AIRBORNE WIND ENERGY:

IMPLEMENTATION AND DESIGN FOR THE U.S. AIR FORCE

THESIS

Troy L. Cahoon, BSE
Captain, USAF

AFIT/GAE/ENY/11-M04

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Troy L. Cahoon, BSE

Captain, USAF

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Troy L. Cahoon, BSE

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Approved:

______________________________________ _________
Frederick G. Harmon, Lt Col, USAF (Chairman) Date

______________________________________ _________
Dr. Mark F. Reeder, AFIT (Member) Date

______________________________________ _________
Dr. James A. Menart, Wright State University (Member) Date

AFIT/GAE/ENY/11-M04

Abstract

Excitement among researchers about Airborne Wind Energy (AWE) technology matches DoD aims to advance and employ renewable energy. AWE seeks to cost-effectively tap the vast supply of wind energy available at altitudes high above the reach of conventional, ground-based wind turbines (e.g. 500-12,000 m). This paper explores the viability and implementation of AWE technology for fulfilling USAF energy needs. The characteristics, potential, and developmental status of the AWE resource are presented. A design tool for a rotor-based AWE system is developed, facilitating the analysis of blade performance to simplify design and provide the best efficiencies for a range of conditions. USAF bases are evaluated based upon energy needs, design requirements, and other factors to determine which bases could benefit most from AWE. Bases most viable for an AWE project, with 75% potential savings on energy costs per base (up to $40M annually for larger bases), are: Tinker, Vance, Wright-Patterson, Arnold, Ellsworth, and Grand Forks. Key results reveal it is possible to achieve notable benefits for the USAF using AWE technology.

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List of Abbreviations

AFB	Air Force Base
AFIT	Air Force Institute of Technology
AFRL	Air Force Research Labs
AWE	Airborne Wind Energy
DoD	Department of Defense
FAA	Federal Aviation Administration
FEG	Flying Electric Generator
OSD	Office of the Secretary of Defense
RPM	Rotations per Minute
U.S.	United States
USAF	United States Air Force
WPAFB	Wright-Patterson Air Force Base
Wright-Patt	Wright-Patterson Air Force Base

Nomenclature

Symbol	Description (Units)
a	Axial induction factor (m^2)
a'	Angular induction factor (m^2)
A	Area (m^2)
A_{eff}	Effective area (m^2)
B	Number of blades
c	Chord length
C_d	Coefficient of drag
C_l	Coefficient of lift
C_p	Coefficient of power
C_T	Coefficient of thrust
D	Diameter of blade
D_h	Hub diameter of rotor
f	Frequency
F	Tip loss factor
g	Gravity (m/s^2)
h	Altitude (m)
i	Current (A)
I_R	Generator rotor current (A)
I_s	Generator stator current (A)
J	Advance ratio
l	Length of blade
l_s	Length of blade station
L_{apse}	Lapse rate (K/m)
L	Lift force (N)
m	Mass (kg)
M	Mach number
M_{air}	Molar mass of dry air (kg/mol)

n	Rotational speed
N	Number of blade stations
n_s	Generator synchronous speed
P	Power (W)
P_{gin}	Mechanical power input into generator (W)
P_{gout}	Generator power output (W)
$P_{mechloss}$	Mechanical power losses (W)
P_o	Sea level pressure (Pa)
P_{oles}	Number of generator poles
P_{rout}	Generator rotor power output (W)
P_{wind}	Power available in the wind (W)
Q	Torque (Nm)
r	Blade station radius (m)
R	Rotor radius (m)
Re	Reynolds number
R_R	Resistance in generator rotor (Ω)
R_s	Resistance in generator stator (Ω)
R_u	Universal gas constant (J/mol-K)
S	Slip of generator
T	Thrust (N)
T_o	Sea level standard temperature (K)
$T_{Vertical}$	Vertical component of thrust (N)
U	Wind velocity (m/s)
U_{rel}	Relative wind velocity (m/s)
v	Voltage (V)
V_s	Speed of sound (m/s)
W	Weight (N)
α	Angle of attack
ΔA_{bs}	Blade station swept area
ΔC_p	Blade station power coefficient

ΔC_{Tr}	Blade station local coefficient of thrust
$\Delta \lambda_r$	Blade station tip speed ratio
η	Efficiency
η_{gen}	Electric motor efficiency
η_{mech}	Mechanical efficiency
η_{prop}	Propeller efficiency
η_{rot}	Wind-rotor efficiency
γ	Specific heat ratio for air
λ	Tip speed ratio
$\lambda_{maxPower}$	Maximum power tip speed ratio
μ	Dynamic viscosity
μ_o	Reference air viscosity (kg/m-s)
ω	Wake rotational speed (rad/s)
Ω	Blade rotational speed (rad/s)
φ	Angle of relative wind
ρ	Density (kg/m^3)
σ'	Local solidity
θ	Rotor axis angle
θ_p	Section pitch angle
$\theta_{p,o}$	Blade pitch angle
θ_T	Section twist angle
θ_{Troot}	Total twist angle at blade root
$\%A$	Blade station percent of total blade swept area
$\%C_p$	Blade station percent of total power contribution

AIRBORNE WIND ENERGY:
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I. Introduction

1. Background

Since the 1980's, the United States' Department of Defense (DoD) has had pressure put upon them to shift away from oil-based energies. Now, Congress and the White House are demanding an even more efficient use of energy to reduce the nation's reliance on imported oil. Specifically, The Defense Authorization Act of 2007 calls for no less than 25% of DoD total energy needs to come from renewable sources by the year 2025. "If the DoD were a state, it would rank between the 35th and 36th largest states, based on total electricity consumption." [1] The DoD is indeed under realistic demands to come up with viable renewable energy solutions.[1]

There are several key points that drive the need for the DoD to invest in renewable energy. These driving factors fall into three categories: security, economics, and the environment. Addressing security, it is important to diversify the U.S. energy supply, reduce or eliminate U.S. dependence on foreign sources of oil, and eliminate vulnerabilities in U.S. supply lines for fuel. Economic driving factors include the need to reduce costs of energy and make energy available in remote areas. Environmental interests incorporate the desire to lead the world in developing clean energy while exploring renewable energy sources to the point that these resources can sustain the country and the world.[2]

Diversifying our energy supply is important so that the U.S. will be less vulnerable to energy politics and shortages. "We must transform the way we use energy—diversifying supplies, investing in innovation, and deploying clean energy technologies. By doing so, we will enhance energy security, create jobs, and fight climate change."[2] Having a diverse energy supply will ensure that there is no single point of failure in the country's energy.

As long as the U.S. is dependent on other countries for energy, the threat of one or multiple countries boycotting or withholding resources from the country exists; realistically, the fight for energy could create a disastrous situation for the U.S. Consequently, the government and DoD are well aware of how energy affects our economy. The 2010 National Security Strategy states:

> Meanwhile, the nation that leads the world in building a clean energy economy will enjoy a substantial economic and security advantage. That is why the Administration is investing heavily in research…promoting developments in energy, and expanding international cooperation. As long as we are dependent on fossil fuels, we need to ensure the security and free flow of global energy resources. But without significant and timely adjustments, our energy dependence will continue to undermine our security and prosperity. This will leave us vulnerable to energy supply disruptions and manipulation….[2]

Oil is the largest energy concern for the U.S., with about 60% of its oil being imported from other countries.[3] Oil is such an intrinsic part of U.S. energy needs…could the U.S. imagine life without oil? Many products including gasoline, lubricants, plastic, and paints are each made from oil. The country would come to a screeching halt in a matter of weeks if oil supplies were cut off, since the U.S. economy is set up to be so dependent upon oil and its daily use.

Decreasing dependence upon oil would simultaneously benefit the DoD by eliminating vulnerabilities in its supply line: "The generation, storage, and distribution of energy on the battlefield have always been essential to sustaining military operations."[4] A recent study indicated that 70% of convoys in Iraq were for transporting fuel; these fuel supply lines continue to be potential, visible targets for enemy combatants. A goal of military logisticians could be to reduce that vulnerability by bringing actual sources of energy with them, not just generators that need continual refueling.[4]

Another aspect of U.S. energy that applies directly to the DoD is the need to use energy that pre-exists and is available in remote areas. On many levels, it would be most beneficial to the DoD (saving time, money, and resources) if they could bring with them some method to harness energy from resources that are available locally, at the remote location. High-altitude wind power is one possible resource, available at virtually all locations across the globe. This energy supply would be perfect for the military to use because they often find themselves deploying to locations with un-established or inadequate infrastructures for bringing in fuel and energy.

The DoD recognizes the importance for the U.S. to lead the world in developing clean energy: "The United States has a window of opportunity to lead in the development of clean energy technology. If successful, the United States will lead in this new Industrial Revolution in clean energy that will be a major contributor to our economic prosperity."[2] The security of the U.S. is dependent upon the economy of the country. Therefore, it is important that the U.S. lead economically to support a secure nation and continue to endorse security for the world. The DoD requires the means to accomplish the U.S. national security strategy, implementing anything the country needs to do, and developing clean energy is vital to doing this.

Exploring renewable energy sources to the point that they can sustain the country and the world is the only way that 25% of DoD needs will be met by the year 2025.[1] This must be done by finding innovative ways to make renewable energy sources, such as wind power and solar power, competitive economically with traditional energy sources such as coal, oil, and natural gas. If the U.S. has already made the transition to using renewables, sustaining the country will be possible because renewable energy *is* renewable—the U.S. will no longer have to worry about the depletion of fossil fuels, and can set other developmental and security goals.

2. Motivation

The DoD's mission to reduce dependence on imported oil makes exploring Airborne Wind Energy (AWE) a timely idea for helping to realize these goals. Just in recent years, harnessing wind power has started to come into maturity with technology so that it can now be a competitive energy. Wind power developed in several areas before even being considered a useful source of energy to the U.S. Developments included creating and enhancing the technology for efficient wind energy conversion, researching and forming materials (like carbon fiber blades), and improving wind power reliability while reducing maintenance costs. In 1981, the low reliability of wind turbines led to under 20% operational availability for these turbines in the U.S. But in a short amount of time, wind turbines managed to increase their availability up to the high 90th percentile.[5]

However, now that ground-based wind power is reaching a peak and advancements are leveling off, it has become difficult to significantly improve the cost-effectiveness of wind power unless someone makes a new leap in the technological approach used to harness wind energy. One innovative way to make a new leap in wind power technology would be to encourage the DoD to look into, and use, the winds at higher altitudes, where vastly more energy is available. Ground-based wind power has proven that it can be competitive with other energy sources when the price of energy is high. However, if the technology of AWE is advanced to the point where it is cost-effective and competitive at *any* energy price, then this would greatly benefit the DoD, citizens, utilities, and the U.S. Thus, the future of the country is dependent on utilizing and enhancing such resources as AWE technology.

Airborne Wind Energy has many interesting attributes that could lead to a potential solution for many of the energy issues that the U.S. faces. AWE is a means to have energy on demand at a remote location, without dependence upon a supply line. AWE is available almost everywhere in the entire world. The leap and potential for energy availability, and the consistency at which this energy can be tapped, is very far-reaching. It is possible that continued development in technology for wind power could push this energy into being fully competitive with fossil fuels. This source of energy could do wonders for the U.S. economy and domestic energy security. AWE has the ability to supplant traditional energy sources on its own, without subsidy. And streamlined AWE could meet all of the DoD's national security goals described.

3. Problem Statement

Since the desire to develop renewable energy is so vital to the United States for the security of the nation economically and militarily, this thesis explores the potential, implementation, and viability of AWE technology for fulfilling DoD needs, specifically those of the USAF.

4. Research Objective

The "DoD faces three key challenges in meeting the renewable energy goals. First, renewable energy projects may sometimes be incompatible with installation's need to use land for primary mission objectives…Second, renewable energy is often more expensive than nonrenewable energy…Third…the use of private sector approaches can be constrained…By addressing these challenges, DoD would strengthen its ability to fully realize the potential of its renewable energy resources, improving its chances of meeting the goals in the most cost effective way."[6] This research will work towards overcoming these DoD challenges for using renewable energy by advancing AWE technology. The thesis will build on the AWE research that has already been done by civilian researchers so that it may be utilized by the DoD.

The specific objectives of this research are, first, to increase the awareness of AWE technology and the potential benefits that it could provide for the USAF and for the DoD. Second, to advance the AWE technology with the development of a design tool that can be used to develop a rotor-based AWE system to efficiently harness wind energy to meet the renewable energy goals of the Department of Defense. Third, to conduct feasibility study to evaluate which USAF bases would provide the best chance for successfully implementing an AWE project. Combining the results of the second and third objectives will also provide some insights on the potential energy production and benefits that an AWE system can provide for the best USAF base candidates.

5. Research Scope

This research focuses on the potential benefits of AWE for the USAF, as well as on the aerodynamics and performance of an AWE system. The scope of the research does not include a detailed structural analysis of an AWE system. A detailed design of the controls and other subsystems of an AWE system will also be left for future research.

6. Methodology

The development and the current status of AWE technology were reviewed, to include exploration of the potential advantages of the AWE wind resource and the challenges AWE presents. In addition, some of the main concepts currently being pursued by researchers and industry for harvesting AWE were examined.

The methodology of this paper focuses on the achievement of two main objectives: to realize the best power production and efficiency for an AWE system, and to identify critical USAF base candidates that would benefit the DoD most from AWE. To accomplish the first objective, a design tool was created that would technically analyze and compare an idealized wind turbine rotor blade to more simplified versions, and then enable a comparison of the performance of the different blade designs. Sample results are produced using the design tool, and these results are then analyzed for trends that can help designers achieve the best balance of performance, reliability, and cost in the AWE systems they design. Then, in order to realize the second objective, a USAF base AWE feasibility decision matrix was created. The decision matrix provides a standard tool used to evaluate and compare which USAF bases are most feasible and likely to succeed using AWE projects to accomplish the energy needs of the DoD while fulfilling the goals of the National Security Strategy.[2]

Finally, the energy requirements of the USAF base locations that were discovered to be the best suited for AWE projects were analyzed. For each of the best base locations, basic estimates for AWE system efficiency, performance, and design requirements were produced and are presented.

7. Thesis Overview

Chapter II of this thesis reviews applicable theory from influential research and contemporary literature. Chapter III discusses the specific methodology used to accomplish the research objectives. Chapter IV provides results from the design tool, and presents analysis of the research. Chapter V relates conclusions drawn from the analysis, and makes recommendations for future AWE research.

II. Literature Review

1. Chapter Overview

People across the world are working on innovative solutions to the never-ending quest for cheaper and cleaner energy. One promising solution that could fit the cheaper and cleaner categories is wind power. The advantages of wind power include: wind is clean, wind has no emissions, wind is locally available, wind is domestically sustainable, and the land around wind turbines is usable. There have been significant improvements in the efficiency and reliability of wind power technology in recent years. It is important for this thesis to study the evolution of and innovations that have occurred in the field of wind power. This history will provide a foundation of knowledge that can be built upon as an AWE system is created.

