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An assessment of potential for utility-scale wind power generation in Eritrea

Karen Rosen
San Jose State University

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**AN ASSESSMENT OF POTENTIAL FOR UTILITY-
SCALE WIND POWER GENERATION IN ERITREA**

A Thesis

Presented to

The Faculty of the Department of Environmental Studies

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Karen Rosen

August 1998

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**APPROVED FOR THE DEPARTMENT OF
ENVIRONMENTAL STUDIES**

Dr. Karina Garbesi
Assistant Professor of Environmental Studies
Graduate Student Coordinator
Committee Chairperson

Dr. Lester Rowntree
Professor of Environmental Studies
Department Chair

Dr. Robert Van Buskirk
Adjunct Professor of Environmental Studies

APPROVED FOR THE UNIVERSITY

ABSTRACT

AN ASSESSMENT OF POTENTIAL FOR UTILITY- SCALE WIND POWER GENERATION IN ERITREA

by Karen Rosen

This thesis advances the understanding of Eritrea's wind energy resources in order to assist development in that country. This paper first provides background information about wind power. The evaluation of Eritrea's wind resource includes a review of available data and discussion of analysis methods. Results imply high wind power potential at the southern port city of Aseb, where data indicate mean annual wind speeds of 9.5 meters per second at 10 meters height. This suggests that wind would be a cost-effective power source for Eritrea. This paper concludes with a discussion of the implications of these results for Eritrean wind energy development and a series of recommendations for Eritrea's wind energy development program.

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1. INTRODUCTION

Because of the negative environmental impacts of fossil fuel use, it is necessary to find ways to economically utilize non-polluting sources of energy. Worldwide, fossil fuel consumption is the largest cause of anthropogenic air pollutants such as carbon dioxide, sulfur and nitrogen oxides. These pollutants are threatening not only to those in the immediate vicinity of their generation, but also to the health of the global ecosystem. In an attempt to limit such emissions, thirty-nine countries have agreed to a combined 5.2 percent reduction of global greenhouse gas emissions by 2008-2012 in what has become known as the Kyoto Protocol (U.N. 1997). This international agreement lays the groundwork for development of environmentally sound alternatives to fossil fuel use.

Developing countries cannot improve their standards of living without increasing energy consumption. Using the same energy mix as is used in developed countries today, a worldwide equalization of per capita energy consumption levels to that of the United States would increase worldwide carbon dioxide emissions more than five-fold. As power capacity expands in the developing world, therefore, it is important that cleaner sources be used to address this future demand. Wind is an abundant resource that produces energy at low cost, with virtually no emissions, and is therefore likely to be an important component of future power generation.

The vast majority of wind power development to date has occurred in developed rather than developing countries. Some developing countries such as India and China are rapidly increasing wind capacity, but in the poorest countries there is a marked absence

of utility-scale wind power development. This study focuses on the feasibility of utility-scale wind power development in one of the world's poorest countries: Eritrea.

Eritrea is a small developing country in northeast Africa. After three decades of war with Ethiopia, the Eritrean government is seeking to greatly increase the capacity of the national power system as a prerequisite to rebuilding social and economic infrastructures. In particular, power is needed in the central highlands surrounding the capital city of Asmara, where about half of the Eritrean population lives. As part of its plans for expanding the energy sector, the Eritrean Department of Energy is investigating the feasibility of generating electricity with renewable energy sources. This project was undertaken at the request of the Eritrean Department of Energy to provide them with information about wind resources in Eritrea.

Previous studies have investigated wind resources in the area of Eritrea. Studies of the region surrounding the Red Sea and Gulf of Aden have issued promising results, especially for coastal areas (Elliott and Renne 1987; Pallabazzer and Gabow 1991; Radwan 1987). Mulugetta and Drake (1996) conducted an introductory study of wind potential for Ethiopia that included Eritrea. Their analysis is incomplete for Eritrea in that it included only four Eritrean sites: three in the central highlands, and one at Aseb on the southern coast. In addition, their study included only one of two sites at Aseb.

This thesis attempts to advance the understanding of Eritrea's wind energy resources in order to assist development in that country. To this end, this paper first provides background information about wind power in Chapter 3. Detailed information about the study area is given in Chapter 4, with a description of the Eritrean geography,

demographics, energy sector and wind patterns. The evaluation of the wind resource in Eritrea then begins in Chapter 5 with a review of available data and preliminary mean annual wind speed estimates for 10 cities in the Eritrean highlands. The remainder of Chapter 5 focuses on analyses of data for the southern coast of Eritrea, including two stations at the port city of Aseb. In addition, an analysis of surface wind speeds over the southern Red Sea is provided to assist in predicting wind potential along the Eritrean coastline. The results of these analyses are presented in Chapter 6. Chapter 7 compares results obtained using different methods of analysis and briefly discusses the projected cost of wind-generated electricity at Aseb. Chapter 8 concludes the thesis with a review of the results and a discussion of their implications for Eritrean wind energy development. In addition, Chapter 8 provides a series of recommendations for the Eritrean wind energy development program.

2. THESIS STATEMENTS

- Eritrea has the potential to incorporate wind power in its energy mix.
- The area surrounding the southern port city of Aseb has sufficient wind power potential to justify a utility-scale wind development program.

3. BACKGROUND

While people have been using wind power for thousands of years, only in the last century has it been used to generate electricity, and only recently has utility-scale electricity generation become economically feasible. In the early 1900's, Denmark became the first country to generate wind powered electricity (Golob and Brus 1993). For many decades thereafter, wind power was not considered a viable energy source in comparison to widely available and inexpensive fossil fuels. The oil shortages of the 1970's changed the perception that fossil fuels could meet all of society's energy needs. This led to a renewed interest in alternative energy options, including wind power. Since that time, great gains have been made in the efficiency and reliability of wind turbines.

Although wind currently accounts for less than one percent of electricity production worldwide, installed wind capacity is rapidly growing. Between 1980 and 1995, world wind capacity increased from 10 megawatts (MW) to nearly 5 gigawatts (GW) (see Figure 1). This increase was largely fueled by the declining cost of wind power and increasing concern about pollution. By 1995, 12 countries possessed more than 20 megawatts of installed wind power capacity (see Table 1), with Europe holding just over 50% of the total. According to Grubb and Meyer (1993), wind could meet 20% or more of the world's electricity demand within the next forty to fifty years.

Figure 1: Installed world wind capacity in kilowatts, 1980-1995

Table 1 Installed world wind capacity by country, 1995

Country	Capacity (MW)
United States	1770
Germany	1137
Denmark	630
India	550
Netherlands	250
United Kingdom	193
Spain	126
Sweden	67
China	36
Greece	28
Italy	23
Canada	21
Rest of the world	69
Total Installed Wind Capacity	4900

Source: IEA 1996

Recently, a large market for wind energy has developed in Asia, particularly in India and China. In 1995, Asia installed 340 megawatts of new capacity, representing an increase of 160% in one year (Anonymous 1996). The large number of wind energy assessments that have been conducted recently for countries near the Mediterranean and Red Seas suggests growing interest in this region as well (Radwan 1987; Habali et al. 1987; NREA 1989; Pallabazzer and Gabow 1991; Katsoulis and Metaxas 1992; Katsoulis 1993; Haralambopoulos 1995; Incecik and Erdogmus 1995; Pashardes and Christofides 1995; Tolun et al. 1995; Turksoy 1995).

One factor that inhibits the widespread use of wind power is the difficulty encountered in selecting sites. Since the 1970's, the United States and Denmark have made significant progress in wind selection techniques, but as yet there is no universal model. Because wind potential assessments are site specific, they tend to be very time consuming. This often means that wind energy developments require a large initial investment for careful wind prospecting studies. This makes wind power unattractive for most developing countries, whose economic situations force them to find the most inexpensive and expedient means of energy production available.

The main goal of this thesis is to aid Eritrea in surmounting some of these obstacles to wind energy development through a detailed, albeit preliminary, evaluation and analysis of Eritrean wind data. In the following sections, wind power characteristics, technology, and economics are discussed. This chapter concludes with a general description of wind assessment methods before moving on to the country-specific component of this study in Chapter 4.

Wind Turbine Technology

Power in the wind is extracted by wind turbines, which have rotor blades shaped like the wings of an airplane. When wind blows over these blades, it moves faster over the curved side of the blade than it does over the flat side, causing the air pressure to be higher on the flat side of the blade. This pressure differential causes a force that turns the rotor. This rotational energy is then converted to electricity by the generator.

Wind turbines may be categorized into four sizes as follows:

- Micro-turbines: < 1 kilowatt
- Small turbines: 10 - 100 kilowatts
- Medium-sized turbines: 100 - 1000 kilowatts
- Large turbines: > 1000 kilowatts

Micro-turbines are a relatively new development designed to compete with very small-scale photovoltaic technology. Small turbines are popular in both off-grid and grid-connected applications. Medium-sized wind turbines comprise the majority of the world's utility-scale wind capacity. Large machines tend to be considerably more complicated than their smaller counterparts. While some large machines are in use today, most are still in the development and testing stage.

For Eritrea, machines between 100 and 300 kilowatts, with simpler technologies and longer field experience seem most appropriate. These smaller machines are easier to transport and install and may also require less maintenance. Furthermore, they can offer reliability through incorporation of a larger number of machines, thereby reducing output variability when one of the machines is not operating.

Turbines with electrical capacities over 500 kilowatts (kW) are likely to be unsuitable for a number of reasons. Transportation and installation requirements are more demanding and costly, requiring larger cranes, larger and better highways, and greater technical expertise.

Characteristics of Wind Power

The materials and technologies required for wind development differ considerably from those used in traditional energy sources. In determining the suitability of the large-scale utilization of wind energy for a given region, costs and benefits of the technology must be carefully weighed. This section discusses the issues that must be taken into account when considering wind power development.

Power Management

Although good wind resources are essentially inexhaustible and are much more widely distributed over the earth's surface than traditional fuels, a major liability is that the wind itself cannot be stored or shipped. However, once wind power has been converted to electricity by turbines, the electricity may be used immediately or stored. The issues of wind power integration and storage are discussed below.

Integration. If wind-generated electricity will be used immediately, the intermittence of the wind resource becomes an issue. Air does not move at a continuous speed, even at the best wind sites. Wind speeds may fluctuate considerably on hourly, daily and even yearly bases. Although the availability of wind power sometimes parallels

demand, the correlation is unlikely to be perfect. Because of this, wind cannot generate 100% of electricity demand without substantial storage capacity.

Due to the intermittence of the wind resource, a high percentage of wind capacity connected to an electricity grid decreases system reliability. Large-scale power systems with low wind penetration create fewer wind integration problems than do those with higher penetration. In most systems without storage, wind can contribute between 25 and 45 percent of the total electricity before operational losses become prohibitive (Grubb and Meyer 1993). If the installed wind capacity is larger than this, the wind power output can be smoothed by erecting many wind turbines in a variety of wind regimes.

Another way to increase system reliability is to install additional power sources, either as backup systems or to work in conjunction with the wind system. Hydropower generators and gas turbines provide the best consistency because they can be quickly turned on and off in response to wind power fluctuations. Diesel generators can also be used when wind velocity is low and stored electricity is not available, but their response times are not as short as those of hydropower and gas turbines.

