.8kW) electrolyzer
Compressor [12] & [13]	Model 4089 single stage compressor
Storage Cylinders [14]	2,000psi steel cylinders
Fuel Cell [11] & [13]	Model developed
Hydrogen-Powered Generator [15]	Model developed
Water Tank [16]	100 gallon plastic tank
Diesel-Powered Generator [1], [4], [5] & [17]	Olympian 40kW single phase generator
Power Electronics [13]	Included in component

Table 2.2 Components of a Wind-Hydrogen System, their sources and specifications

2.2.2.1 Wind Turbine

As the wind turbine is the primary source of electricity for the base station, it is important to size it correctly. Wind turbines are typically sized according to their kW or MW power output. There is a huge range of sizes for wind turbines, ranging from 100W to roughly 5MW. However, there is a shortage of manufacturers of wind turbines in our range of interest. Wind turbines for home use, in the range 100W to 2kW are readily available, Bergey Wind being the major supplier in the United States. Also, utility size turbines for use in wind farms, in the 500kW to roughly 5MW range, are built and sold around the world. For these machines, dominant players are General Electric and Vestas. In the tens of kW range, in which we are interested, there are only a handful of manufacturers worldwide. Of these, Atlantic Orient Canada (AOC) is the highest profile. The basic specifications of the AOC 15/50 turbine are shown below in Table 2.3, while its power curve is shown in Figure 2.2 [10]. It is only wind turbine in this size range for which performance data was available.

Rated electrical power	50kW (AC) @ 11.3m/s (25.3mph)
Cut-in wind speed	4.6m/s (10.2mph)
Cut-out wind speed	22.4m/s (50mph)
Centerline hub height	25m (82ft)
Rotor diameter	15m (49.2ft)
Capital cost	\$135,000
O&M cost	\$165/year
Lifetime	30 years

Table 2.3 Basic Specifications of an AOC 15/50 50kW Wind Turbine

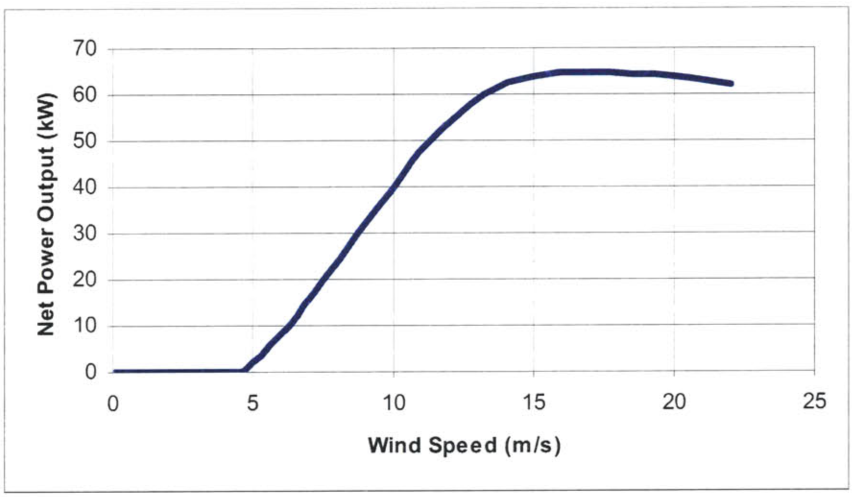


Figure 2.2 Power Curve of an AOC 15/50 50kW Wind Turbine

2.2.2.2 Electrolyzer

The function of the electrolyzer is to convert excess electrical energy from the wind turbine into storable chemical energy in the form of hydrogen. This is achieved by electrochemically splitting water into hydrogen and oxygen. The basics of the process are the following:

- Current is passed through an electrolytic cell in the presence of water and a catalyst, causing the following reactions at the cathode and anode:

For an acidic electrolytic cell:

Cathode: $2H^{+} + 2e^{-} \rightarrow H_2$

Anode: $H_2O \rightarrow \frac{1}{2}O_2 + 2H^{+} + 2e^{-}$

For an alkaline electrolytic cell:

Cathode: $2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$

Anode: $2OH^{-} \rightarrow \frac{1}{2}O_2 + H_2O + 2e^{-}$

- The hydrogen produced in the cell can then be captured for compression and storage.

There are numerous electrolyzer manufacturers around the world: Hydrogenics and Stuart Energy in Canada; Proton Energy Systems and UTC in the United States; Norsk Hydro in Norway to name a few. Proton Energy Systems proved very helpful in providing technical and costing data for their products, so the electrolyzer used in this work is a Proton Energy Systems HOGEN H 6Nm^3/hr (37.8kW) unit. Table 2.4 shows basic specifications for the electrolyzer [11].

Electrolyte	Proton Exchange Membrane
Hydrogen production rate	6Nm^3/hr maximum
Delivery pressure	15barg (218psig)
Power consumption	6.3kWh/Nm^3
Ambient temperature range	5-50°C (indoor) -20-50°C (outdoor)
Altitude range	Sea level to 2400m
Capital cost	\$105,000
O&M cost	\$9,000/year
Lifetime	15 years

Table 2.4 Basic Specifications of a Proton Energy Systems HOGEN H 6Nm^3/hr (37.8kW) Electrolyzer

2.2.2.3 Compressor

As seen above, the electrolyzer delivers hydrogen at 15bar or 218psi gage pressure. Due to the fact that hydrogen is the least dense of any gas, compression is usually used to store an appreciable amount of it. Specifications for hydrogen compressors were obtained from PPI Compressors. The system under consideration requires compression at a maximum flow rate of 6Nm^3/hr from 218psi at the electrolyzer outlet to about 2,000psi for storage in cylinders, and a high level of hydrogen purity to be maintained. Oil entering the hydrogen stream in the compressor would lead to eventual degradation of a fuel cell. A PPI Model 4089 single stage compressor is used here. Table 2.5 shows the basic specifications of the compressor [12].

Maximum flow rate	10Nm^3/hr
Inlet pressure	250psi
Outlet pressure	2,000psi
Capital cost	$26,000
O&M cost	$3,000/8,000 hours
Lifetime	20 years

Table 2.5 Basic Specifications of a PPI Model 4089 Single Stage Compressor

2.2.2.4 Fuel Cell

A fuel cell, or a hydrogen powered generator, provides the secondary power to the base station. The hydrogen fuel is supplied by the storage cylinders via a pressure regulator. The fuel cell essentially operates as an electrolyzer in reverse. We will see in later sections that the maximum electrical load required by the base station is in the region of 16-17kW, so this determines the size of the fuel cell system. No commercial fuel cell data was available, so a fuel cell model was developed for the purpose of this work. This model will be discussed in the modeling chapter.

2.2.2.5 Hydrogen Powered Generator

The reason for including a hydrogen powered generator (hydrogen genset) in this analysis is the fact that it is a cheaper, less efficient alternative to using a fuel cell. These factors compete so the hydrogen genset may be suited to certain conditions more than the fuel cell. Again, the size of the base station requirement determines the generator size. A hydrogen powered generator is a hydrogen powered internal combustion engine driving an alternator. They are not a widespread technology, so commercial data was not available, necessitating the development of a model. This will be discussed in the modeling chapter.

2.2.2.6 Storage Cylinders

Hydrogen can be stored in any of a number of ways, including: Compressed gas; Cryogenic liquid; Reversible metal hydrides; and Alkali metal hydrides. Metal hydride storage is only now becoming commercialized and has not yet reached a suitable level of maturity to be considered in this work. Hydrogen is stored as a cryogenic liquid for industrial and chemical processes and also for transportation. Cooling hydrogen to below its boiling point of 22K is quite energy intensive and is typically not done on a small scale such as this. Therefore, compressed gas is chosen as the preferred method of hydrogen storage. The storage pressure is an important consideration since it determines how much gas is contained in a given volume. There are two main families of compressed hydrogen storage; low and high pressure.

Low pressure typically refers to around 2,000psi (roughly 140bar). The storage container is usually a steel cylinder 1-2m in height and 15-50cm in diameter. These cylinders are used for many gases in many industries and processes, and are widely available, simple to use and inexpensive. High pressure storage occurs at up to 12,000psi. Aluminum and carbon fiber composite cylinder are used. These cylinders offer improved volumetric and gravimetric energy densities at much higher costs, and are mostly used in transportation applications. Natural gas and hydrogen powered buses and cars use high pressure composite cylinders for fuel storage. As volumetric and gravimetric energy densities are not major concerns for this system, low pressure cylinders are used in the analysis. Basic specifications of a typical 2,000psi hydrogen storage cylinder were obtained from BOC Gas and are shown in Table 2.6 [14].

Storage pressure	2,000psi
Internal volume	50L
Maximum storage mass of H_2	0.56kg
Capital cost	$150
O&M cost	$0-100/year
Lifetime	50 years

Table 2.6 Basic Specifications of a BOC Gas 2,000psi Hydrogen Storage Cylinder

2.2.2.7 Water Tank

The water storage tank is perhaps the simplest and cheapest component of the system. The water vapor exhaust from the fuel cell condenses and is collected in the water tank. Obviously, water vapor will be lost to the environment as not all of it can be captured. Also, water will be lost in the electrolyzer. Due to the low cost of the water tank, it can be vastly over-sized and topped up from time to time to ensure adequate water levels. A brief calculation of water tank capacity follows:

One 2,000psi cylinder contains 0.61kg of H_2

1 mole of H_2=0.00202g

$\therefore$ One 2,000psi cylinder contains 303 moles of H_2

Overall fuel cell reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

So, one 2,000psi cylinder of H_2 leads to the production of 303 moles of H_2O

1 mole of H_2O=0.01802g

$\rightarrow$ One 2,000psi cylinder of H_2 leads to the production of 5.45kg of H_2O

Density of H_2O ; 1,000kg/m^3

$\therefore$ One 2,000psi cylinder of H_2 leads to the production of 5.45L of H_2O

$\rightarrow$ Or 1.44gallons of H_2O

Dimensions of a 20 gallon tank are:
Diameter: 16"
Height: 28"
Cost: $60
Dimensions of a 200 gallon tank are:
Diameter: 40"
Height: 48"
Cost: $225

These dimensions and costs are entirely reasonable for this proposed system. A plastic water tank of the specifications shown in Table 2.7 was chosen from www.plastictank.ca [16].

Internal volume	246L (65 gallons)
Dimensions	23"D x 42"H
Capital cost	$108
O&M cost	$0-100/year
Lifetime	20 years

Table 2.7 Basic Specifications of a www.plastictank.ca Water Tank

2.2.2.8 Diesel Powered Generator

Wind energy is an intermittent resource, which is why energy storage is used in this system. It is impossible to predict the duration of the longest period of low wind over the course of the system, so it is impossible to exactly size the hydrogen storage for the fuel cell to provide all of the required power. We could over-design the system, but this would lead to ridiculously large storage, which would only very rarely be fully used. A more reasonable approach is to choose a realistic hydrogen storage size even though we know will not provide all the hydrogen required, and have a backup diesel powered generator (diesel genset) to supply the base station when the hydrogen stores are expended. Diesel gensets are an extremely well developed and mature technology, and are used in remote wind-battery-diesel power systems. By using a diesel genset, we still have to face regulatory issues, but we may be able to size our system such that the genset works a minimum of the time.

It was decided to use the model of backup genset that is used at numerous base stations visited during the work. An Olympian 40kW single phase generator sold by Caterpillar was chosen. Basic specifications are shown in Table 2.8 [1], [4], [5] & [17]. Data absent from the table will be discussed in the modeling chapter.

Rated power	36-40kW
Fuel consumption	3.6 gallons/hour
Diesel-electricity efficiency	~29%
Capital cost	No data
O&M cost	No data
Lifetime	12,000 hours

Table 2.8 Basic Specifications of an Olympian 40kW Single Phase Generator

2.2.2.9 Power Electronics

Power electronics are needed in many instances in the proposed wind-hydrogen system, including:

- Smoothing power output from the wind turbine, fuel cell, hydrogen genset and diesel genset
- Rectifying AC power from the wind turbine and diesel genset to DC power for the telecommunications equipment in the base station
- Rectifying AC power from the wind turbine, used as input power for the electrolyzer, to DC power used for electrolysis
- Converting DC power from the fuel cell to AC power for the environmental control units in the base station

For the purposes of this analysis, it is assumed that each component in the system has its own inbuilt power electronics package.

2.3 Peak-Shaving Hydrogen System

2.3.1 Peak-Shaving

At times of high demand on the electricity grid, utility companies impose surcharges on electricity consumed. The fundamental purpose of this is to cover the costs of building and running extra generating capacity, which is not used all the time. In the United States this extra capacity, peaking capacity, is primarily fueled by natural gas, an increasingly expensive fuel. Electricity consumed during these times of high demand is known as peak rate electricity. There are four main types of electricity cost peaks:

1. Seasonal peaks: Many countries and regions around the world experience different electrical loads at different times of year. This is particularly true in countries which have defined seasons. For this purpose, regions may be categorized as summer-peaking or winter-peaking. An example of a summer-peaking region is the southern states of the US. The air conditioning load during the hot, humid summer is much greater than any heating load needed during the relatively mild winters. Temperate maritime climates such as those found in the British Isles are examples of winter-peaking regions, where colder, wetter winters require much greater loads for heating and indoor activities than the mild summers. In these two categories, whenever the peak occurs, local utilities may add a surcharge to electricity consumed during that period. In places where there are no obvious peaks, or the peaks are of similar size, surcharges might not be added.
2. Weekly peaks: On weekends in regions with good climates, less electricity is electricity is consumed as people typically spend more time outdoors. Therefore, electricity is usually more expensive when it is consumed during the week as opposed to the weekend. It is perhaps more correct to refer to the weekend as an off-peak period since it is of shorter duration than the week.
3. Daily peaks: In virtually part of the world, regardless of climate, roughly the same daily peaks occur due to consumer and industry work patterns. Electricity consumption is very low during the night. At 6 or 7am, consumption starts to rise

and it typically stays high throughout the work day. After dinnertime and television primetime, electrical consumption returns to low nighttime levels. Again, night hours can also be referred to as off-peak hours.

4. Excess Usage Peaks: Some utility companies charge consumers extra for exceeding standard prearranged electrical load levels for sustained periods of time. If a customer's power consumption exceeds a certain level, any power consumed above that level is charged at an increased rate. These rates can be quite high, in some cases, many times the regular rate.

Peak-shaving is a method of avoiding some, if not all, of these different types of peaks. Seasonal peaks, because of their duration, are typically unavoidable. In order to peak-shave, a consumer must have a secondary power supply to which he or she switches when a peak is encountered. This can either be a peak related to the time or the day, or a peak related to the consumer's load. Of course, the secondary power supply must be able to supply power at a rate sufficiently cheaper than ordinary grid connection, so that it justifies the extra capital and O&M costs over its lifetime. Distributed Generation (DG) technologies such as microturbines, generator sets, fuel cells and solar PV cells are being developed for this purpose [18].

Figure 2.3 shows a schematic of a peak-shaving system, which uses hydrogen storage. This part of the work proposes a peak-shaving system which works in the following way:

- Cheap off-peak electricity is used to electrolyze water, producing hydrogen, which is compressed and stored.
- During peaks, grid electricity is disconnected and the stored hydrogen is consumed in a fuel cell or hydrogen powered generator to provide power.

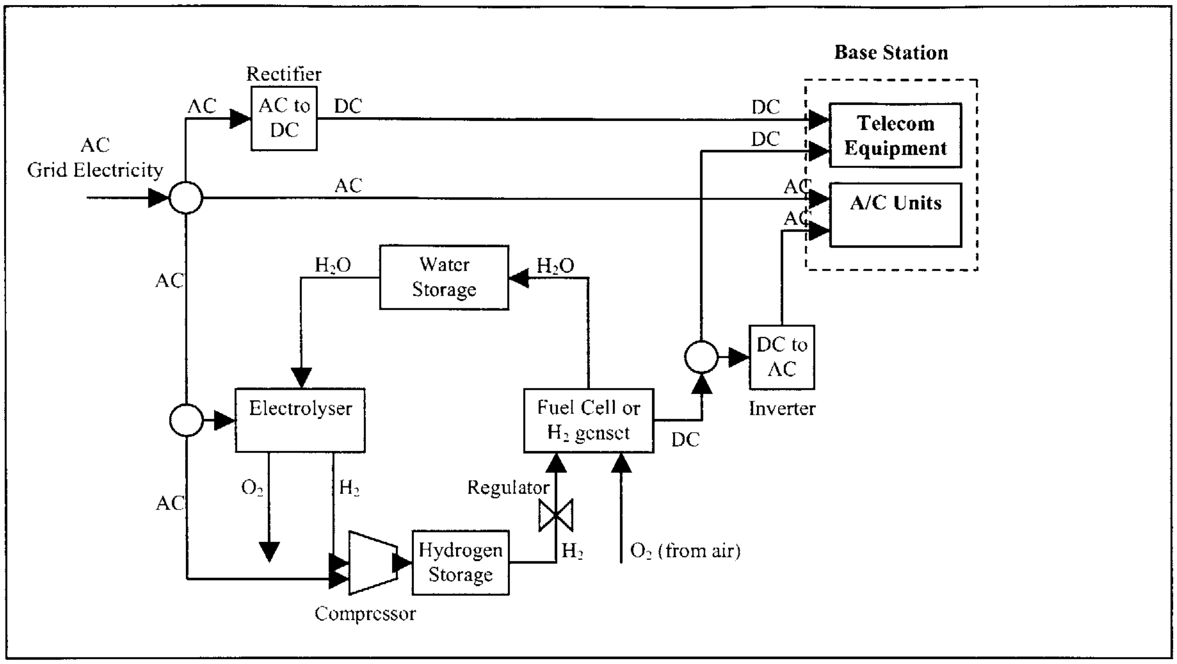


Figure 2.3 Components, Energy and Mass Flows of proposed Peak-Shaving Hydrogen Power Supply System

2.3.2 Components of a Peak-Shaving Hydrogen System

All of the components used in this system are used in the wind-hydrogen system, discussed above. A list of the components used in this system, the sources of the data, and specifications used for the model is shown in Table 2.9. Development of all the components except the electricity grid can be found in the previous section on the Wind-Hydrogen Power System. The different electricity grid connections are discussed below.

Component	Specifications for model
Electricity Grid Connections [3] & [19]	NSTAR Rates G-1 & G-2 ESB General Purpose & Maximum Demand Charges
Electrolyzer [11]	HOGEN H 6Nm^3/hr (37.8kW) electrolyzer
Compressor [12] & [13]	Model 4089 single stage compressor
Storage Cylinders [14]	2,000psi steel cylinders
Fuel Cell [11] & [13]	Model developed
Hydrogen-Powered Generator [15]	Model developed
Water Tank [16]	100 gallon plastic tank
Power Electronics [13]	Included in component

Table 2.9 Components of a Peak-Shaving Hydrogen System, their sources and specifications

2.3.2.1 Electricity Grid Connections

Virtually every electrical utility company has its own individual pricing structure, making it difficult to analyze a peak-shaving system under all available conditions. In this work, two electrical utility companies were considered; NSTAR Electric in Massachusetts, and ESB (Electricity Supply Board) in Ireland. For comparison, two separate price structures for each utility were considered; a structure for small load consumers, and a structure for larger load consumers. The main points of the four price structures are discussed below. The specifics of each price structure are presented in Appendices 1-4.

NSTAR Electric, Rate G-1: This is the rate at which consumers whose average load is between 10kW and 100kW are charged. This price structure has higher rates for excess electricity consumption. For the first 10kW, the rate is \$0.87/kW, while for over 10kW, the rate is \$4.12/kW. For peak-shaving in this case, the secondary power supply switches on when the load exceeds 10kW (i.e. when the environmental control units begin operation).

NSTAR Electric, Rate G-2: This is the rate at which consumers whose average load exceeds 100kW are charged. The load requirement of the base station we are using for this analysis never even approaches 100kW. The reason this price structure is analyzed is because it has seasonal, weekly, daily and excess usage peak characteristics. In analyzing this price structure, we scaled up the electrical requirements of the base station by 10. This analysis is purely for comparison with NSTAR Electric Rate G-1.

ESB, General Purpose Charges: This is the rate at which small commercial and industrial consumers are charged, similar to NSTAR Rate G-1. Electricity consumed during the day is charged at a higher rate than that consumed at night; therefore only daily peaks are present in this structure.