Some researchers are currently studying the possibility of utilizing the higher wind speeds at altitudes higher than ground-based wind turbines can reach. The idea of harnessing Airborne Wind Energy is not new. There has been considerable research done, dating back to the 1970's. There is also an Airborne Wind Energy Consortium,[7] which holds a yearly conference,[8] where researchers and interested investors come together to make connections and share innovative ideas for advancing AWE systems. Several researchers have built and tested AWE prototypes, and in some cases are close to AWE system production.[9-11]

Tapping into these higher altitude winds will have many advantages and challenges—this chapter will discuss four main aspects of this research. First, the characteristics of the high-altitude wind resource are explored. Next, some of the advantages and challenges related to accessing this high-altitude power are discussed. Then, three of the current implementation concepts for harvesting AWE will be described, compared, and contrasted. Finally, the main components that will be used in the AWE system, like the generator and rotors, are investigated. Understanding these components will help to fulfill the thesis goals to build an AWE design tool and analyze the feasibility of using an AWE system to meet the energy needs of the DoD on an U.S. Air Force base.

2. Characteristics of the Airborne Wind Energy Resource

2.1. Power in Wind

The most important part to exploiting the wind's power is first understanding the wind resource and how much energy it offers. The equation for power available in wind (Equation 1) is given in *Wind Power Explained*:[5]

$$P = \frac{1}{2}\rho A U^3 \quad (1)$$

Where ρ is the air density, A is the cross-sectional area of the wind being considered, and U is the wind speed. The important features of this equation, when comparing wind power harvesting on the ground with wind harvesting at higher altitudes, are density and wind velocity. Air density decreases with increased altitude. Wind velocity tends to increase with altitude. The wind power equation shows that wind speed is *extremely* important to the amount of power produced because power is a function of wind velocity cubed. The magnitude of this effect is seen when considering that if wind speed is doubled, this results in eight times more power ($2^3 = 8$)! This large dependence on wind speed is the driving factor for many as they attempt to increase wind power production by seeking to tap the winds at higher altitudes.[5]

The reduction in power due to the density drop with altitude also needs to be considered. Wind power generation is regarded as high-altitude at altitudes above what can normally be harvested by a ground-based wind turbine. Common large-scale wind turbines are about 80 m in tower height, so Airborne Wind Energy can be from about 200 m to about 16,000 m. Jet streams tend to be the strongest between 6,000 m and 12,000 m. The density of air drops from 1.224 kg/m^3 at sea level to 0.413 kg/m^3 at 10,000 m. This density (at 10,000 m) is a third of the sea level density; thus, the power produced at a given wind speed at 10,000 m would be a third of the power produced by the same wind turbine at sea level. The change in density is approximately linear with altitude. So, at lower altitudes the effect of density changes with altitude is fairly small. At 1,000 m, the density drops to 1.111 kg/m^3; which is only a reduction of 9% from the density at sea level.[12, 13]

2.2. Planetary Boundary Layer

The wind resource at ground level is limited for a few reasons. The contours of the land, and large features like hills, buildings, etc., can block the wind and reduce the locations available for effective wind power production. Wind close to the ground is also affected by the planetary boundary layer (Figure 1). This is a phenomenon where the air at the ground has zero velocity and, because of shear forces, there is greatly reduced wind speed close to the ground when compared to wind in the free stream far away from the earth's surface. This boundary layer can range between a few hundred meters to 2 km high, depending on atmospheric conditions and the roughness of the terrain.[14]

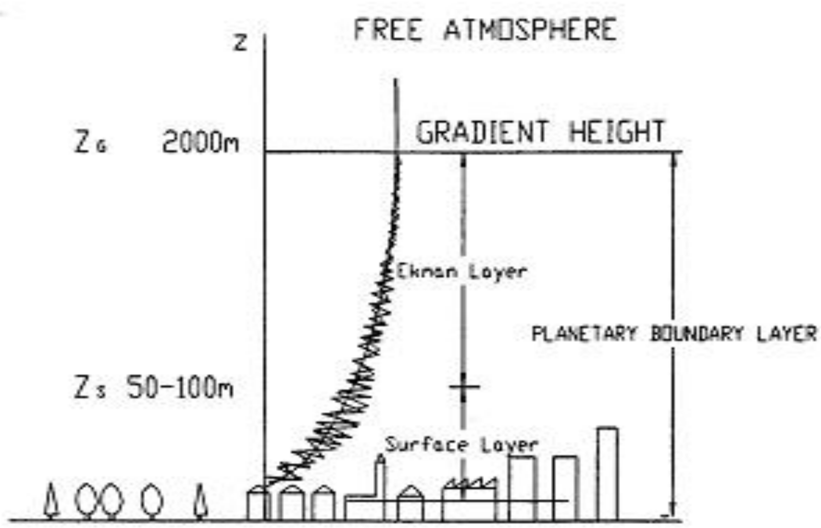


Figure 1. Planetary boundary layer shear profile[15]

As is seen in Figure 1, if the wind power generation system can access winds that are not affected by the worst part of the planetary boundary layer, this will provide much higher mean wind speeds. The main advantage of using high-altitude winds at altitudes from 1,000-2,000 m is that an AWE generation system can then access the higher energy available. Figure 2 shows that the average wind speeds for Europe are about 3 m/s at low altitudes where ground-based wind turbines can reach. But up at 1,000 m, the average wind speed of the wind power being extracted is essentially tripled to 9 m/s. Moreover, up to 2,000 m, the average wind speed continues to increase to 10 m/s, instead of the 3 m/s being harnessed at ground level. Again, considering the power that a wind generation system can extract is a function of wind velocity cubed. This means a *huge* increase in power, even for these relatively lower high-altitudes (for example, tripled wind speed gives $3^3 = 27$ times more power).[16]

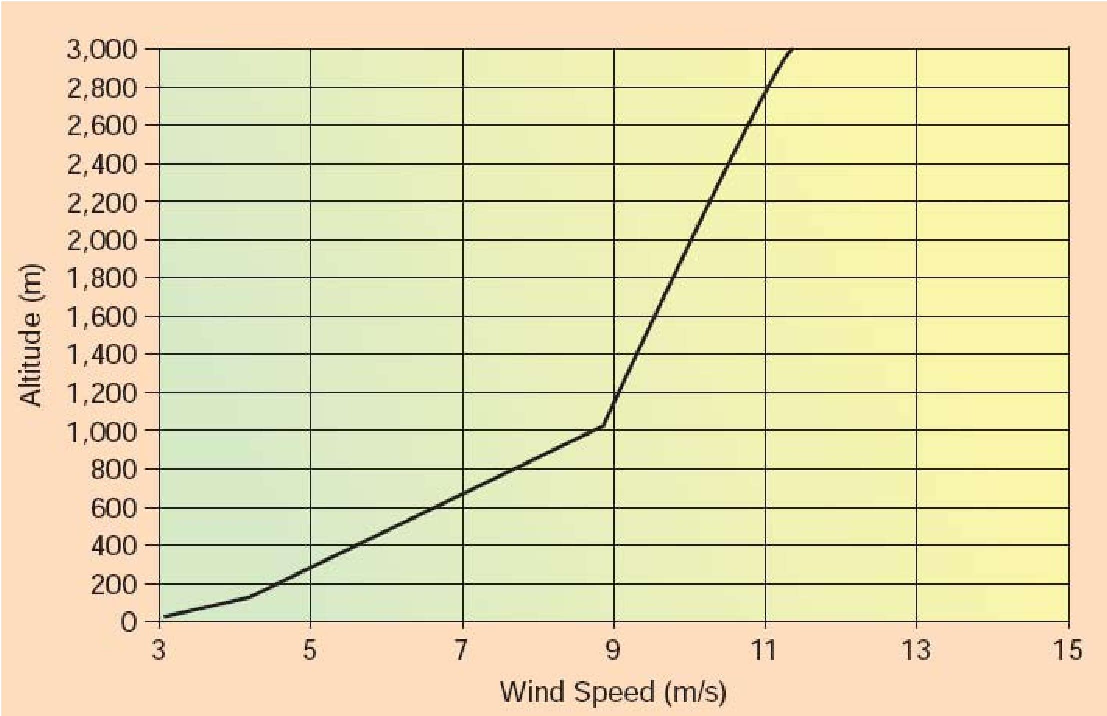


Figure 2. Wind-speed variation as a function of altitude; this data is based on the average European wind speed of 3 m/s at ground level[16]

2.3. Jet Streams & Global Wind Patterns

Figure 2 shows that even after the planetary boundary layer altitude is exceeded, the average wind speed continues to increase. This is because of a different effect called jet streams. These jet streams are caused by the rotation of the earth and atmospheric heating.[17] The jet streams are meandering currents of fast winds, generally located between 7-16 km of altitude, and they peak between 8,000-12,000 m.[13] These wind speeds are 10 times faster than those near the ground, and Figure 3 shows that there are two jet streams in each hemisphere.[13]

Figure 3. A typical jet stream pattern, with two jet streams per hemisphere[17]

Because of these jet streams, all of the wind above the boundary layer continues to increase in speed gradually until it reaches a jet stream. Again, increasing wind speed increases the power available in the wind. The importance of harnessing more power at higher volumes per system is that it will result in less cost per kWh of energy produced, which emphasizes one reason for the DoD to pursue this energy.

In the article, "Global Assessment of High-Altitude Wind Power," environmental scientist Christina Archer took 28 years of atmospheric data to create a worldwide atlas of wind speed distributions and persistency.[13] Archer presents the data in wind power density (kW/m^2), a format convenient for estimating the potential for energy harvesting. The wind power density takes into account the effects of changes in both wind velocity and air density at each altitude. In Figure 4, the wind power density is shown for a few of the altitudes studied.

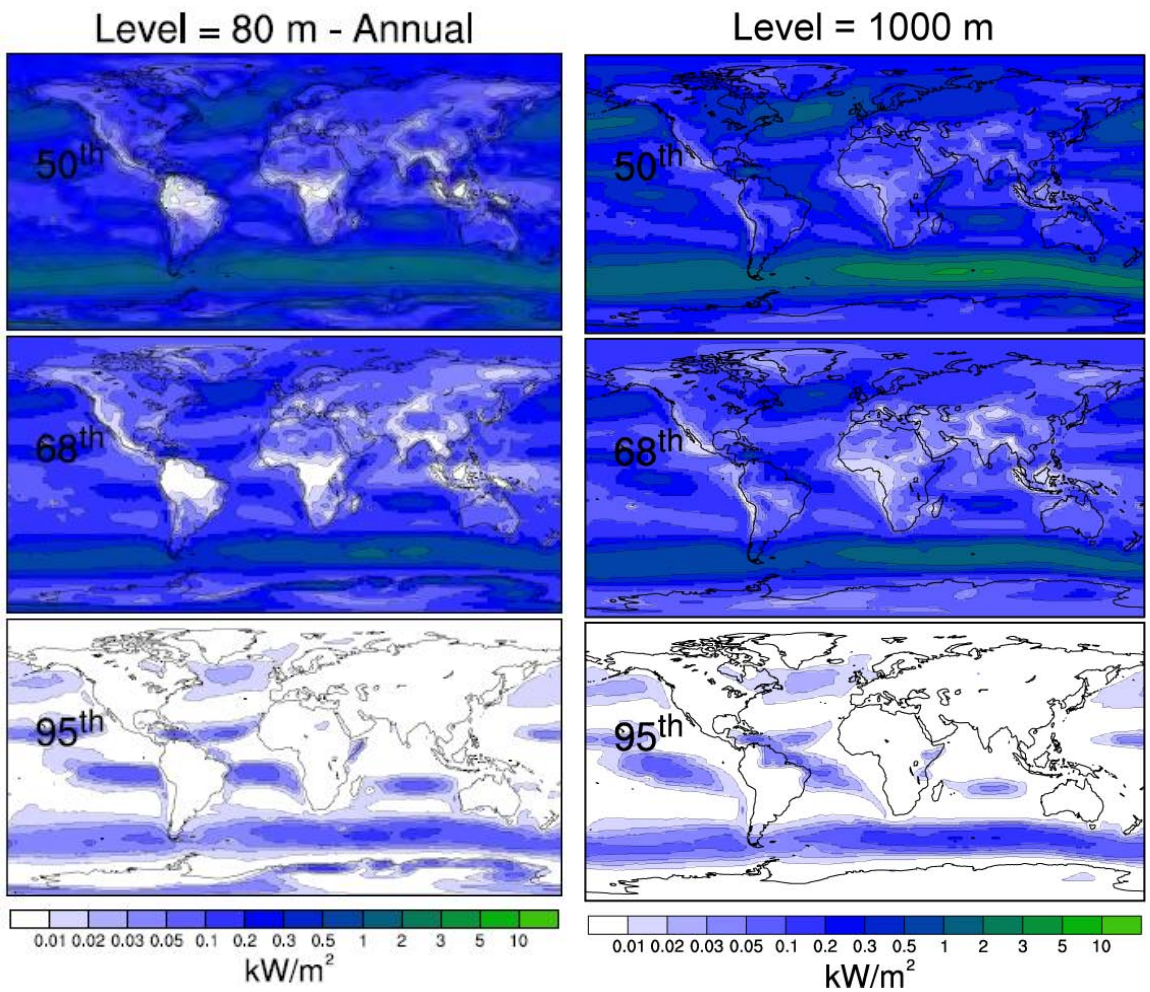


Figure 4a. Wind power density (kW/m^2) that was exceeded 50%, 68%, and 95% of the time during 1979-2006 at 80 m (left) 1,000 m (right) [13]

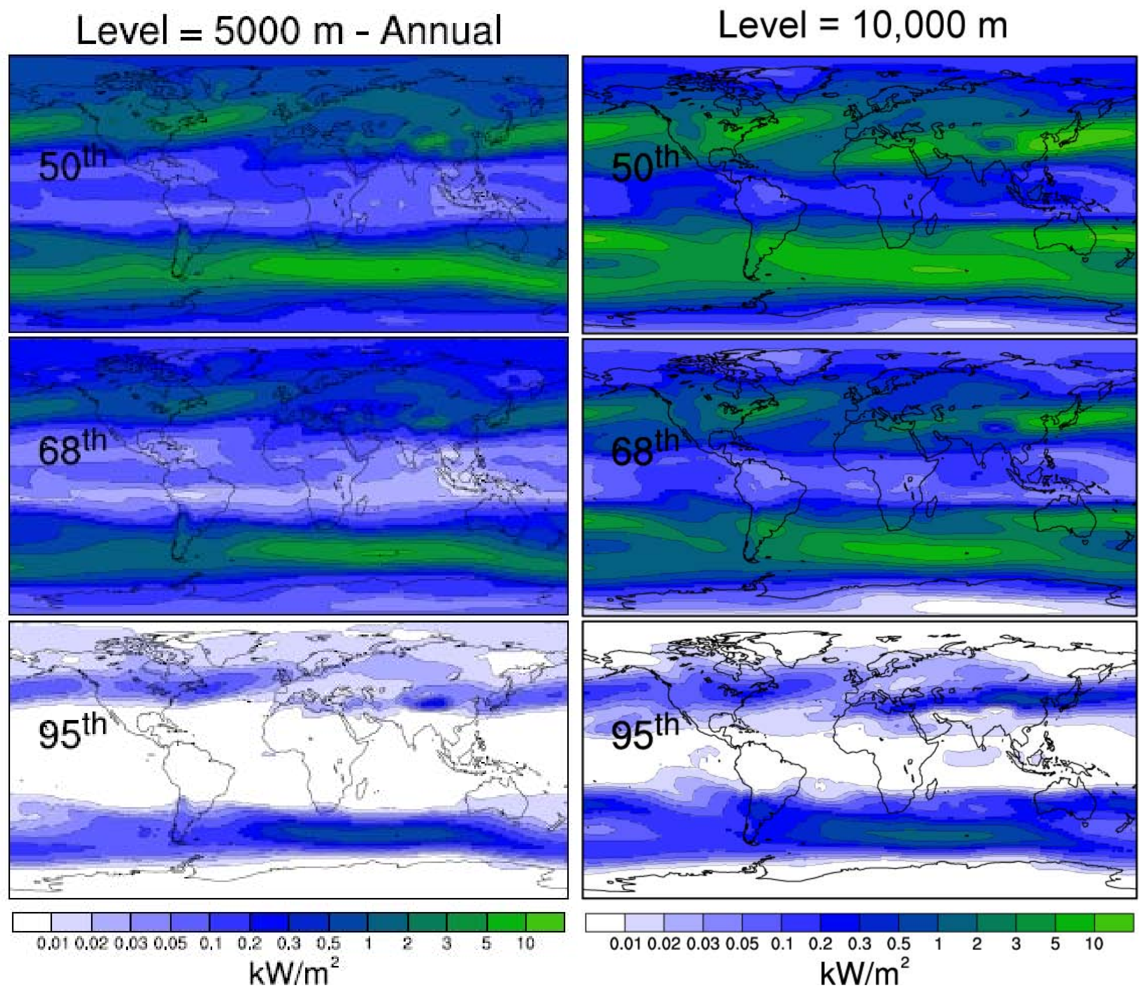


Figure 4b. Wind power density (kW/m^2) that was exceeded 50%, 68%, and 95% of the time during 1979-2006 at 5,000 m (left) and 10,000 m (right)[13]