Storage. Since wind power is an intermittent energy source, some method of storing energy is necessary for high wind penetration systems to ensure adequate supply during periods of peak consumption. Some candidate storage technologies include batteries, pumped hydro, and hydrogen fuels. For smaller applications, battery storage can be cost-effective. This is especially true for hybrid systems that include a diesel engine, where the cost of diesel fuel is very high. A cost-effective technology that can be used for large wind power applications is pumped hydro, which uses excess energy

during times of low demand to pump water from a low reservoir to a high reservoir. This water is then released through a turbine to generate electricity when it is needed.

Chemical energy storage in the form of hydrogen fuels may be a promising application for coastal wind plants in the future.

Production, Installation and Maintenance

One of the main benefits of wind power is the small size of wind turbines compared to conventional power plants. This allows the manufacture, transportation and installation of wind turbines to be achieved in a shorter period of time and with fewer requirements for heavy machinery. This characteristic of wind systems also makes them extremely modular, and therefore, scaleable. Wind power can be produced with one, ten, hundreds or even thousands of machines. Increasing or decreasing capacity as needed does not require the outlay of huge capital expenditures at any one time. In addition, wind systems can continue generating electricity even when one or more machines are down for maintenance. Although new combined-cycle gas generation offers similar modularity benefits, conventional large-scale power plants require years of planning and building, and must be built on-site. In addition, they cannot produce power during periods of maintenance or repair.

Environmental Issues

Compared to most other methods of power generation, wind power generation is environmentally benign. Common negative aspects of conventional power production, such as air pollution and water consumption, are negligible in wind power production.

Following are some environmental and aesthetic impacts that are commonly associated with wind power systems.

Land requirements. For utility-scale wind applications, a large number of turbines must be installed to intercept a large amount of wind power. To minimize interference with each turbine's wind resource, turbines in large wind farms are typically separated by 5 to 10 rotor diameters. Therefore, a medium-sized wind turbine requires about 10,000 square meters, or one hectare, of surrounding land.

Field studies in California indicate that wind projects occupy about 7.1 hectares per installed megawatt (Gipe 1991). Using this figure, a wind farm with the capacity of an average nuclear power plant (about 1 gigawatt) may require an area of over 70 square kilometers. These requirements may seem demanding at first glance, but actually compare favorably with land requirements for coal or nuclear generation when the full life-cycle requirements of mining, processing, transportation, and waste disposal are considered. In addition, since only about 10 percent of a wind farm area is actually occupied by the turbine base and access roads, the remainder can be used for farming or grazing, as is currently the practice in Europe and California, respectively.

Visual impact. Because wind turbines are typically between 20 and 50 meters in height, a significant visual impact of a large number of turbines in an open area is unavoidable; however, the effect of a wind farm's presence is subjective and opinions vary widely. Surveys have shown that uniformity of size and spacing improves aesthetic acceptability considerably (Clarke 1991). In addition, tolerance of other large structures

such as pylons, utility towers and telephone poles suggests that negative opinions may be more a matter of habituation than of the appearance of the objects involved.

Noise. Noise created by gearboxes and blades can be a problem in populated areas and may even limit settlement within audible range. This issue has received considerable focus in densely populated areas, such as Europe. For both noise and safety reasons, care should be taken to ensure a distance of several hundred meters between the turbines and the nearest habitation.

Electromagnetic interference. To avoid problems of interference with vital radio transmission services such as aircraft navigation systems, the locations of such facilities in relation to the wind turbines should be carefully studied. Where potential problems exist, careful choice of turbine design and materials can reduce radio interference. Otherwise, a booster receiver/transmitter can be installed at the facility.

Wildlife disturbance. Birds seem to be the only wildlife adversely affected by wind turbines. The wind farm most often cited in relation to avian issues is Altamont Pass in California, where bird strikes occur often enough to raise concerns over the issue. A 1992 study commissioned by the California Energy Commission (CEC) estimated that several hundred raptors are killed by turbine collisions, wire strikes, and electrocutions at Altamont Pass each year. According to the study, 39 of the birds killed in 1992 were golden eagles, a significant figure given a total population of only 500 breeding pairs (Orloff and Flannery 1992).

Bird kills can be limited by avoiding wind farm development in known bird migration routes, especially in locations of known rare and endangered bird species. At

present, a joint effort between turbine manufacturers and scientists is underway to research rotor and tower modifications to reduce this danger (Predatory Bird Research Group 1995).

Political and Economic Issues

Wind energy offers many political and economic benefits, including:

- greater fuel diversity
- decreased dependency on foreign fuel imports
- decreased dependence on fossil fuels, which are often subject to rapid price fluctuations and supply problems
- greatly reduced negative environmental impacts, avoiding the necessity for future environmental regulation
- more jobs per unit of energy produced than other forms of energy

One economic drawback of wind power is its capital-intensive technology, which may require poorer countries to become dependent on the acquisition of foreign financing. Similarly, because wind power is a relatively new technology, less technologically advanced nations that use wind power are likely to become dependent on foreign countries for technology and related information.

The actual price per kilowatt of wind-generated electricity depends on many factors. Therefore, the following section has been dedicated to a more detailed discussion of the cost wind power.

The Cost of Wind Power

The California Energy Commission (1997) estimates that the cost of new wind power in the U.S. is about 4.6 cents per kilowatt-hour, compared to 4.6 to 6.0 cents per kilowatt-hour for coal technologies. Recently, new technologies have also lowered the cost of electricity generated with natural gas or gasified coal. Cost estimates for new combined-cycle natural gas generation are as low as 2.5 cents per kilowatt-hour (kWh). However, these prices reflect neither the environmental nor the public health costs from emissions of carbon dioxide and volatile organic compounds. When social and environmental costs are included in the price comparison, oil combustion, nuclear fission, and coal are among the highest cost technologies, whereas efficiency, wind, and biomass are among the lowest-cost technologies (DeAngelis and Rashkin 1989).

Optimal conditions for the economical development of wind power include high wind speeds, low interest rates, and low labor costs. At over \$1,000 per installed kilowatt, high capital costs can be a problem when capital or loans are not available, or where interest rates are high. However, because wind is a clean energy source, it may be possible for developing countries to obtain loan subsidies from industrialized countries. Such loan subsidies have been proposed in the clean development mechanism in Article 12 of the Kyoto Protocol (U.N. 1997).

The cost of wind power depends on many factors. The most important are the cost of the turbines and the average wind speed at the installation site. Other factors that could affect the price of wind power in Eritrea include the cost of land and labor, financing charges on loans, and need for new transmission lines. An approximate breakdown of

U.S. wind farm construction costs is shown in Table 2. It is expected that many costs, particularly land and permitting costs, would be substantially lower in Eritrea.

Table 2. 1995 U.S. wind farm installation costs	
Component	Unit cost (1992\$/kW)
Wind turbine	888
Substation	68
Transmission	6
Service Center	5
Land	40
Indirect/Permitting	26
Total	1032

NOTE: Costs assume a 10.5% financing charge.
Source: Brower et al. 1993; Gipe 1995

Factors that could vary considerably in the Eritrean context are discussed individually below.

The effect of wind speed on cost. The cost of wind-generated electricity depends on both the mean annual wind speed and the annual distribution of wind speeds. Figure 2 shows the effect of changes in the average annual wind speed on the cost of wind power using the Mod-5B Horizontal Wind Turbine (Spera 1994).

Land costs. Data suggest that land costs have not contributed significantly to the price of wind energy in the United States. According to Table 2, land costs were less than 5% of installation costs. Therefore, we can conclude that low land costs in Eritrea will not offer a very substantial savings relative to current cost estimates based on U.S. and European experience.

Figure 2. Effect of wind speed on cost of wind-generated electricity

Turbine costs. The cost of the turbines is the largest portion of any wind power project cost. Based on experience in the U.S. and Europe, turbines typically comprise more than 70% of the total wind plant installation costs (Table 2); therefore, the price of the wind turbines is critical in determining the cost-effectiveness of the wind system.

Turbine costs are generally the least uncertain of the component costs, and can be fairly well predicted for any given project. It is possible, however, for turbine costs to vary considerably. For example, in California, the price charged for the same machine installed at about the same time has varied by as much as 80%, where the higher price

was charged to the site with better wind potential (Gipe 1995). Thus, prices for wind machines may be determined by the market in a somewhat inconsistent manner.

Another factor that could change the cost per installed watt is the size and type of wind machines installed. Prices given in Table 2 are based on U.S. and European experiences, which involved larger and more complicated machines. Such machines may not be appropriate in the Eritrean context as described in *Wind Turbine Technology* above. It is important to consider, therefore, whether smaller machines will have higher installed costs because of the lost opportunity of economies of scale. Data from Gipe (1995) suggest there will be little cost compromise of using smaller machines. A summary of this data is given in Table 3.

Table 3. Varying costs of installing a wind system in the U.S. based on turbine size

	Rotor Diameter (m)	Rated Capacity (kW)	Installed Cost (US\$)	Installed Cost/Watt (US\$/watt)
Micro-Turbines	1	0.25	\$2,500	\$10.00
	2	0.75	\$5,000	\$6.67
Small Turbines	3	1.5	\$10,000	\$6.67
	7	10	\$30,000	\$3.00
Medium-Sized Turbines	18	100	\$125,000	\$1.25
	25	200	\$250,000	\$1.25
	35	400	\$500,000	\$1.25
	40	500	\$600,000	\$1.20

Source: Gipe 1995

Although economies of scale are apparent in the micro-turbines and small turbines, at about 100 kilowatts these economies of scale fall off, so that the 100-300 kilowatt turbines are nearly as cost-effective as the 400-500 kilowatt turbines.

Furthermore, Gipe (1995) cites many individual examples of German wind turbines for which the price per kilowatt is actually less for 80 - 100 kilowatt turbines than for the larger 450 - 500 kilowatt turbines.

Financing charges on loans. Since approximately 80% of wind generation costs are capital costs, loan repayment could have a large impact on wind energy development costs. Loan repayment costs depend mainly on project lifetime and interest rates. Project lifetimes tend to be about 25 years, but interest rates can vary substantially. Gipe (1995) reports a range of annual interest rates from 3.3 percent in Germany to 10.1 percent in Great Britain. Annual interest rates on wind projects for private utilities in California were reported to be 10.5 percent (Brower et al.1993). However, for developing countries like Eritrea, there is a possibility of obtaining interest free loans or grants to develop wind projects (U.N. 1997).

Operation and maintenance. The final cost of energy will also depend on operation and maintenance costs. Operation and maintenance costs in the U.S. and Europe average about 1 cent per kilowatt-hour. This is about half the cost of operation, maintenance and fuel for nuclear and coal plants, and about one third of the cost of the same for gas plants (Gipe 1991).

Labor. More research needs to be done to determine what fraction of U.S. and European installation, operation and maintenance costs are attributable to labor wages. Labor costs, which are usually substantial in the U.S. and Europe, should be lower in Eritrea, resulting in substantial cost savings. In addition, the local manufacture of components such as towers or rotor blades could further reduce costs.

Wind Assessment

Because the cost of wind energy development depends sensitively on the nature of the wind resource, any detailed evaluation of wind energy economics requires a series of wind assessment studies. A wind energy assessment is an integrated analysis of the potential wind energy resources of a particular area. Such an assessment begins with an understanding of the general wind patterns of the area, and progresses to the collection and analysis of wind data. Wind assessment may also involve a monitoring program and, at the most advanced stages, computer simulations of wind flow to determine wind turbine micro-siting. In this study we focus on regional wind flow patterns, and the collection, evaluation and analysis of existing wind data.