ESB, Maximum Demand Charges: This is the rate at which larger commercial and industrial consumers are charged, similar to NSTAR Rate G-2. It has seasonal, weekly, daily and excess usage peak characteristics.

Analysis performed on the various price structures will be discussed in the following chapters.

Chapter 3 Modeling the Power Supply Systems

3.1 Overview of the Modeling Process

We have identified possible alternative technologies and systems, so now we must determine if their deployment is feasible. This will be done primarily on a net present cost (NPC) basis. Simply put, whichever power supply system has the lowest NPC for a given set of conditions is judged to be the best choice for those conditions. Also though, consideration must be given to adherence of the various systems to regulations governing generator usage.

NPC for small power supply systems such as those under consideration is made up of four components:

- Capital cost
- Energy cost
- Operation and maintenance (O&M) cost
- Replacement costs

These costs will be discussed in greater detail below. For now it is important to note that all of the costs are dependent on what power system is used. Energy, O&M, and Replacement cost usually depend on the actual performance of the system in question. For example, the amount of energy obtained from burning diesel and the cost associated with that, or the duration of use for certain components. In order to determine these inputs for the NPC calculations (economic analysis), a technical analysis of each system must be carried out. This technical analysis examines how a power system meets a given load for a given set of operating conditions. In the next section, we will discuss the electrical load requirements of base stations. The technical and economic analysis was carried out in MATLAB, with data presentation in MS Excel and MATLAB.

3.2 Base Station Analysis

In Spring 2004 visits to base stations in Massachusetts and New Hampshire were made and electrical load data collected. This data was used in modeling the performance of prospective power systems. In total, six base stations were visited; two in urban areas of Massachusetts, two in urban/suburban areas of New Hampshire, and two in rural New Hampshire. All of the base stations visited have roughly the same load characteristics: DC supply to radio equipment of 80-120 Amps at a potential of 54V, intermittent air conditioning load of 5-10 tons of cooling power.

In addition, all of the base stations visited are connected to the electricity grid. All of the stations have 2-4 hours of battery backup. However, in all cases this backup only covers the radio equipment, and not the environmental control units. Radio units generate heat during normal operation, hence the need for environmental control. They switch themselves off at temperatures above 38°C (100F). Only three out of the six stations have onsite backup generators; diesel in two cases and propane in another. The others rely on technicians picking up mobile generators from depots and towing them to the base stations before the battery backup is exhausted.

Due to the similarity in load requirements for the base stations, one is taken as a representative example. In Table 3.1 below, the power requirements of the former NEXTEL base station on Cross St., Cambridge are shown. The base station was relocated to Green St., Cambridge in Summer 2004.

DC Requirement	
Telecommunications Equipment (Radios)	Current: 120 Amps
	Voltage: 54 Volts
	Rectifier efficiency: ~95%
Total DC Requirement:	**Power: 6.82 kW Constant**
AC Requirement	
5 Ton A/C Unit (Intermittent use)	Cooling Power: 60,000 btu/hr
	SEER*: 10 [20]
	Power: 6 kW
2.5 Ton A/C Unit (Intermittent use)	Cooling Power: 30,000 btu/hr
	SEER*: 10.2 [20]
	Power: 2.94 kW
Total AC Requirement:	**Power: 8.94 kW Intermittent**
*SEER: Seasonal Energy Efficiency Ratio (btu/hr cooling / kW input)	

Table 3.1 Power Requirement for former NEXTEL base station, Cross St., Cambridge, MA

In using these values, some assumptions have been made. They are:

- The electrical load of the telecom equipment. This was taken to be constant, although this is not the case in reality. Data was not available for power consumption with changing call volume. Numerous visits were paid to the base station and the average current value was chosen.
- The proportion of time the environmental control equipment operates. This was worked out from knowing how much energy is consumed by the telecom equipment, reading the electricity meter and knowing the power rating of the A/C units. The proportion of time the environmental control equipment operates was established to be 25%.
- The length of time the environmental control equipment operates. This data could not have been found without constant monitoring of the base station. From above, we know that the units operate 25% of the time. As will be seen later, the performance model relies on time intervals of one hour. Therefore, the A/C units

were assumed to operate in a cycle of one hour of operation and three hours of inactivity.

We can now establish a model for the base station load profile based on the measurements obtained from site visits and the assumptions made above. Figure 3.1 shows the profile over the course of six hours (360 minutes). The peak loads are when the A/C units are running. This load profile model will be used as an input for modeling alternative power systems and comparing them with current systems.

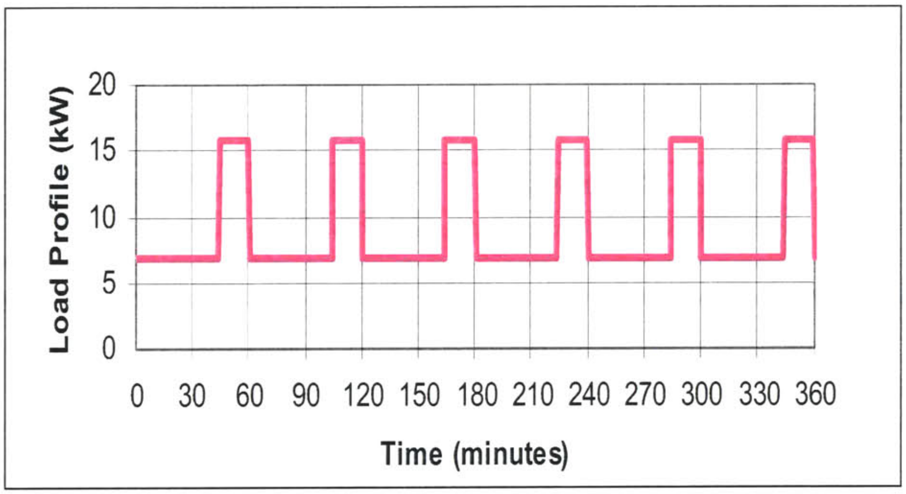


Figure 3.1 Load Profile Model for former NEXTEL Base Station, Cross St., Cambridge, MA

3.3 Modeling Wind-Hydrogen Systems

3.3.1 The Various Wind-Hydrogen Systems

The term "Wind-Hydrogen Power System" is a general one. In fact, to be precise we should name power systems according to their components. When considering wind-hydrogen systems, we have the following possibilities:

- Wind turbine–Fuel cell –Diesel generator system
- Wind turbine–Hydrogen powered generator–Diesel generator system
- Wind turbine–Dual hydrogen & diesel powered generator system

Wind-hydrogen systems using the electricity grid as the ultimate backup power supply can be disregarded for the following reason. If a cell phone service provider was going to go to the trouble and expense of building an electricity grid extension to a base station, it would not go to the extra expense of building a wind-hydrogen power system. Wind-generated electricity is typically more expensive than electricity generated by today's electricity mix, even more so on this small scale [21].

The main difference between these systems is the choice of the use of fuel cells or hydrogen powered generators as the secondary supply of power. Fuel cells use hydrogen more efficiently than hydrogen powered generators, but at greater capital cost. The use of a dual-fuel (hydrogen and diesel) generator only affects the economic performance of system, not the technical performance.

These possible alternatives are to be compared with the current power supply systems on their NPC. The current systems are:

- Electricity grid–VRLA–Diesel generator system
- Diesel generator only system

The possible alternatives are also compared to a system consisting of the following:

- Wind turbine–VRLA–Diesel generator system

These systems are not in common use, but are being recognized as possible remote power supply systems of the future.

3.3.2 Modeling the Components

3.3.2.1 Wind Turbine

As shown in the previous chapter, the AOC 15/50 wind turbine has a power curve that relates instantaneous wind speed to instantaneous electrical power output. The input of wind speed data into the model will be discussed in the section on variable inputs. For the purpose of modeling this system, we need a mathematical function to relate wind speed to power output. Figure 3.2 shows the power curve and two polynomial functions which model the turbine performance.

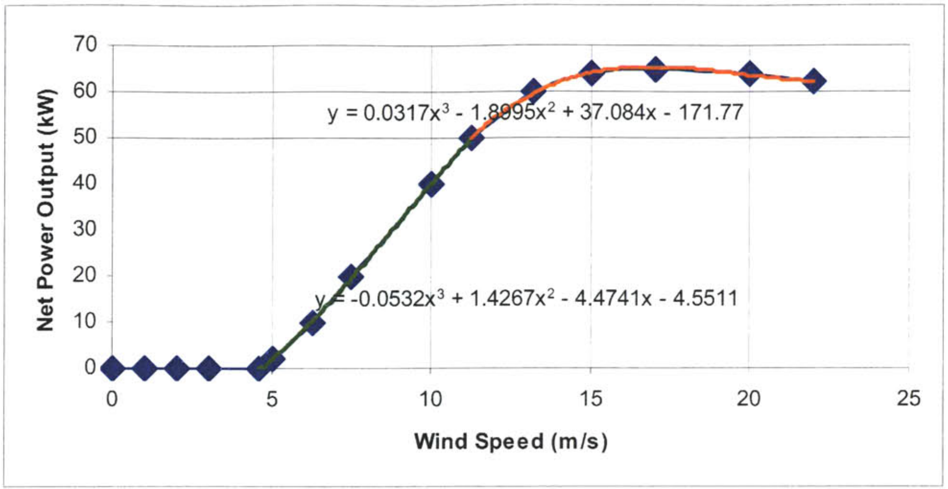


Figure 3.2 Power Curve & Polynomial Functions for the Wind Turbine Model

Therefore, the wind turbine model has the following electrical power output as a function of wind speed:

$$\dot{W}_{turbine}(\vartheta) = \begin{cases} = 0, \text{ for } \vartheta < 4.6m/s \text{ (Cut-in Speed)} \\ = -0.0532\vartheta^3 + 1.4267\vartheta^2 - 4.4741\vartheta - 4.5511, \\ \qquad \text{for } 4.6m/s < \vartheta < 11.3m/s \text{ (Green line)} \\ = +0.0317\vartheta^3 - 1.8995\vartheta^2 + 37.084\vartheta - 171.77, \\ \qquad \text{for } 11.3m/s < \vartheta < 22.4m/s \text{ (Orange line)} \\ = 0, \text{ for } \vartheta > 22.4m/s \text{ (Cut-out Speed)} \end{cases}$$

Where:

ϑ = Instantaneous wind speed

3.3.2.2 Electrolyzer

The electrolyzer used for this analysis, a Proton Energy Systems HOGEN H 6Nm^3/hr unit, has power consumption per flow rate of gas of 6.3kWh/Nm^3. The maximum production rate of hydrogen is 6Nm^3/hr, which corresponds to a maximum electrical power supply of 37.8kW. The electrolyzer consumes any power excess to base station requirements, less than its maximum capacity. Therefore the electrolyzer model has the following instantaneous hydrogen mass flow rate as a function of power supplied:

$$\dot{m}_{H_2,elec}=\begin{cases}=0,\ \text{for } \dot{W}_{turbine}-\dot{W}_{b-s}<0\\ =\dfrac{\rho_{H_2}\left(\dot{W}_{turbine}-\dot{W}_{b-s}\right)}{C_{elec}},\ \text{for } 0<\dot{W}_{turbine}-\dot{W}_{b-s}<\dot{W}_{elec,\max}\\ =\dfrac{\rho_{H_2}\left(\dot{W}_{elec,\max}\right)}{C_{elec}},\ \text{for } \dot{W}_{turbine}-\dot{W}_{b-s}<\dot{W}_{elec,\max}\end{cases}$$

Where:

$\dot{W}_{turbine}$ = Instantaneous power output of wind turbine

$\dot{W}_{b-s}$ = Instantaneous power requirement of base station

ρ_{H_2} = Density of hydrogen at STP = $0.08078 kg/m^3$

C_{elec} = Electrolyzer power consumption per flow rate of gas = $6.3kWh/Nm^3$

$\dot{W}_{elec,\max}$ = Maximum allowable electrolyzer power consumption = $37.8kW$

So:

$$\dot{m}_{H_2,elec}=\begin{cases}=0kg/h=0kg/s,\ \text{for } \dot{W}_{turbine}-\dot{W}_{b-s}<0\\ =12.82\times10^{-3}\left(\dot{W}_{turbine}-\dot{W}_{b-s}\right)kg/h=3.56\times10^{\ 6}\left(\dot{W}_{turbine}-\dot{W}_{b-s}\right)kg/s,\\ \qquad \text{for } 0<\dot{W}_{turbine}-\dot{W}_{b\ s}<\dot{W}_{elec,\max}\\ =0.485kg/h=1.35\times10^{-4}kg/s=\dot{m}_{H_2,elec,\max},\ \text{for } \dot{W}_{turbine}-\dot{W}_{b-s}<\dot{W}_{elec,\max}\end{cases}$$

3.3.2.3 Compressor

For costing and sizing purposes, a PPI Model 4089 single stage compressor is used. However, exact performance parameters were unavailable. Therefore a model was constructed for technical analysis of the power systems. In the power systems, the compressor works to increase the pressure of the hydrogen from the electrolyzer from 218psi to 2,000psi for storage in cylinders. Modeling the hydrogen as an ideal gas, we first assume reversible, adiabatic (isentropic) operation of the compressor.

$$\frac{T_{out,s}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}}$$ For reversible adiabatic (isentropic) compressor operation

$\dot{W}_{comp} = \dot{m}_{H_2,elec}\, c_p \left(T_{out} - T_{in}\right)$ For irreversible operation

$$\dot{W}_{comp,rev} = \dot{m}_{H_2,elec}\, c_p \left(T_{out,s} - T_{in}\right)$$

η_{comp} = Isentropic efficiency

$$\eta_{comp} = \frac{\dot{W}_{comp,rev}}{\dot{W}_{comp}} = \frac{\dot{m}_{H_2,elec}\, c_p \left(T_{out,s} - T_{in}\right)}{\dot{m}_{H_2,elec}\, c_p \left(T_{out} - T_{in}\right)} = \frac{\left(T_{out,s} - T_{in}\right)}{\left(T_{out} - T_{in}\right)}$$

$$\therefore T_{out} - T_{in} = \frac{T_{in}}{\eta_{comp}}\left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)$$

$$\dot{W}_{comp,total} = \frac{\dot{W}_{comp}}{\eta_{mech}} = \frac{\dot{m}_{H_2,elec}\, c_p}{\eta_{mech}}\left(T_{out} - T_{in}\right)$$

We end up with:

$$\dot{W}_{comp,total} = \frac{\dot{m}_{H_2,elec}\, c_p T_{in}}{\eta_{mech}\eta_{comp}}\left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)$$

Where:

P_{out} = Compressor outlet pressure $= 2{,}000 psi = 13.8\times10^{6} Pa$

P_{in} = Compressor inlet pressure $= 218 psi = 1.5\times10^{6} Pa$

$$\gamma = \frac{c_p}{c_v} = 1.4$$

$\dot{m}_{H_2,elec}$ = Instantaneous hydrogen mass flow rate from electrolyzer (kg/s)

c_p = Average constant pressure specific heat capacity for hydrogen $= 14{,}350 J/kgK$

T_{out} = Compressor outlet temperature

T_{in} = Compressor inlet temperature $= 80^{o}C = 353K$

η_{comp} = Compressor isentropic efficiency ~ 0.60 [13]

η_{mech} = Compressor motor mechanical efficiency ~ 0.90 [13]

$$\dot{W}_{comp,total} = \frac{\dot{m}_{H_2,elec} \times 14,350 J/kgK \times 353K}{0.9 \times 0.6}\left(\left(\frac{13.8\times10^6 Pa}{1.5\times10^6 Pa}\right)^{\frac{1.4-1}{1.4}} - 1\right)$$

$$\dot{W}_{comp,total} = 13.41\times10^6\, \dot{m}_{H_2,elec}\, W$$

$$\dot{W}_{comp,total} = \begin{cases} = 13.41\times10^3\, \dot{m}_{H_2,elec}\, kW, \text{ for } \dot{m}_{H_2} < \dot{m}_{H_2,elec,\max} \\ = 1.81 kW, \text{ for } \dot{m}_{H_2} = \dot{m}_{H_2,elec,\max} = 0.485 kg/h = 1.35\times10^{-4} kg/s \end{cases}$$

3.3.2.4 Fuel Cell

As no data was available directly from fuel cell manufacturers, a complete fuel cell model was constructed. Both technical and economic performance models were developed. Let us first look at the fuel cell technical performance model.

For a single fuel cell:

$$q = 2Fn_{H_2}$$

Where:

q = Charge = $I \times t$, where I = *current*

F = Faraday's constant = 96,485 *Coulombs*

n_{H_2} = Moles of hydrogen = $\dot{n}_{H_2} \times t$

So

$$\dot{n}_{H_2} = \frac{I}{2F}$$

Now, for a stack of n cells

$$\dot{n}_{H_2} = \frac{I \times n}{2F}$$

The instantaneous power output from a fuel cell stack is:

$$\dot{W}_{FC} = V_c \times I \times n$$

Where

V_c = Voltage across a single cell ~ $0.65V$ [13]

$$\dot{n}_{H_2} = \frac{\dot{W}_{FC}}{2V_c F}$$

$$\dot{m}_{H_2,FC} = \dot{n}_{H_2} M_{H_2}$$

Where

M_{H_2} = Molar mass of hydrogen = $0.00202 kg/mol$

$$\dot{m}_{H_2,FC} = \frac{\dot{W}_{FC} M_{H_2}}{2V_c F}$$

Now, consider an entire fuel cell system, not just the stack:

$$\dot{m}_{H_2,FC} = \frac{\dot{W}_{FC,gross} M_{H_2}}{2V_c F}$$

Where:

$$\dot{W}_{FC,gross} = \dot{W}_{FC,net} + \dot{W}_{parasitic}$$

$\dot{W}_{FC,net}$ = Instantaneous base station requirement,
or part thereof, to be met by fuel cell (Watts)

$$\eta_{system} = \frac{\dot{W}_{FC,net}}{\dot{W}_{FC,gross}} \sim 0.82 \text{ [13]}$$

$$\dot{m}_{H_2,FC} = \frac{\dot{W}_{FC,net} M_{H_2}}{2\eta_{system} V_c F} = \frac{\dot{W}_{FC,net} \times 0.00202 kg/mol}{2 \times 0.82 \times 0.65V \times 96{,}485 Coulombs}$$

$$\dot{m}_{H_2,FC} = \begin{cases} = 1.96\times10^{-8}\, \dot{W}_{FC,net}\, kg/s = 7.06\times10^{-5}\text{kg/h, for } \dot{W}_{FC,net} < \dot{W}_{FC,net,\max} \\ = 3.34\times10^{-4} kg/s = 1.20 kg/h = \dot{m}_{H_2,FC,\max}, \\ \quad \text{for } \dot{W}_{FC,net} = \dot{W}_{FC,net,\max} \approx 17\times10^{3} W \end{cases}$$

For the economic modeling of the fuel cell, the data shown in Table 3.2 was used.

Input	Value used
Capital cost per installed kW	\$4,000/kW [22]
Annual O&M cost per installed kW	\$238/(kW-year) [11]
Lifetime	15 years [11]

Table 3.2 Data for Economic Modeling of a Fuel Cell

3.3.2.5 Hydrogen Powered Generator

As no data regarding the technical or economic performance of hydrogen powered generator sets was available, the following model has been created. The hydrogen powered generator (H_2 genset) was assumed to have similar efficiency to a diesel powered genset, around 29%.

$$\eta_{H_2genset} \approx 29\% = 0.29$$

$$\eta_{H_2genset} = \frac{\dot{W}_{H_2genset}}{\dot{m}_{H_2,H_2genset}\, LHV_{H_2}}$$

Where:

$\dot{W}_{H_2genset}$ = Instantaneous base station requirement, or part thereof, to be met by H_2 genset (Watts)

$\dot{m}_{H_2,H_2genset}$ = Instantaneous hydrogen mass flow rate to H_2 genset (kg/s)

LHV_{H_2} = Lower heating value of hydrogen $= 241.83\times10^3 J/mol = 119.7\times10^6 J/kg$

So

$$\dot{m}_{H_2,H_2genset} = \begin{cases} = 2.88\times10^{-8}\,\dot{W}_{H_2genset}\ kg/s = 1.04\times10^{-4}\,\dot{W}_{H_2genset}\ kg/h, \\ \quad \text{for } \dot{W}_{H_2genset} < \dot{W}_{H_2genset,\max} \\ = 4.90\times10^{-4} kg/s = 1.76\times10^{4} kg/h, \\ \quad \text{for } \dot{W}_{H_2genset} = \dot{W}_{H_2genset,\max} \approx 17\times10^3 W \end{cases}$$

For the economic modeling of the H_2 genset, the data shown in Table 3.3 was used. The figure for capital cost per installed kW is based on the upper limit of figures for diesel gensets. This is probably a reasonable estimate since both hydrogen and diesel gensets are the same technology.