With this wind power density information, planners can estimate how much power production they can expect at a proposed location, even a DoD location. Note that the scale shown on the bottom of Figure 4 indicates that each subsequent step represents approximately a doubling of the power density. Figure 5 shows the optimum power density that a high-altitude wind turbine can exploit by always flying at the altitude with the best winds; it is an example from the "High-Altitude Wind Power Atlas,"[13] which shows the optimal wind power density for an AWE system on the left. The right portion of Figure 5 illustrates the optimal altitude for an AWE system that would reach those power densities. Figure 5 allows a designer to first determine the potential output of their power system at the selected location, and to then determine the best altitude for their AWE system.

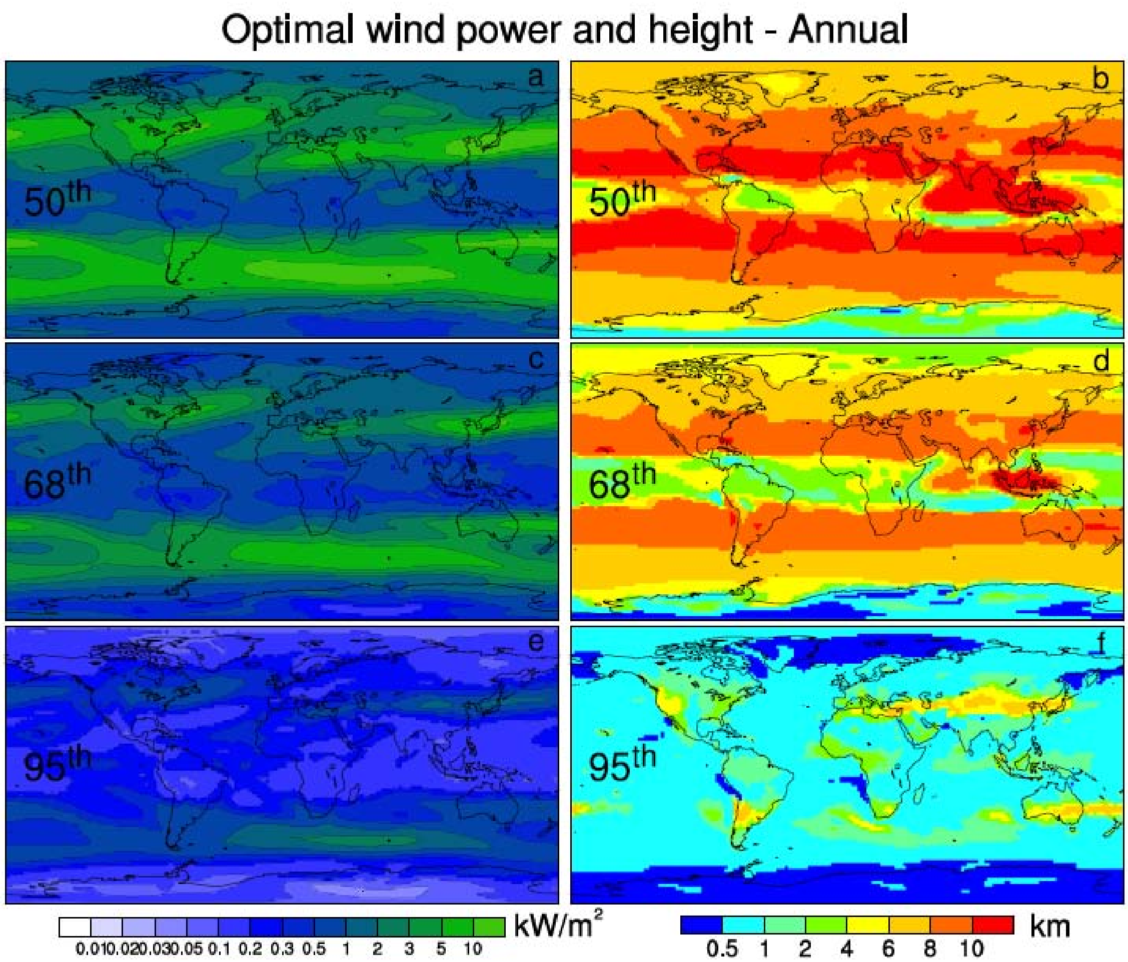


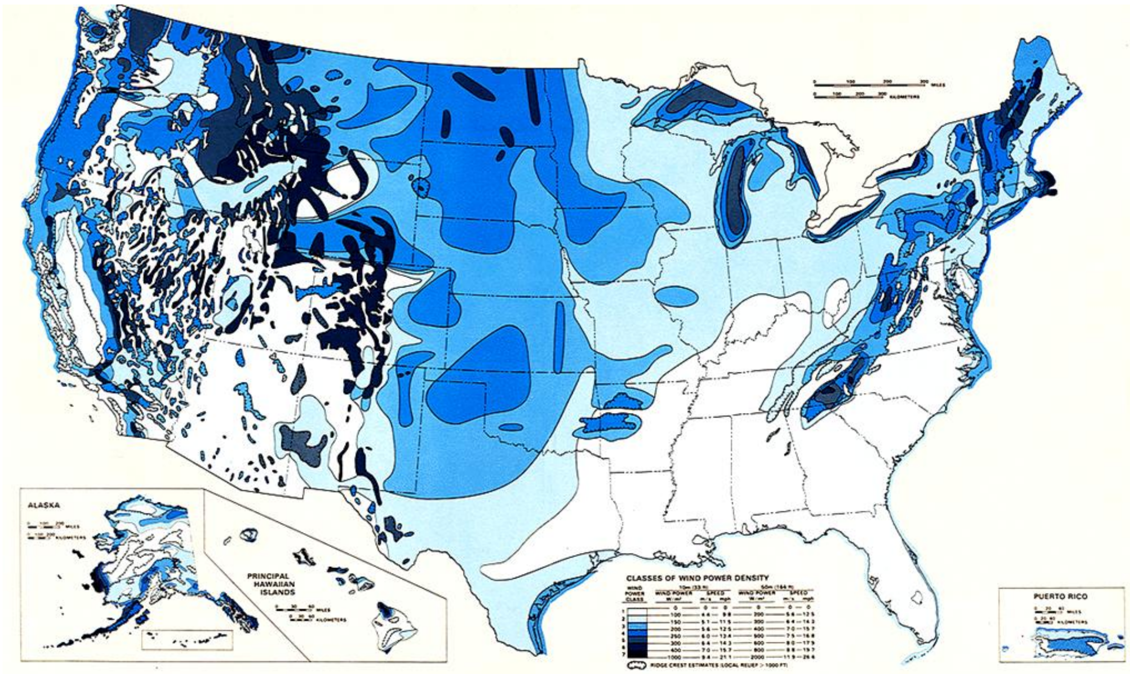
Figure 5. Optimal wind power density (kW/m^2, left panels) and optimal height (km, right panels), exceeded 50%, 68%, and 95% of the times during years in 1979-2006[13]

Note that most of the U.S. can obtain power densities greater than 3 kW/m^2 over 50% of the time if always flying the AWE system at the optimum height. In Figure 4a, at 80 m (ground level), the U.S. wind power density is 0.2 kW/m^2, or less, 50% of the time.

This suggests gains of greater than 15 times the power production at higher altitudes 50% of the time. These are very impressive energy gains if the DoD can find a means to cost-effectively tap them.

Another comparison of AWE power density to conventional wind turbine systems can be seen in Figure 6. Figure 6 shows a more detailed map of the ground-based power densities for the U.S. The key item to notice when comparing Figure 5 and Figure 6 is how the high-altitude power densities range between 2 to over 10 kW/m^2 across the entire U.S. at least 50% of the time. In Figure 6 for wind at ground-based wind power altitudes (50m), the average wind power density ranges from 0.2 to 2 kW/m^2, with the higher power densities available in very small portions of the country. This again suggests that AWE technologies can harvest wind energy with power densities well over 10 times higher than what is available at ground level.

Figure 7 shows a sample of the wind power density as a function of altitude for a sampling of the world's largest cities. Notice that there is large variability in the power density from location to location; this is dependent on whether or not the location is in or close to one of the major jet streams.



Classes of Wind Power Density at Heights of 10 m and 50 m				
Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m^2)	Speed m/s (mph)	Wind Power Density (W/m^2)	Speed m/s (mph)
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1,000	9.4 (21.1)	2,000	11.9 (26.6)

Figure 6. Map of U.S. average annual wind power densities at heights of 10 m & 50 m[18]

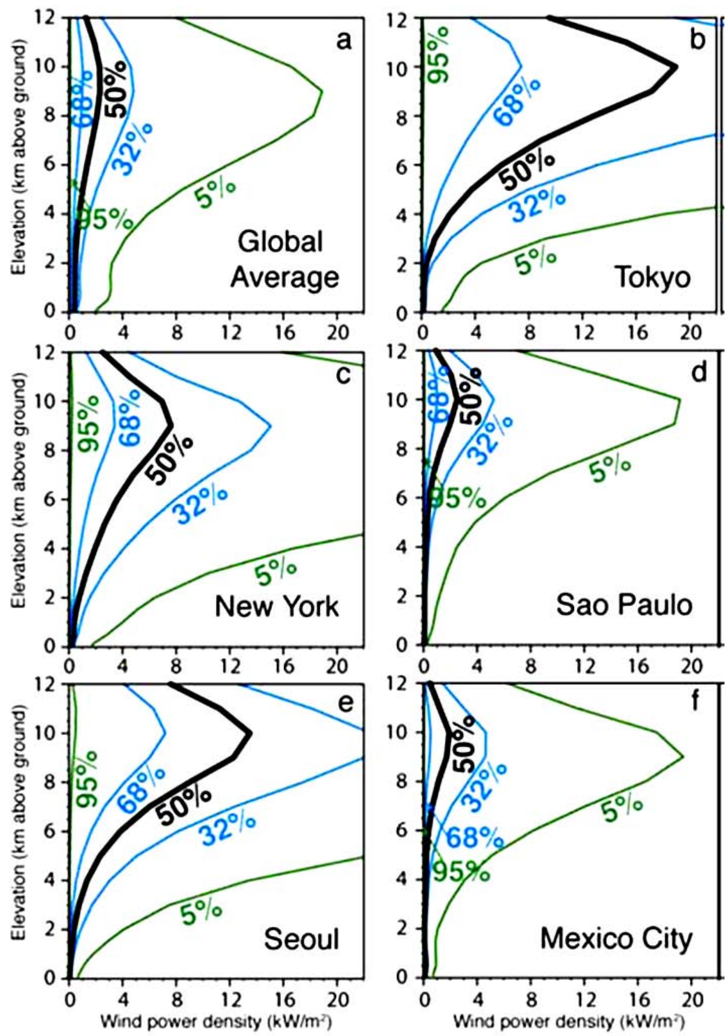


Figure 7. Wind power density (kW/m^2) that was exceeded 5%, 32%, 50%, 68%, and 95% of the time as a function of altitude; profiles at the five largest cities in the world, shown in (b-f); the global average profile (a) is the area weighted mean at all grid points[13]

New York has the best power density in the U.S., with greater than 8 kW/m^2 at least 50% of the time, and an amazing 14 kW/m^2 approximately 32% of the time at an altitude of about 9,000 m. For comparison, a GE 3.6s wind turbine study presented in *Wind Energy Explained*[5], with a 74 m tower and 104 m diameter rotor, is rated for 3.6 MW. Consider that a wind turbine with the same rotor area, used to harvest power over New York at an altitude of 9000 m, could generate 70 MW of power 32% of the time.

2.4. Capacity Factor

Another important factor to consider in wind power is the consistency of the wind. A measure of the consistency of the wind resource at a particular site is the capacity factor, which is the fraction of power actually generated by a wind turbine compared to the rated power of the turbine. Ground-based wind power sites typically have a capacity factor of less than 35%.[14] Table 1 shows calculated capacity factors for U.S. locations at altitudes of 15,000 ft (4.6 km) and 10 km. These high capacity factors are extremely important, not only because of the additional total energy produced, but also because electric companies need consistent power to feed to the grid. Having consistent wind energy can decrease the need for energy storage or other power generation facilities, and it helps to fill in energy production gaps, which in turn enables an increase in the total fraction of the energy grid that can be powered by wind.

The total amount of wind power available is also a question of interest. Researchers estimate that there is roughly 100 times more energy available in the wind than is currently being used by all of human civilization. Humans currently consume about 10^{13} W of power, yet winds are estimated to contain about 10^{15} W of power. Therefore, the DoD only needs to tap 1% of this vast resource to nearly meet world demand.[10] Considering the vast size of the wind resource and the dramatic increases in wind power density and capacity factor at high-altitudes, it is no surprise that there are several researchers and companies developing a variety of concepts designed to tap into this enormous resource (examples of AWE progress are presented later in the chapter).

Table 1. Capacity factor table for U.S. locations[14]

Location	State	4,600 m	10,000 m
Aberdeen	South Dakota	75%	92%
Albany	New York	73%	87%
Amarillo	Texas	66%	82%
Bismarck	North Dakota	68%	87%
Brownsville	Texas	57%	72%
Buffalo	New York	71%	87%
Chatham	Massachusetts	79%	89%
Denver	Colorado	44%	77%
Detroit	Michigan	72%	90%
Jacksonville	Florida	55%	74%
Medford	Oregon	54%	83%
Miami	Florida	34%	61%
Midland	Texas	60%	75%
Morehead City	North Carolina	64%	77%
Oakland	California	50%	80%
Quillayute	Washington	62%	83%
Rapid City	South Dakota	64%	86%
San Diego	California	40%	71%
Topeka	Kansas	77%	91%
Tucson	Arizona	42%	69%

3. Advantages and Challenges for Airborne Wind Energy Systems

If the DoD is to employ AWE technology, then they need to understand the advantages and challenges of different approaches for AWE systems. Three main concepts for harvesting Airborne Wind Energy are the rotor, kite, and balloon concepts. Each approach has strengths and challenges. There are some advantages over ground-based wind power or other fossil fuels that all of these AWE approaches share. In the next section, the main advantages and challenges facing each of the three AWE systems will be discussed.