Regional Wind Flows

To predict the windiest spots in a large area – for example, an entire country – it is useful to understand regional wind flows. Air flows from place to place as a result of differences in air pressure. Natural forces cause air in higher pressure systems to move in the direction of lower pressure systems. This movement of air is called wind.

There are two major forces that drive and direct the wind. The first is heat from the sun. As the sun heats the earth, air at the surface becomes less dense. Since the sun's intensity and the earth's heat capacity vary on local and global levels, multi-scale differential pressure systems are formed. In coastal regions, for example, the land heats and cools more quickly than the nearby water. The effect is that the hot air over the land rises during the day and is replaced by the cooler, denser air from over the sea. In the

evening, the temperature of the land drops more quickly than the temperature over the water, and the effect is reversed. This is known as a sea breeze. Examples of this phenomenon can be found at California's Altamont pass and in Eritrea's highland passes. In a similar way, continent-sized pressure systems drive larger-scale regional winds.

The second major force that influences the wind is the rotation of the earth, which causes what is called the Coriolis effect. As described above, natural forces tend to drive winds in a straight line from areas of low pressure toward areas of high pressure. However, because the earth is turning under the wind, the path of the wind from the perspective of a fixed location on the earth appears to be curved – to the right in the Northern Hemisphere, or to the left in the Southern Hemisphere. The result is that the wind moves nearly parallel to isobars instead of across them. Therefore, in the Northern Hemisphere, air movement around a high pressure system is clockwise, while movement around a low pressure system is counterclockwise. The direction of air movement around pressure systems in the Southern Hemisphere is just the opposite.

The combination of these forces gives rise to many types of wind that may contribute to the wind resource of a given area. On a planetary level, trade winds extend from the equator to about 30 degrees latitude in both hemispheres, while westerly winds extend from about 30 to about 65 degrees latitude in both hemispheres. Monsoons are seasonal winds caused by large annual temperature and pressure differences over land and sea areas. Synoptic scale winds are associated with periodic systems, typically spanning a period of about 3 to 5 days. Mesoscale wind systems are generally associated with topographical features, including physical and differential heating elements. Breezes

are the mesoscale equivalent of monsoons, lasting only a few hours, often on a daily basis (Aspliden, Elliott and Wendell 1986).

Local topography physically affects winds at the earth's surface. Over relatively level terrain, winds are slowed by friction at the earth's surface so that wind speeds tend to increase with height. Wind speeds can be enhanced through constriction over hills or through valleys due to the conservation of mass principle, which implies that a volume of air forced through a smaller area will travel faster than the same volume of air forced through a larger area.

The many types of winds and the physical elements that affect them must be taken into account when estimating the wind potential for a given region. Topography and major wind flows contributing to wind patterns in Eritrea are discussed in Chapter 4.

Wind Data Collection

Once an area has been chosen for assessment, it is necessary to collect wind speed and direction data. A complete wind resource assessment involves a dense network of anemometers (wind monitoring stations) recording continuous wind data for at least one year. Since such wind monitoring efforts are time consuming and costly, wind researchers often obtain data sets that have been previously recorded.

There are several sources that may be helpful in obtaining existing meteorological databases. Climatological stations and airports are likely to maintain reliable records. The World Meteorological Organization maintains a record of such stations worldwide. For resource assessments conducted near coastal areas, marine wind information taken

from ships, buoys and satellites may also be useful. For details on these and other data sources that were examined in the context of this study, see Appendix A.

If possible, existing data sets should be supplemented with spot measurements. When choosing sites to examine for potential wind development, the researcher should focus on areas likely to have enhanced wind speeds. Some topological features that are likely to enhance wind speeds are (Aspliden, Elliott and Wendell 1986):

- gaps, passes and gorges in areas of frequent strong pressure gradients
- long valleys extending down from mountain ranges
- high elevation plains and plateaus in areas of strong upper-air winds
- plains and valleys with persistent winds associated with pressure gradients
- exposed ridges and mountain summits in areas of strong upper-air winds
- exposed coastal sites in areas of thermal/pressure gradients

Data Analysis

The next step in the wind resource assessment is to analyze the wind data set to determine patterns in the magnitude, duration and direction of the wind.

Mean wind speeds. Mean wind speed (MWS) is the most commonly used indicator of wind production potential. A mean annual wind speed (MAWS) of about 6 meters per second at 10 meters height is considered economically viable for a utility-scale wind farm (Grubb and Meyer 1993). The mean wind speed is defined as:

$$MWS = \frac{1}{N} \sum_{i=1}^N v_i \quad (1)$$

where N is the sample size, and v_i is the wind speed recorded for the i^{th} observation.

Where the sample size is large, it is useful to group the wind speed data into intervals to create a histogram of the wind speed distribution. The probability of the observed wind speed being within an interval can be written as:

$$p(v_j) = \frac{n_j}{N} \quad (2)$$

where v_j is the median value and n_j is the number of observations in the j^{th} interval. The mean wind speed can then be calculated as:

$$\text{MWS} = \sum_{j=1}^M p(v_j) \cdot v_j \quad (3)$$

where M is the number of intervals, or:

$$\text{MWS} = \int_0^{\infty} v \cdot f(v) \cdot dv \quad (4)$$

where $f(v)$ is the non-cumulative probability distribution function.

The Weibull distribution. Studies show that a wind speed distribution can typically be described in terms of the Weibull distribution (Rohatgi and Nelson 1994).

The equation of the cumulative Weibull distribution is:

$$F_{\text{Weibull}}(v) = \exp\left[-\left(\frac{v}{A}\right)^k\right] \quad (5)$$

and the non-cumulative Weibull distribution is:

$$f_{\text{Weibull}}(v) = \frac{k}{A} \left(\frac{v}{A}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{A}\right)^k\right] \quad (6)$$

where k is the shape parameter and A is the scale parameter. Finding a "best fit" Weibull distribution is a convenient way to approximate a continuous wind speed distribution from the discrete observed values. In addition, this method is also useful in that the wind regime of an area can then be described using only the two Weibull parameters, k and A .

Once Weibull parameters have been determined, mean wind speeds can be computed as (from Equations 4 and 6):

$$MWS = \int_0^{\infty} v \cdot \frac{k}{A} \left(\frac{v}{A} \right)^{k-1} \cdot \exp \left[- \left(\frac{v}{A} \right)^k \right] \cdot dv \quad (7)$$

This equation can be simplified using the Gamma function, defined as:

$$\Gamma(z) = \int_0^{\infty} t^{z-1} \cdot e^{-t} \cdot dt \quad (8)$$

Setting $(v/A)^k = t$ and $(z - 1) = 1/k$, mean wind speed can then be expressed as:

$$MWS = A \cdot \Gamma(z) = A \cdot \Gamma \left(1 + \frac{1}{k} \right) \quad (9)$$

Vertical estimation of wind speed using the power-law model. As described above, winds are slowed by friction at the earth's surface, so that wind speeds tend to be greater at higher elevations. The standard height for wind speed observations is 10 meters (WMO 1996). Since wind turbine hub heights are typically between 20 and 50 meters, extrapolation of wind speeds to the planned hub height is usually required to estimate wind potential. For regions with relatively level terrain and little vegetation, the method most commonly used to obtain this extrapolation is the 1/7 power-law model. The equation of the 1/7 power-law model is:

$$\frac{v(z)}{v(z_0)} = \left(\frac{z}{z_0} \right)^{\frac{1}{7}} \quad (10)$$

where z is the height at which the wind speed is to be estimated, $v(z)$ is the wind speed to be estimated, and z_0 and $v(z_0)$ are the reference height and wind speed, respectively.

Temporal wind speed patterns. Temporal wind speed patterns are useful to determine when the greatest wind energy potential exists. Depending on the region, wind resources can vary from year to year, seasonally, from day to day, diurnally, and even from minute to minute. Long-term means for wind speed and direction are most important for estimating power output at a given site, but seasonal and diurnal variations are important when considering peak demand and power supply. Variations of very fine temporal resolution, although necessary for choosing appropriate wind turbines, are beyond the scope of this study. Temporal wind speed patterns in Eritrea are presented in Chapter 6.

Theoretical Capacity Factor. For future estimates of potential wind power plant output, it is useful to derive a theoretical capacity factor. The capacity factor is a measure of power plant efficiency, defined as the ratio of actual energy output to the amount of energy a plant would produce if it operated at full rated power within a given time period. The best sites are those with wind regimes that allow the turbines to run at their maximum output the largest fraction of the time. In California wind farms, operating capacity factors for 200-kilowatt turbines are observed to be approximately 22% (Lynette and Gipe 1994).

The theoretical capacity factor (CF) is estimated by the equation:

$$CF = \frac{\sum_{i=a}^b f(v_i) \cdot P(v_i)}{P_r} \quad (11)$$

where a is the cut-in speed of the turbine, b is the cut-out speed, $P(v)$ is the power curve for the turbine, and P_r is the rated power capacity of the turbine. The power curve and rated capacity are turbine-dependent and must be obtained from the turbine manufacturer.

Wind power. Calculations of wind power are derived from the equation for kinetic energy (KE), which is:

$$KE = \frac{1}{2} m \cdot v^2 \quad (12)$$

where m is mass. Air mass is equal to the product of its density and volume. Volume is dependent on the area through which the air is passing, the speed with which it is moving, and the amount of time it travels. Air mass can therefore be calculated as:

$$m = \rho \cdot A \cdot v \cdot t \quad (13)$$

where ρ is the air density, A is the area through which the air passes, and t is time. Since power is energy divided by time, the equation for wind power (WP) can be written as:

$$WP = \frac{1}{2} \rho \cdot A \cdot v^3 \quad (14)$$

Wind power density. Wind power density is the amount of wind power available per unit of area perpendicular to the wind flow. In practice, wind power density is used to estimate the potential electrical output of a wind farm once the area swept by wind turbine rotors and the power system efficiency are known. The equation for wind power density (WPD) is simply the wind power (Equation 14) divided by the area, or:

$$\text{WPD} = \frac{1}{2} \rho \cdot v^3 \quad (15)$$

Wind power class. In the U.S. Wind Atlas (Elliott et al. 1986), wind power class denominations of between 1 and 7 are used, where a wind class of 7 indicates the highest potential. Table 4 compares these methods of describing wind resource potential.

Table 4. Wind speed, power density, and power class		
Mean Annual Wind Speed at 10 meters (m/s)	Wind Power Density at 10 meters (W/m²)	U.S. Wind Atlas Wind Power Class
0 - 4.4	0 - 100	1
4.4 - 5.1	100 - 150	2
5.1 - 5.6	150 - 200	3
5.6 - 6.0	200 - 250	4
6.0 - 6.4	250 - 300	5
6.4 - 7.0	300 - 400	6
7.0 - 9.4	400 - 1000	7

Source: Grubb and Meyer 1993

Power output. Power is extracted from the wind as it moves through the area swept by a turbine's blades. Using equations 11 and 15, the amount of power (P) converted to electricity by a wind turbine with radius r, can be written as:

$$P = \text{WPD} \cdot \text{CF} \cdot \pi \cdot r^2 \quad (16)$$

where $\pi \cdot r^2$ is the area swept by the wind turbine rotors.