Input	Value used
Capital cost per installed kW	\$2,000/kW [22]
O&M cost per hour of operation	\$1.20/hour [4]
Lifetime	12,000 hours [5]

Table 3.3 Data for Economic Modeling of a Hydrogen Powered Genset

3.3.2.6 Storage Cylinders

For the specified BOC cylinders, the maximum storage mass is 0.56kg. Obviously there will be no flow from the cylinders if the pressure inside them drops below that of the destination of the hydrogen (i.e. the fuel cell). A good estimate for PEM fuel cell hydrogen delivery pressure is 135kPa (absolute) or about 35kPa (gage) [13].

$$m_{H_2,cyl} = m_{H_2,cyl,previous} + \left(\dot{m}_{H_2,elec} \times t\right) - \left(\dot{m}_{H_2,FC} \times t\right)$$

$$or$$

$$m_{H_2,cyl} = m_{H_2,cyl,previous} + \left(\dot{m}_{H_2,elec} \times t\right) - \left(\dot{m}_{H_2,genset} \times t\right)$$

$Where:$

$\dot{m}_{H_2,elec}$ = Instantaneous hydrogen mass flow rate from electrolyzer (kg/s) or (kg/h)

$\dot{m}_{H_2,FC}$ = Instantaneous hydrogen mass flow rate to fuel cell (kg/s) or (kg/h)

$\dot{m}_{H_2,genset}$ = Instantaneous hydrogen mass flow rate to hydrogen genset (kg/s) or (kg/h)

t = Interval between readings (seconds) or (hours)

$$m_{H_2,cyl,\max} = \frac{P_{\max} V}{RT}$$

$$m_{H_2,cyl,\min} = \frac{P_{\min} V}{RT}$$

$$\frac{m_{H_2,cyl,\min}}{m_{H_2,cyl,\max}} = \frac{\frac{P_{\min} V}{RT}}{\frac{P_{\max} V}{RT}} = \frac{P_{\min}}{P_{\max}} = \frac{0.135 \times 10^6 Pa}{13.8 \times 10^6 Pa}$$

$$m_{H_2,cyl,\max} = 0.56kg$$

$$Therefore$$

$$m_{H_2,cyl,\min} = 0.0055kg$$

3.3.2.7 Water Tank

The model for the water tank is similar in concept to the model for the hydrogen storage. Again maximum and minimum storage masses are important. Losses from the tank are not considered as the tank can be greatly oversized without serious economic consequences.

$$m_{H_2O} = m_{H_2O,previous} + \left(\dot{m}_{H_2O,FC} \times t\right) - \left(\dot{m}_{H_2O,elec} \times t\right)$$

$$or$$

$$m_{H_2O} = m_{H_2O,previous} + \left(\dot{m}_{H_2O,genset} \times t\right) - \left(\dot{m}_{H_2O,elec} \times t\right)$$

$Where:$

$\dot{m}_{H_2O,FC}$ = Instantaneous water mass flow rate from fuel cell (kg/s) or (kg/h)

$\dot{m}_{H_2O,elec}$ = Instantaneous water mass flow rate to electrolyzer (kg/s) or (kg/h)

$\dot{m}_{H_2O,genset}$ = Instantaneous water mass flow rate from hydrogen genset (kg/s) or (kg/h)

t = Interval between readings (seconds) or (hours)

To calculate the appropriate mass flow rates of water, we consider the hydrogen production and consumption reactions taking place.

In the electrolyzer, the overall reaction is:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

$$\left|\dot{n}_{H_2O,elec}\right| = \left|\dot{n}_{H_2,elec}\right|$$

$$\left|\frac{\dot{m}_{H_2O,elec}}{M_{H_2O}}\right| = \left|\frac{\dot{m}_{H_2,elec}}{M_{H_2}}\right|$$

$So:$

$$\dot{m}_{H_2O,elec} = \frac{M_{H_2O}}{M_{H_2}}\left|\dot{m}_{H_2,elec}\right|$$

Similarly, for the fuel cell or hydrogen genset we find:

$$\dot{m}_{H_2O,FC} = \frac{M_{H_2O}}{M_{H_2}}\left|\dot{m}_{H_2,FC}\right|$$

$Where:$

$$M_{H_2O} = 0.01802 kg/mol$$

$$M_{H_2} = 0.00202 kg/mol$$

3.3.2.8 Diesel Powered Generator

The diesel powered generator (diesel genset) chosen for this model, consumes diesel at a rate of 3.6gallons/hour when running at 40kW. This translates to roughly 29% efficiency. The data shown in Table 3.4 was used for the economic modeling of the diesel genset.

Input	Value used
Capital cost per installed kW	$1,000/kW [22]
O&M cost per hour of operation	$1.20/hour [4]
Lifetime	12,000 hours [5]

Table 3.4 Data for Economic Modeling of a Diesel Powered Genset

3.3.3 Variable Inputs

3.3.3.1 Fixed and Variable Inputs

In developing the model, it is important to differentiate between fixed and variable inputs. Fixed inputs are those which can be thought of as having only one possible value that does not change over the course of the analysis. Examples of fixed input parameters are:

- The capital cost per installed kW of a diesel genset
- The costs associated with hydrogen storage cylinders
- The costs associated with the specific wind turbine chosen for analysis
- The thermodynamic efficiency of a diesel genset (assuming adequate maintenance)

Variable inputs are those which do not have one definitive single value, or those which may change over the course of time. In the modeling of the wind-hydrogen system, it became apparent that there were many variable inputs to be considered. Two classes of variable inputs were discovered; technical and economic. The inputs, ranges and suggested base values are shown in Table 3.5. They will be discussed in greater detail in the next section.

Variable inputs	Sample Range	Base value
Variable Technical Inputs		
Annual Average Wind Speed	4 – 10 m/s	6 m/s
Electrolyzer & Fuel Cell Efficiencies	50 – 75 % 32 – 50 %	57 % 40 %
Electrolyzer Size	4 – 40 kW	37.8 kW
Size of Hydrogen Storage	1 – 20 kg	10 kg
Variable Economic Inputs		
Electrolyzer & Fuel Cell Cost Multiplier	100 – 50 %	100 %
Diesel Price	\$1.80 - \$3.40 /gallon	\$1.80 /gallon
Interest Rate	4 – 7 %	5 %

Table 3.5 Variable Inputs, their Sample Ranges and suggested Base Values, for a Wind-Hydrogen Power Supply System

Since the performance of the wind-hydrogen system is being compared to that of the current power supply systems, we need to know the variable inputs for the current systems. Table 3.6 shows these and their ranges and base values.

Variable inputs	Sample Range	Base value
Distance from Existing Electricity Grid	0 – 40 km	1 km
Diesel & Electricity Prices	\$1.80 – \$3.40 /gallon 6 – 20 c/kWh	\$1.80 /gallon 10 c/kWh
Interest Rate	4 – 7 %	5 %

Table 3.6 Variable Inputs, their Sample Ranges and suggested Base Values, for Current Power Supply Systems

3.3.3.2 Annual Average Wind Speed

As shown in the previous section, the instantaneous wind speed determines the instantaneous power output of the wind turbine. This obviously affects the technical performance of the entire system. Finding the annual average wind speed for a particular location gives us a general idea of the wind energy potential at that location. This is not the full picture, as it does not say anything about the consistency of wind speed. However, standard deviations for wind speeds are not as available as averages. Another method for determining the wind energy potential at a particular location is to find the annual average kinetic power of the wind. This is done by calculating the power at regular time intervals throughout the year, and averaging them over the year. Betz' Law relates the maximum power a wind turbine can extract to the kinetic power of the wind.

$$KE_{wind} = \frac{1}{2} m_{air} \vartheta_{wind}^2$$

$$\dot{KE}_{wind} = \frac{1}{2} \dot{m}_{air} \vartheta_{wind}^2$$

$$\dot{m}_{air} = \rho_{air} A_{swept} \vartheta_{wind}$$

$$So:$$

$$\dot{KE}_{wind} = \frac{1}{2} \rho_{air} A_{swept} \vartheta_{wind}^3$$

$$\dot{W}_{turb,\max} = \frac{16}{27}\left(\frac{1}{2} \rho_{air} A_{swept} \vartheta_{wind}^3\right) \text{ (Betz' Law)}$$

So the theoretical maximum efficiency of a wind turbine is 16/27 or 59%. Of course, viscous losses, turbulence, non-uniform velocity profile, generator efficiency and other factors ensure this figure is never reached.

The variation of wind speed over time is what creates the need for energy storage for this power supply system. For this reason, it was decided to input wind speed data at regular time intervals throughout the year. One hour intervals were chosen. Review of the literature revealed very few projects of this type. Among those found was [23], which used the above approach. Recorded hourly wind data was input into HOMER, NREL's hybrid power system design software. HOMER performs a similar task to the model developed here, with one important exception: HOMER does not analyze peak-shaving electrical systems.

Originally, it was decided to input simulated wind speed data into the model. This would give greater flexibility in establishing a range performance with respect to annual average wind speed. Wind speed at a particular point over the course of a year can be roughly modeled as having a Weibull probability distribution [24]. Figure 3.3 shows idealized Weibull distributions for annual modal wind speeds of 5m/s and 8m/s. It can be seen from the plot that low wind speeds are always more probable than higher ones.

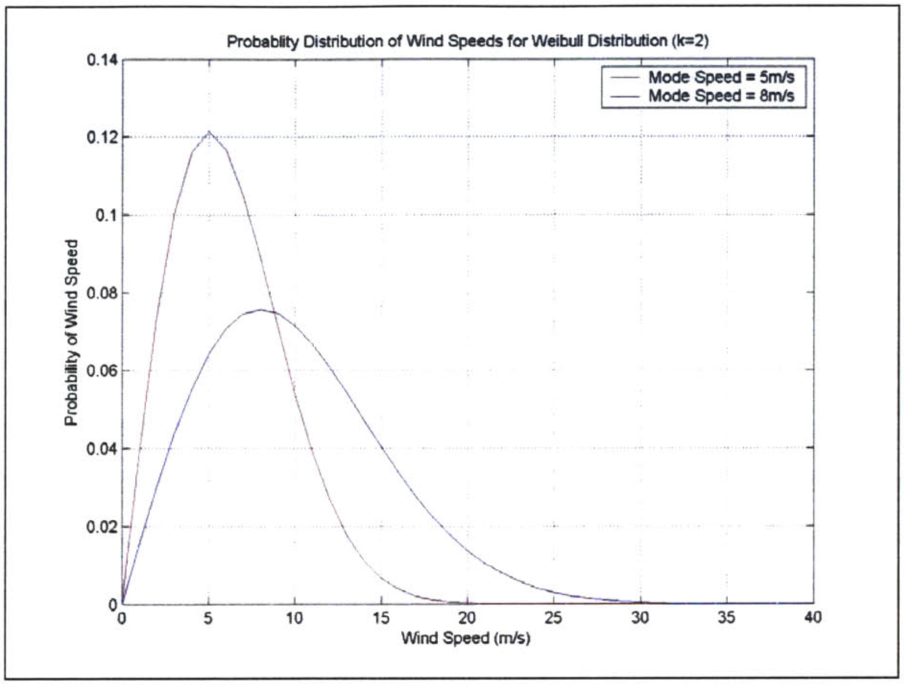


Figure 3.3 Weibull Probability Distributions for Annual Modal Wind Speeds of 5m/s and 8m/s

However, the Weibull probability distribution tells us nothing about the daily and seasonal variations in wind behavior. To address the seasonal variation, four separate Weibull plots were created; one each for spring, summer, autumn and winter. Each plot had its own mean and modal values, to reflect the fact that in general in the northern hemisphere, wind speed is greater in the winter than summer. A random wind speed pattern for each season could then be plotted and joined to establish the pattern for a year. Figure 3.4 shows the simulated wind speed over the course of a year.

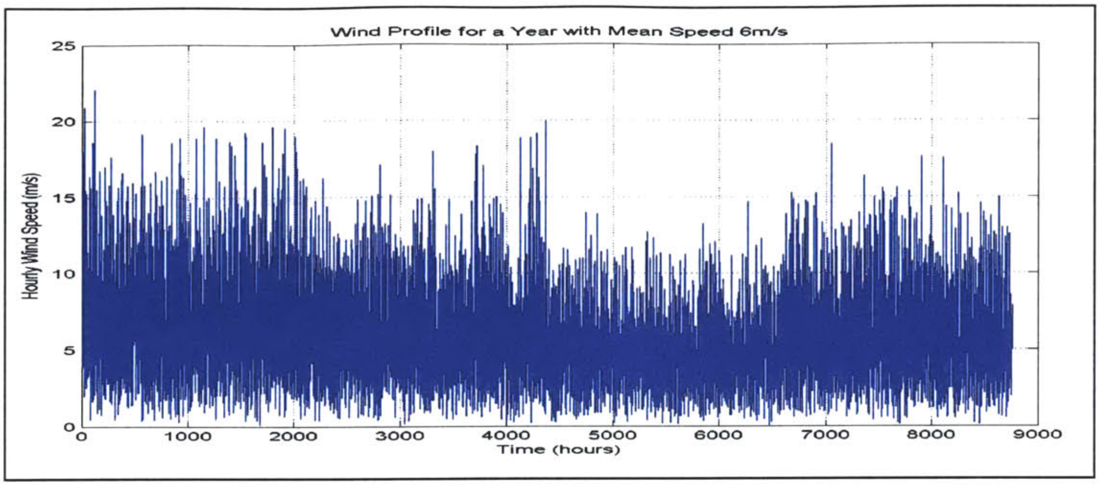


Figure 3.4 Plot of Simulated Wind Speed over a year with Seasonal Variation

When the simulated wind speed data was used in the model and the result compared to that from using real wind speed data for the same annual average speed, the following points were noticed: Economic analysis results matched very well, with errors less than 5%. Technical analysis results did not match well, with errors as large as 25% being recorded. This means that the model predicted different values for the amount of time each component would work for throughout the year. For this reason, it was decided that actual wind speed data would be used in the model.

Hourly wind speed data over a wide range of values were very difficult to obtain. Most meteorological stations keep only monthly averages, while wind energy utility companies are reluctant to share data. Data was finally found for the range 3.95m/s (~4m/s) to 7.81m/s (~8m/s) annual average speed for sites throughout Minnesota through Airtricity [25]. Final results for each value of annual average wind speed were averaged over three simulations of different data sets. The purpose of this was to lessen the effect of any meteorological anomalies on a single data set. Table 3.7 shows the wind speed data used. It can be seen that 7.81m/s is the highest average over three sites that could be found. This is not a very high average, but it must be stated again that adequate wind speed data was difficult to obtain.

Station	Location in Minnesota	Annual average wind speed	Average over three sites
Breckenridge	W	3.77	3.95
Clark's Grove	S	3.97	
Chandler	SW	4.10	
Breckenridge	W	4.63	4.98
Clark's Grove	S	4.90	
Chandler	SW	5.40	
Breckenridge	W	5.96	6.09
Sabin	W	6.10	
Elizabeth	W	6.20	
Chandler	SW	6.99	7.18
Breckenridge	W	7.10	
Chandler	SW	7.46	
Chandler	SW	7.71	7.81
Chandler	SW	7.86	
Chandler	SW	7.87	

Table 3.7 Wind Speed Data and Sources used in Modeling

3.3.3.3 Electrolyzer and Fuel Cell Efficiencies

It is obvious that improved electrolyzer efficiency enables a greater hydrogen production rate for a given power input. Likewise, an improvement in fuel cell efficiency means less hydrogen is needed for the same output. As the model stands, the thermodynamic efficiency of the electrolyzer system is 57%, while that of the fuel cell system is 40%. Let us assume that over the coming years, advances can be made, as they have over the past years, and efficiencies of electrolyzers and fuel cells can be increased. As electrolyzers and fuel cells are essentially the same fundamental science and very similar in construction, let us assume that if the efficiency of one increases by 10%, so does the efficiency of the other. As hydrogen gensets are based on diesel genset technology, which is a very mature and developed technology, we assume that no appreciable increase in efficiency is possible.

3.3.3.4 Electrolyzer Size

Unlike the fuel cell or hydrogen genset, which are sized according to the load requirement, we are free to choose the size of electrolyzer that best suits the power system's needs. The following simple trade-off must be considered: Larger electrolyzers cost more but produce more hydrogen, while smaller electrolyzers are cheaper but produce less hydrogen. The electrolyzer model used in this analysis is rated for a maximum power supply of 37.8kW. In considering alternative sizes of electrolyzers, we assume that performance and cost scale linearly. That means that an electrolyzer half the size, 18.9kW, produces half the flow rate of hydrogen and costs half as much, compared to the original. The purpose of varying the electrolyzer size is to find an optimum size for this power system. The compressor also scales according the size of the electrolyzer. Here we also assume linear performance and cost with size.

3.3.3.5 Size of Hydrogen Storage

The number of compressed gas cylinders determines the energy storage capacity of our power system. Again, a simple trade-off needs to be considered: More cylinders can store more hydrogen, and therefore more energy, at greater expense, while fewer cylinders are cheaper and store less energy. This parameter is varied for two reasons: To determine if it has an important bearing on the performance of the system and if it does, to find its optimum value.

3.3.3.6 Electrolyzer and Fuel Cell Cost Multiplier

At present, fuel cells are among the most expensive energy conversion technologies [22]. The reasons for this are: the use of expensive noble metal catalysts in the membrane electrode assemblies (MEAs), the fact that fuel cells are not mass-produced. The second reason given is a symptom of the so-called "chicken-and-egg" dilemma of fuel cells. Fuel cells are not mass-produced because there is no market for them in large numbers. There is no market for large numbers of fuel cells because there is no hydrogen fuelling infrastructure. This is an acute problem for the development of fuel cell cars. However, the reason there is no fuelling infrastructure is because there are not large numbers of fuel cells in service. The problem boils down to is the fact that fuel cells will stay expensive until they start to be mass-produced. Let us assume that in the near future, fuels cells will be mass-produced, and their cost will come down accordingly. Let us also assume that if the cost of fuel cells decreases so too will the cost of electrolyzers. We are not saying how this happens; we simply want to see the effect of decreased fuel cell and electrolyzer costs. So, at present, the electrolyzer and fuel cell cost multiplier is 1 (100%), while in the future if costs half, the multiplier would be 0.5 (50%).

3.3.3.7 Diesel Price

The price of diesel varies both spatially and temporally. It is cheapest in the southeastern states while it is most expensive in California. The price of diesel roughly scales with the price of gasoline, which has been rising sharply for over the past year [26].

3.3.3.8 Interest Rate

The rate at which interest is applied affects future expenditures and depreciation of components. Different power systems involve different expenditure patterns. For example, a wind-hydrogen system involves more capital cost and less fuel cost than a similarly sized system using only a diesel genset. Interest rate (or discount rate) provides a way of comparing these different systems.

3.3.3.9 Distance from Existing Electricity Grid

Due to the cost associated with extending an electricity distribution line, the degree of remoteness has an impact on the costs associated with current grid-connected power systems. Grid extension costs are in the region of $30,000 per km [3].

3.3.4 Technical Analysis

A flow chart of the technical analysis part of the model is shown in Appendix 5. The technical analysis part of the model works in the following way.

The first wind speed value ($t=t_1$) is input into the wind turbine model. The instantaneous power from the wind turbine is calculated. If it is less than the power required, the turbine supplies what it can to the base station and the balance of power is made up by either the fuel cell/H_2 genset or the backup diesel genset. This will be discussed again later. If the turbine output power is greater than the instantaneous requirement of the base station, the turbine supplies the base station and feeds excess power to the electrolyzer and compressor. The electrolyzer model, along with the variable inputs for electrolyzer efficiency and electrolyzer size, determines the mass flow rate of hydrogen from the electrolyzer and through the compressor.