Compared to fossil fuels, there is very little impact on the environment when harnessing wind power. Wind power generation does not contribute harmful emissions to the atmosphere, nor waste products outside of the energy and materials required to manufacture the systems. For many, this is one of the most attractive features of wind power. See "Global Assessment of High-Altitude Wind Power"[13] for an analysis showing negligible climate effect if Airborne Wind Energy extraction were employed at a scale comparable to total global electricity demand.

In addition to these advantages, because wind harvesting occurs at higher altitudes in three-dimensional space and with higher power densities when compared to ground-based wind generation, there could be a very small land footprint. One analysis estimates that a kite energy farm with multiple kite energy systems, placed far enough apart to avoid entanglement could produce about 7 to 13 times the yearly-generated power per km^2 compared to a ground-based wind farm at the same location.[9]

The high-altitude nature of the wind power generation means that it is bird and bat-safe, unlike ground-based wind power that kills birds. This would make high-altitude systems more acceptable to the public when compared with their ground-based wind turbine counterparts.

Located at a high altitude also has the benefits of reduced visual impact for the public and for the DoD. With an AWE system running at a high altitude, systems will appear very small.

A fourth advantage that the Airborne Wind Energy could provide is power generation portability. Since there is no requirement for a large and expensive tower and foundation, these systems could be implemented at temporary sites. AWE systems could be extremely useful in instances where power has been knocked out, such as emergency or disaster relief efforts. And they would be invaluable to the DoD in remote locations or many other situations, operational or supportive.

Next, because Airborne Wind Energy is so highly available across the globe, these high-altitude systems could be placed relatively close to cities or bases. Since these systems are up and out of the way, this advantage could help to bring the AWE resource near users. This feature of the AWE system could save on infrastructure and electrical losses typically required for long-distance power transmission.

Security for the public and for AWE systems could also be enhanced over the security of ground-based systems. With shorter transmission lines, there would be less exposure to potential vandals. The airborne systems would also be well out of reach of most ground-based threats.

One of the most important advantages of high-altitude systems is that the resource of wind is *plentifully* available domestically. This is a benefit because there is a large drive in public opinion to reduce U.S. dependence on foreign oil. But this is also a national security issue—the less dependent the U.S. is on other countries for energy, the more secure the economy and energy availability will be for the country.

One challenge for AWE systems when compared to ground-based systems are the components, such as flying wind-rotors, that increase the level of complexity for AWE systems. For example, the technology for low-weight, high-strength cables has recent improvements that will make AWE more viable than it has been in the past. But low-weight, high-strength cables are not yet widely available, and remain semi-expensive.[10] This makes AWE systems more complex and, therefore, more expensive to operate than systems that are simply sitting on the ground. Also, a challenge would be to ensure compatibility with the DoD mission requirements; for example, allowing aircraft operations may require the AWE system to be geographically separated from the installation and within a certain safety distance from the base so that cables do not pose a safety hazard.

One of the biggest problems with green energy sources, such as wind and solar power, is that energy flow is intermittent. This means that there is always some period of time, even in the best locations, where absolutely zero power will be produced. Even for AWE, the best locations will still produce no power at least 5% of the time.[13, 19] Power intermittence is a major problem for utility companies, even for devices like solar generators. If a company or military operation has to have a fossil fuel power station or massive energy storage to act as a backup for the wind power, then it drastically reduces any cost savings that the AWE might provide.

Another concern is lightning striking upon systems that are in a higher altitude. This has to be mitigated by either bringing down the high-altitude system during lightning storms, or by designing it so that it can withstand the lightning strikes. This can be done: but it, too, increases the expense and complexity of the system.[11]

The challenges to the development of AWE are significant, but there do not appear to be any obstacles that cannot be overcome by combining and applying current technologies. The advantages of the high-density wind power resource at high-altitudes provide the potential to give *tremendous* returns to those who can innovatively overcome the challenges and produce a competitive system. There are currently several researchers and companies that are trying to do just that.[9,10,11] Three specific types of innovative approaches being pursued are a rotor based concept, a kite based concept, and a balloon based concept.

4. Overview of Specific Types of Airborne Wind Energy Systems

4.1. Rotor Concept

The rotor concept is the most similar to the classic ground-based, horizontal axis, wind turbine, wind power system. The main difference between traditional ground-based systems and this AWE system is that the spinning rotor (or multiple rotors) is flown like a kite up into altitudes with the best winds (see Figure 8). The wind provides a torque on the rotor that produces the rotational motion and the power generation. The wind also imparts a thrust force on the rotor, which is used to lift the system to the desired altitude. This flying rotor kite requires a control system to orient and steer the apparatus for maximum power production. These controls can include wings and tails with control surfaces. The thrust force can also be controlled by adjusting the torque applied by the generator, as it draws power, and by adjusting the rotor's blade pitch control.[10]

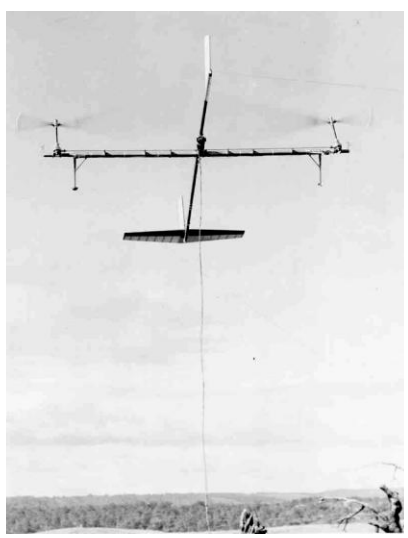


Figure 8. Photograph of early two-rotor prototype in flight[10]

This flying rotor-type of AWE system requires that the generator be an actual part of the kite; therefore, the system transmits the power down to the ground through the cable. The tether must be made of very light materials, yet still provide enough strength to manage the powerful forces generated by the wind turbine *and* the weight of the kilometers-long cables themselves. The cables must also provide a sufficient amount of conductivity to transmit the power to the ground with minimal losses. This is a difficult engineering challenge: however, there are currently commercial vendors that have developed this kind of tether technology for NASA and for military applications.[14] The system transmits the power to the ground using high voltages to minimize electrical losses.[14] Tethers that appear to have the best combination of properties are a composite combination of insulated aluminum conductors and high-strength Kevlar-type fibers.[10] Figure 9 shows a demonstration of a similar composite cable, made by Applied Fiber. The cable shown on the right lifted six cars, while the cable made from conventional steel snapped with only three cars.[20]

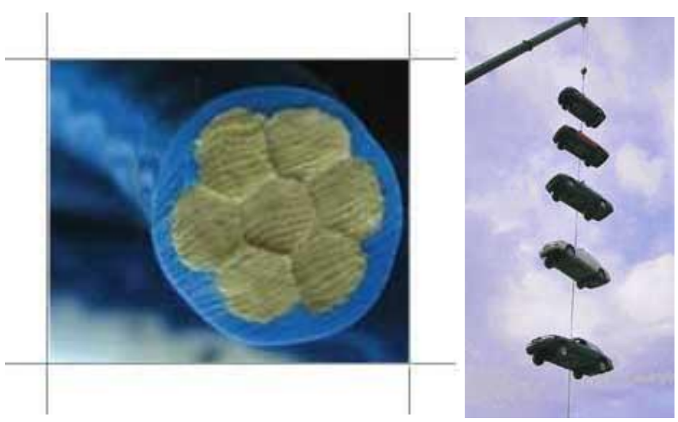


Figure 9. High strength low weight cables by Applied Fiber[20]

One advantage of the rotor-type of system is that it can be highly efficient at converting wind energy into electrical power. Because it operates so similarly to the ground-based systems, the expected performance would also be similar. Thus, the rotor system should be able to convert up to approximately 50% of the power available in the wind that is intercepted by the rotor area.[5]

The flying electric generators also have the advantage of being quieter and less visible than ground-based systems. Since a system could run at about 10 km (32000 ft), what someone might see and hear from an AWE rotor system could be compared to what they would see and hear as a large aircraft flies overhead at the same altitude. Think about how small these large aircraft appear at that altitude! Also, the noise level would be much less than ground-based systems, because of the large distance between the rotor system and anyone on the ground.

The rotor-type of system also handles turbulence very well. Any large disturbances tend to be easily absorbed by a temporary adjustment to the slack in the cable. The rotors also generate a tremendous amount of thrust that is proportional to the wind speed squared. The turbulence handling and high thrust characteristics of the rotor-type of AWE system enables it to potentially reach the highest altitudes with the most powerful jet streams.[14]

Of course, the extreme heights that these AWE systems operate in also create some major obstacles. Chiefly, a 10 km high tethered system requires a massive region of restricted air space. This altitude occurs at about the same altitude that airlines like to fly at; this could cause significant resistance in the aviation industry to AWE systems operating at these heights, not to mention that the rotor systems require a logistical, creative solution for military installations where AWE is used simultaneously near an airfield. But in such cases, a circular area of AWE systems spaced around the DoD site could be established to ensure safety of all aircraft.

Another factor to consider is that some wind energy is required to provide the lift for these systems. To keep the system aloft, the rotors must be tilted partially upward in order to point the thrust vector upward. Doing so slightly reduces the cross-sectional area of the wind intercepted by the rotors. To diminish this, the structure, cables, generators, and gear systems must all be light. This adds to the level of complexity of the design that the ground-based systems do not have to be as concerned about.

Safety is also a major concern for AWE systems. The idea of a massive wind-rotor falling out of the sky and landing on a populated area is frightening. Therefore, the systems would need to be designed with safety and redundancies as a top priority. Obviously, the first generations of designs would not be flown close to population centers. Eventually, the reliability and safety record of the systems could be improved to the same degree of other flying aircraft. This would allow the systems to take advantage of the high-altitude wind energy in close proximity to the largest energy users.

To address safety issues of a rotor system, safety features could be incorporated into tethers between the AWE system and the ground. In the event of something large, such as an aircraft, striking the system, the tether could be designed to safely sever. One method that could be used to reduce the damage in the event of a cable severing would be to use the rotors as a helicopter. Onboard sensors could detect the problem and use automatic controls to glide the unit safely back to the earth.

Despite the technical challenges faced by this type of AWE system, the researchers developing this technology estimate that it will still be profitable. It is predicted that the cost of the power produced will be about 2 cents per kWh (including land lease, maintenance, operations, and capital costs), which is cheaper than any other current source of power.[10] Currently, one company is in the process of building a relatively large-scale prototype version of this rotor-type AWE system. Sky WindPower Corporation is building and plans to fly their demonstration rotorcraft, seen in Figure 10, at altitudes up to 4,600 m (15,000 ft).[10,14]

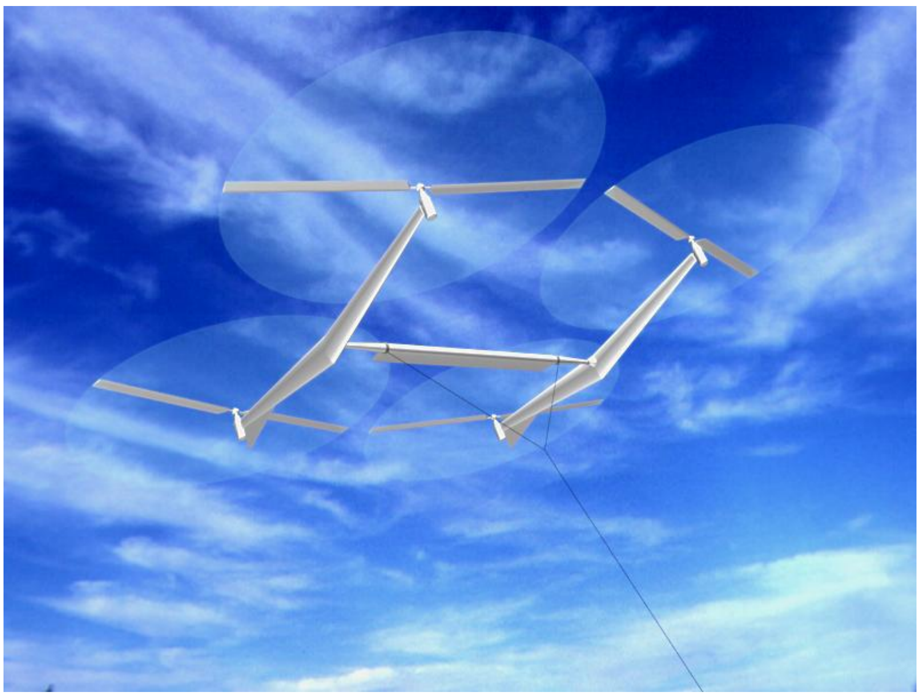


Figure 10. Artist's rendering of Sky WindPower Corporation's planned 240 kW four-rotor AWE generation system called the Flying Electric Generator (FEG)[10,14]

4.2. Kite Concept

The kite concept typically uses a kite attached with cables to a ground-based portion of the system. The ground station has cable spools that are attached to generator-motors. The kites use sweeping figure-eight motions (Figure 11 and Figure 12) to cut across the wind, generating aerodynamic forces. The powerful forces generated by the sweeping motion of the kite pull the cables, generating power as they turn the generator attached to the spool. Once the kite has reached its maximum altitude, it goes into a low-resistance dive that allows the spool to reel in the cable, attached to the kite, closer to its beginning altitude. Then, the pattern is repeated. The energy required to reel the kite in is much less than the energy generated as the kite sweeps across the wind, resulting in a large net gain in power with each cycle.[9, 16]