On the down-wind side of a turbine, the wind speed is reduced because kinetic energy has been taken by the turbine. As a result, less wind power is available to a

turbine sited downwind of another. Therefore, when calculating the power output of an array of turbines, P must be multiplied by the efficiency of the array.

Wind direction. Wind direction is usually described in terms of degrees, where north is 360° , south is 180° , east is 90° and west is 270° . In assessing wind resource potential, wind direction frequency distributions are typically calculated for 8, 12 or 16 direction intervals. The probability that the wind will blow from within a given direction interval is:

$$p(D_j) = \frac{n_j}{N} \quad (17)$$

where D_j is the median value of the j^{th} interval. Results are often displayed on a wind rose, which is a radar graph where direction (degrees) is plotted on the circular x axes, and frequency (%) is plotted on the y-axes.

Wind Maps

A wind map indicates regions of equal wind speeds. Such maps have been generated for the U.S., Europe, and many other regions. Approaches to creating wind maps depend on the nature of regional wind flows, the complexity of the terrain, and the availability of climatic station data. In regions with very simple terrain, predictable regional wind flows, and reasonably dense monitoring networks, wind maps may be generated using simple extrapolations of meteorological station data, such as was done in the wind assessment of Somalia by Pallabazzer and Gabow (1991). For somewhat more complex terrain, station data may be extrapolated using commercially available models that estimate perturbations due to uneven terrain. Such models are not suitable for Eritrea

due to the complexity of the terrain. In addition, large-scale vertical movements of air masses, such as can be found in Eritrea, cannot be described using these models.

In Eritrea, thermally driven winds and extreme elevation changes cause regular disruptions in regional wind flows. Under these conditions, locations only a few kilometers apart may show little or no correlation in wind speed and direction. Standard wind modeling methods are not well defined for such sites. Because of the complexity of the wind flows and terrain, and the limited number of meteorological stations for which wind speed data are available, this study will not attempt to create a wind map for Eritrea. Instead, the results of this study will identify high wind areas for further study.

In the following chapters, this understanding of wind assessment will be applied to the specific case of Eritrea.

4. STUDY AREA

The feasibility and applicability of wind energy development depends on the particular social, economic, and physical characteristics of both the study area and the wind resource. In this section we describe the Eritrean geography and demographics, the conditions of the energy sector, including a description of the two main national grids at Asmera and Aseb, and the large wind flow patterns in the area.

Geography and Demographics

Eritrea is a small, developing country in northeastern Africa with an estimated population of 3.6 million (CIA 1997). Eritrea occupies the southernmost 1200 kilometers of the Red Sea's western shoreline, including hundreds of islands near the major ports of Mitsiwa'e in central Eritrea and Aseb in the south (see Figure 3).

The capital, Asmera, is located in central Eritrea on a plateau at over 2000 meters elevation. This high plateau and the surrounding hillsides are known as the central highlands. Roughly 20% of the Eritrean population lives in Asmera, and, although accurate population counts for other major cities are not available, it is estimated that more than half of the Eritrean populace lives in the towns and cities of the highlands. This area is cooler and wetter than the lower elevations in Eritrea, with up to 61 centimeters of rainfall annually (Landsberg 1972).

Figure 3. Map of Eritrea showing topography, major cities, the national electrical grid, surrounding countries, and major bodies of water.

To the west and east are the western and coastal lowlands, respectively. The western lowlands have a semiarid climate and consist chiefly of desert hills and savanna. To the east, the high plateau drops abruptly to a wide, arid coastal plain that stretches the

entire length of Eritrea. South of Mitsiwa'e, this coastal plain dips to 100 meters below sea level at the Danakil depression, which divides the central highlands in the west from a much smaller range of mountains in the east. This second range parallels the shoreline from the Danakil depression to beyond the Djibouti border, reaching almost 2000 meters at its highest point. The extremely hot and arid Danakil depression to the west, the mountains to the south, and the Red Sea to the north and east contribute to the isolation that inhibits settlement in this part of Eritrea. Current maps of Eritrea show settlements in this area to be relatively few and far between.

The Eritrean coastal plain is a hot, dry desert. Summer temperatures from June to September average 35-45°C and rain is rare. Annual rainfall ranges from about 3 centimeters in the driest years to about 26 centimeters in the wettest (Landsberg 1972). Because of the extreme heat and aridity, few people live along the coast.

The largest city in this part of the country is Aseb, a port city of about 50,000 people located at the southernmost tip of the Eritrean coastline. The annual rainfall in Aseb is about two inches, and the landscape consists of wind-blown sand near the ocean, basaltic lava flows, cinder cones and salt flats. The Aseb economy relies on the port, the national petroleum refinery, and a small fishing industry. Drinking water at Aseb is available through groundwater resources and the local inhabitants supplement their diet and income with fishing and trading. The Aseb Airport, about 10 kilometers northwest of Aseb, provides the best transportation to and from the town since roads in the region, where they exist, are badly damaged.

The Eritrean Energy Sector

The Eritrean energy sector is characterized by a relatively low level of electricity supply, an over-reliance on biomass, and a large latent energy demand. About 80% of the population is without residential electricity, with demand exceeding supply by as much as 150%. An estimated 82% of energy needs are met with biomass resources, while 16.8% are met with liquid petroleum fuels. Only 1.2% of energy is consumed in the form of electricity (Habtesion 1994).

From 1992 to 1995, actual electricity production in Eritrea increased at an annual rate of 10%. By 1997, Eritrea had a firm electric capacity of about 60 megawatts and generated about 150 gigawatt-hours (GWh) per year. The cost of electricity production in Eritrea is approximately 0.45 Birr/kWh, or 6.5 cents in U.S. currency. Current Eritrean government energy policy goals include expanding the electricity supply by at least 6% per year.

The Main National Grid at Asmera

The main national electric grid in the central highlands has a formal capacity of 40 megawatts. In practice, however, the actual generation capacity is approximately one half the formal generation capacity because many generators are old and inefficient. Transmission lines stretch from Mitsiwa'e to Asmera, and then continue south, for a combined length of about 500 kilometers (see Figure 3).

From 1992 to 1995, expansions in the Eritrean electric utility sector occurred primarily through improvements and expansion of the main grid in the Eritrean

highlands. The Eritrean government has approved further expansion with the construction of an 84 megawatt heavy fuel-oil fired power plant near Mitsiwa'e that is expected to be completed in 1998.

The Secondary Grid at Aseb

A second grid, with a capacity of 17 megawatts, is located at Aseb. There are three power generating institutions in Aseb: the Eritrean Electric Authority (EEA), the Aseb port, and the petroleum refinery. The EEA and the refinery are the largest producers, with the refinery generating slightly more than the EEA. During minimum loads, the refinery produces all power for both itself and the town. Meanwhile the port is a smaller user that prefers to operate independently, and that incurs the largest unit generation costs. Demand at the port fluctuates depending on the number of ships docked, as they require 300 kilowatt cranes for unloading.

Electricity demand at Aseb is currently met by several aging diesel generators, many of which are not very efficient and, therefore, expensive. The combined capacity of the power system is approximately 17 megawatts, though this may soon decrease to 11 megawatts as the generators at the refinery undergo rehabilitation. The average combined demand of the town, the refinery and the port is 5.3 megawatts, fluctuating from a low of 4.0 megawatts during the cooler winter monsoon season to a high of 8.1 megawatts in the hot summer monsoon season. The Aseb power generation system and associated costs are summarized in Figure 4 (Van Buskirk 1997).

* Gas oil 1.53 Birr/l; EEA fuel oil 0.78 Birr/l; refinery fuel oil 0.735 Birr/kg, where 6.45 Birr = 1 US\$.

Figure 4. Diagram showing power supply, power demand and energy costs at Aseb

Wind Patterns

Pressure systems due to differential heating and cooling of Asia, Africa and the Indian Ocean are the main forces behind air movement in the Red Sea region. These systems give rise to two distinct monsoons. From November to March, the southern half of the Red Sea is dominated by what is called the Northeast Monsoon. Early in winter, the cold Siberian high pressure zone is formed near 50°N 95°E, while the African equatorial low is formed near 10°N 30°E. The clockwise air movement around the Siberian high and counterclockwise air movement around the Sudanese low converge at the Gulf of Aden. This creates a strong southeast wind that forces air through the narrow Bab el Mandeb at the southern mouth of the Red Sea. At the same time, clockwise air movement around the Saharan high over northern Libya and west-central Egypt forces air

in the northern half of the Red Sea to blow from the northwest (Brower, Baldwin and Franks 1993). The two winds converge at about 15°N, creating the relative calm winds off the coast of Mitsiwa'e, where much of the combined air mass is drawn southwestward across the Eritrean highlands toward the African equatorial low pressure system centered in southern Sudan. These air motions produce two high wind locations: the southern Red Sea, and the lower passes of the Eritrean highlands, where cooler denser air is accelerated as it is forced through topographic constrictions (Van Buskirk, Garbesi and Rosen 1997).

From May to September, winds in the Red Sea are affected by what is called the Southwest Monsoon. Increased insolation and low heat capacity of the Asian land mass during the early summer months promotes the formation of the warm Pakistani low centered near 30°N 65°E. In Africa, the Azores high produces a strong northwest wind over the northern half of the Red Sea (Brower, Baldwin and Franks 1993). The result is that surface winds along the entire length of the Red Sea blow from the northwest, down the length of the Red Sea, and out into the Gulf of Aden.

While seasonal wind patterns in Eritrea are caused by the Northeast and Southwest Monsoons as described above, diurnal wind patterns are caused in large part by local land-sea breeze effects. When the land mass south and west of Eritrea warms during the daytime, the air mass above it is also warmed. This warm air rises, while cooler, denser air from over the Red Sea flows in to replace it. The result is a cyclic diurnal wind speed pattern, with wind speeds peaking during and after the hottest parts of the day and then dying down during the nighttime.

5. METHODS

As discussed in the previous chapter, a detailed wind assessment requires an extensive wind prospecting effort to collect a year or more of reliable wind data. Since such efforts are time consuming and expensive, it is advisable to first make a preliminary assessment based on available data. A preliminary assessment not only determines whether further effort is warranted, but also locates regions of significant potential for further study.

The full preliminary wind resource assessment for Eritrea, of which this thesis was a part, involved a number of parallel efforts to identify promising wind resource locations, including:

- Analysis of wind flow patterns in and around Eritrea
- Identification and collection of wind data for Eritrea
- Preliminary wind speed analysis for Aseb and the Red Sea coast
- Correlation analysis of wind and temperature characteristics
- Ground search for promising wind sites and spot measurements

This paper describes the identification and collection of wind data for Eritrea and the ensuing wind speed analysis for Aseb and the Red Sea. For a discussion of parallel efforts not covered in this thesis, please refer to Van Buskirk, Garbesi and Rosen (1997), Yosief (1996) and Appendix B.

Identification and Collection of Wind Data

In the search for wind data, several potentially useful databases were found. Among them were direct surface observations, satellite derived wind data and assimilation products.^{*} The resolution (2-2.5 degrees) of the satellite derived wind data and assimilation products were insufficient for the purposes of this study. Therefore, this analysis uses only those data sets containing direct surface observations.