For this same time, the model checks whether a fuel cell or a H_2 genset is being used as a secondary power source. This information, along with whether or not the fuel cell or H_2 genset is meeting the base station requirement, determines the mass flow rate of hydrogen from the storage cylinders. The instantaneous mass of hydrogen in storage is computed by knowing how much H_2 we started with, how much comes in from the electrolyzer, and how much leaves to the secondary power supply. A check is performed to ensure the mass of hydrogen in storage falls between the maximum and minimum limits. If the previous mass of stored hydrogen is at the minimum level, and no more is added then the power supplied by the fuel cell/H_2 genset is set to zero. The portion of power supplied by the backup diesel genset is computed by subtracting the power from the wind turbine plus the power from the fuel cell/H_2 genset from the power requirement of the base station.

The model then moves into the next hour ($t=t_2$) and eventually makes the same calculations for the entire year. At this point, the model calculates the energy each power supply component contributions to the total annual base station energy requirement. The number of hours for which each component works is also computed for later use in the economic analysis part.

3.3.5 Economic Analysis

3.3.5.1 Introduction

A flow chart of the economic analysis part of the model is shown in Appendix 6. The economic analysis part of the model works in a similar manner to NREL's HOMER program. The purpose of the economic analysis part is to determine the Net Present Cost (NPC) of the system in question. NPC is comprised of four basic components: Annualized Capital Cost, Annual Maintenance Cost, Annualized Replacement Cost and Annual Energy Cost. For this analysis, all costs are annualized. That means the capital costs and replacement costs are broken up into annual payments over the lifetime of the system totaling the value of the costs. This will be explained below in greater detail. The sum of the annual and annualized costs gives us the Total Annualized Cost (TAC) of the power system.

$$TAC = ACC + AMC + ARC + AEC$$

$$Where:$$

$$ACC = \text{Annualized Capital Cost}$$

$$AMC = \text{Annual Maintenance Cost}$$

$$ARC = \text{Annualized Replacement Cost}$$

$$AEC = \text{Annual Energy Cost}$$

From the TAC, we can find the Net Present Cost, using a Capital Recovery Factor (CRF). The CRF is a very important term as it takes into account the discount rate. It will appear at many times throughout the economic analysis.

$$NPC = \frac{TAC}{CRF\left(r, L_{system}\right)}$$

Where:

$$CRF\left(r,t\right) = \frac{r\left(1+r\right)^{t}}{\left(1+r\right)^{t}-1}$$

r = Interest rate

t = Time scale in question

L_{system} = Lifetime of power system

The time scale in question refers to the object for which the CRF is being determined. In the case of finding the annualized capital cost of a power supply system, the time scale is the life time of the project. In other instances, we shall see the time scale may be the life time of an individual component. The MATLAB model calculates the NPC for each power system to be analyzed, over the range of variable parameters. Different power systems can then be compared anywhere in the parameter space.

3.3.5.2 Annualized Capital Cost

Total Capital Cost is the sum of the capital costs of all of the components of the power system.

$$CC = \sum_{i} CC_i$$

Where:

CC_i = The capital cost of an individual component

For this model, capital cost figures were obtained from the component manufacturers, or when needed, from the literature. See the sections on system components for specifics. To annualize the capital cost, we must use a discount factor, or interest rate. Annualized Capital Cost is obtained in the following way:

$$ACC = CRF \times CC$$

Where:

ACC = Annualized Capital Cost

CRF = Capital Recovery Factor

3.3.5.3 Annual Operation and Maintenance Cost

Annual Maintenance Cost (AMC) is the sum of the annual maintenance costs for each component of the system.

$$AMC = \sum_i AMC_i$$

Where:

AMC_i = The annual maintenance cost of an individual component

As it is already an annual payment, AMC does not have to be annualized. For certain components (e.g. diesel gensets and the compressor) maintenance costs are given in terms of hours in use. In these cases, we must determine from the technical analysis, the number of hours in operation per year so we can find an annual figure.

3.3.5.4 Annualized Replacement Cost

The Annualized Replacement Cost (ARC) is the sum of the annualized replacement costs for each component. Every component depreciates to a point where it is more economical to buy a new one rather than maintain and repair an old one. These life time figures were obtained from the component manufacturers or the literature.

$$ARC = \sum_i ARC_i$$

Where:

ARC_i = The annualized replacement cost of an individual component

For each component, the ARC was calculated in the following way:

$$ARC_i = RC_i\left(\left(RF_i \times SFF_i\right) - \left(\frac{RL_i}{L_i} \times SFF_{system}\right)\right)$$

Where:

RC_i = The component replacement cost

RF_i = The component replacement factor

SFF_i = The component sinking fund factor

RL_i = The component lifetime remaining at the end of the system's life

L_i = The component lifetime

SFF_{system} = The total power system sinking fund factor

These terms must be determined and discussed in detail. First, the component lifetime is defined by the manufacturer. If this is not available, a figure can be used from the literature. The component replacement is the cost of buying a replacement component. This is typically the same as the capital cost of the component. The component replacement factor is found in the following way:

$$RF_i = \begin{cases} = \dfrac{CRF\left(r, L_{system}\right)}{CRF\left(r, L_i\right)}, \text{ if } L_{i,rep} > 0 \\ = 0, \text{ if } L_{i,rep} = 0 \end{cases}$$

Where:

L_{system} = The lifetime of the power system

$$L_{i,rep} = L_i \times INTEGER\left(\frac{L_{system}}{L_i}\right)$$

The component sinking fund factor takes into account the depreciation of the component and its worth at the end of the power system's life. Deprecation is assumed to be linear.

$$SFF_i = \frac{r}{\left(1+r\right)^{L_i} - 1}$$

The component lifetime at the end of the system life is the total power system life subtracted from the component's life. The sinking fund factor for the total power system is calculated similarly to that for the individual component:

$$SFF_{system} = \frac{r}{\left(1+r\right)^{L_{system}} - 1}$$

3.3.5.5 Annual Energy Cost

The Annual Energy Cost (AEC) is the total cost of all energy supplied to the power system. In our model, energy in supplied via two energy carriers, electricity and diesel.

$$AEC = AElC + ADC$$

Where:

$AElC$ = The annual cost of diesel consumed by the system

ADC = The annual cost of electricity consumed by the system

$$AElC = P_{elec} \times kWh$$

Where:

P_{elec} = The price of electricity $(\$/\text{kWh})$ [27]

kWh = Annual electricity consumption (kWh)

$$ADC = P_{diesel} \times G_{diesel}$$

P_{diesel} = The price of diesel $(\$/\text{gallon})$ [26]

G_{diesel} = Annual diesel consumption (gallons)

3.3.6 Sensitivity Analysis

In order to get results in a presentable and coherent form, it is necessary to reduce the number of variable input parameters upon which the outputs depend. The method of doing this is sensitivity analysis. In this analysis, we determine the relative importance of the various input variables to the final result, the NPC of the system. Those variable parameters of less importance can be considered constant values for the purpose of the modeling process. The aim of sensitivity analysis is to find which parameters drive the output.

For the model, we perform sensitivity analysis in the following way:

- Reasonable base values and ranges are chosen for each of the variable input parameters.
- Holding all others steady, a single parameter is varied along its range. The model performs the technical and economic analyses for each parameter value and gives an NPC.
- The same action is performed for each variable input parameter.
- The range of outputs for each variable parameter are compared and ranked. Any input variable whose effect on the final results is significantly small compared to the others is considered constant for the purpose of modeling.
- These actions are performed for each power system to be considered.

The hope is that by the end of the sensitivity analysis, the number of effective variable parameters will sufficiently reduced so as to make the final result more coherent.

3.3.7 Output of Results

After reducing the number of variables upon which the results are dependent by sensitivity analysis, the results are plotted graphically. For each point in the parameter space, the power system with the lowest NPC is chosen. Each power system is assigned a color in the graphical output of the parameter space. The color representing the power system of lowest NPC at a point in the space is shown at that space. Figure 3.5 shows a sample output tile.

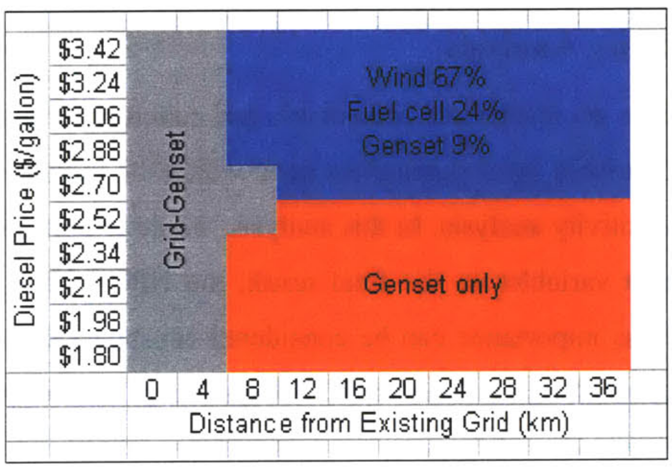


Figure 3.5 Sample Model Output over two Variable Inputs

The tile has two axes, which correspond to two of the variable input parameters deemed important by sensitivity analysis. The different colors represent the system of lowest NPC at that point in the parameter space. In this example, gray means a grid-connected system with diesel backup, red means an off-grid diesel genset, and blue means a wind-fuel cell-diesel genset system. The output also shows the annual energy mix for the preferred power system when more that one power source is used. If there are more than two variable inputs to be considered, more tiles are shown in the output. Figure 3.6 shows a sample output for four variable inputs of importance. The tiles are themselves arranged in a parameter space. The actual results from the modeling process are shown in the relevant chapter.

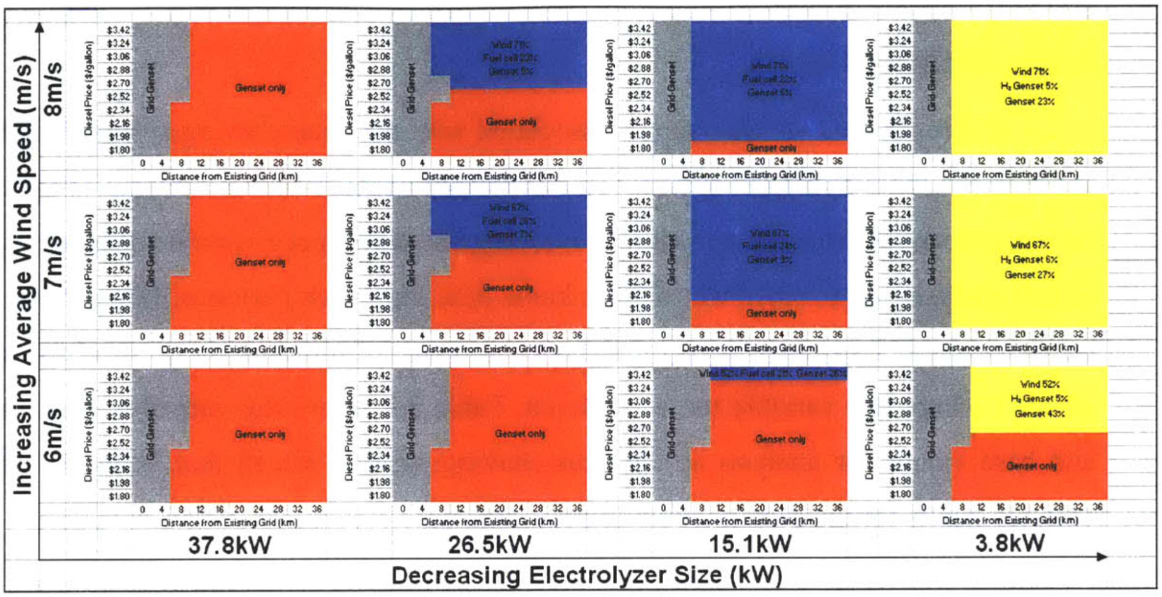


Figure 3.6 Sample Model Output over four Variable Inputs

3.4 Modeling a Peak-Shaving Hydrogen System

3.4.1 Modeling the System

The modeling process for the peak-shaving system was heavily influenced by the initial results of the analysis. As will be discussed in the chapter on results, no economic analysis beyond an Annual Energy Cost (AEC) analysis was needed. This is because the annual energy cost of any peak-shaving system using an electrolyzer turns out to be higher than the current costs. It was therefore irrelevant to analyze other costs, when adding all the complexity of the peak-shaving system could only increase them. The modeling process for the peak shaving system therefore consists of a technical part and an annual energy cost part.

The components of the peak-shaving system that are common to the wind-hydrogen system are modeled in exactly the same way as they are in the wind-hydrogen system. These components are: Electrolyzer, Compressor, Fuel Cell, Hydrogen Powered

Generator, Storage Cylinders, Water Tank, and Power Electronics. See the relevant chapters above for details.

3.4.2 Variable Inputs

There are less variable inputs associated with the peak-shaving system than there are with the wind-hydrogen system. This is mainly because the uncertainty of the wind has been removed from the equation. Obviously, the wind speed variable does not appear in this analysis. Also, since we roughly know how long each period of fuel cell use will be, the variable hydrogen storage parameter is removed. As there is no need for diesel genset backup, this variable too is removed. Table 3.8 shows the variables, their ranges and base values for analysis of the peak-shaving system. Recall that Table 3.6 shows variable inputs for the current power supply systems

Variable inputs	**Sample Range**	**Base value**
Variable Technical Inputs		
Electrolyzer & Fuel Cell Efficiencies	50 – 75 % 32 – 50 %	57 % 40 %
Electrolyzer Size	4 – 40 kW	37.8 kW
Variable Economic Inputs		
Electrolyzer & Fuel Cell Cost Multiplier	100 – 50 %	100 %
Distance from Existing Electricity Grid	0 – 40 km	1 km
Interest Rate	4 – 7 %	5 %

Table 3.8 Variable Inputs, their Sample Ranges and suggested Base Values, for a Peak-Shaving Hydrogen Power Supply System

3.4.3 Technical Analysis

The technical analysis part for the peak-shaving system is performed in a similar manner to that for the wind-hydrogen system. In this case, however, what determines whether or not the fuel cell supplies power at a particular time is the instantaneous cost of electricity. If the local electricity price structure includes excess usage peaks, the grid connection is broken when the base station requires high power (i.e. when the A/C units come online). In the case of weekly and daily peaks, the grid connection is broken at the pre-determined peak times. Seasonal peaking is difficult to shave because of the duration of the peaks. When the instantaneous cost of electricity is off-peak, the grid powers the base station and supplies extra power to the electrolyzer and compressor to replenish the hydrogen stores. The power to the electrolyzer must be enough to have sufficient hydrogen ready for the next peak period. It must also be less than the maximum power input for the electrolyzer. The model establishes the following:

- The amount of power supplied by the grid to the base station
- The amount of power supplied by the fuel cell or H_2 genset to the base station
- The amount of power supplied by the grid to the electrolyzer

The analysis is performed for the different technical variable inputs; namely electrolyzer size and electrolyzer and fuel cell efficiencies, for each of the different NSTAR and ESB price structures.

3.4.4 Annual Energy Cost Analysis

The annual energy cost analysis simply adds the cost of the electricity used to meet the off-peak base station demand and the cost of the electricity needed to replenish the hydrogen stores. The economic variables shown in Table 3.8 do not affect the annual energy cost (AEC), so they do not come into the picture. The AECs for power systems using various electrolyzer sizes and electrolyzer and fuel cell efficiencies are graphed alongside those of the current power supply systems. The results of this analysis are shown in the chapter on results.

Chapter 4 Sensitivity Analysis for the Wind-Hydrogen Systems

4.1 Overview of Sensitivity Analysis

As mentioned in the previous chapter, sensitivity analysis involves selecting reasonable base values and ranges for the variable inputs. The model performs its analysis for one input parameter varying along its range, with all the others held at their base values. This is done for each variable input parameter in turn. The variables of least importance are then considered to be fixed for the purpose of modeling. The results of the sensitivity analysis are graphical. Figure 4.1 shows a sample output of the sensitivity analysis.

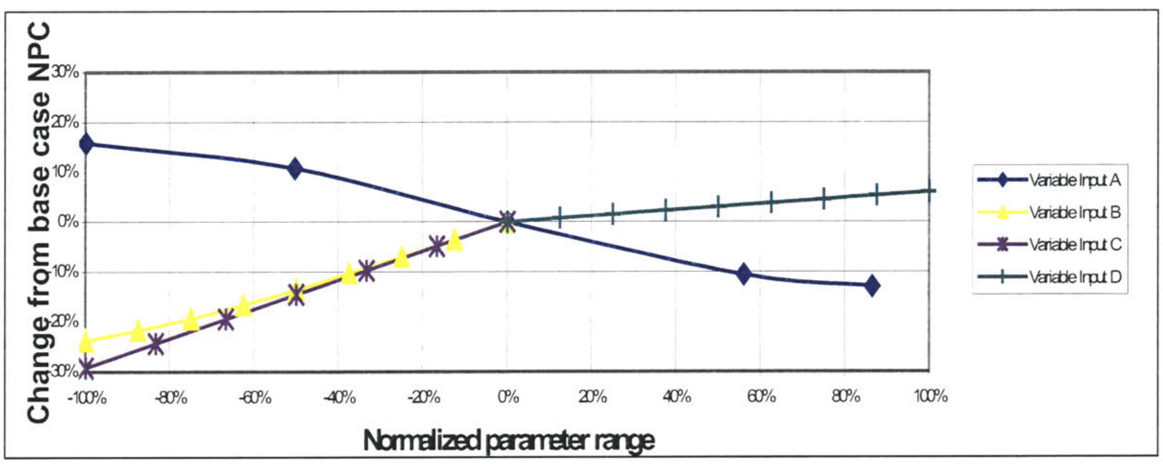


Figure 4.1 Sample of a Sensitivity Analysis Result

The plot shows the important input variables for a particular wind-hydrogen power supply system. These are the curves on the plot. On the x-axis, the Normalized Parameter Range shows the value of each of the variables relative to its base value and range. The base value of each of the variable inputs is the 0% position on the x-axis. The minimum and maximum values of the range of each of the variable inputs are -100% and

100% respectively. The y-axis shows the percentage change from the base case NPC. Base case NPC (0% on the y-axis) is the Net Present Cost of the particular system when all the base values of the variable input parameters are used. The extent to which a particular variable input parameter affects the NPC can be found from observing the change in NPC as the variable is moved from its base to its minimum and/or maximum values. Note that some variables start at their base value and move in only one direction, positive or negative. This means that the base value of the variable is either a maximum or minimum value. An example of this is the electrolyzer and fuel cell cost multiplier, which has a base value of 1.

For the example in Figure 4.1, the most important variable input is C, followed by B, A and D, in that order. For the purposes of clarity, less important variable inputs are not shown on the plots.

4.2 Wind-Fuel Cell-Diesel Genset System Sensitivity Analysis

The sensitivity plot for a Wind–Fuel cell–Diesel genset system is shown in Figure 4.2. We see that the controlling variables, in descending order of importance are Electrolyzer and Fuel Cell Cost Multiplier, Electrolyzer Size, Annual Average Wind Speed, and Diesel Price.

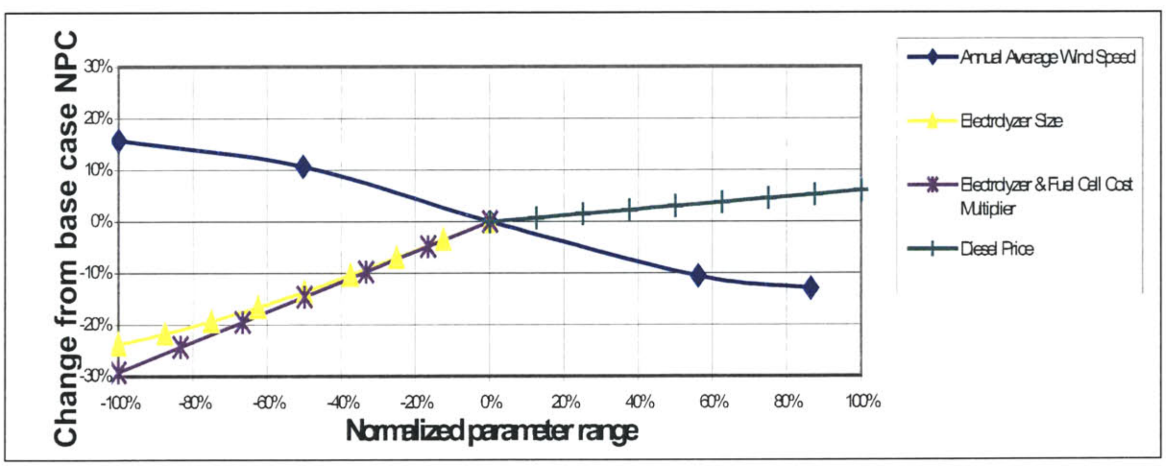


Figure 4.2 Sensitivity Analysis Results for a Wind–Fuel Cell–Diesel Genset Power System

4.3 Wind-H_2 Genset-Diesel Genset System Sensitivity Analysis

The sensitivity plot for a Wind–H_2 genset–Diesel genset system is shown in Figure 4.3. We see that the controlling variables, in descending order of importance are Electrolyzer Size, Electrolyzer and Fuel Cell Cost Multiplier, Annual Average Wind Speed, and Diesel Price.