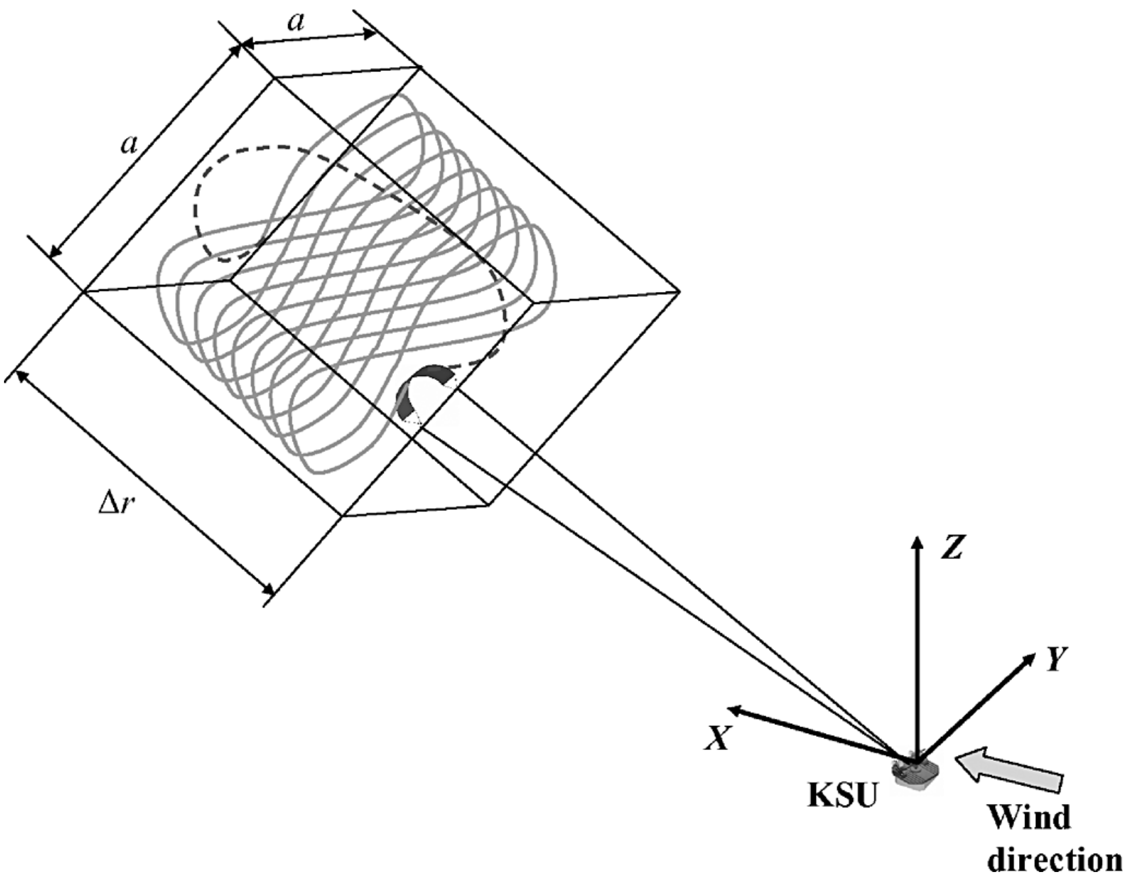


Figure 11. KE-yoyo (Kite Energy) configuration cycle: traction (solid) and passive (dashed) phases; the kite is kept inside a polyhedral space region whose dimensions are (a × a × Δr) meters, which allows users to stack and control many kites closely together[9]

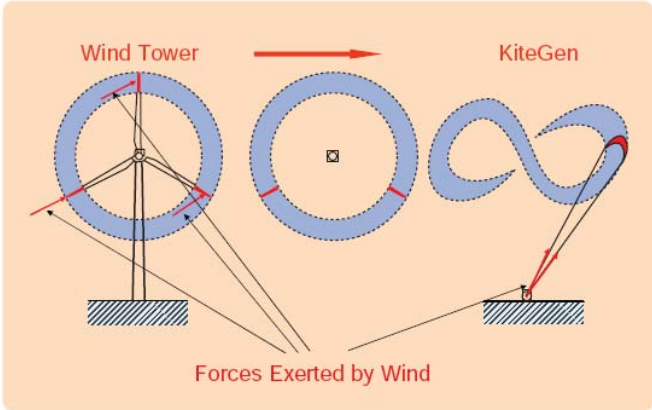


Figure 12. Comparison between wind turbines and airfoils in energy production; in wind towers, limited blade portions (red) contribute predominantly to power production; the kite acts as the most active portions of the blades, without the need for mechanical support of the less active portions and the tower[16]

Fagiano and his research team were initially responsible for developing and testing small-scale kite prototypes, as seen in Figure 13. Results looked promising, so a large company called Kite Gen was formed. Kite-Gen is now planning for the development of large-scale AWE kites.[16]

Figure 13. KE-yoyo small-scale prototype operating near Torino, Italy[9]

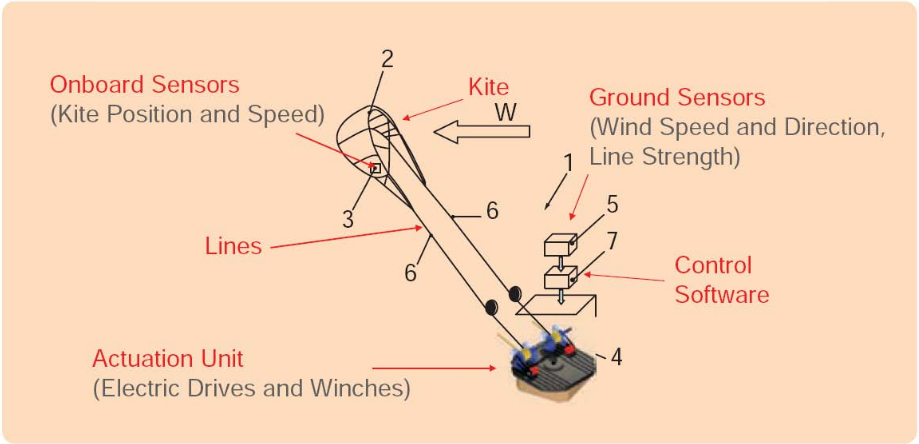


Figure 14. Scheme of the kite steering unit; the kite steering unit, which provides automatic control for KiteGen, includes the electric drives, drums, and all of the hardware needed to control a single kite[16]

Figure 14 shows that these kite generation systems are controlled similarly to a recreational kite, with two cables, but they also have GPS and position censors to keep them moving in the most efficient pattern. This controlled pattern can also allow multiple kites generating energy to operate in relatively close proximity to each other. Figure 15 below shows a concept, by the company Kite Gen, to implement large-scale energy production using kite-based generation. Multiple kite systems are automatically controlled simultaneously through a central base-station.[21] At the end of each of the arms would be a kite steering unit like the one in Figure 14.[16, 22, 23]

The advantages of such kite based high-altitude systems are: the AWE airborne portion of the system is very simple, the cross-sectional area of the wind harvested can be very large, and a kite system could be relatively cheaper than ground-based wind turbines and even fossil fuels.[9] Because the kite system is simple, like a kite, the materials can be soft and flexible like a parachute. This feature improves the safety factor because there is no potential of a heavy rotor system crashing to the ground. Next, the harvested area of the kite can be very large as it sweeps across immense patches of sky, since the kite system is not restricted to the size of a rotor. And compared to ground-based power, this system eliminates a large, expensive tower, making it more cost-effective and worthwhile to continue developing.

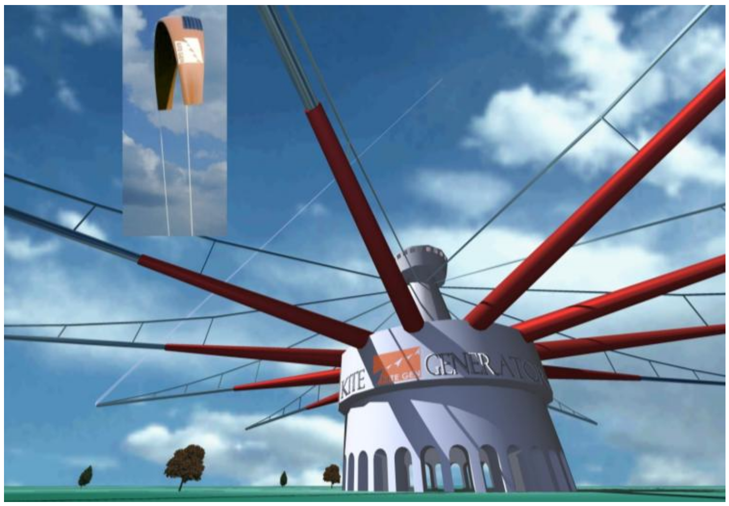


Figure 15. Kite Gen[21, 24]

One disadvantage of this approach is that the kite method would not be as aerodynamically efficient at capturing the wind, when compared to a rotor system, per unit area of sky. The kite system is not generally considered as capable of handling turbulent winds because the kite cables can become tangled—especially when multiple kites are attached to the same line.[14] Also, because the power is transmitted to the ground mechanically from the pulling forces on the cables, there are diminishing returns as longer lengths of cable are extended. The weight of the cable eventually outweighs the extra force added by attempting to reach the higher winds at extreme heights. This means that kite wind power solutions have an optimal point to be operated at, and are generally better suited for lower altitudes, up to about 1000 meters.[9] Scaling up the size of these kites, and really improving cable technology, could potentially allow them to reach higher altitudes. One advantage of flying at lower altitudes is that the size of required restricted air space, particularly around DoD sites, would not need to be as large. 1000 m or 2000 m of restricted airspace could be easier for people and for the government to accept than a rotor system that may go up to 10,000 m.

The current status of the kite system technology is that research into the cost feasibility of generating power using this method has been conducted. Also, small-scale prototypes have been tested, as seen in Figure 13. The operation of small-scale prototypes match well with predicted performance.[9, 25] The predicted cost of kite energy is shown in Table 2. The estimated cost includes all costs associated with the power production, including land lease, maintenance, operations, and capital costs. At an average of 2¢/kWh, kite energy cost estimates are lower than any other power source.

Table 2. Comparison based on estimates of the cost of energy per MWh[9]

Source	Minimal estimated ($/MWh)	Maximal estimated ($/MWh)	Average estimated ($/MWh)
Coal	25	50	34
Gas	37	60	47
Nuclear	21	31	29
Wind	35	95	57
Solar	180	500	325
KiteGen	10	48	20

Because of the advantages listed previously, using this method of power generation suggests it is feasible that these predicted cost figures could be realized. Yet, the caveat is this: there could be an unknown learning curve before such energy rates could be obtained.

4.3. Balloon Concept

Balloon-type AWE systems use a large helium balloon, with flaps arranged around the balloon to catch the wind (Figure 16). Each end of the balloon has a generator attached between the cables and the balloon. As the wind strikes the balloon, the flaps on the top catch the wind, while the flaps on the bottom flatten. Thus, the high drag on top, coupled with the low drag on the bottom, causes a torque that spins the balloon around its horizontal axis. This is a drag type machine, meaning that it does not use lift forces, as the rotor and kite type systems do, but instead uses only the drag forces of the wind to rotate. The major disadvantage of this type of system is that it is only about half as efficient at extracting power from the wind as a rotor-type system that can utilize both lift and drag. But this reduction in efficiency, compared to ground-based wind power generation, is expected to be more than offset by the increased wind speeds and consistency of the wind at the higher altitudes that it could reach. This could translate to an overall cost for energy production per KWh to be less than the cost of energy from the ground-based systems.[11]

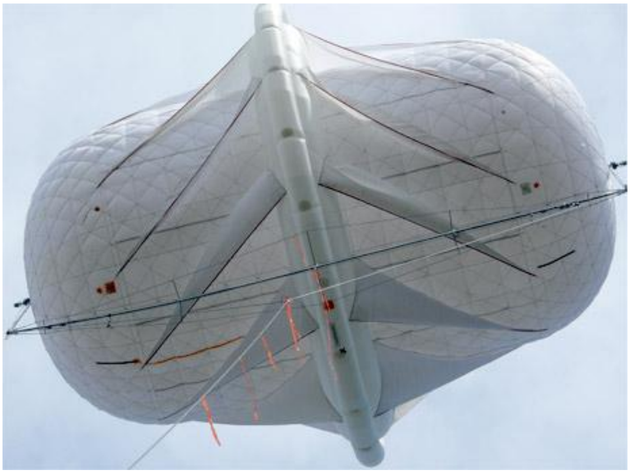


Figure 16. The Magenn Air Rotor System (MARS)[11]

There are some other advantages to this system. The spinning of the balloon causes what is known as the Magnus effect. The Magnus effect is when the spinning of the balloon causes more of the wind airstream to flow over the top of the balloon than the bottom. The faster airflow above the top of the balloon creates a lower pressure region over the top. This results in extra lift, in addition to the lift of the helium. The extra lift allows the system to reach altitudes that it could not reach using helium alone. The Magnus effect also stabilizes the balloon and helps to keep the system naturally aligned with the wind, within a strictly controlled position.[11]

The balloon system is interesting because it holds itself up in the air without being dependant on lift from the wind. This is good because the risk of the system crashing into the ground is low, and it can stay aloft in very low winds. This also allows the system to be able to lift off the ground, even if the wind speed at ground level is too low for power generation.[11]

One challenge that this type of system faces is that the lift force available is highly dependent on the size of the balloon. This means that to reach the very high-altitude jet streams with the highest wind speeds, the balloon would need to be quite large to overcome the weight of the tether.

Another challenge is that the balloon system requires a very large amount of helium. This helium is a very significant portion of the startup and operating costs. Helium also tends to leak over time. But if the balloon membrane is designed well, the leakage rate can be kept down to about 6% per year.[11]

The current status of the development of this type of wind power system is that a company called Magenn Power Inc. has designed, built, and is currently testing a 100 kW system (seen in Figure 16). Magenn expects to begin selling similar production versions sometime in late 2011. Current target for this product is for remote locations, and for temporary sites like construction or disaster relief, which could directly benefit the DoD goals (Figure 17, left and center). Eventually, Magenn expects to introduce larger versions that can be used in large-scale wind farms to generate power for the power grid (see Figure 17, right).[11]

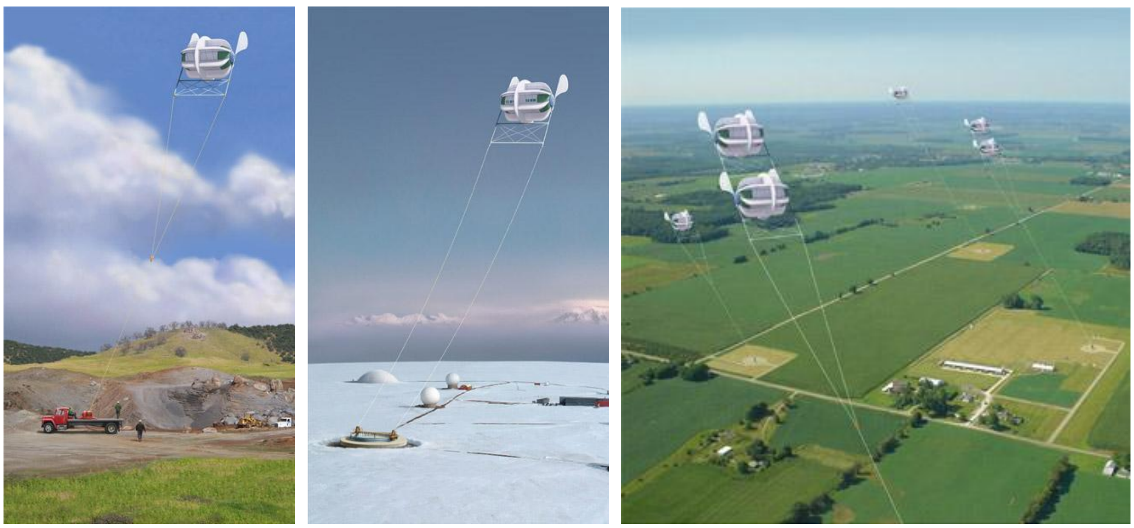


Figure 17. Implementation concepts for the Magenn Air Rotor System (MARS)[11]

In summary, these are the three main approaches being used to harvest AWE (the rotor concept, the kite concept, and the balloon concept). Since AWE is still in the early stages of development, there is still a wide variety of variations in these approaches. One example is a hybrid AWE strategy that uses a combination of the rotor and the kite concepts where there is a kite with rotor-blades on the front that generate electricity as the kite sweeps across the sky (see Figure 18).[26]

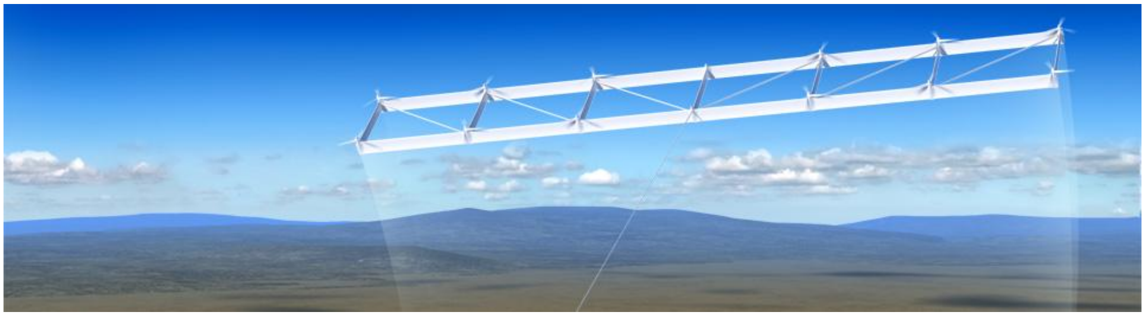


Figure 18. Kite and rotor combination concept by Joby Energy[26]

As the technology for AWE matures, it is probable that a dominant design will emerge. However, there is still a lot of innovation in the field of AWE that is occurring, and this section has presented a basic overview for the current state of the technology.