Four sources of direct surface wind information were found and analyzed: recent Eritrean station data, historical Italian station data, U.S. Air Force DATSAV2 surface records, and a climatic study of the Red Sea conducted by the U.S. Navy. These data sources are briefly described below. For detailed information on these and other databases investigated, see Appendix A.

Eritrean data (1994-1995). In 1994, the Eritrean Department of Water Resources began recording 15 minute wind speed averages at 7 stations located in towns and cities scattered throughout the highlands and western lowlands of Eritrea. Although less than one year of data was available for this study, rough (± 1 m/s) mean annual wind speeds were estimated and are summarized in Table 5.

^{*} An assimilation product is the result of an analysis of several databases. See Appendix A for a more detailed description of the assimilation product considered for this study.

Table 5. Approximate (± 1 m/s) mean annual wind speeds (MAWS) based on data recorded at seven stations in the Eritrean highlands and western lowlands

Station	Geographical Coordinates		MAWS (m/s)
Asmera	15° 17' N	38° 55' E	3
Filfil	15° 36' N	38° 57' E	1
Kerkebet	16° 18' N	37° 24' E	3
Omhajer	14° 20' N	36° 39' E	2
Shambiko	14° 57' N	37° 53' E	2
Sh'eb	15° 51' N	39° 03' E	2
Tsorena	14° 39' N	39° 13' E	2

Italian data (1930-1933). During the Italian occupation in the 1930's, daily average wind speeds were recorded at stations along the Italian-built railroad line from Mitsiwa'e to Keren in the Eritrean highlands. Mean annual wind speeds at four such stations are provided in Table 6.

Table 6. Mean annual wind speeds (MAWS) based on historical Italian data for four stations in the Eritrean highlands

Station	Geographical Coordinates		MAWS (m/s)
Asmera	15° 17' N	38° 55' E	2.7
Faghena	15° 10' N	39° 28' E	2.1
Keren	15° 46' N	38° 27' E	1.9
Mitsiwa'e	15° 37' N	39° 27' E	3.7

U.S. Air Force DATSAV2 data (1973-1992). Twenty years of DATSAV2 hourly meteorological records were available for several Eritrean cities, including Aseb (42° 43' E, 12° 58' N), for which a data set containing fourteen discontinuous years of observations (1977-80, 82-91) was obtained. The arithmetic mean of the 10-meter wind speeds in this data set indicated a mean annual wind speed of about 8 meters per second.

U.S. Navy Climatic Study of the Red Sea. A 1982 climatic study of the Red Sea conducted by Brower, Baldwin and Franks (1993) for the United States Navy mapped monthly mean wind speeds with 1 degree spatial resolution. For 7 of the 12 months (October through April), the report shows mean annual speeds of between 6 and 10 meters per second off the southern half of the Eritrean coastline. For the remaining months (May through September) the report indicates mean wind speeds of between 3 and 5 meters per second.

While these estimates suggest that wind resources in the highlands may be inadequate for utility-scale wind generation, one must keep in mind that the highland stations were not sited for wind prospecting purposes, and so are unlikely to have recorded the highest wind speeds in the region. Van Buskirk, Garbesi and Rosen (1997) argue that the channeling of wind through the hills and valleys of the highlands will create areas in which wind speeds are significantly enhanced. The Eritrean Department of Energy has been collecting additional wind data in the mountain passes near Asmera in an attempt to locate such sites. Estimates based on preliminary measurements indicate the existence of sites with mean annual wind speeds exceeding 5 meters per second.

Wind data obtained for Aseb and the Red Sea produced more promising results than did data for central Eritrea. The DATSAV2 data for Aseb indicated a mean annual wind speed of 8 meters per second, while the results of the Red Sea study by Brower, Baldwin and Franks (1993) indicated mean monthly wind speeds as high as 10 meters per second just off the southern coast. Although electricity demand in Eritrea is greatest in the central highlands, a more detailed study of winds in the Aseb area was conducted

because of the high wind speeds recorded there. Analyses of winds at two Aseb sites and of winds over the Red Sea are presented below.

Analysis of Wind Data for Aseb

This study analyzes the DATSAV2 hourly data for Aseb to provide the following estimates for two sites at Aseb:

- Mean seasonal and annual wind speeds
- Diurnal wind speed patterns
- Annual wind speed frequency distributions
- Theoretical capacity factors
- Wind power densities and wind power classes
- Annual wind direction frequency distributions

The Eritrean Civil Aviation Department maintains two meteorological stations at Aseb: one at the Airport about 10 kilometers northwest of Aseb, and one at the Seaport within the city.* The Airport is in a flat, open plain at 14 meters elevation, while the Seaport is at the shoreline, sheltered by buildings on the northwest side (see Figure 5).

* The DATSAV2 database did not indicate the existence of two separate stations. A dramatic change in mean annual wind speed and observation patterns late in 1986 alerted the author to the situation. The actual date was affirmed by a visit to the two stations and a review of the log books.

Figure 5. Map showing the Airport and Seaport meteorological stations at Aseb, where DATSAV2 data were recorded.

Data

The DATSAV2 data for Aseb consists of weather observations recorded by the Eritrean Civil Aviation Department. Wind speed values are human estimates calibrated to the standard 10 meter height, reported to the nearest meter per second. Until the end of

Ethiopian occupation in 1991, observations recorded every 3 hours were archived by the United States Air Force Environmental Technical Application Center (USAFETAC) in the DATSAV2 Surface Database^{*}. Observations reported before 1986 were taken at the Airport station, while observations reported after 1986 were taken at the Seaport station.

The National Climatic Data Center (NCDC) provided fourteen years (1977-80, 1982-91) of DATSAV2 surface observations for Aseb. Each yearly subset contained between 13% (367 records) and 42% (1229 records) of the possible number of discrete 3-hour observations. The database included date, time, position, wind speed, wind direction and other weather related observations (see Appendix A). After removing incomplete or otherwise inconsistent data records, over 5,000 observations remained for each station.

Division of Data. The DATSAV2 database was first divided into two subsets according to whether the observations were recorded at the Airport or the Seaport station. In addition, mean monthly wind speed and direction data presented in Brower, Baldwin and Franks (1993) were used to further divide each subset to correspond with the two monsoon seasons in Eritrea. From this point on, the five months from the beginning of May through the end of September will be referred to as the summer season, while the seven months from the beginning of October through the end of April will be referred to as the winter season.

The resulting four subsets were analyzed independently. A preliminary analysis of these four data subsets is presented in Table 7

^{*} As of 1998, weather observations continue at both Aseb stations, but are not reported to USAFTEC.

Table 7. Initial results of a statistical analysis of seasonal wind speeds in meters per second at the two Aseb stations

	Airport Summer	Airport Winter	Seaport Summer	Seaport Winter
N of observations	2593	3258	1899	3244
Minimum	0.0	0.0	0.0	0.0
Maximum	31.0	42.2	30.0	44.0
Arithmetic mean	7.7	12.1	4.8	9.1
Variance	18.3	25.0	13.1	20.8
Standard deviation	4.3	5.0	3.6	4.6
Standard Error	0.08	0.09	0.08	0.08
Skewness	0.26	0.14	0.92	0.21
Kurtosis	0.19	1.33	1.64	0.92

Although the number of observations did not differ significantly on a month to month basis, observations did vary on a daily basis. Midnight and early morning observations were comparatively few, and for the first eight years were practically non-existent. To compensate for the fact that more observations were made during the daytime when wind speeds are highest, the four data subsets were further divided into eight 3-hour bins. The resulting 32 data subsets were analyzed separately. Figure 6 illustrates the data divisions and the number of observations in each subset.

	Airport								Seaport							
	0	3	6	9	12	15	18	21	0	3	6	9	12	15	18	21
Summer	-	-	214	836	633	666	224	-	32	96	206	452	227	401	255	229
	0	3	6	9	12	15	18	21	0	3	6	9	12	15	18	21
Winter	-	-	320	1002	761	865	275	-	51	207	324	724	392	696	407	440

Figure 6. Division of DATSAV2 data for the two stations at Aseb

Because records for late evening and early morning hours were not recorded on a regular basis until after the observation site was moved to the Seaport, some 3-hour Airport data bins did not have sufficient data for analysis (minimum $N=30$). Of the sixteen data subsets for the Airport, six contained insufficient data for analysis: 21:00, 00:00 and 03:00 for each season.

Analysis

To estimate the nature of the missing data, we assumed similar wind regimes at the two stations, as they are separated by only about 10 kilometers of relatively flat, open land. To provide rough estimates of the empty data bins at the Airport, seasonal 3-hour wind speed averages and Weibull parameters for each station were calculated and graphed to determine correlations between the sites. This analysis is described in detail in the following sections.

Calculation of mean wind speeds. To estimate the mean annual wind speed at the Airport, it was necessary to approximate mean seasonal wind speeds for the 21:00, 0:00 and 3:00 data subsets. First, mean values were calculated for the Airport and Seaport data subsets that contained sufficient data, i.e. the data subsets including 6:00 through 18:00. These mean values were then graphed, with the mean seasonal 3-hour Airport wind speeds as the x-coordinate, and the mean seasonal 3-hour Seaport wind speeds as the y-coordinate. The resulting scatter plot is presented in Figure 7.

Figure 7. Correlation between wind speeds at the two Aseb stations

Using regression analysis, a linear correlation was derived between the time-correlated pairs of mean wind speeds at the two stations ($R^2 = 0.96$) as shown in Figure 7. Each of the three missing values for the two seasons were then calculated as $\mu_a = m \cdot \mu_s + b$, where μ_a and μ_s are the seasonal 3-hour mean wind speeds at the Airport and Seaport respectively, and $m = 1.043$, and $b = 2.179$ are the slope and y-intercept found in the regression analyses, respectively. The excellent correlation indicated by Figure 7 strongly supports the assumption that the Airport and Seaport stations have similar wind regimes.

Calculation of frequency distributions. To compensate for the uneven distribution of observations among the 3-hour bins, we planned to determine a frequency distribution for each subset, and then average the distributions to obtain the seasonal and

annual wind speed frequency distributions for each site. As described above, however, some 3-hour subsets for the Airport station contained insufficient data to calculate the wind speed frequency distributions. To estimate these distributions, we planned to calculate Weibull parameters for the subsets with sufficient data, and then use them to estimate the Weibull parameters for the subsets with insufficient data. From these estimated parameters, model distributions for these subsets could then be constructed.

At this point it became clear that the wind speed database for Aseb contained an unusually high frequency of observations where the wind speed was zero (calms). This presented a problem because the standard Weibull distribution does not allow for a wind speed of zero. To resolve this problem, we employed a method described by Mulugetta and Drake (1996) in which a Weibull distribution is fit to the observed frequency distribution above zero meters per second, and calms are considered separately. This method tends to provide a more conservative estimate of mean wind speed by assuming that the reported frequency of calms is correct, whereas the standard Weibull distribution assumes that the frequency of calms is zero.* This is particularly important in the case of the Aseb data, where the frequency of observed wind speeds commonly drops abruptly between zero and one meter per second, and then follows the expected Weibull distribution closely.

* In the study by Mulugetta and Drake (1996), wind speeds estimated using this three-parameter Weibull technique were within 5% of observed wind speed values for all wind speed intervals.