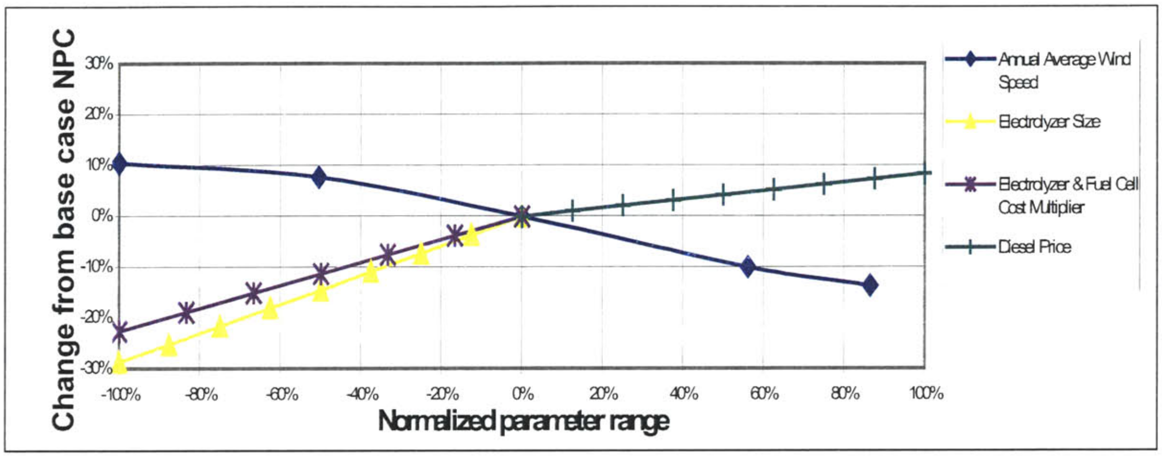


Figure 4.3 Sensitivity Analysis Results for a Wind–H_2 Genset–Diesel Genset Power System

4.4 Wind-Dual H_2 & Diesel Genset System Sensitivity Analysis

The sensitivity plot for a Wind–Dual H_2 & diesel genset system is shown in Figure 4.4. We see that the controlling variables, in descending order of importance are Electrolyzer Size, Electrolyzer and Fuel Cell Cost Multiplier, Annual Average Wind Speed, and Diesel Price.

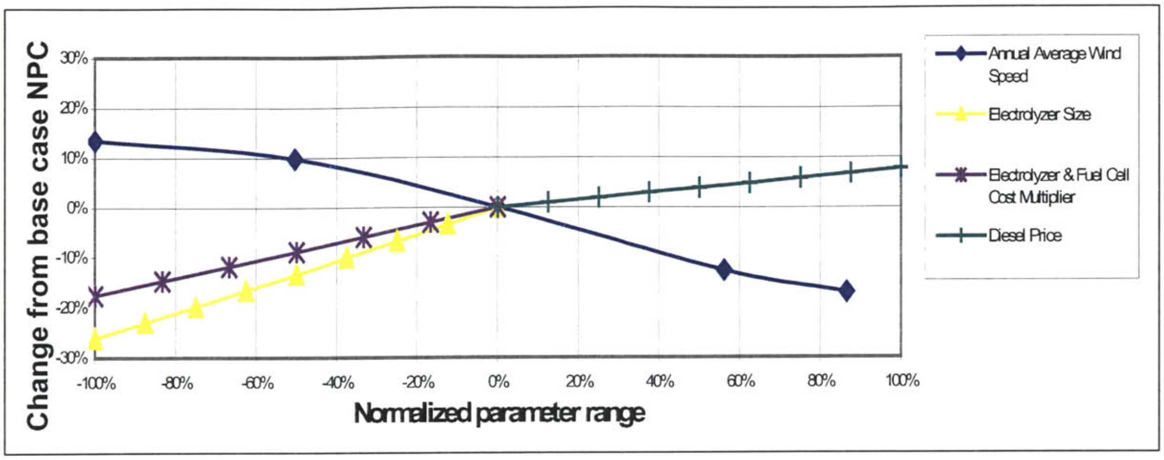


Figure 4.4 Sensitivity Analysis Results for a Wind–Dual H_2 & Diesel Genset Power System

4.5 Current Grid-Connected System Sensitivity Analysis

The sensitivity plot for a current grid-connected system is shown in Figure 4.5. We see that the controlling variables, in descending order of importance are Distance from Existing Electricity Grid and Diesel & Electricity Prices.

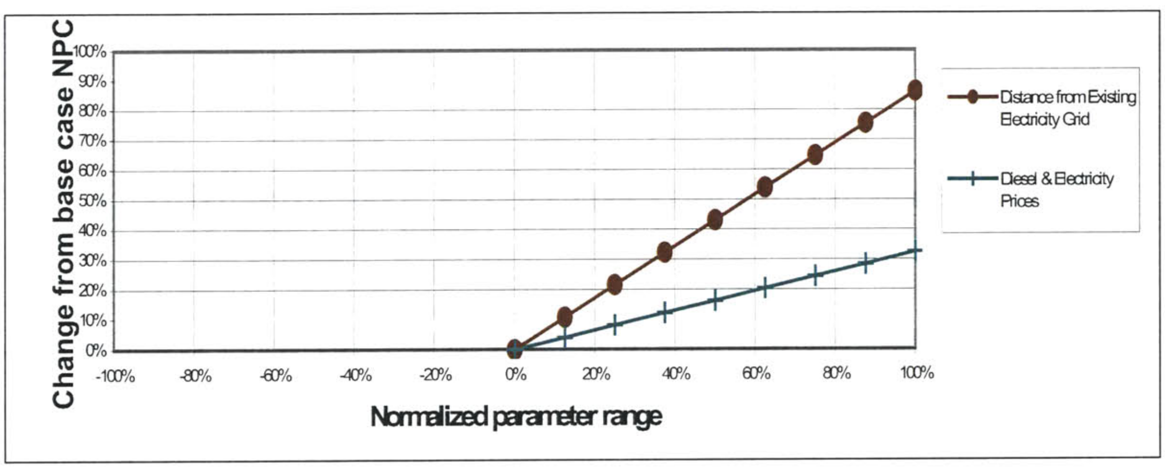


Figure 4.5 Sensitivity Analysis Results for a Current Grid-Connected Power System

4.6 Current Diesel Genset Only System Sensitivity Analysis

The sensitivity plot for a current diesel genset only system is shown in Figure 4.6. We see that the only controlling variable is Diesel Price.

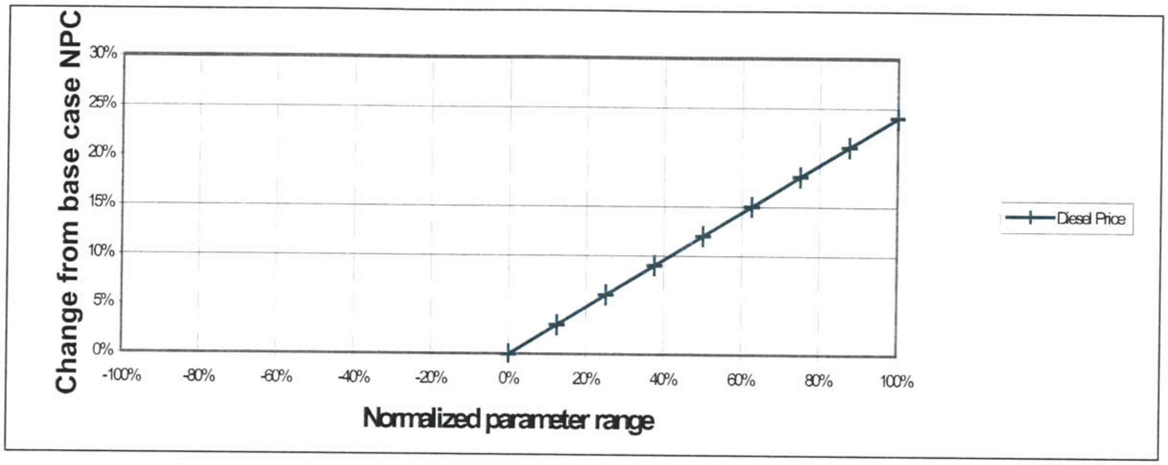


Figure 4.6 Analysis Results for a Current Diesel Genset Only Power System

4.7 Summary of Sensitivity Analysis Results

Table 4.1 shows the important input variables for each of the wind-hydrogen systems analyzed. We see the same four variables in places of importance for the three wind-hydrogen systems analyzed. Added to these four is the Distance from Existing Electricity Grid variable. This gives five important variables. We can now go about considering the other variable inputs as constants.

Important variables for each System Analyzed	NPC Change due to varying input
Wind turbine–Fuel cell–Diesel system	
1. Electrolyzer & Fuel Cell Cost Multiplier	30%
2. Electrolyzer Size	25%
3. Annual Average Wind Speed	15%
4. Diesel Price	8%
Wind turbine–H_2 genset–Diesel system	
1. Electrolyzer Size	30%
2. Electrolyzer & Fuel Cell Cost Multiplier	22%
3. Annual Average Wind Speed	15%
4. Diesel Price	8%
Wind turbine–Dual-fuel genset system	
1. Electrolyzer Size	25%
2. Electrolyzer & Fuel Cell Cost Multiplier	25%
3. Annual Average Wind Speed	18%
4. Diesel Price	8%
Current grid-connected system	
1. Distance from Existing Electricity Grid	85%
2. Diesel & Electricity Prices	32%
Current diesel genset only system	
1. Diesel Price	24%

Table 4.1 Important Input Variables for Wind-Hydrogen Power Systems

The efficiencies of the electrolyzer and fuel cell can be regarded as constant, even though technological breakthroughs may improve performance. The efficiencies to be used in the modeling are 57% for the electrolyzer and 40% for the fuel cell. The electrolyzer efficiency is specified by Proton Energy Systems, while the fuel cell efficiency is specified by the literature. Please see the relevant sections on model the components.

Due to the relatively low cost of hydrogen storage cylinders, the size of the hydrogen storage does not affect the NPC to a great degree. Therefore, we can choose a hydrogen storage mass that minimizes the amount of energy the diesel generator contributes to the base station requirement. Of course, consideration must be given to the actual area needed for storage cylinders. Figure 4.7 shows the energy mix of the Wind–Fuel cell–Diesel genset system as a function of hydrogen storage size. Notice that the energy fraction provided by the fuel cell increases with increasing storage size. A calculation of estimated storage area is shown below:

$$20kg \text{ of } H_2 \text{ @ } 0.55\frac{kg}{cylinder} \equiv 36 \text{ cylinders}$$

$$\text{Cylinder OD} \approx 0.3m$$

$$\text{Cylinder floor area} \approx 0.3m \times 0.3m \text{ square} \approx 0.09m^2 \text{ square}$$

$$36 \text{ cylinders} \equiv 3.24m^2 \text{ of floor area}$$

This is a reasonable floor area for hydrogen storage. Therefore the maximum stored mass of hydrogen is 20kg, a constant value.

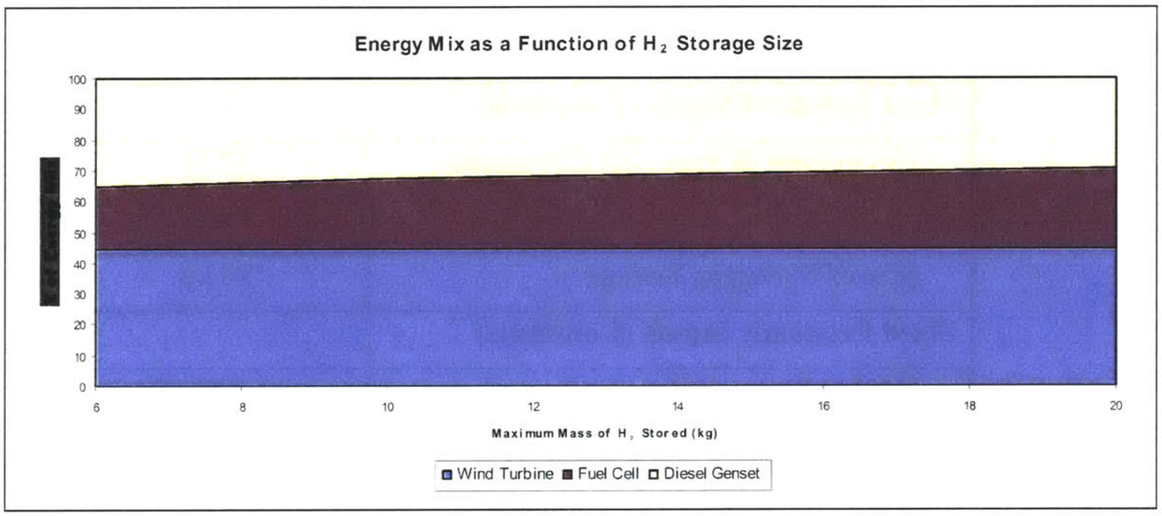


Figure 4.7 Energy mix of the Wind–Fuel Cell–Diesel Genset System as a Function of Hydrogen Storage Size

Varying the interest rate between 4% and 7% does not have appreciable effect to the NPC of any system. For this reason, the interest rate is assumed to be 5%. Table 4.2 shows the remaining variable input parameters and those which have been made fixed for the analysis. These remaining variables will be those used in the final analysis of the wind-hydrogen power systems. This will be discussed in the next chapter.

Inputs	**Value**
Remaining Variable Technical Inputs	
Annual Average Wind Speed	4 – 10 m/s
Electrolyzer Size	4 – 40 kW
Remaining Variable Economic Inputs	
Electrolyzer & Fuel Cell Cost Multiplier	100 – 50 %
Distance from Existing Electricity Grid	0 – 40 km
Diesel & Electricity Prices	\$1.80 - \$3.40 /gallon 6 – 20 c/kWh
Fixed Technical Inputs (Constants)	
Electrolyzer & Fuel Cell Efficiencies	57 % 40 %
Size of Hydrogen Storage	20 kg
Fixed Economic Inputs (Constants)	
Interest Rate	5 %

Table 4.2 Remaining Variable Inputs, and those considered Constant for the Wind-Hydrogen Systems

Chapter 5 Results and Discussion

5.1 Wind-Hydrogen Systems Results

The format of the results presented here are described and explained in the chapter on modeling. Recall the tile in Figure 3.5, which showed the parameter space and the most cost-effective system at each point in the parameter space. Similar to that example, the individual tiles in the actual results output will have Distance from Existing Electrical Grid on the x-axis, and Diesel Price on the y-axis. Also recall Figure 3.6, which showed twelve tiles arrayed on another parameter space. Again the x-axis in the larger space will be Electrolyzer Size and the y-axis will be Annual Average Wind Speed. So far, four of our variable input parameters are represented on the final results graph. The final variable, Electrolyzer & Fuel Cell Cost Multiplier, is represented in the following way. One four-dimensional parameter space, similar to Figure 3.6 is needed for each value of the Electrolyzer & Fuel Cell Cost Multiplier variable.

For the purpose of this document, only two values of Electrolyzer & Fuel Cell Cost Multiplier will be used; 1 and 0.8. Figures 5.1 and 5.2, on the following pages are the model outputs, showing the most cost-effective power system when the wind-hydrogen systems are compared to the current power supply systems, at today's and tomorrow's electrolyzer and fuel cell costs. Figures 5.3 and 5.4 show the most cost-effective power system when the wind-hydrogen systems are compared to the current power supply systems and also to a Wind-Battery-Diesel power system, at today's and tomorrow's electrolyzer and fuel cell costs. As previously discussed, Wind-Battery-Diesel systems are rarely used for base station applications, but they are gaining recognition in the field of standalone power. Table 5.1 shows the values of the variable input parameters shown in the results graphs.

Inputs	**Values on the graphs**
Variable Technical Inputs	
Annual Average Wind Speed	6m/s, 7m/s, 8m/s
Electrolyzer Size	37.8kW (Hogen H Size) 26.5kW (70% Size) 15.1kW (40% Size) 3.8kW (10% Size)
Variable Economic Inputs	
Electrolyzer & Fuel Cell Cost Multiplier	100% & 80%
Distance from Existing Electricity Grid	0-36km in 4km increments
Diesel Price	$1.80-$3.42/gallon in $0.18 increments

Table 5.1 Values of the Variable Input Parameters shown in the Results Graphs

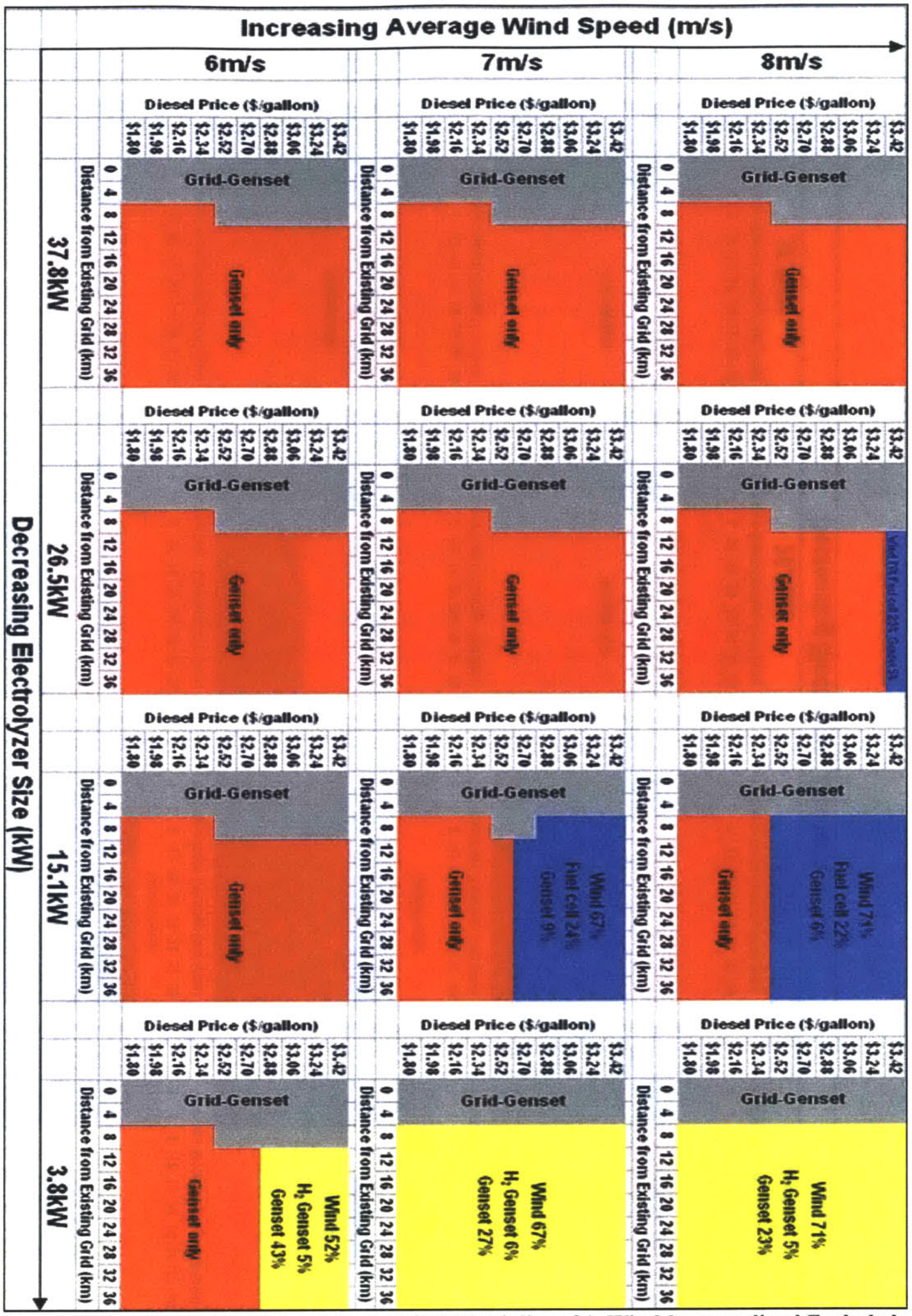


Figure 5.1 Results for Electrolyzer & Fuel Cell Multiplier of 1. Wind-battery-diesel Excluded