5. Important Component Studies

It is important to understand the key concepts and equations related to the main components of wind power generation systems. The most important components for AWE systems are the rotor and the generator. A review of literature related to these components has been conducted, and some of the main ideas for these components are presented below.

5.1. Electric Generators

It is important to understand the main components of the AWE rotor system so that one can successfully be designed. Generators and electric motors are essentially the same: the difference is that energy is put into the system to run it as a motor, and power is drawn from the device while a mechanical power source drives the system to run it as a generator. In finding information about electric generators, the research found that several key power equations for analyzing these generators could be used.

In the “Validation of Small Scale Electric Propulsion System Models,” motors are studied.[27] Yet, this study also applies to generators because it demonstrates that optimizing the “propulsion system” can be more important than optimizing the aerodynamics. This report additionally teaches that designers have to be careful when purchasing off-the-shelf parts, such as motors, because the actual measured efficiencies may not match the advertised efficiencies given by the manufacturer.

Examining further analysis of generators helped to investigate the different kinds of generators: direct current (DC) generators and alternating current (AC) generators. Within the AC generators, there are two main kinds used in wind power applications—synchronous and induction generators.[5] The key equations governing the performance of induction generators are:

$$n = \frac{60f}{P_{oles}/_{2}} \tag{2}$$

$$s = \frac{n_s - n}{n_s} \tag{3}$$

$$P_{gout} = I_R^2 R_R \frac{1-s}{s} + I_R^2 R_R + I_s^2 R_s \tag{4}$$

$$P_{gin} = P_{rout} - P_{mechloss} = 3 I_R^2 \frac{1-s}{s} R_R \tag{5}$$

$$\eta_{gen} = \frac{P_{gout}}{P_{gin}} \tag{6}$$

In these key equations, n is the rotational speed (Equation 2) of the generator, and s is the slip of the generator (Equation 3). n_s is the synchronous speed of the generator. If the generator is driven at a speed faster than the synchronous speed, then it results in power generation (Equation 4). However, if the generator is going at a speed slower than the synchronous speed, then the generator is operating as a motor.

Next, f is the frequency of alternating current. The number of poles that the induction generator contains is a design choice. The efficiency (η_{gen}) of the generator (Equation 6) is the ratio of electrical power output (P_{gout}) from the generator to the mechanical power (P_{rout}) supplied to the generator by the rotor (Equation 5). I_R and I_S are the current in the generator rotor and in the stator, respectively. R_R and R_S are the resistance in the generator rotor and in the stator. The mechanical loss ($P_{mechloss}$) represents the mechanical losses experienced in the shaft and in the gearbox between the rotor and the generator. Considering this information will allow selection of a generator appropriate for an AWE design.

5.2. Rotors

Rotors are another key component of an AWE rotor system. Rotors are similar in design to propellers except that the rotor is designed to convert the energy in the wind to mechanical, rotational energy, while a propeller does the opposite. Rotors are essentially airfoils that operate rotationally; therefore, all of the same principles of lift and other aerodynamic forces that can be applied to wings are applicable to rotors.

The equations and principles of aerodynamics applied to rotors are laid out in detail in *Wind Energy Explained*.[5] The key governing equations for rotors are the equations for thrust and power, given here:

$$P_{wind} = \frac{1}{2}\rho A U^3 \tag{7}$$

$$P_{rout} = \frac{1}{2}\rho A U^3 4a(1-a) \tag{8}$$

$$\eta_{rot} = \frac{P_{rout}}{P_{wind}} \tag{9}$$

$$T = \frac{1}{2}\rho A U^2 4a(1-a) \tag{10}$$

Rotor power out (P_{rout}) measures how much power the rotor has extracted from the wind. The axial induction factor is a measure of the ratio between the free stream velocity of the wind and the wind speed seen at the rotor plane. As with the power and wind equation given in Equation 7, the power output is proportional to the wind velocity (*U*) cubed. The difference between Equations 7 and 8 is that the power that one can extract from the wind by the rotor is limited by the laws of conversation of momentum, which is manifested in the axial induction factor (*a*). This knowledge is used to determine the efficiency (η) of a rotor in converting the power in wind to mechanical rotational power (see Equation 9).

Once power has been determined, thrust (*T*) is the important factor in determining the lift that the AWE device will have available to stay aloft (see Equation 10). Notice that the equation for thrust is very similar to the equation for power, except that it is proportional to wind speed squared. This information allows calculation of the forces and loads required for the AWE design to manage.

6. Literature Review Summary

The concepts described in this chapter are the result of many years of study and effort that are now on the verge of becoming a practical and viable source of clean and cheap energy that the DoD could utilize. The AWE technologies still have a lot of room to develop and improve, but the studies conducted to date show that these technologies all offer the potential for great improvements in wind power.

The vast size of the high-altitude wind resource, along with its close proximity to users and its consistency, make it a tempting, viable source to tap as the country searches for more ways to find clean, reliable, and inexpensive energy. The inexpensive component is the most important aspect because it makes AWE resources competitive with current energy resources.[9] If AWE is truly competitive with current energy sources, the technology will rise on its own based upon its profits, and this will allow the high-altitude technologies to be independent of government subsidies.

The challenges that this AWE resource face are significant. First, AWE systems require restricted air space to operate—this will take a lot of discussion among people, such as the FAA and Congress, to determine how the U.S. and the DoD can take this step. The systems need to be proven reliable and safe, because no one wants any accidents such as wind generators falling on houses or massive cables crashing down. In addition, if technology can develop (for example, in such a way as to reduce cable weight per unit length), *then* this will allow the AWE systems to consistently reach the highest altitudes. The capacity factor reveals that if the systems are operated perfectly, they will still not be as consistently available as fossil fuel sources. Even the best AWE sites will provide no power at least 5% of the time.[13, 19]

Yet in conclusion, pursuing high-altitude energy is recommended because this vast resource is more reliable than ground wind power, and AWE can be more cost-competitive than other resources. In the U.S. economy, AWE will save money for both utilities and consumers such as the DoD. One reason it is important to drive the cost of wind power down is that current ground wind power is only cost-competitive when the price of other energy (like the price of oil or coal) is high. The effect of this is that interest in wind-power and capital tends to dry up when the price of energy drops. Therefore, if AWE prices can be competitive, even at low energy prices, it will make interest and development in the AWE technology consistent regardless of the price of energy. Additionally, the high-altitude systems could be beneficial because they can be very close to users, the systems can be portable (they are only attached to the ground with a cable), and they can be used in varied locations and in a wide range of operating situations. Realizing each of these items will help the USAF to accomplish the goals of the National Security Strategy.[2]

It seems that the objectives of AWE can be reached. The goal to generate power at the lowest possible cost per kW produced has been realistically cost analyzed. Investigation has been done to use the minimum possible land in these AWE systems so that the maximum energy per area on the ground (kW/km^2) can be achieved. Some of the benefits to AWE systems are monetary (reduced land use and low environmental impact), but there is also a realistic potential that the high-altitude approaches for more effectively harvesting wind power will collectively provide cheaper, cleaner, and inexhaustible energy technologies that the DoD can directly utilize.

III. Methodology

1. Chapter Overview

The methodology of this paper focuses on the achievement of two main objectives: to realize the best power production and efficiency for an AWE system, and to identify critical USAF base candidates that would benefit the DoD most from AWE. To accomplish the first objective, the creation of a design tool that would technically analyze and compare an idealized wind turbine rotor blade to a more simplified version, and then compare the performance of the two, was conducted. In this chapter, the equations that go into the design tool to yield solutions for the most efficient AWE rotor-based wind turbine are presented. Then, in order to realize the second objective, it was essential that a USAF base decision matrix be created. The second half of this chapter presents how the evaluation was conducted, and compares which bases in the decision matrix are most feasible and most likely to succeed using AWE projects to accomplish the energy needs of the DoD and fulfill the goals of the National Security Strategy.[2] The methodology of the base decision matrix presents categories that the USAF bases were evaluated on, the data that was used for the evaluations, and how each base was scored.

Each of the approaches for harnessing AWE (rotor-type, kite-type, and balloon-type) has very interesting advantages and challenges. It is not possible to study all three in this research, so in order to limit the research scope, the rotor-type AWE system was selected for in-depth study. The rotor-type approach has a few advantages that were appealing to the author. One advantage is that the author was already familiar with the theory behind a ground-based rotor-type wind turbine. In addition, the rotor type turbines are very efficient at harnessing energy in a given area of wind stream. The relatively stationary nature of the rotor-type turbine also allows a greater degree of three-dimensional placement of the AWE systems, which should lead to a much smaller ground footprint per kWh of energy produced.

Creating a design tool for rotor blades was necessary in order to determine the lowest cost for an AWE system, identify ways to make systems easier to produce, and to find the most reliable designs to be used that had the best minimal significant efficiency losses. Each of these factors guided the research equations into discovering which airborne wind-rotor style concept would have the most reasonable benefits for the USAF.

The methodology also presents that the first step in determining feasibility of USAF bases was to select a few sample bases that could most benefit from increased power supply from renewables. The second step was to analyze and compare results of the USAF bases based upon the good prediction estimates for the power production and efficiencies the design tool yielded, and match up those bases with locations that are ideal for AWE based on the capacity factor and energy density at that particular location. The methodology consequently found a sampling of six USAF bases that are best for operating AWE systems.

The results of the methodology analysis are presented in Chapter 4. Sample outputs from the design tool and analyses of these outputs are put forward to achieve the first objective of most efficiently designing an AWE system. The second objective is met through the methods used to conduct an analysis of the sample bases' energy needs, and then comparing base needs to the performance of the designed AWE system. The key conclusions and recommendations will be presented in Chapter 5.

2. Design Tool for AWE Blade Design

Why is it important to analyze energy conversion on different blade designs? Analysis of energy conversion on varying blade designs will allow the USAF to build the most efficient and reliable AWE systems. Optimized designs for wind turbine blades result in a complex shape that includes high twist (which varies along the blade nonlinearly), as well as a chord length that changes nonlinearly along the length of the blade. Often, the airfoil shape varies along the blade radius in order to squeeze every bit of energy out of the wind that is harvestable. These complex shapes can be very difficult and expensive to manufacture, and they can cause complex stresses in the blade structure. The high wind speeds and high rotation rates that AWE devices will operate in will magnify the effect of these stresses.[5]

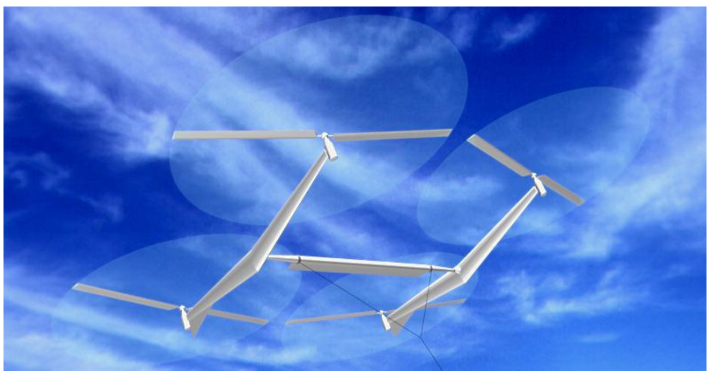


Figure 19. Sky WindPower's Flying Electric Generator (FEG)[14]

Complex stresses can make it difficult to maximize the reliability of the blades. The design tool assists in comparing these optimized blade designs with simplified designs that can be more easily manufactured (e.g., off-the-shelf helicopter blades). The simplest design would be one with constant chord, no twist, and a single airfoil cross-section shape along the entire blade. Other variations could include small amounts of linear twist, while still holding the chord and airfoil constant. Being able to analyze simplified blade design performance under the high-altitude conditions they are to be operated in will allow designers to make design simplifications that will lead to high reliability and low cost, while still producing power efficiently.

Again, if renewables are to be massively adopted, the key is that the cost of renewables (such as AWE) must be lower than fossil fuels. Renewables need to be cheaper than fossil fuels and become the go-to source of energy, leaving the fossil fuels as the backup when the availability of the preferred renewable source is not available.

Airborne Wind Energy devices must be highly reliable and inexpensive to produce and maintain in order to keep lifetime costs low. Simple blade designs will better meet these goals because they are cheaper to produce and will have less internal stresses causing fatigue.

The conceptual design tool that was developed during this research can be used to analyze various blade designs, both optimized and simplified. Figure 20 provides a summary of the inputs, process, and outputs used by the design tool for the design of a rotor-based AWE system. Much of the theory and equations used in the design tool come from the text of *Wind Energy Explained.*[5]

The design tool compares the power coefficient (efficiency) and thrust for the various designs. The design tool allows analysis of different airfoil designs, different number of blades, and different blade rotor diameters. The design tool is capable of analyzing trends across variable flight conditions, such as wind speed and altitude changes. Being able to use the design tool to analyze simplified blade design performance under the high-altitude conditions they are to be operated in will allow designers to make design simplifications that will lead to high reliability and low-cost, while still producing power efficiently.