To the standard Weibull parameters of k and A is added a variable s denoting the frequency of calms. The equation of the non-cumulative, three-parameter Weibull distribution then becomes:

$$f_{\text{Weibull-3}}(v) = \begin{cases} s, & \text{at } v = 0 \\ (1-s) \cdot \frac{k \cdot v^{k-1}}{A^k} \cdot \exp\left[-\left(\frac{v}{A}\right)^k\right], & \text{for } v > 0, k > 0, A > 1 \end{cases} \quad (18)$$

such that $f_{\text{Weibull-3}}(v) \cdot dv$ is the fraction of time the wind speed is in a bin centered at v , with bin size dv .

For each season, this three-parameter Weibull model was fit to the wind speed frequency distributions for the 13 subsets containing sufficient data. A best fit was obtained by minimizing the sum of the squared differences between points on the observed frequency distribution and the Weibull distribution.

The three-parameters of k , A , and s were calculated for each subset. To determine correlations between the parameters at the two stations, points with the Airport parameters as the x-coordinate and the Seaport parameters as the y-coordinate were plotted as shown in Figure 8.

(a)

Figure 8. Scatter plots showing Weibull parameter correlations

As can be seen in Figure 8(a), the scatter plot of the k parameters found at the Aseb Airport and Seaport did not indicate a particularly good correlation. Therefore the seasonal averages of the k values at the Airport were used as the k values of the empty bins.* For both A and s , acceptable linear correlations were determined between the two stations. The missing values were then calculated as $y = m \cdot x + b$, where y and x are the parameters at the Airport and Seaport respectively, and m and b are the slopes and y -intercepts found in the regression analyses.

According to the three-parameter method, mean wind speeds can be calculated as (Mulugetta and Drake 1996):

$$MWS = (1 - s) \cdot A \cdot \Gamma\left(1 + \frac{1}{k}\right) \quad (19)$$

Seasonal wind speed frequency distributions for the Airport were calculated as the mean of the five observed and three estimated frequency distributions for each season. Seasonal wind speed frequency distributions at the Seaport were calculated as the mean of the eight observed frequency distributions.

Since the data were originally divided into a summer season of five months and a winter season of seven, annual distributions for each station were calculated as:

$$f_a(v) = \frac{5}{12}f_s(v) + \frac{7}{12}f_w(v) \quad (20)$$

where $f_a(v)$ is the annual wind speed frequency distribution, and $f_s(v)$ and $f_w(v)$ are the summer and winter wind speed frequency distributions, respectively. To summarize the

* Several methods were used to estimate k -values for the empty bins, including arithmetic averages, and linear and non-linear correlations. We chose to present the results obtained using the average k -value because, of the methods tested, it resulted in the most conservative estimate of mean wind speed.

wind regime at the two Aseb sites, a best-fit three-parameter Weibull distribution to the non-cumulative annual wind speed distribution, $f_a(v)$, was determined for each site.

Calculation of capacity factors. The calculation of capacity factor for this study is based on the Flowind AWT-27 wind turbine, which has a rotor diameter of 27 meters and a rated capacity (P_r) of 250 to 300 kilowatts. The power curve, $P(v)$, for the Flowind AWT-27 turbine is shown in Figure 9.

Figure 9. Graph showing $P(v)$, the power curve for the Flowind AWT-27 wind turbine

Wind power density, power output, and wind direction frequencies. Values for wind power density, potential power output and wind direction frequencies are calculated using Equations 15, 16 and 17, respectively.

Analysis of Wind Data for the Red Sea

An analysis of wind data over the Red Sea based on COADS is conducted as part of this study to provide seasonal and annual 0.1 degree resolution wind speed maps of the Red Sea. This is done to provide a reference against which qualitative estimates of wind potential along the southern Eritrean coastline can be derived based on the relationship between winds at Aseb and winds off the coast of Aseb.

Data

COADS is a global collection of instantaneous marine observations recorded between 1854 and 1993. The wind speed data recorded in COADS are based on the Beaufort scale, human estimates that relate marine surface roughness with wind speed. Wind speed records in the database are provided to the nearest knott.

COADS is available from the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. An electronic data file containing the portion of COADS bounded by 12°N 32°E and 30°N 44°E, was received in two files: the Compressed Marine Reports (CMR) and the Long Marine Reports (LMR). These two data sets differ in both time period and format. The earlier set (CMR) covers the period 1854-1969. The later set (LMR) covers the period from 1969 to 1993.

Due to insufficient spatial resolution in early observations, this analysis will utilize COADS data beginning in 1940. Until the 1930's, the majority of observations were reported to the nearest 1.0 degree. All observations recorded after 1940 were reported to the nearest 0.1 degree. After removing pre-1940 records and records with missing data, the database contained a combined total of over 650,000 observations.

Analysis

To compensate for uneven temporal sampling in the data set, the combined CMR/LMR database was divided into seasonal 6-hour bins, resulting in 8 data subsets. Mean wind speeds were calculated only for positions containing data in all 8 data subsets. For each of the 8 temporal data subsets, the arithmetic average of wind speeds in each 0.1 degree bin was calculated. The arithmetic averages of corresponding bins in the 4 winter and 4 summer data subsets were calculated to estimate seasonal wind speeds. For each corresponding bin in the two seasonal subsets, mean annual wind speeds were calculated as the sum of $\frac{5}{12}$ the summer average and $\frac{7}{12}$ the winter average.

6. RESULTS

The results of the analysis described in Chapter 5 are presented below.

Mean Wind Speeds

Results presented here represent wind speed values at 10 meters height; however, it is expected that wind speeds at typical turbine hub heights of 30 meters or more would be higher than those presented here (see *Vertical estimation of wind speed using the power-law model* in Chapter 3).

Table 8 summarizes the results of the analysis of DATSAV2 wind speed data. Values presented in Table 8 were calculated from observed wind speed data, with the exception of 21:00, 0:00 and 3:00 at the Airport. These values, printed in italics, were estimated as described in Chapter 5.

Table 8. Results of the analysis of DATSAV2 data, showing mean seasonal and annual 10-meter wind speeds (in m/s) for 3-hour periods at the Aseb stations.

Time	Airport			Seaport		
	Summer	Winter	Annual	Summer	Winter	Annual
6:00	3.6	7.8	6.0	2.1	5.8	4.3
9:00	6.0	11.2	9.0	3.8	8.0	6.2
12:00	8.9	13.1	11.3	5.6	10.2	8.3
15:00	9.3	13.6	11.8	6.2	10.8	8.9
18:00	8.8	11.8	10.5	6.1	10.6	8.7
21:00	<i>7.9</i>	<i>11.6</i>	<i>10.1</i>	5.2	9.2	7.5
0:00	<i>6.1</i>	<i>10.9</i>	<i>8.9</i>	3.9	8.4	6.5
3:00	<i>5.2</i>	<i>10.1</i>	<i>8.0</i>	3.2	7.6	5.8
Average	7.0	11.3	9.5	4.5	8.8	7.0

NOTE: Figures in italics represent values estimated by linear correlation between station wind speeds

Table 9 shows the parameters obtained using three-parameter Weibull fits to the observed seasonal 3-hour wind speed distributions as described in *Calculation of Frequency Distributions* in Chapter 5. Again, values for 21:00, 0:00 and 3:00 are estimated as described in Chapter 5. Mean wind speeds presented in Table 9 are based on Equation 19.

Table 9. Three-parameter Weibull parameters of k, A and s, and 10-meter wind speeds derived from those parameters, for seasonal 3-hour periods at the Aseb stations.

Time	Airport				Seaport			
	k	A	s (%)	MWS (m/s)	K	A	s (%)	MWS (m/s)
Summer								
6:00	2.1	6.6	0.41	3.5	2.0	3.8	0.49	1.7
9:00	1.9	7.5	0.10	6.0	2.0	4.5	0.21	3.2
12:00	2.9	9.8	0.00	8.7	2.2	6.1	0.07	5.0
15:00	2.7	10.3	0.00	9.2	2.2	6.7	0.02	5.8
18:00	3.2	10.0	0.00	8.9	2.0	6.9	0.05	5.8
21:00	2.6	8.7	0.06	7.3	2.0	5.6	0.10	4.5
0:00	2.6	8.1	0.11	6.4	2.1	4.8	0.16	3.6
3:00	2.6	7.9	0.25	5.2	2.3	4.5	0.32	2.7
Summer Average	2.3	8.8	0.12	6.9	2.0	5.5	0.18	4.0
Winter								
6:00	2.4	10.0	0.10	8.0	2.0	7.6	0.12	5.9
9:00	3.2	12.8	0.02	11.2	2.5	10.0	0.06	8.3
12:00	3.3	14.7	0.00	13.2	2.6	12.4	0.03	10.7
15:00	3.5	15.3	0.00	13.7	3.0	12.9	0.01	11.4
18:00	3.8	13.4	0.01	12.0	3.4	12.6	0.02	11.1
21:00	3.2	13.3	0.00	12.0	3.2	11.1	0.03	9.6
0:00	3.2	12.1	0.02	10.6	4.1	9.7	0.06	8.2
3:00	3.2	12.1	0.02	10.6	3.2	9.6	0.05	8.2
Winter Average	3.4	13.2	0.02	11.4	2.4	10.3	0.05	8.7
Annual Average	2.4	11.5	0.06	9.6	1.8	8.9	0.10	7.1

NOTE: Figures in italics represent values estimated by correlations between station Weibull parameters

The majority of mean seasonal 3-hour wind speed values estimated using the three-parameter Weibull method (Table 9) are within 2 percent of observed mean wind speeds (Table 8). The greatest difference between calculated values and observed values was 3.3 percent at 0:00 at the Seaport.

Figure 10 shows the mean diurnal wind speed variations at the Aseb stations. The higher wind speeds indicated at midday would increase power supplies during the peak demand period. Here, again, it is clear that the wind speeds at the two stations are closely related.

Figure 11 shows the three-parameter Weibull fits to the annual wind speed distributions at the two Aseb stations. In Figure 11(a), the "Observed" distribution at the Airport is the average of the 5 observed distributions and 3 predicted distributions as described in Chapter 5. The "Observed" distribution in Figure 11(b) is the arithmetic average of the 8 observed 3-hour distributions at the Seaport.

(a)

(b)

Figure 10. Graphs showing mean diurnal wind speed variations at the Aseb stations

(a)

(b)

Figure 11. Graphs showing three-parameter Weibull fits to the observed annual wind speed distributions at the Aseb Airport and Seaport

Figure 12 shows mean annual wind speeds in the Red Sea along the southern Eritrean coastline. According to these results, mean annual wind speeds over the southern Red Sea are in excess of 6 meters per second for about two hundred kilometers of the lower Eritrean coast. This suggests that wind sites with high wind power potential may be found along the entire length of the southern Eritrean coastline.

Figure 12. Map showing mean annual wind speeds along the southern Eritrean coastline

Projected Available Wind Power

Table 10 shows the estimated wind power densities, capacity factors, and projected energy output values calculated for the two Aseb stations. The calculations presented in Table 10 use the following assumptions:

Rotor diameter D:	20 meters
Average turbine spacing:	10D x 5D
Array and system efficiency:	75%

Table 10. Projected wind speed, power, and energy output at Aseb

	Airport		Seaport	
	10 m	30 m	10 m	30 m
Mean Annual Wind Speed (m/s)	9.5	11.1	7.0	8.2
Mean Annual Wind Power Density (W/m²)	905	1454	480	769
Capacity Factor (%)	54%	66%	35%	44%
Wind Power available per turbine (kW)		457		242
Electrical Power generated per turbine (kW)		226		80
Annual Energy Output per turbine (GWh)		2.0		0.7
Annual Energy Output per kilometer (GWh/km)		100		35

NOTE: Extrapolations to 30 meters are based on the 1/7 power law.