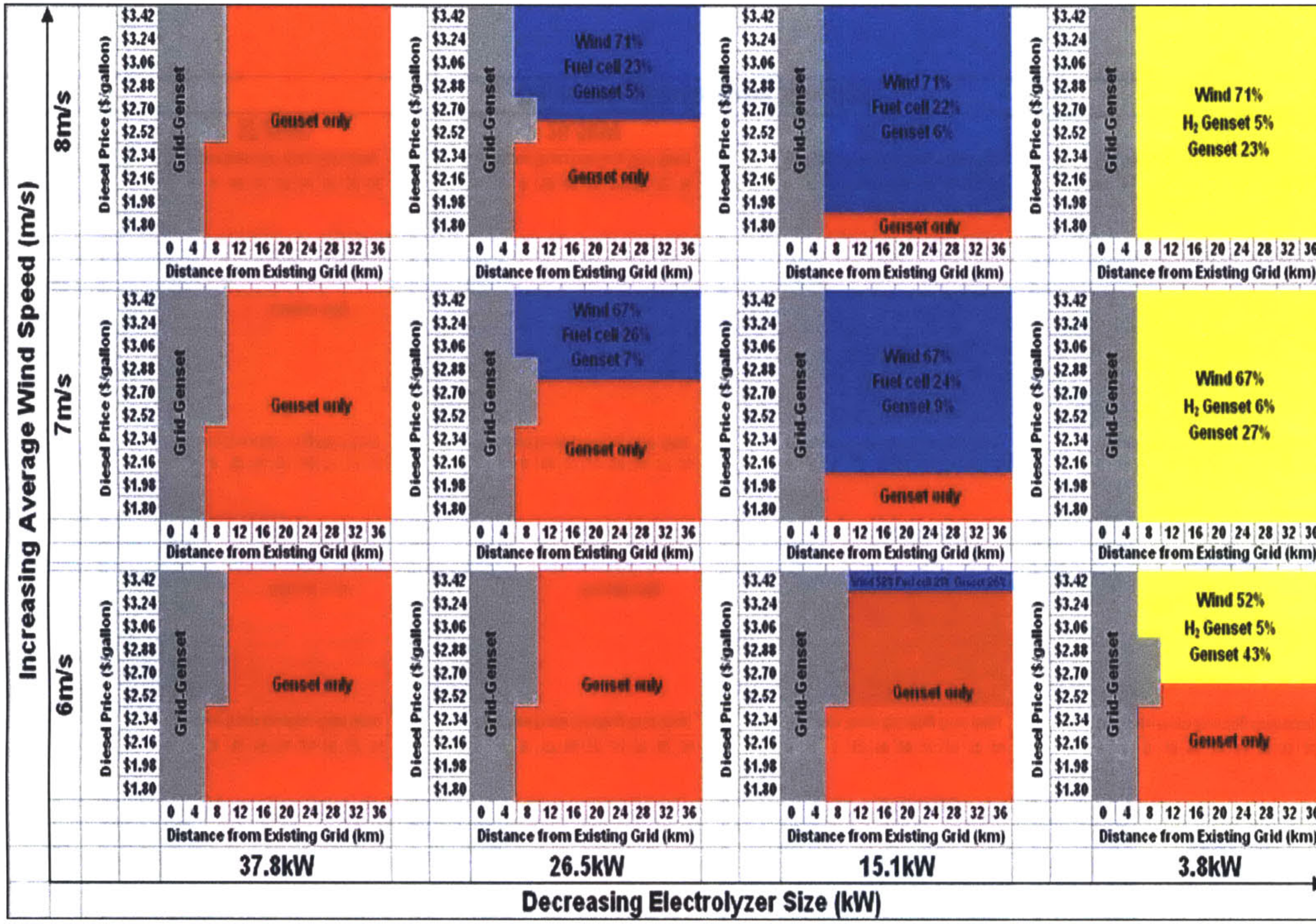


Figure 5.2 Results for Electrolyzer & Fuel Cell Multiplier of 0.8. Wind-battery-diesel Excluded

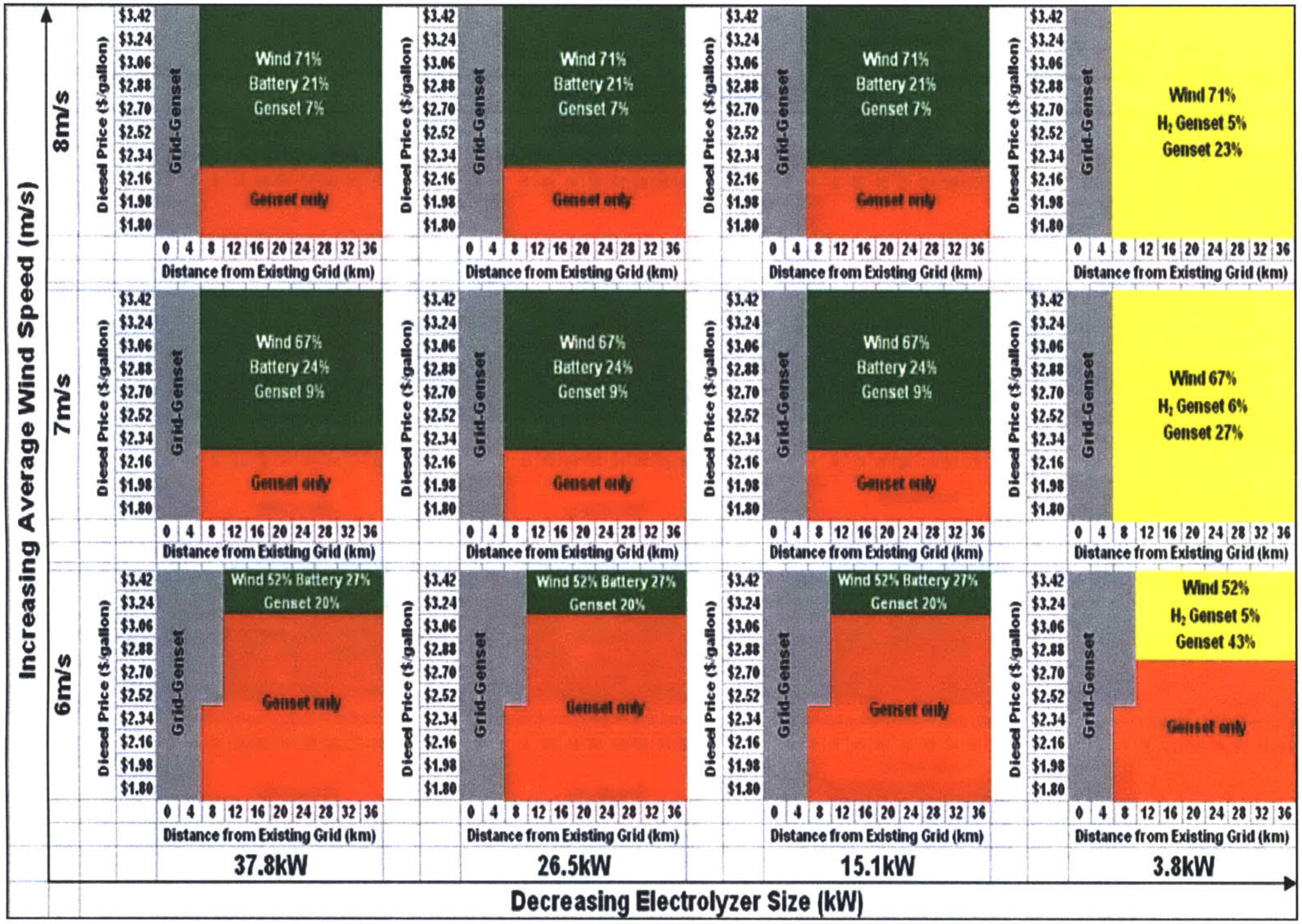


Figure 5.3 Results for Electrolyzer & Fuel Cell Multiplier of 1. Wind-battery-diesel Included

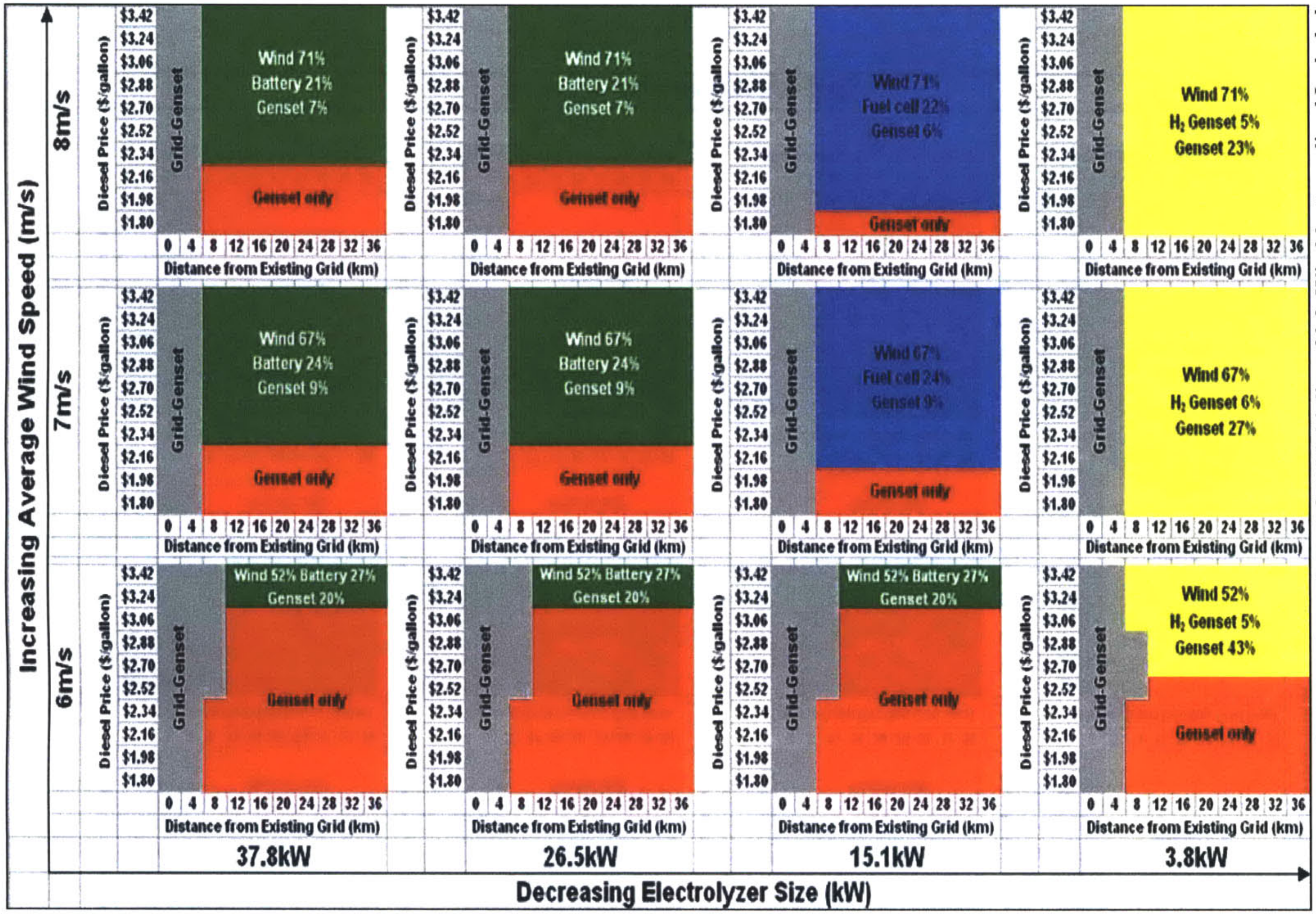


Figure 5.4 Results for Electrolyzer & Fuel Cell Multiplier of 0.8. Wind-battery-diesel Included

5.2 Wind-Hydrogen Systems Discussion

We see the following features of the results:

- Within 8km of an existing electricity grid connection, a grid-connected system is always more cost effective. This confirms information from [1]. See Figures 5.1-5.4.
- Low diesel prices favor diesel genset only systems. See Figures 5.1-5.4.
- At today's electrolyzer and fuel cell cost, when Wind-Battery-Diesel systems are not considered, Wind-Fuel cell-Diesel genset systems are cost-effective at higher average wind speeds (above 7m/s), distances greater than 8km from the grid, and when small electrolyzers are used. See Figure 5.1.
- At today's electrolyzer and fuel cell cost, when Wind-Battery-Diesel systems are considered, Wind-Fuel cell-Diesel systems are never cost effective. See Figure 5.3.
- There is no appreciable difference in the energy fraction provided by a fuel cell in a wind-fuel cell-diesel system when the electrolyzer size is varied from 37.8kW to 15.1kW. See Figures 5.1 & 5.2.
- Wind-H_2 genset-Diesel genset systems become cost effective at very small electrolyzer sizes. However, the energy fraction provided by the diesel genset is very large. This does not favor adherence to diesel genset regulations. See Figures 5.1-5.4.
- At electrolyzer and fuel cell costs at 80% of today's values, the results show a Wind-Fuel cell-Diesel system is cost effective at high wind speeds (above 7m/s), diesel prices currently found in the US (around $2/gallon), and distances greater than 8km from the grid. For this to be the case, a small electrolyzer (15.1kW) is used. See Figure 5.4.

As we would expect close to an existing electricity grid, grid-connection is the best option. As we start move out to 8-12km this picture starts to change. As we do this, at low diesel prices, diesel genset-only systems are the most cost-effective. The exception to this is when we consider a Wind-H_2 genset-Diesel genset system with a very small

(3.8kW) electrolyzer in wind speeds of 7m/s or greater. This system is cost-effective, but a look at its energy mix reveals that the diesel genset provides between 23% and 43% of the total annual energy of the base station. Thinking about the operation of this system, we can postulate the following:

- The NPC is low because the electrolyzer is small
- The diesel energy fraction is high because the electrolyzer does produce much hydrogen and the H_2 genset is less efficient than a fuel cell.
- The use of a H_2 genset is more cost effective than a fuel cell, because it is a cheaper less efficient engine that does not incur much maintenance cost, because it does operate much.

However, because the diesel genset provides a lot of the energy, this system does not help us get around regulatory issues because the diesel genset is in use at least a quarter of the year.

Considering systems at today's costs and comparing wind-hydrogen systems with current power systems show that Wind-Fuel cell-Diesel systems are cost-effective at diesel prices of at least \$2.50, annual average wind speeds of at least 7m/s and greater than 8km from the grid. In these systems, 15.1kW electrolyzers are used. However, when we also consider a Wind-Battery-Diesel system, which uses the same wind turbine, has 72kWh of VRLA storage capacity with charge and discharge efficiencies of 85% each, maximum 3 year lifetime for the VRLAs (which is very short), and 10% of capital for disposal costs, we see that wind-fuel cell-diesel systems are no longer cost-effective. The Wind-Battery-Diesel system has an almost identical energy mix to the Wind-Fuel cell-Diesel system, and so also has a regulatory advantage over the diesel-intensive Wind-H_2 genset-Diesel genset system.

Projecting our analysis into the future, when cheaper electrolyzers and fuel cells may exist, we see that in the absence of the wind-battery-diesel system, the region of the parameter space where wind-fuel cell-systems are cost effective has grown. Notice though, that using vastly increasing electrolyzer sizes does not noticeably increase the fuel cell energy fraction. NPC, however, increases in a linear fashion with electrolyzer size. When the wind-battery-diesel system is again considered, we now see that Wind-

Fuel cell-Diesel systems can be cost effective, when a 15.1kW electrolyzer is used. This may be because the battery storage size of the Wind-Battery-Diesel system might not be optimized for this wind speed and load requirement.

Consideration should be given to the resolution of the results. Because there are a finite number of points on the parameter space, there may be data that is not shown on the results presentation. The intention is to give a general idea of the conditions under which the various systems are cost-effective. It is for the purpose of clarity that more resolution has not been added.

5.3 Peak-Shaving System Results

Recall that for the peak-shaving system, only an analysis of the Annual Energy Cost (AEC) was carried out. This is because a hydrogen-based peak-shaving system has a higher AEC than the current system. Obviously, the capital cost, maintenance cost and replacement cost for the more complex hydrogen-based system would also be higher. The results of the analysis are shown below in Figures 5.5 to 5.8. The four Figures correspond to the results for NSTAR Rate G-1, ESB General Purpose Charges, NSTAR Rate G-2 and ESB Maximum Demand Charges, respectively.

Recall that NSTAR Rate G-1 and ESB General Purpose Charges are similar price structures which cater to residential and smaller commercial loads. NSTAR Rate G-2 and ESB Maximum Demand Charges are both for customers drawing about 100kW. As stated before, the base station in question is not that size. However, these price structures are included for the purpose of comparison. The base station load requirements are multiplied by ten for analysis using these two price structures.

The only variable inputs to be considered in the analysis are the Electrolyzer Size and Electrolyzer and Fuel Cell Efficiencies. No sensitivity analysis was performed as there are only two variable inputs. In the results plots, electrolyzer size is shown on the x-axis. Annual energy cost is shown on the y-axis. Each curve corresponds to different electrolyzer and fuel cell efficiencies.