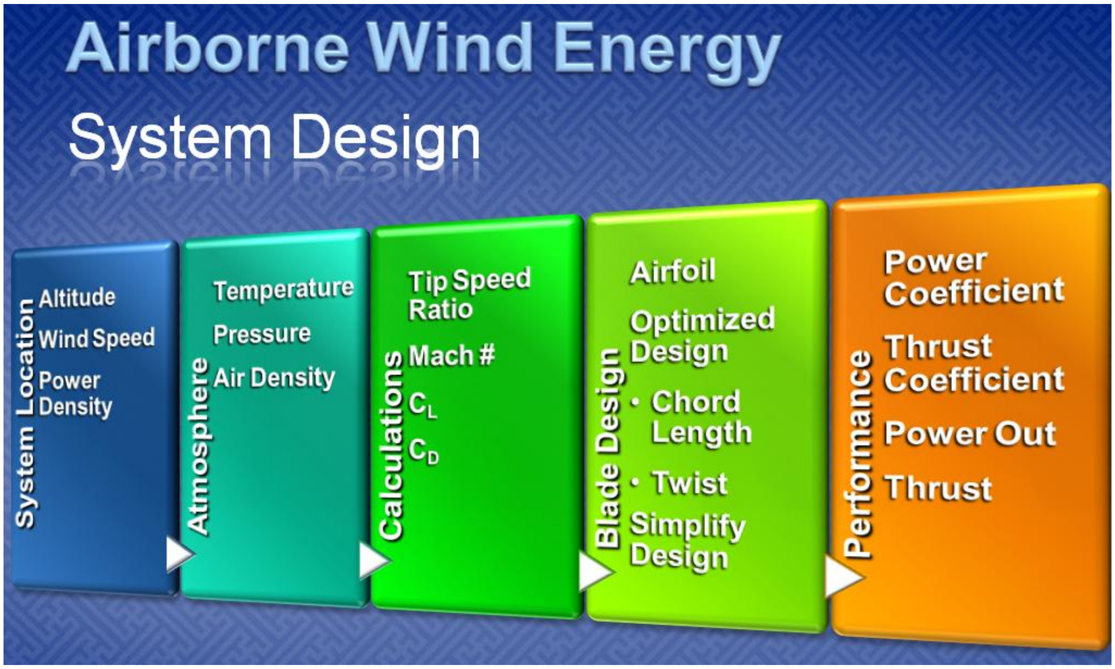


Figure 20. Summary of the AWE system design process

The following sections of the paper provide a detailed description of the equations used to develop the design tool. The tool can then be utilized to compare the power coefficient (efficiency) and thrust for the various designs. The tool can also be used to conduct analysis of different airfoil designs, different number of blades, different blade rotor diameters, and to analyze trends across variable flight conditions, such as wind speed and altitude changes.

2.1. High-Altitude Wind Properties

The first step in analyzing the performance of an AWE device was to determine the properties of the atmosphere at the operating altitude. The following table provides known constants used in determining the properties of the air at an altitude of interest.

Table 3. Calculation constants

Parameter	***Value***	***Units***
Sea Level Standard Temperature (T_0)	288.15	K
Sea Level Standard Pressure (P_0)	101325	Pa
Reference Air Viscosity (μ_0)	1.827E-5	kg/(m-s)
Lapse Rate (L_{apse})	.0065	K/m
Universal Gas Constant (R_u)	8.31447	J/mol-K
Molar Mass of Dry Air (M_{air})	0.0289644	kg/mol
Gravity (g)	9.80665	m/s^2
Specific Heat Ratio for Air (γ)	1.4	-

One of the first parameters to determine for an AWE system is to select the desired operating altitude. This is a design choice for the designer. The choice can be based upon factors that answer such questions as: What altitudes are the strongest winds at? What altitudes will the FAA allow the AWE system to fly? What altitudes can physically, feasibly be reached with the design? For this design tool, the calculator is able to estimate the properties of the air, up to an altitude of at least 12,000 meters.

The most important characteristic of the atmosphere for wind-powered generation is the density of the air, since the function for the power available in wind is directly proportional to the air density. The air density can be estimated using Equations 11, 12, and 13.[28]

$$T = T_0 - L_{apse}h \tag{11}$$

$$P = P_0 \left(1 - \frac{L_{apse} h}{T_0}\right)^{\frac{g M_{air}}{R_u L_{apse}}} \quad (12)$$

$$\rho = \frac{P M_{air}}{R_u T} \quad (13)$$

Density is dependent upon the temperature and pressure of the air. Equation 11 shows that the temperature can be estimated as T_0 (the sea level standard air temperature of 288.15 K) at sea level, and then decreases at a constant rate, L_{apse} (called the lapse rate), as altitude (*h*) increases. Equation 12 estimates the air pressure as a function of the altitude (*h*). In addition, Equation 13 gives the air density as a function of the estimated pressure and temperature.

These estimates should be reasonable throughout the troposphere, the region of the atmosphere extending from sea level up to 8,000 m to 16,000 m, depending on latitude. The troposphere is thicker at the equator and thinner at the poles. The air density estimates given by Equations 11-13 will provide sufficient accuracy for the altitudes most important for analysis of AWE systems because the strongest jet streams tend to range from 8,000 m to 12,000 m, with the higher jet streams closer to the equator. The importance of the reduction of density with altitude is shown by comparing the density at sea level with the density at 12,000 m. The density at 12,000 m is about ¼ the density at sea level. Thus, the power in the wind at 12,000 m would also be ¼ of the power at sea level for the same wind speed.[29]

Another important characteristic of the air for analyzing an AWE system is the speed of sound. This will be used later to calculate the Mach number and Reynolds number, numbers which will be used to determine the lift and drag coefficients. Equation 14 gives the speed of sound, where $R_{air} = \frac{R_u}{M_{air}}$ and T was determined previously.

$$V_s = \sqrt{\gamma R_{air} T} \tag{14}$$

Dynamic viscosity (μ) of air is a function of temperature and is obtained from Sutherland's Formula[30, 31], given in Equation 15. The Reynolds number is calculated later using the dynamic viscosity.

$$\mu = \mu_0 \frac{(291.15+120)}{(T+120)} \left(\frac{T}{291.15}\right)^{\left(3/2\right)} \tag{15}$$

Now that the characteristics of the atmosphere are defined, the amount of energy in the wind can be estimated.

2.2. Design Parameters

After defining the atmosphere, the next step in analyzing the performance of an AWE rotor is to define the design parameters for the device. One of the most important design choices is the diameter (*D*) of the blade, because the power generation is proportional to the area swept out by the rotor. This choice is based on the desired power output—the larger the blade diameter, the more power produced, but the diameter will be limited by the physical limits of the blade's structural strength.[5]

Upfront, the diameter (*D*), number of blades (*B*), and hub diameter (D_h) are selected. Initially, these numbers are estimated; however, they will be adjusted based on the results of the performance calculations. Once the diameter and hub diameter have been selected, Equation 16 gives the blade length. A blade element analysis will be used to analyze the blade/rotor performance, so the blade is divided into a certain number (N) of blade stations. Ten blade stations will be used for this project (ten to twenty is commonly used). Equation 17 gives the length of each blade station (l_s).[5]

$$l = \frac{D - D_h}{2} \tag{16}$$

$$l_s = \frac{l}{N} \tag{17}$$

Next, tip speed ratio (λ) is a very important parameter because it affects the amount of power that can be pulled out of the wind and the amount of thrust on the wind-rotor. The tip speed ratio can be controlled in a number of different ways, such as adjusting the amount of power drawn from the wind or by using blade stall or blade pitch angle.[5] For this performance analysis, focus is on the performance at the maximum power tip speed ratio, which can be estimated using Equation 18.[32]

$$\lambda_{maxPower} = \frac{4\pi 1.25}{B} \tag{18}$$

With tip speed ratio set, the next thing to do is to calculate the blade rotation speed (Ω) using Equation 19. With (R) as the rotor radius in meters, and the wind speed (U) in meters per second, the result of this equation will be in radians per second (to get rpm, multiply by $60/2\pi$).[5]

$$\Omega = \frac{\lambda U}{R} \tag{19}$$

2.3. Optimum Wind-Rotor Blade Design

The ideal shape for a wind-rotor blade design can be determined using the combination of blade element theory and momentum theory. The derivation of the equations used to determine the ideal shape of a wind-rotor blade is given in *Wind Energy Explained*.[5] The method gives the ideal twist angle and chord lengths for each blade station, which result in the maximum power. This maximum power occurs when all of the blade elements are at the angle of attack that produces the best lift-to-drag ratio for the airfoil used.

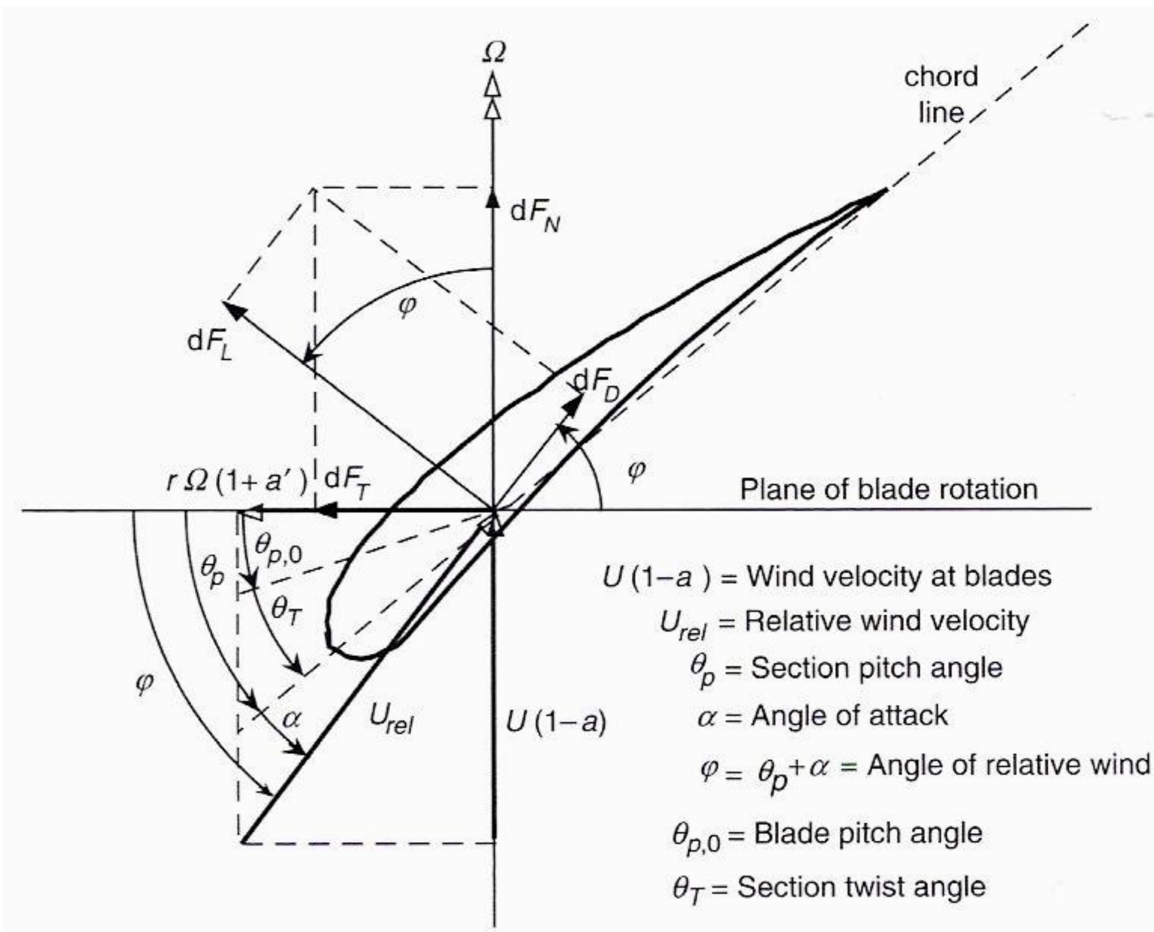


Figure 21. Blade geometry[5]

Figure 21 shows the blade geometry defining the blade and wind angles associated with the blade element analysis. The axial induction factor (a) is defined as the fractional decrease in wind velocity between the free stream and the rotor plane.[5]

With the blade geometry defined, the properties at each blade station can then be computed. Equation 20 gives the local speed ratio (λ_r) for an intermediate radius (r). The blade element theory and momentum theory give Equations 21 and 22 for the local angle of relative wind (φ) and ideal local chord length (c), respectively. The ideal chord length is one of the necessary blade design parameters.[5]

$$\lambda_r = \frac{\lambda(r)}{R} \tag{20}$$

$$\varphi = \left(\frac{2}{3}\right) tan^{-1}\left(\frac{1}{\lambda_r}\right) \tag{21}$$

$$c = \frac{8\pi r}{BC_l}(1 - cos\,\varphi) \tag{22}$$

Once the angle of relative wind is found, the section pitch angle (θ_p) that will give the angle of attack for minimum drag is calculated using Equation 23. The section twist angle (θ_T) is then found by subtracting the blade pitch angle ($\theta_{p,0}$), as shown in Equation 24. The pitch angle is an important operating parameter to the AWE system, and the twist angle is an important design parameter that defines the twist in the system blades.[5]

$$\theta_p = \varphi - \alpha \tag{23}$$

$$\theta_T = \theta_p - \theta_{p,0} \tag{24}$$

Once the blade chord and twist angles are defined, the rotor performance is estimated using Equation 25. The coefficient of power (C_p) is a measure of the fraction of power in the wind that is extracted by the wind-rotor.[5]

$$C_p = \left(\frac{8}{\lambda^2}\right) \int_{\lambda_h}^{\lambda} sin^2(\varphi)\,(cos\,\varphi - \lambda_r\,sin\,\varphi)(sin\,\varphi + \lambda_r\,cos\,\varphi)\left[1 - \left(\frac{C_d}{C_l}\right) cot\,\varphi\right] \lambda_r^2 d\lambda_r \quad (25)$$

This integral could also be estimated by splitting the blade up into elements contributed by each blade station (ΔC_p). The contribution of each blade station to the power coefficient is calculated with Equation 26.[5]

$$\Delta C_p = \left(\frac{8}{\lambda^2}\right) sin^2(\varphi)\,(cos\,\varphi - \lambda_r\,sin\,\varphi)(sin\,\varphi + \lambda_r\,cos\,\varphi)\left[1 - \left(\frac{C_d}{C_l}\right) cot\,\varphi\right] \lambda_r^2 \Delta\lambda_r \quad (26)$$

The term $\Delta\lambda_r$ is the increment of tip speed ratio from one blade station to the next. All the blade stations have the same value of $\Delta\lambda_r$ if the blade stations are each the same length (see Equation 27).[5]

$$\Delta\lambda_r = \lambda_{ri} - \lambda_{r(i-1)} \quad (27)$$

The coefficient of lift and drag (C_l and C_d) in Equations 25 and 26 are the lift and drag coefficients for the blade airfoil at the angle of attack of minimum drag. Next, sum the ΔC_p's for all blade stations to get the total power coefficient (C_p), as in Equation 28. The power output of the optimized rotor is then calculated with Equation 29.[5]

$$C_p = \sum \Delta C_p \quad (28)$$

$$P = C_p \frac{1}{2} \rho A U^3 \quad (29)$$

The coefficient of power essentially represents the efficiency of an AWE system. The power (P) represents the main goal of these calculations, finding the actual power output of the wind turbine's rotor. The power output will be used when designing the system for its applications' power requirements.[5]

It is interesting to evaluate the percent of power contribution ($\%C_p$) from each blade station, Equation 30, and compare it to the percent of area swept out by each blade station ($\%A$) using Equations 31 and 32. ΔA_{bs} is the area swept out by a blade station at radius (r). The percentage of power contributed by each portion of the blade is important because the portions of the blade delivering the most power to the overall system power output can be evaluated. By comparing $\%C_p$ to $\%A$, portions of the blade that are contributing more to the total output than could be accounted for just based on the area swept out by that portion of the blade, are revealed.

$$\%C_p = \frac{C_{p,bs}}{C_p} 100\% \tag{30}$$

$$\Delta A_{bs} = \pi \left[\left(r + \frac{1}{2} l_s \right)^2 - \left(r - \frac{1}{2} l_s \right)^2 \right] \tag{31}$$

$$\%A_{bs} = \frac{\Delta A_{bs}}{A} 100\% \tag{32}$$

Some other parameters of interest in designing the AWE system blades are the local solidity (σ'), the axial induction factor (a), and angular induction factor (a'). The local solidity (Equation 33) is the fraction of the circle swept out by the blade that is actually solid blade structure. The axial induction factor is given in Equation 34. The angular induction factor (a') is a measure of the wake rotational speed (ω) induced on the wind flow as it travels through the rotor. The angular induction factor can be calculated in the case of optimum rotor at max power using Equation 35.[5]

$$\sigma' = \frac{Bc}{2\pi r} \tag{33}$$

$$a = \frac{1}{\left[1 + \frac{4 \sin^2 \varphi}{\sigma' C_l \cos \varphi}\right]} \tag{34}$$

$$a' = \frac{1-3a}{4a-1} \tag{35}$$

Thus far, these calculations do not include the effects of tip losses. Tip losses for optimal wind-rotor blade design can be accounted for and the equation for these losses will be given in the next section under "General Blade Design." Tip loss analysis is used to more closely reflect realistic flight for the AWE system.