These values indicate that both stations qualify for the highest wind power class of 7.

A typical annual average wind power density for utility scale energy production is 450 W/m² at turbine hub height (Cavallo, Hock and Smith 1993). The wind power densities shown in Table 10 are high because of the very high wind speeds during the winter months at Aseb. It should be noted, however, that the wind power supply between May and September is expected to be considerably lower.

Wind Direction

Figure 13 shows seasonal wind roses based on the analysis of DATSAV2 data for the two Aseb stations.

Figure 13. Wind roses showing wind direction frequency distributions during the summer and winter monsoon seasons at Aseb

Once again, it can be seen that the winds at the two stations follow each other very closely. It is also noteworthy that the strong winter winds blow predominantly from the southeast. In areas with unidirectional or bi-directional winds, more efficient wind

turbine spacing may be possible as turbines may be erected closely together in a line perpendicular to the wind direction. As a result, the array efficiency of 75% assumed for this analysis may be an underestimation.

Limitations of Analysis

Any resource assessment based on meteorological data is only suggestive and serves merely as an indicator of a promising resource. Such estimates cannot be used as the basis of economic calculations for utility-scale power generation without extensive site-specific monitoring. For example, consider a site with an estimated annual average wind speed of 6 ± 1 m/s, implying that the average annual wind speed might be anywhere between 5 and 7 m/s. This corresponds to a factor of 2.7 difference in power. An error this large can make the difference between a wind site that is economical for energy production and one that is not. At Aseb, however, the estimated mean annual wind speed of 9.5 meters per second would be economical even if this value is off by 1 or even 2 meters per second.

There are reasons to believe that a study such as this would underestimate the wind resources of an area. Wind monitoring stations are typically found in towns or cities. Since people do not normally choose to live in areas with extremely high wind speeds, it is likely that there are sites with better wind resources. In addition, regional studies, such as the one presented here, show only large areas of high wind resource potential. The preliminary study may not detect a mountain pass, within an otherwise low

potential area, into which strong winds are regularly funneled. Such an area will likely be overlooked, even though it may be a very promising site.

Mathematical models may be the cause of inaccuracy. This is especially likely in regions such as Eritrea that have complex terrain (e.g. mountains) and wind flows (e.g. convective flows). Because mathematical models are less likely to be accurate when used in such areas, this study utilized such models minimally. However, use of the 1/7 power law (see *Wind Assessment* in Chapter 3), which assumes relatively flat terrain, was necessary to estimate wind power potential at the expected turbine hub height. Although the Aseb Airport is located on a flat plain at only 14 meters elevation, there is still some chance that the estimated 30-meter values presented in this chapter overestimate the true potential.

Most wind speeds presented in this study are based on human estimates. Although these estimates are given by experienced personnel, human estimates may not be as accurate as modern equipment, such as anemometers with automatic data loggers. In addition, wind speed values at the Aseb stations were recorded to the nearest meter per second, with the result that each observation had a possible error of ± 0.5 meter per second. Due to conversion from the Beaufort scale to knots to meters per second, wind speed estimates for the Red Sea may be off by as much as 2 meters per second or more. However, since the main focus of this study is Aseb, and the Red Sea analysis was done only for comparison, higher accuracy for the Red Sea results is not critical.

7. DISCUSSION

The data analysis presented here indicates that the mean annual wind speed at the Airport is about 9.5 m/s while the mean annual wind speed at the Seaport is about 7.0 m/s. We attribute this difference to the different levels of wind exposure at the two stations. The Airport is located outside the city and has excellent wind exposure, whereas the Seaport station is located in a developed area within the town.

Variability of Results Obtained Using Different Methods of Analysis

Before realizing that there were two stations at Aseb – a fact not indicated in the DATSAV2 data set – the annual average wind speed at Aseb appeared to be about 8 meters per second. This value compares favorably to the results obtained by Mulugetta and Drake (1996), who reported an observed mean annual wind speed of 8.1 meters per second and a predicted mean annual wind speed of 7.9 meters per second at Aseb.

After dividing the data set into Airport and Seaport station data, several other problems were encountered in finding an accurate estimation of mean annual wind speeds. In solving these problems, many different methods were utilized. Table 11 provides a summary of the Weibull parameters, mean annual wind speeds and wind power densities obtained using four different methods of data analysis.

Table 11. Results of different data analysis methods for the Aseb Airport and Seaport, showing Weibull parameters k and A, mean annual wind speeds (MAWS), and wind power densities (WPD), all at 10 meters height.

Method	Airport				Seaport			
	k	A	MAWS (m/s)	WPD (W/m ²)	k	A	MAWS (m/s)	WPD (W/m ²)
Unadjusted ^a			10.3				7.3	
Linear Correlation ^b			9.5	905			7.0	480
Three-parameter Weibull ^c	2.4	11.6	9.6	915	1.8	8.9	7.1	538
Standard Weibull ^d	2.5	11.7	10.4	1025	1.8	9.3	8.3	688

^a Unadjusted arithmetic mean of all data

^b Data divided into subsets as shown in Figure 6. Linear correlation between subset means used to estimate means for empty bins (see *Calculation of Mean Wind Speeds* in Chapter 5).

^c Data divided in to subsets as shown in Figure 6. Correlations between subset three-parameter Weibull parameters k, A, and s used to estimate k, A, and s for empty bins (see *Calculation of Frequency Distributions* in Chapter 5).

^d Data divided in to subsets as shown in Figure 6. Correlations between subset standard Weibull parameters k and A used to estimate k and A for empty bins.

It is interesting to note the significant difference in these results. As discussed in Chapter 5, inconsistent sampling methods favored the high wind speeds found during the daytime, resulting in the artificially high values listed after "Unadjusted." The standard Weibull fits to the adjusted wind speed distributions also produced higher values because they failed to recognize the high percentage of calms recorded at Aseb. The linear correlation and three-parameter Weibull fit methods used in this analysis resulted in more conservative, and presumably more accurate, mean annual wind speed values.

The disparity between values shown in Table 11 highlights the skepticism one must have when dealing with data records, particularly when the accuracy of the data cannot easily be confirmed. Based on these findings, it is recommended that any data set to be used for wind assessment be examined carefully before proceeding with analyses.

The other source of disparity is derived from the standard method of using the Weibull distribution to describe the wind speed frequency distribution at a given site. Based on the findings presented here, it seems that the Weibull distribution is not always a good representation of a wind regime. In particular, the Weibull distribution does not allow for a wind speed of zero, and may therefore overestimate wind speeds in certain regions. More research needs to be conducted on this subject to determine whether the high frequency of calms indicated by the DATSAV2 data for Aseb is a real phenomenon or an idiosyncrasy.

Cost of Wind Generated Electricity at Aseb

Because of the uncertainties in wind speeds, financing and other factors, cost estimates at this stage are highly unreliable. However, the cost of wind generated electricity at Aseb will almost certainly be lower than the current cost of electricity, which is generated from imported diesel fuel.

As noted previously, the California Energy Commission (1997) estimates that the cost of wind power at "good" sites is about 4.6 cents per kilowatt-hour. All else being equal, the cost of wind power at 4.6 cents is already less than the cost of diesel fuel at Aseb, which is about 6.5 cents per kilowatt-hour. Based on the unusually high mean annual wind speeds and capacity factors at Aseb, it is safe to assume that the cost of wind power would be even lower than 4.6 cents per kilowatt-hour.

8. CONCLUSIONS AND RECOMMENDATIONS

According to these results, the Eritrean coastline has an outstanding wind resource, particularly in the Aseb area. Of the two sites monitored at Aseb, the Aseb Airport site appears to be the more promising. Existing data sources indicate mean annual wind speeds of over 9 meters per second at the Aseb Airport, with a theoretical capacity factor exceeding 50%. These values indicate that Aseb could generate over 200 kilowatts for each 20-meter diameter turbine installed at 30 meters height.

Due to the plentiful and inexpensive land resources in the Aseb area, a wind farm using available land could generate far more power than the current demand in the entire country. Without storage, Aseb could integrate only about 3 megawatts of wind power into the existing power grid (Van Buskirk 1997). Options for transmitting power generated at an Aseb wind farm to the more populated areas near Asmera are currently being investigated.

There are several factors that might justify Eritrea taking a relatively advanced position regarding wind energy development. First and foremost, Eritrea has some unquestionably favorable wind resources. The analysis presented here indicates that there are unusually high wind speeds along the southern coast. Other good sites have been found in highland passes in central Eritrea (see Appendix B). In addition, some of the physical properties of the wind flows at these sites increase its potential value. These include a highly periodic wind pattern with low variability and a positive correlation between wind power availability and electricity demand in the highlands.

Wind energy in Eritrea is an economically attractive option. In economically advanced nations, the main constraint on wind energy development is the competition from natural gas generators (Grubb and Meyer 1993). This is not the case in Eritrea. Because of the high capital costs of transportation and distribution facilities for natural gas, such generators are not expected to be an option for Eritrea within the next decade at least. In addition, diesel-generated electricity costs 6.5 cents per kilowatt-hour, while electricity generated at good wind sites should be significantly less expensive.

Currently, Eritrea's economic development is constrained by the lack of long-term investment capital. Due to international concern about global carbon emissions, wind energy development is likely to provide access to grants or loans at subsidized interest rates that otherwise would not be available for electricity development. Also, since energy supply is one of the main constraints on national economic development, such investments would increase the pace of national reconstruction, further improving the economic situation in Eritrea.

Finally, Eritrea has already taken steps to perform an evaluation of wind resources. A major constraint on wind energy development is the wind resource assessment (Grubb and Meyer 1993), while lack of expertise is another major barrier in developing countries. This work, along with current monitoring activities and other work examining institutional barriers in Eritrea, are rapidly removing these impediments.

Due to these unusually favorable factors for Eritrean wind energy development, it may be to Eritrea's advantage to plan a relatively high level of wind power penetration for

the energy sector. What remain are questions involving the technical, economic and physical feasibility of wind energy development in the Eritrean context.

Potential Problems

In developing wind power for the electric grid in Eritrea, the primary considerations are economic. Currently, only the southern coastal region of Eritrea has been shown highly promising for wind energy development. Yet the main electricity load in Eritrea is currently in the central highlands region. Therefore, for extensive wind power development, either economical wind sites closer to the load center in the Eritrean highlands must be found, or transmission from the southern coast to Mitsiwa'e needs to be considered.

The main factors constraining Aseb wind power development are the relatively low demand and small size of the existing grid. Since the combined capacity of the Aseb power system is currently about 17 megawatts, the Aseb utility could accommodate only about 3 megawatts of wind. Due to the abundant wind resource at Aseb, this could easily be supplied by between 5 and 10 small to medium size turbines.

Another problem with the wind resource at Aseb is that the peak supply is in the winter, while the peak demand is in the summer. One plan that would both further exploit the wind resource and level the seasonal loads is a cooperative effort with Ethiopia, in which winter wind power from Aseb is traded for summer hydropower from the Blue Nile region. However, this option may no longer be feasible because of recent political conflict between the two countries.