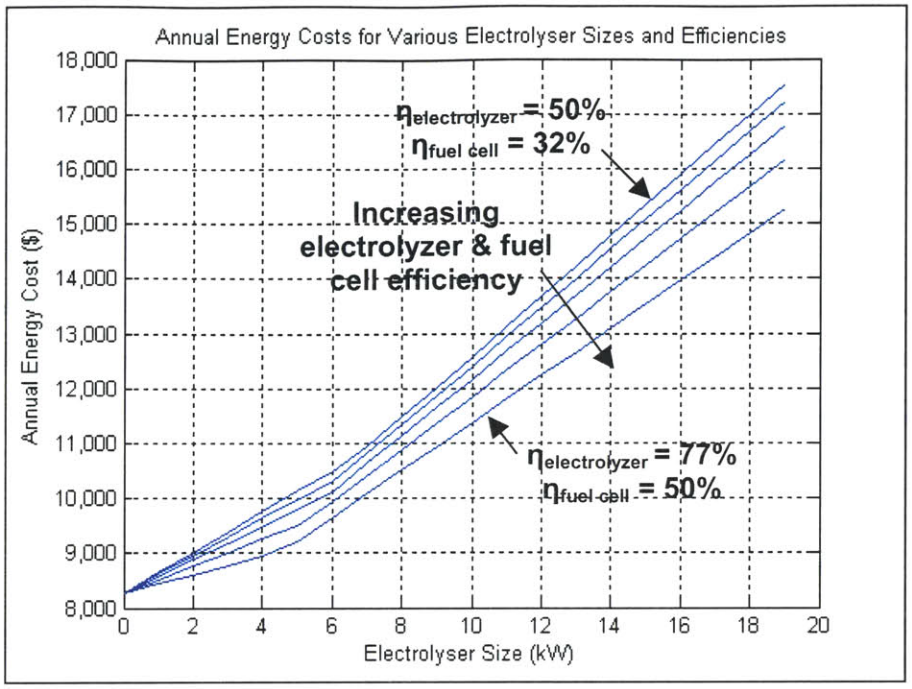


Figure 5.5 Results for Hydrogen Peak-Shaving System for NSTAR G-1 Rate

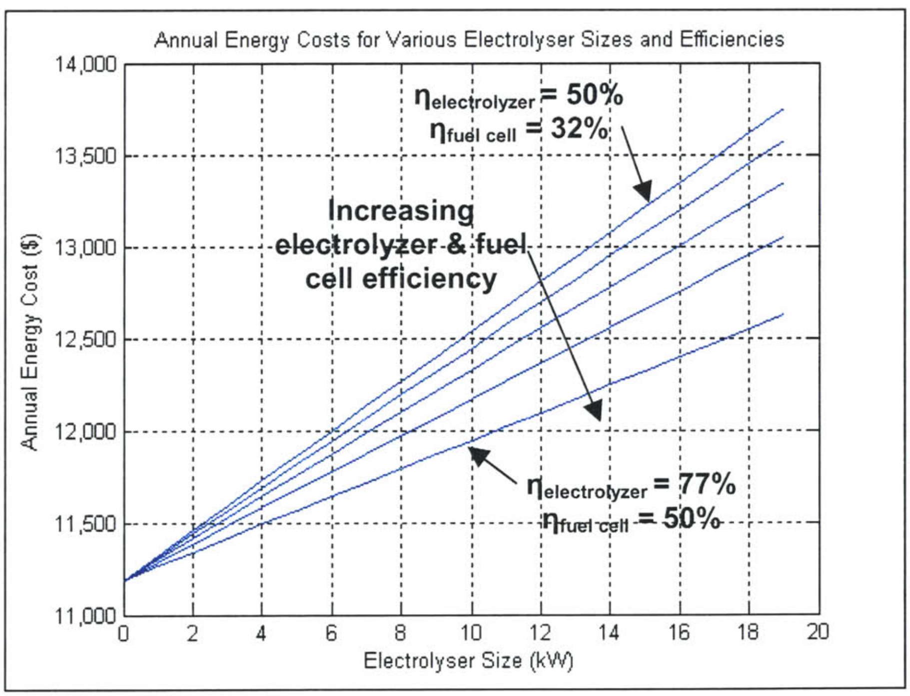


Figure 5.6 Results for Hydrogen Peak-Shaving System for ESB General Purpose Charges

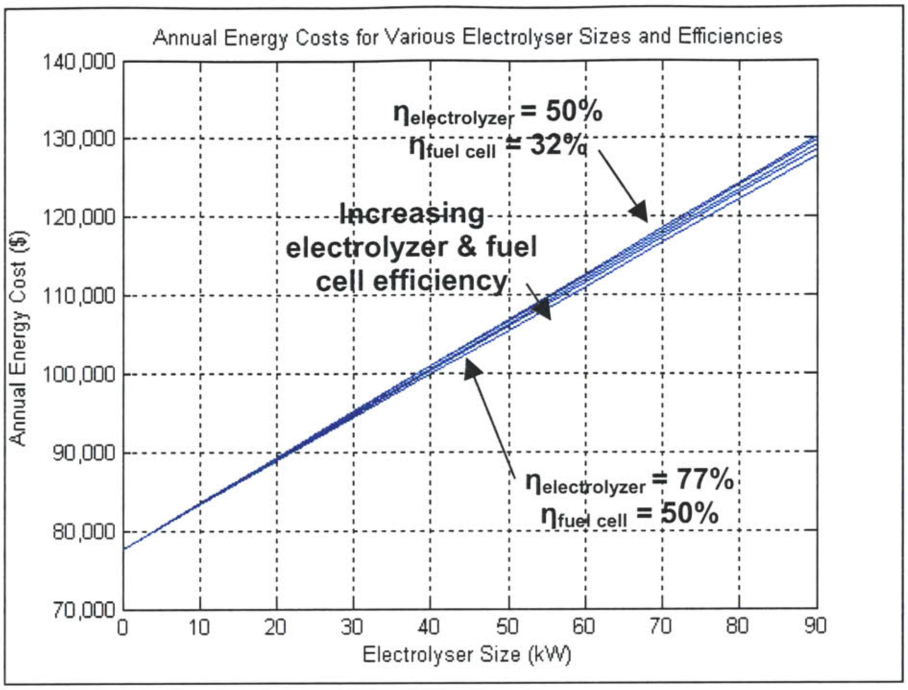


Figure 5.7 Results for Hydrogen Peak-Shaving System for NSTAR G-2 Rate and 10 times Base Station Load

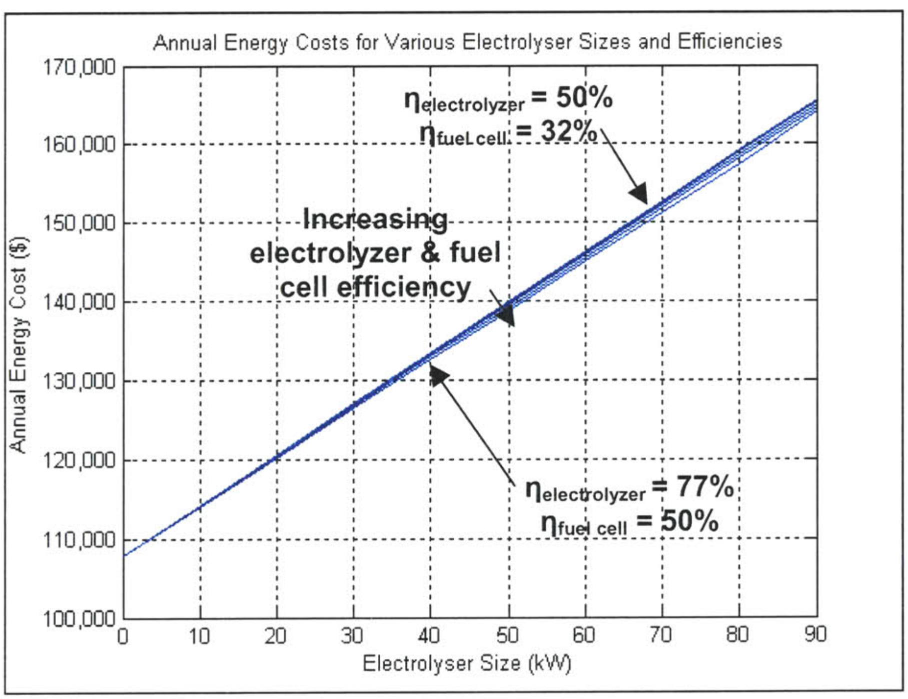


Figure 5.8 Results for Hydrogen Peak-Shaving System for ESB Maximum Demand Charges and 10 times Base Station Load

5.4 Peak-Shaving System Discussion

The graphs in Figures 5.5 to 5.8 show that under no circumstances are peak-shaving power systems with hydrogen storage cost-effective. For all the price structures analyzed, even with maximum electrolyzer and fuel cell efficiencies, the use of any hydrogen-based system raises the Annual Energy Cost (AEC). The x-axis origin, where no electrolyzer is used, is always the lowest point for any curve.

The poor economic performance of these systems is due to the inefficiencies associated with electrolyzers and fuel cells. The off-peak replenishment of hydrogen stores is so energy intensive that it creates its own peak in electricity consumption. In the case of price structures that use excess usage peaks, this obviously means we are defeating ourselves by eliminating one peak, only to create another. Where daily or weekly peaks are used, the problem is less severe, but it still leads to much more off-peak electricity being used. The effect of this is increased electricity cost.

Because the AECs are higher for hydrogen-based peak-shaving systems than for current power systems, no further analysis was considered.

Chapter 6 Conclusions

Models were developed to simulate the technical and economic performance of various small power supply systems that use hydrogen storage. One model compared the performance of wind-hydrogen power systems with current grid-connected and diesel genset systems, and also with a Wind-Battery-Diesel system. The other model compared the performance of a hydrogen-based peak-shaving system with current grid-connected power systems.

The analysis suggests that at present electrolyzer and fuel cell costs, Wind-H_2 genset-Diesel systems with very small (3.8kW) electrolyzers are cost effective. It also suggests that when comparing wind-hydrogen systems just with current base station power supply systems, Wind-Fuel cell-Diesel system are cost effective where wind speed is high, diesel is expensive, and sites are remote. However, when these systems are compared to a hypothetical Wind-Battery-Diesel system, fuel cell based systems cease to be viable. Despite the drawbacks of VRLA batteries; short lifetime, heavy transportation weight, disposal difficulties and operating dangers; they are still an extremely efficient and cheap technology when compared to hydrogen-based systems.

The Wind-H_2 genset-Diesel system with a 3.8kW electrolyzer is more cost effective than the Wind-Battery-Diesel system. However, it suffers from the fact that a very large proportion of the energy mix of the former is met by the diesel genset. Running the diesel genset 23-43% of the time is negative from a regulatory standpoint. By contrast, the Wind-Battery-Diesel system has a very similar energy mix to the Wind-Fuel cell-Diesel system, with the diesel genset operating 7-9% of the time. With this in mind, it is suggested that at today's electrolyzer and fuel cell costs, Wind-Battery-Diesel power systems are preferred under the following circumstances: Annual average wind speed of at least 7m/s, diesel prices above $2.20, distances greater than 8km from an existing electricity grid.

Thinking into the future when electrolyzer and fuel cells may be cheaper due to technological breakthroughs or mass-production, gives a different set of results. A Wind-Fuel cell-Diesel system with a 15.1kW electrolyzer is now cost effective. Again we see the Wind-H_2 genset-Diesel system with a small electrolyzer in a cost effective position, but again we see that the energy fraction of diesel is significant. With this is mind, we can suggest that with a 20% reduction in electrolyzer and fuel cell costs, Wind-Fuel cell-Diesel systems are cost effective for cell phone base station power under the following circumstances: Annual average wind speed of at least 7m/s, diesel prices above $2.00/gallon, distances greater than 8km from an existing electricity grid.

Peak-shaving power systems using hydrogen storage are not cost-effective under any realistic conditions. This is due to the creation of peaks of power usage while recharging hydrogen stores by electrolysis.

Chapter 7 References

1. Telephone and email communication with Mr. Michael Murphy, NEXTEL (2003-2004).
2. Keiser, B & Strange, E (1995). *Digital Telephone and Network Integration. 2nd Edition.* New York.
3. Telephone and email communication with Mr. Jack O'Brien, NSTAR Electric (2004).
4. Walker, B (2001). *Renovation of the Photovoltaic-Diesel Generator System at Natural Bridges National Monument.* National Renewable Energy Laboratory.
5. Telephone and email communication with Mr. Gene Stone, All-World Diesel Generator, Inc. (2004).
6. Energy Users News, August 2004, Volume 29, Number 8, page 10.
7. Quint, J (2003). *The Role of Batteries in Cell Site Survivability.* BatteryCorp, Inc.
8. Sacramento Fire Department Press Release (2001). *Explosion at Rancho Cordova.*
9. Van Arsdell, B (2003). *Around the World by Stirling Engine.* Page 48.
10. Telephone and email communication with Mr. Malcolm Lodge, Atlantic Orient Canada, Inc. (2004).
11. Telephone and email communication with Mr. Dean Halter, Proton Energy Systems (2004).
12. Telephone and email communication with Mr. Alex Klima, Pressure Product Industries, Inc. (2004).
13. Larminie, J & Dicks, A (2000). *Fuel Cell Systems Explained.* Wiley
14. Telephone and email communication with Mr. Stewart Dow, BOC Group (2004).
15. www.fuelcellstore.com
16. www.plastictanks.ca
17. Caterpillar Product Specifications

18. Scott, S, Holcomb, F & Josefik, N (2003). *Distributed Electrical Power Generation – Summary of Alternative Available Technologies.* US Army Corps of Engineers.
19. Telephone and email communication with Ms. Una McNellis, Electricity Supply Board (ESB), Ireland (2004).
20. Telephone and email communication with Mr. Davis Shuford, Airxcel Inc. (2004).
21. American Wind Energy Association
22. Tarud, S (2004). *Feasibility of Fuel Cell Systems for Building Applications.* Massachusetts Institute of Technology.
23. Iqbal, T & Pynn, P (2003). *Hybrid Energy System for St. Brendan's, Newfoundland.* Memorial University of Newfoundland.
24. Danish Wind Energy Association. *Guided Tour of Wind Energy.*
25. Telephone and email communication with Mr. Brian Hurley and Mr. Colin Murray, Airtricity (2004).
26. EIA (2004). *Gasoline and Diesel Fuel Update.*
27. EIA (2002). *State Electricity Profiles.*

Chapter 8 Appendices

Appendix 1 – NSTAR Electric Rate G-1

Delivery Services:		
Customer Charge:	$7.23	per month
Distribution (Demand):		
First 10 kW	$0.87	per kW
Over 10 kW	$4.12	per kW
Distribution (Energy):	0.815	cents per kW
Transition (Demand):	$1.26	per kW
Transmission (Demand):	$1.26	per kW
Supplier Services:		
Standard Offer:	6.323	cents per kWh
Default Service:	6.736	cents per kWh
Rate Adjustments:		
Pension Adjustment	0.124	cents per kWh
Energy Efficiency Charge	0.250	cents per kWh
Renewable Energy Charge	0.050	cents per kWh
Default Service Adjustment	0.265	cents per kWh

Appendix 2 – ESB General Purpose Charges

Standing Charge	15.76	Euro per 2 months
P.S.O Levy		
Where Customer's MIC < 30 kVA	9.16	Euro per 2 months
Where Customer's MIC > 30 kVA	1.66	Euro per kVA of MIC per 2 months
Day kWh		
First Block	14.19	c per kWh
Second Block	12.09	c per kWh
Night Storage Heating kWh	5.41	c per kWh
Standing Charge	1.00	Euro per 2 months
Low Power Factor Surcharge	0.76	c per kVARh

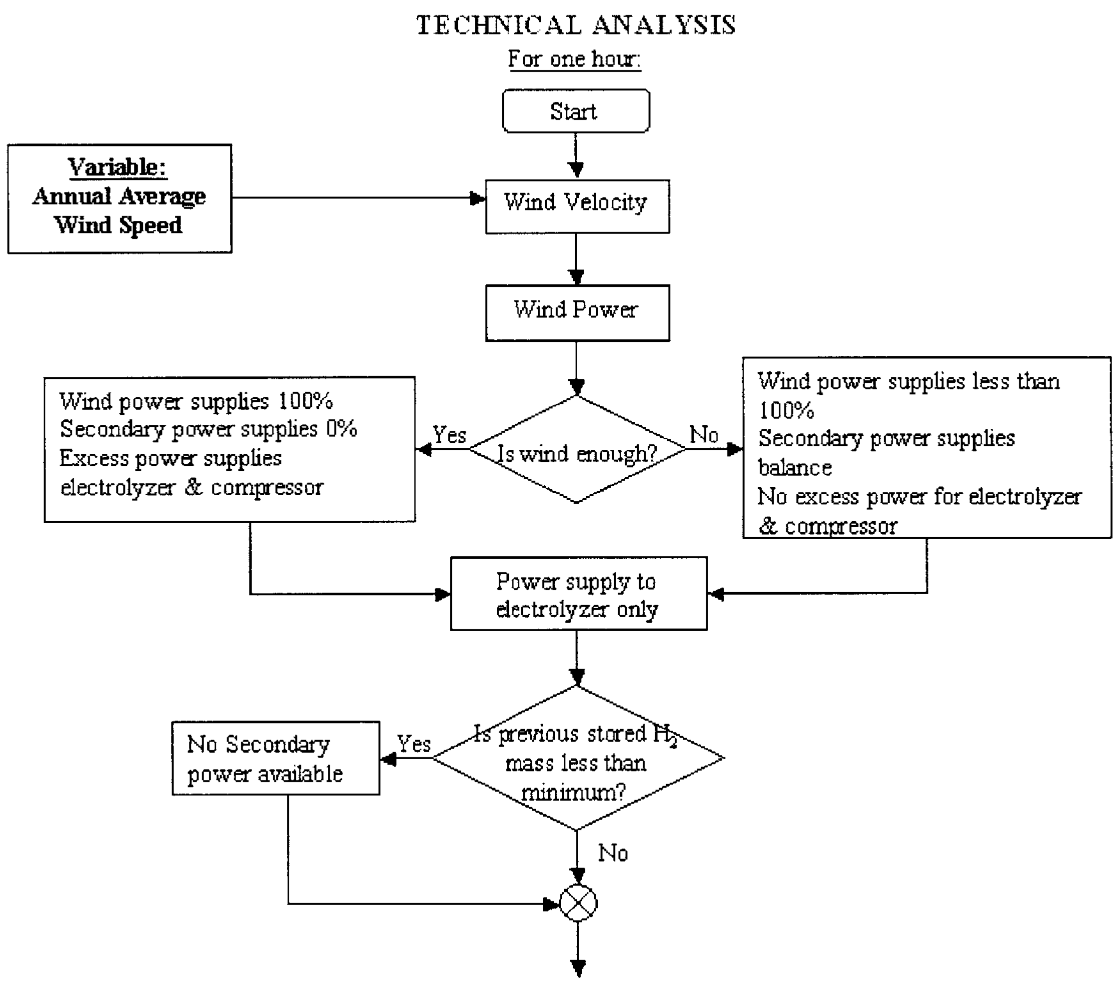
Appendix 3 – NSTAR Electric G-2 Rate

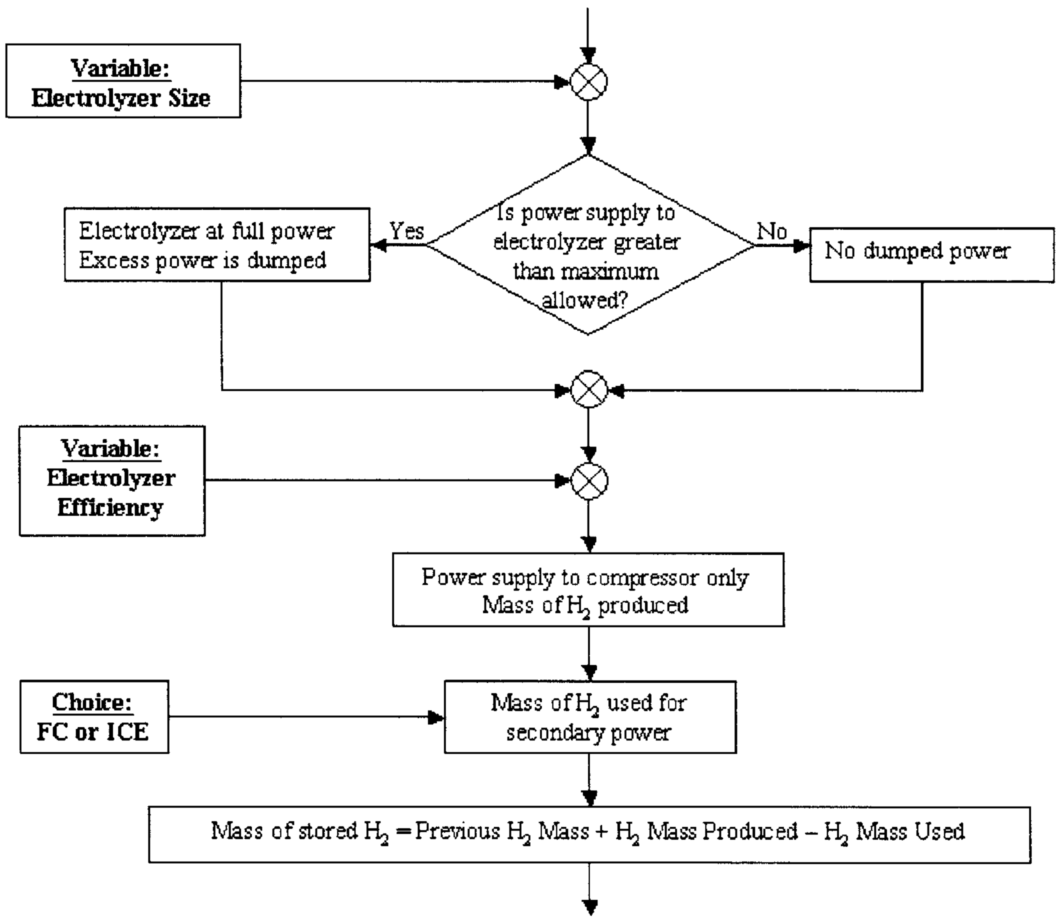
Delivery Services:		
Customer Charge:	$90.00 per month	
Distribution (Demand):		
First 100 kVA	$1.09	per kW
Over 100 kVA	$2.06	per kW
Distribution (Energy):	0.493	cents per kW
Transition (Demand):	$1.35	per kW
Transition (Energy):		
Peak Load Period	0.162	cents per kWh
Low Load Period A	$0.00	cents per kWh
Low Load Period B	$0.00	cents per kWh
Transmission (Demand):		
First 100 kVA	$4.50	per kVA
Over 100 kVA	$6.24	per kVA
Supplier Services:		
Standard Offer:	6.323	cents per kWh
Default Service:	6.736	cents per kWh
Rate Adjustments:		
Pension Adjustment	0.124	cents per kWh
Energy Efficiency Charge	0.250	cents per kWh
Renewable Energy Charge	0.050	cents per kWh
Default Service Adjustment	0.265	cents per kWh