Another option for distributing excess supply may be to connect the power system at Aseb to the national grid in the central highlands. Although this option is preferable in many respects, construction of transmission lines along the 500 km route may be prohibitively expensive and power losses unacceptably high. It may be possible, however, to find high-quality coastal wind power sites that are closer to the central grid.

Future Work

Based on the promising results obtained from this preliminary resource assessment, wind power could be an attractive future source of energy for Eritrea. To realize this potential, the following work needs to be pursued:

Complete the Physical Resource Assessment

Procedures adhering to international sampling standards for station monitoring and maintenance need to be developed and a data processing and distribution system needs to be established and institutionalized. Wind site prospecting should continue, with considerations for factors such as ease of access, distance to transmission and distribution facilities, logistical impediments to maintenance and technical support, land use and land availability, security, and local community reactions. The completed physical resource assessment should result in the identification of several candidate sites for future pilot projects. Progress is occurring on several of these fronts.

Since 1996, the Eritrean Department of Energy has been conducting a wind prospecting and wind survey program that has employed a variety of tactics to find and

evaluate wind energy sites with high potential. Preliminary results of this program are provided in Appendix B. Although these spot measurements were not conducted as part of this thesis work, the results are linked to this study through the collaborative effort and are included for completeness.

Further funding for the coastal component of this assessment has been procured from the Global Environment Facility (GEF), a joint program between the United Nations Development Program (UNDP), the United Nations Environment Program (UNEP) and the World Bank. This new project will include dedicated on-site monitoring, the results of which are expected in 1999.

Improve the Aseb power system

For full exploitation of the wind energy potential at Aseb, measures need to be taken to increase the reliability of the city power distribution system (Van Buskirk 1997). Although wind prospecting continues in the Eritrean highlands, further investigation into power transmission from Aseb to the highland is also warranted.

Implement pilot projects

One or more pilot projects should be implemented to demonstrate feasibility and to develop skills. A pilot project of this scale requires careful preparation and planning in order to be successful. Essential components in pilot project formulation and implementation include: cost and performance data from wind turbine manufacturers; information about current electricity generation; preliminary and final project designs; project evaluation criteria; financing options; operational procedures; and project staff

training. The final decision on pilot project implementation is dependent on site assessment completion; however, as site evaluation awaits the year of data collection, pilot project formulation can proceed simultaneously. It is unclear at this point whether the GEF funded project described above will include pilot projects.

Conduct a thorough economic assessment of wind power integration

Wind data collected in the prospecting effort should be used to perform a detailed economic evaluation of wind power at each site. Prior to the availability of such data, any economic predictions are highly speculative.

Initiate a joint utility and government plan for wind development

Given the successful outcome of the previous stages, the government and utility can initiate an orderly plan and institute appropriate institutional mechanisms for the development of wind resources in Eritrea. Issues to be settled include: wind energy development priorities and policy goals; evaluation of wind power based on comparisons with competing fuel options; incorporation of environmental and energy security concerns; reliability; technical requirements; and social acceptability. In addition, possible institutional barriers of wind energy development in Eritrea should be considered.

If these steps are actively pursued, Eritrea will soon be in a good position to take advantage of its indigenous wind energy resources in an effective manner.

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APPENDIX A: DATA RESOURCES

Eritrean Department of Water Resources Data

Source:	Hydrometeorological Services Unit of the Water Resources Department Of the Ministry of Mines, Energy, and Water Resources
Sensor:	Weather stations
Coverage	
Spatial:	Asmara, Shambuko, Fil-Fil, She'eb, Om Hajer, and Tzerona
Temporal:	April 1994 to present, 15 minute averages
Wind Data:	Speed, Direction
Height:	3m
Other data:	Temperature, Solar radiation, Relative humidity
Medium:	Diskette
Form:	ASCII
Cost:	Free

DATSAV2 Surface Observations

Source:	National Climatic Data Center US Air Force DATSAV2 Surface Observations (TD9950) Air Weather Service Global Climatology Division, Federal Climate Complex
Sensor:	Weather stations
Coverage	
Spatial:	Global
Temporal:	May 1973 to present, Hourly averages
Wind Data:	Speed, Direction
Height:	10m
Other data:	Temperature Max temperature Dew Point Min Temperature Sea level pressure Precipitation Station pressure Snow depth Visibility fog, rain, snow, hail, thunder, or tornado
Medium:	8 mm tape
Form:	ASCII
Cost:	\$20 per year per station (discount for whole countries)

Global Surface Summary of Day Data

Source: National Climatic Data Center
US Air Force DATSAV2 Surface Observations (TD9950)
Air Weather Service Global Climatology Division, Federal
Climate Complex

Sensor: Weather stations

Coverage

Spatial: Global

Temporal: March 1994 to present, Daily averages

Wind Data: Speed, Maximum sustained speed, Maximum gust

Height: 10m

Other data: Temperature Max temperature
Dew Point Min Temperature
Sea level pressure Precipitation
Station pressure Snow depth
Visibility fog, rain, snow, hail, thunder, or tornado

Medium: Internet accessible electronic documents

Form: ASCII

Cost: Free

Comprehensive Ocean-Atmosphere Data Set (COADS)

Source: National Center for Atmospheric Research (NCAR)

Sensor: Ships and buoys

Coverage

Spatial: Global (water surfaces only), 0.1 x 0.1 degree

Temporal: 1854 to the present, Hourly

Wind data: Speed, Direction

Medium: 8mm tapes

Form: UNIX Tar

Size: One month is approximately 350 MB

Cost: Free

ERS-1 AMI Scatterometer Value Added Wind Vectors

Source: NASA Jet Propulsion Laboratory PODAAC (Product 045)
The original ERS-1 data files are unavailable to the public

Sensor: ERS-1 AMI scatterometer

Coverage

Spatial: Global (water surfaces only), 25 x 25 km

Temporal:	January 1992 to the present
Wind data:	Speed, Direction
Medium:	8mm tapes
Form:	UNIX Tar
Size:	One month is approximately 350 MB
Cost:	Free

SSM/I Wentz Geophysical Products

Source:	NASA Jet Propulsion Laboratory PODAAC SSM/I Pathfinder daily HDF Antenna Temperature (TA) files Produced by the Marshall Space Flight Center (MSFC)
Sensor:	SSM/I (Special Sensor Microwave Imager) instrument on the DMSP F-8 and F-10 satellites
Coverage	
Spatial:	Global (water surfaces only), 24 x 24 km
Temporal:	July 1987 to December 1992 (14.1 revolutions per day)
Wind data:	Speed
Height:	19.5m
Medium:	8mm tape
Form:	HDF
Size:	One month is approximately 1 GB
Cost:	Free

NASA/Goddard Earth Observing System Data Assimilation System

Source:	NASA/Goddard Space Flight Center
Sensor:	Global data assimilation system which utilizes ship and buoy sea level pressure and surface wind estimates to produce a surface wind analysis over water. Only sea level pressure observations are used over land. An upper air height and wind analysis is performed using height and wind information from rawinsonde ascents, cloud track winds, and satellite height data.
Coverage	
Spatial:	Global, 2 x 2.5 degrees
Temporal:	1 Mar 85 through 1 Oct 93, Monthly averages
Wind data:	Speed, Direction
Height:	2m and 10m winds available
Medium:	Internet accessible electronic documents
Form:	ASCII; GrADS
Size:	One month is approximately 5 MB
Cost:	Free

Navy Regional Climatic Study of the Red Sea and Adjacent Waters

Source:	National Climatic Data Center Naval Oceanography Command Detachment, Asheville, N.C.
Sensor:	Ships, buoys
Coverage	
Spatial:	Red Sea area, 1 x 1 degree
Temporal:	Monthly averages (based on 40 years data)
Wind data:	Speed, Direction
Height:	10m
Medium:	Bound report, 252 pages
Form:	Wind roses and isopleths
Cost:	\$40

USGS 30 arc-second Digital Elevation Map of Africa

Source:	United States Geological Survey (created from the Defense Mapping Agency's Operational Navigation Chart series)
Coverage:	Africa, 30 arc-second grids (about one square km)
Medium:	8mm tape, Internet accessible electronic document
Form:	16-bit straight raster image files in a latitude/longitude coordinate system
Size:	200 MB (can be obtained as four separate 50 MB blocks)
Cost:	Free

African Data Sampler

Source:	World Resources Institute, Washington D.C. (created from the Defense Mapping Agency's Operational Navigation Chart series)
Coverage:	Eritrea 1993 (entire continent of Africa available) 30 arc-second grids (about one square km)
Data:	Topography, Vegetation, Lakes and rivers, Infrastructure (cities, roads, utility lines, etc.)
Medium:	Diskette
Form:	PC ArcView format
Size:	about 2 MB
Cost:	\$50

APPENDIX B: PRELIMINARY SPOT MEASUREMENT RESULTS

Since 1996 the Eritrean Department of Energy has been conducting a wind prospecting and wind survey program that has employed a variety of tactics to find and evaluate wind energy sites with high potential. This program has included occasional spot measurements at a variety of locations both in the Eritrean highlands and along the coast. Some sites have been visited only occasionally due to either their remote location, or lack of promise, while for other sites nearly continuous monitoring has begun. The locations subject to spot measurements are described in the Table B1.

Table B1. Results of the Eritrean Department of Energy spot measurements

Name	Latitude	Longitude	MAWS (m/s)
Highland Sites			
Adi Tekelezan (hill)	15° 35' N	38° 45' E	~5
Debresina (pass)	15° 44' N	38° 43' E	5.5
Dekemhare (pass)	15° 04' N	39° 04' E	~4.5
Ma'ereba	15° 02' N	39° 08' E	~4
Nefasit (pass)	15° 21' N	39° 03' E	~3
Wara (hill)	15° 37' N	38° 47' E	5.0
Coastal Sites			
Aseb Telecom (@ 40m & hill)	13° 02' N	42° 40' E	9.5
Rahayta	12° 44' N	43° 09' E	7.8
Salasegna (hill)	13° 04' N	42° 43' E	8.2
Saroyta	14° 25' N	41° 19' E	~7
Tio	14° 40' N	40° 57' E	~6

Of these sites, most have been visited only occasionally. Very approximate estimates of mean annual wind speeds are indicated by the '~' sign. These values are

usually determined by comparison with wind speeds at Asmera where the mean wind annual wind speed is measured to be 3 m/s at 10 m height. Unless indicated otherwise, the sites are flat, and measurements are at 10 m height.

Several sites have had wind odometers installed, including Debresina, Wara, Aseb Telecommunications Tower, Rahayta, and Salasegna. For those sites, more precise estimates can be made based on measurements taken from June 1997 to January 1998. To make these estimates, the months are grouped into a summer monsoon season and a winter monsoon season. Averages are taken for each of the monsoon seasons, and a weighted average of the monsoon averages is used to estimate the mean annual wind speed. These measurements indicated that sites with mean annual wind speeds of above 5.5 m/s at 10 meters can be found in highland passes where there is channeling of the monsoon winds. This indicates that there are probably sites with mean speeds of 6-7.5 m/s at turbine hub heights of 30 meters, and that feasible sites for utility-scale wind power development may exist at selected locations in the Eritrean Highlands.

IMAGE EVALUATION TEST TARGET (QA-3)

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989

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