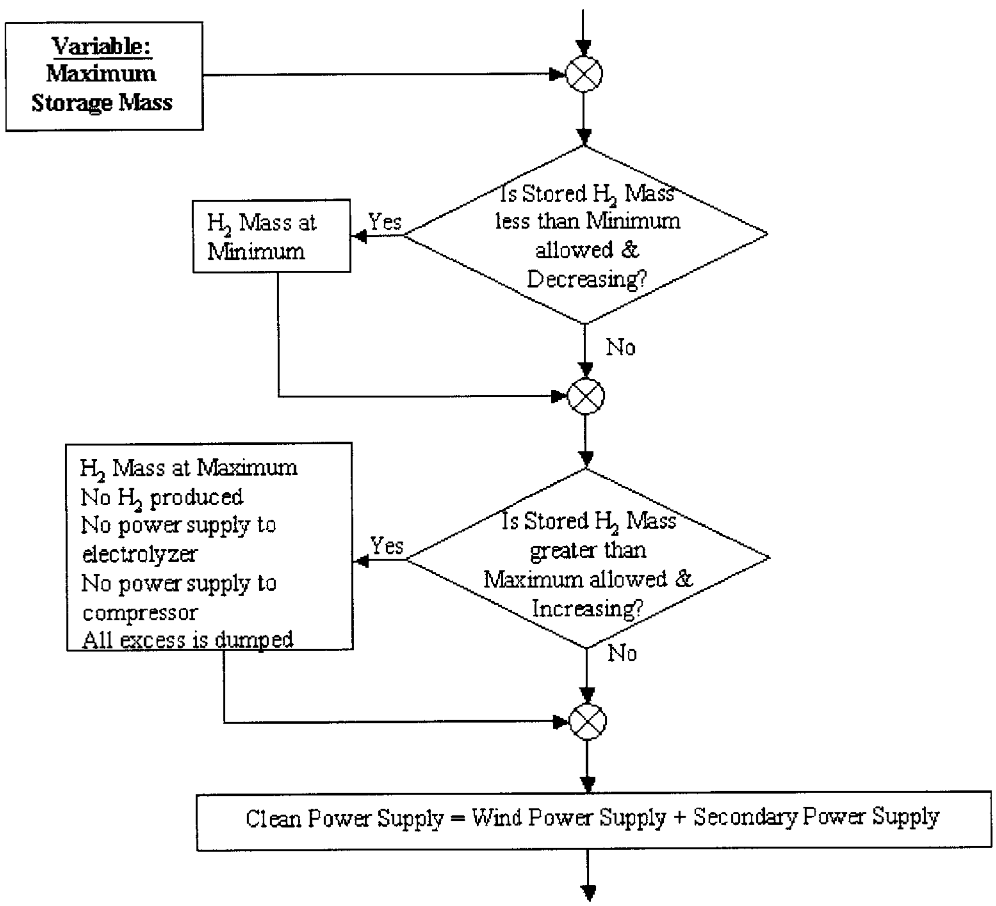
Appendix 4 – ESB Maximum Demand Charges

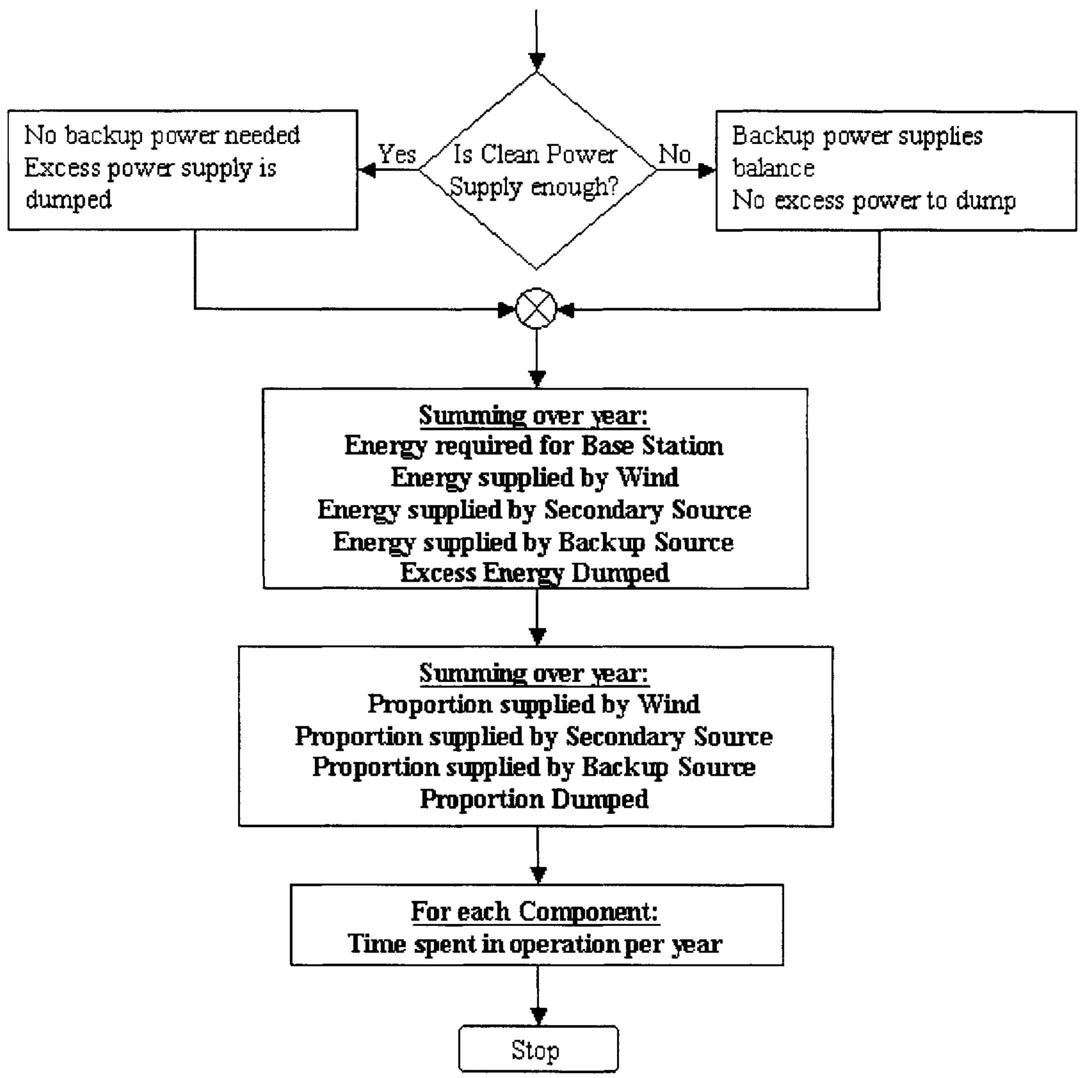
Standing Charge	145.00 Euro per 2 months			
P.S.O Levy				
Where Customer's MIC < 30 kVA	9.16	Euro per 2 months		
Where Customer's MIC > 30 kVA	1.66	Euro per kVA of MIC per 2 months		
Service Capacity Charge				
Charge	4.35	Euro per kVA of MIC per 2 months		
Excess Capacity Charge	8.70	Euro		
	Summer		Winter	
Demand Charge	5.60	Euro per kW	11.17	Euro per kW
Day kWh	Summer		Winter	
First Block	10.02	c per kWh	11.17	c per kWh
Second Block	6.86	c per kWh	7.26	c per kWh
Night Storage Heating kWh	4.60	c per kWh	4.60	c per kWh
Low Power Factor Surcharge	0.76	c per kVARh		

Appendix 5 – Flowchart of the Technical Analysis Model




Variable:
Electrolyzer Size
Is power supply to electrolyzer greater than maximum allowed?
Yes
No
Electrolyzer at full power
Excess power is dumped
No dumped power
Variable:
Electrolyzer Efficiency
Power supply to compressor only
Mass of H_2 produced
Choice:
FC or ICE
Mass of H_2 used for secondary power
Mass of stored H_2 = Previous H_2 Mass + H_2 Mass Produced – H_2 Mass Used

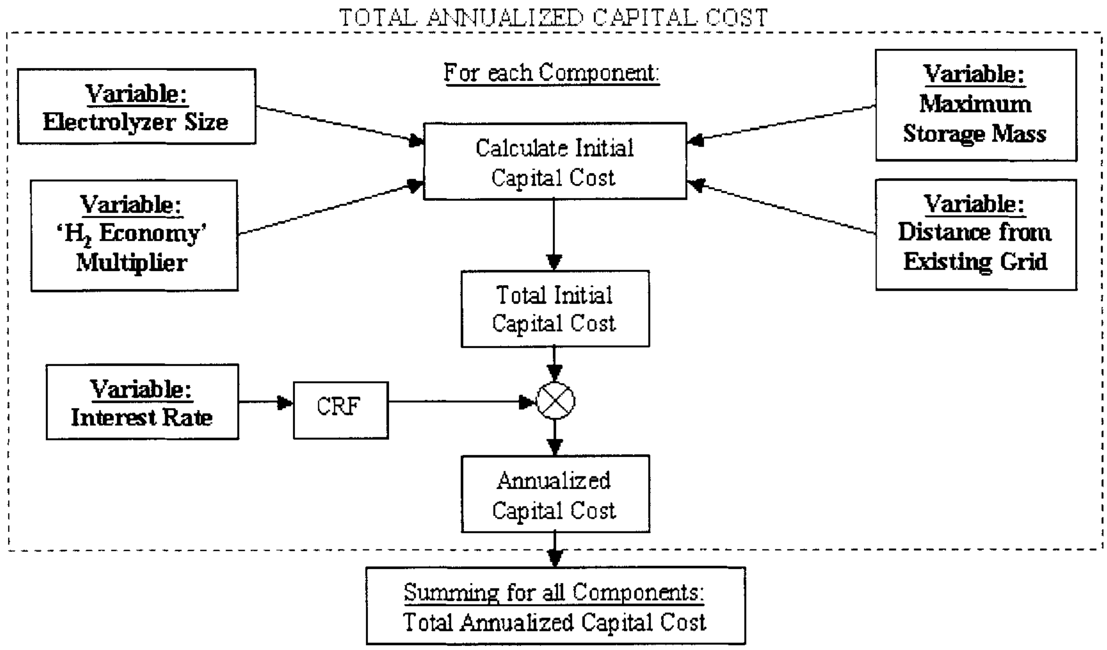

Variable: Maximum Storage Mass
Is Stored H_2 Mass less than Minimum allowed & Decreasing?
Yes
H_2 Mass at Minimum
No
H_2 Mass at Maximum
No H_2 produced
No power supply to electrolyzer
No power supply to compressor
All excess is dumped
Yes
Is Stored H_2 Mass greater than Maximum allowed & Increasing?
No
Clean Power Supply = Wind Power Supply + Secondary Power Supply

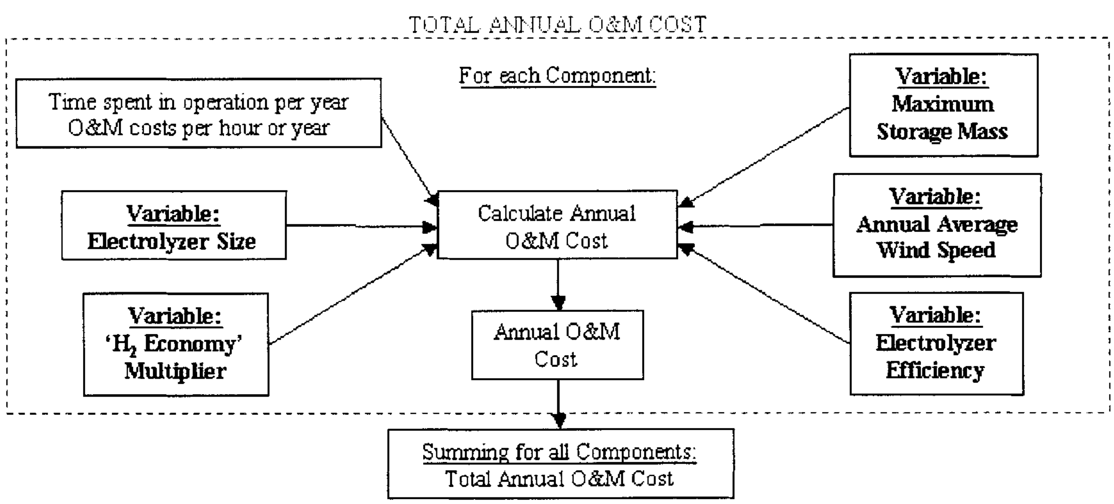


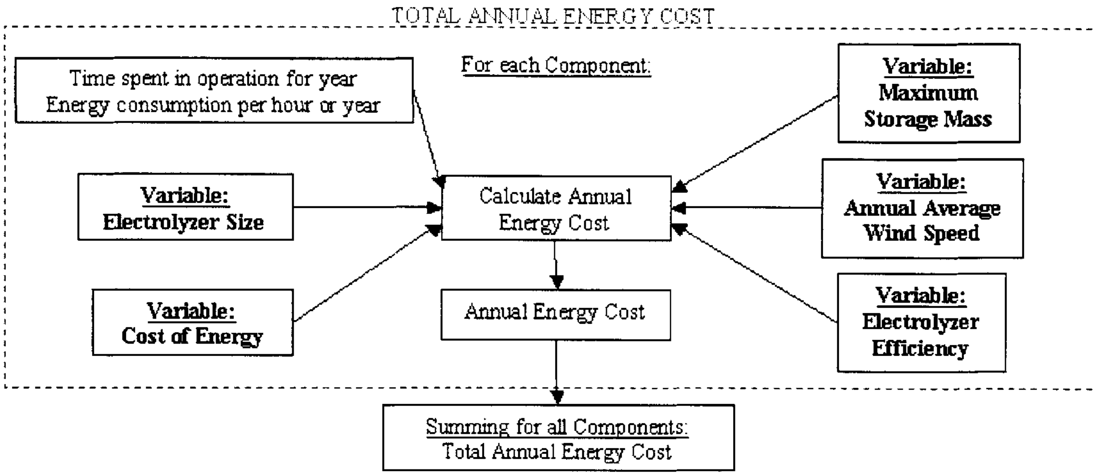
END OF TECHNICAL ANALYSIS

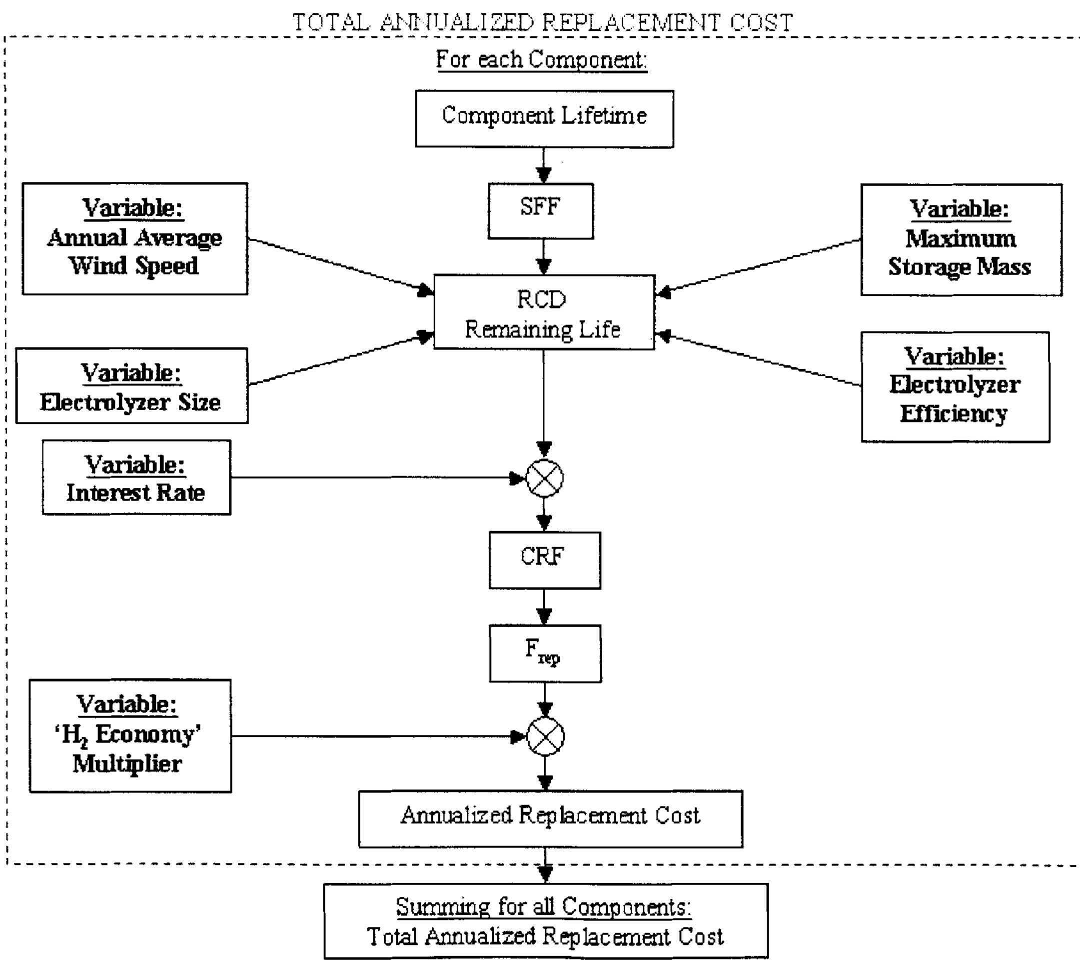
Appendix 6 – Flowchart of the Economic Analysis Model

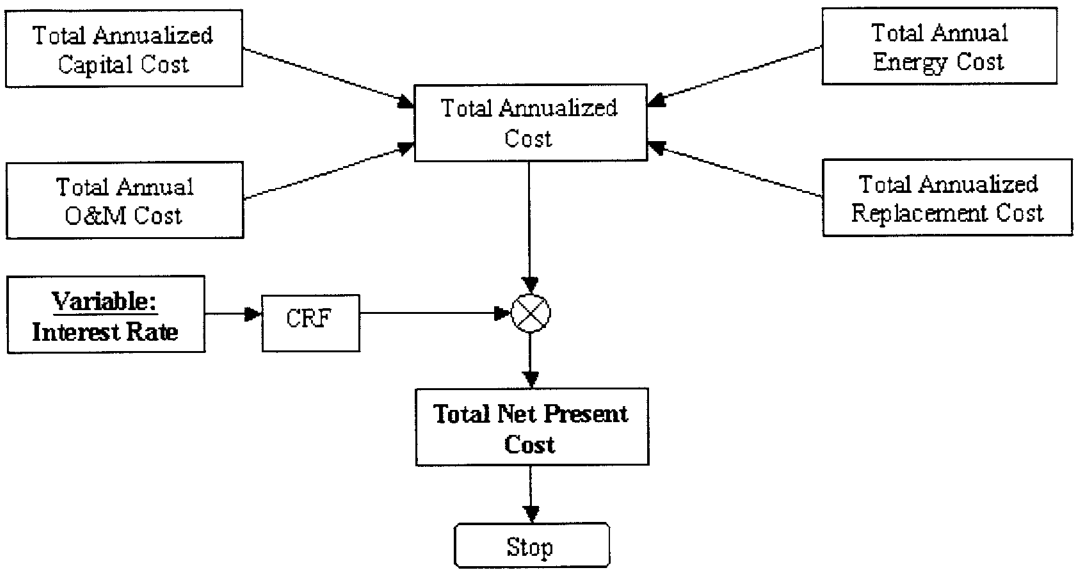
ECONOMIC ANALYSIS






TOTAL ANNUAL ENERGY COST
For each Component:
Time spent in operation for year
Energy consumption per hour or year
Variable: Maximum Storage Mass
Variable: Electrolyzer Size
Calculate Annual Energy Cost
Variable: Annual Average Wind Speed
Variable: Cost of Energy
Annual Energy Cost
Variable: Electrolyzer Efficiency
Summing for all Components:
Total Annual Energy Cost


TOTAL ANNUALIZED REPLACEMENT COST
For each Component:
Component Lifetime
SFF
Variable: Annual Average Wind Speed
Variable: Maximum Storage Mass
RCD
Remaining Life
Variable: Electrolyzer Size
Variable: Electrolyzer Efficiency
Variable: Interest Rate
CRF
F_{rep}
Variable: 'H_2 Economy' Multiplier
Annualized Replacement Cost
Summing for all Components:
Total Annualized Replacement Cost



END OF ECONOMIC ANALYSIS