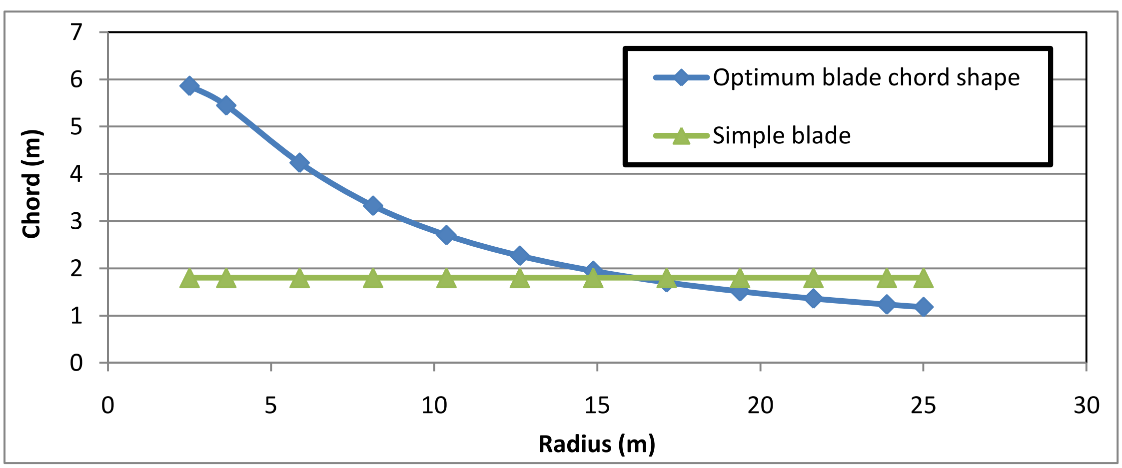


Figure 22. Chord shape comparison for an optimum design blade and a simplified constant chord blade with a 50 m diameter and a 5 m hub diameter

A sample calculation of an optimum design rotor using a 50-meter diameter at an altitude of 10,000 meters with a wind speed of 25 m/s was conducted using the design tool. Figure 22 shows the resulting chord shape as a function of blade radius.

The resulting calculations for twist angle, chord, and power coefficient are given in the table below; Table 4 shows a sample of the results based on the equations from the previous section.

Table 4. Optimum blade sample results for a 50 m diameter blade

Blade Station	*r* (m)	θ_T	chord	*ΔCp*
0	2.5	29.732	5.863	
1	3.625	22.687	5.450	0.013
2	5.875	14.129	4.237	0.023
3	8.125	9.425	3.327	0.033
4	10.375	6.533	2.705	0.042
5	12.625	4.597	2.268	0.051
6	14.875	3.215	1.948	0.059
7	17.125	2.182	1.705	0.068
8	19.375	1.382	1.515	0.076
9	21.625	0.745	1.362	0.084
10	23.875	0.225	1.237	0.092
tip	25	0.000	1.183	
				Cp 0.5416

Factors to notice from these calculations are the large nonlinear changes in twist and chord along the radius. In addition, the power coefficient (C_p) of 0.542 is relatively high compared to the theoretical limit of 0.593 (called Betz limit). This result is reduced by 5% to 0.489 when tip losses are accounted for.

2.4. General Blade Shape Performance

The optimum design calculated in the previous section requires blades with complex twist and cord shapes that vary non-linearly with radius. These blade designs would be difficult to build and would be expensive in an AWE system. This section explains the procedure for predicting the performance for any given general blade shape. Then, the performance of blades with simplified designs can be analyzed. Blade simplifications can include no twist or linear twist, and constant or linear chord variations. The equations in this section have also been derived in *Wind Energy Explained*, using blade element theory and momentum theory. The local speed ratio (λ_r) is again calculated using Equation 20, and $\Delta\lambda_r$ is calculated using Equation 27.[5]

The designer sets the twist angle, blade pitch angle ($\theta_{p,0}$), and chord. A good starting point for theses values are the blade pitch and twist angles similar to the ones calculated in the optimum design. For twist that varies linearly with radius, use the total twist angle at the root (θ_{Troot}) and Equation 36 for (θ_T) at each blade section. Calculate the section pitch angle (θ_p) using Equation 37.

$$\theta_T = \theta_{Troot}\left(1 - \frac{r}{R}\right) \tag{36}$$

$$\theta_p = \theta_{p,0} + \theta_T \tag{37}$$

The next step is to solve iteratively for the axial induction factor (a) and angular induction factor (a') for each blade station. Start with an initial guess for these values. A good starting guess could be the values from the optimum blade design. Then, using these values, calculate the angle of relative wind (φ) and angle of attack (α) using Equations 38 and 39.

$$\varphi = tan^{-1}\left(\frac{1-a}{(1+a')\lambda_r}\right) \tag{38}$$

$$\alpha = \varphi - \theta p \tag{39}$$

To include tip loss effects, calculate the tip loss factor (F) using Equation 40. F is a value between zero and one. To neglect the tip losses, set F equal to one.

$$F = \frac{2}{\pi} cos^{-1} \left[exp \left(- \left\{ \frac{(B/2)[1-(r/R)]}{(r/R) \sin \varphi} \right\} \right) \right] \tag{40}$$

The local solidity (σ') is calculated using Equation 33. Use the calculated values for φ, F, and σ' to calculate the next guess for (a) and (a') with Equations 41 and 42.

$$a = \frac{1}{\left[\frac{4F \sin^2 \varphi}{\sigma' C_l \cos \varphi} - 1 \right]} \tag{41}$$

$$a' = \frac{1}{\left[\frac{4 F \cos \varphi}{\sigma' C_l} - 1 \right]} \tag{42}$$

If no coefficient of lift (C_l) data is available, then estimate (C_l) using Equation 43.

$$C_l = 4 \sin \varphi \frac{(\cos \varphi - \lambda_r \sin \varphi)}{\sigma' (\sin \varphi + \lambda_r \cos \varphi)} \tag{43}$$

If airfoil data is available, use the coefficient of lift (C_l) and drag (C_d) data for the calculated Mach (M) or Reynolds (Re) numbers and angle of attack (α). The Mach number for each blade station is calculated in Equation 45 using the relative wind velocity (U_{rel}) seen by the airfoil at the blade station. U_{rel} is determined with Equation 44. The Reynolds number (Equation 46) is a function of density, chord, relative wind velocity and dynamic viscosity, which were estimated earlier.

$$U_{rel} = U \sqrt{1 + \lambda_r^2} \tag{44}$$

$$M = \frac{U_{rel}}{V_s} \quad (45)$$

$$Re = \frac{\rho c U_{rel}}{\mu} \quad (46)$$

Once the new guesses for (a) and (a') are calculated, the values are substituted back into Equation 38 to recalculate φ and iterate the process over again. The process is repeated a few times until the difference between the guess and the calculated values for (a) and (a') is sufficiently small.

2.5. Automated Calculations

This process would be extremely time-consuming if done by hand, but it can be automated using a spreadsheet or other computer math tool. For this to work, the data for the lift and drag coefficients must be imported into the spreadsheet in such a form that the software can automatically select the correct coefficients based on the calculated Mach or Reynolds numbers and angle of attack. One way to get this data is to import it from an airfoil software tool, such as XFOIL or XFLR5. The advantage of this method is that designers can obtain data for any airfoil shape they can find or create. This method, however, has the disadvantage of losing accuracy at high speeds where compressibility effects become an important factor.

Another very convenient source for lift and drag data is found using C-81 Tables. These tables have been used in the past for helicopter development programs. The airfoil lift and drag data is tabulated for angles of attack from -180 degrees to zero to +180 degrees, and for several Mach numbers from zero to about one. These tables are very flexible because they cover the full spectrum of possible angles of attack and Mach numbers. Unfortunately, this method only works for airfoils for which C-81 table data can be found.

Now, calculations for the blade station coefficient of power (ΔC_p) and the total power coefficient (C_p) with Equations 47 and 48, respectively, can be done.

$$\Delta C_p = F\left(\frac{8}{\lambda^2}\right)\lambda_r{}^3 a'(1-a)\left[1-\left(\frac{C_d}{C_l}\right)\cot\varphi\right]\Delta\lambda_r \tag{47}$$

$$C_p = \sum \Delta C_p \tag{48}$$

The power output (P) of the AWE rotor is the power available in the wind (P_{wind}) times the power coefficient (see Equations 49 and 50). Since the efficiency (η) is the fraction of the power available that is extracted, the efficiency is also the coefficient of power (Equation 51).

$$P = C_p \frac{1}{2}\rho A U^3 \tag{49}$$

$$P_{wind} = \frac{1}{2}\rho A U^3 \tag{50}$$

$$\eta = \frac{P}{P_{wind}} = C_p \tag{51}$$

Additionally, the blade station local coefficient of thrust (ΔC_{Tr}), and the total thrust coefficient (C_T) are computed via Equation 52 and Equation 53 respectively. Again, the coefficient of power represents the efficiency of the system and P represents the amount of power the system can generate.

$$\Delta C_{Tr} = \frac{\sigma'(1-a)^2(C_l \cos\varphi + C_d \sin\varphi)}{\sin^2\varphi} \quad (52)$$

$$C_T = \sum\left(\frac{\Delta A}{A}\Delta C_{Tr}\right) \quad (53)$$

The total thrust (T) on the rotor is given by Equation 54. This result is very important to the AWE system because it represents the force keeping the system airborne.

$$T = C_T \frac{1}{2}\rho A U^2 \quad (54)$$

Again, these calculations are essential to designing an AWE system because they determine the coefficient of power, which represents the efficiency of the system, and power (P). The power result is the key since it is used to design the system in order to meet energy requirements.

2.6. Keeping the AWE System Airborne

To get vertical lift, the thrust vector must be pointed upward. The thrust vector always points in the direction of the axis of rotation. Thus, in order to provide vertical lift, the axis of rotation must point at some angle (θ) above the horizontal. Assuming the prevailing wind is in the horizontal direction, this reduces the projected rotor disk area facing into the wind. The effective area swept out by the wind-rotor is calculated with Equation 55.

$$A_{eff} = A\cos\theta \quad (55)$$

The reduced power and thrust generated is determined by substituting the effective area (A_{eff}) into power and thrust Equations 49 and 54 instead of the total area

(A). The vertical component of the thrust is determined using the component of the thrust in the vertical direction, as shown in Equation 56. The units of this result will be in Newton's, and the lift capacity at the calculated flight conditions in kilograms is found by dividing the vertical thrust by gravity (g), shown in Equation 57.

$$T_{Vertical} = T \sin\theta \tag{56}$$

$$Lift\ Capacity = \frac{T_{Vertical}}{g} \tag{57}$$

A set of calculations with a simplified blade design have been conducted for comparison to the optimum blade design. The blade design is a constant chord blade with no twist, using a Sikorsky SC1095 helicopter airfoil as shown in Figure 23 below.[33]

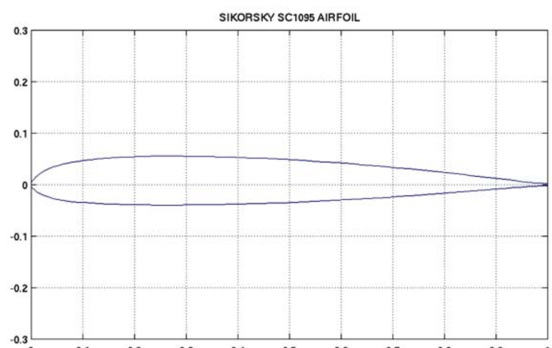


Figure 23. Sikorsky SC1095 rotorcraft airfoil[33]

The operating conditions are set at 10,000 m altitude with 25 m/s wind speed. In addition, the blade design is again a 50 m diameter and a 5 m hub diameter. The calculations for power coefficient and thrust coefficient are given in Table 5 below.

Table 5. Constant chord, no twist blade calculations

Blade Station	*r* (m)	*ΔCp*	ΔC_T
root	2.5		
1	3.625	-0.0035	0.0111
2	5.875	-0.0012	0.0191
3	8.125	0.0039	0.0313
4	10.38	0.0338	0.057
5	12.63	0.0473	0.0772
6	14.88	0.0564	0.0911
7	17.13	0.0627	0.1046
8	19.38	0.0475	0.0915
9	21.63	0.0025	0.0572
10	23.88	-0.0092	0.0528
tip	25		
		Cp 0.2402	C_T 0.5927

The power coefficient for this scenario (*Cp* of 0.24) is about half of the power coefficient for the optimized blade (*Cp* of 0.49). The power coefficient values for the simplified blade change a great deal depending on the operating conditions and blade pitch angle.

In summary, Airborne Wind Energy devices must be highly reliable and inexpensive to produce and maintain in order to keep lifetime costs low. Simple blade designs will better meet these goals because they are cheaper to produce and will have less internal stresses causing fatigue. The equations presented represent a design tool that allows blade design of a rotor-based Airborne Wind Energy system. The design tool assists in capturing the AWE resource in a way that will produce power for the least cost, while being highly efficient over a wide range of operating conditions. Results and analysis from the blade design tool will be presented and discussed in Chapter 4.

3. Base AWE System Feasibility

To develop the AWE technology, it is important to select good DoD locations for pilot AWE systems to be deployed. These early AWE systems will help to determine the best implementation methods, as well as build reliability and confidence in the technology. Therefore, the first locations selected should be ones that will provide the best probability of project success. To evaluate which USAF bases would provide the best chance for success, a decision matrix was developed where a random sample of several bases were scored on four categories. The four categories used for the assessment are: base vulnerability to power outages; wind energy available locally in the higher-altitude winds; space available; and energy and cost savings.

Each of these categories were given equal weight, and the methods used to determine the score for each category are described in the following sections. For this study, 27 major continental USAF bases were randomly selected. Additional Air Force bases, or any other location, can also be compared using the same methodology described in this chapter. Thus, AWE project planners can use these steps as a standard of comparison to use when finding suitable locations for their project.

3.1. Base Vulnerability

The score for base vulnerability to power outages was based on the work of Sabatowski, Thal, and Sitzabee.[34, 35] This score reflects a motivational factor for the installation. An USAF base installation and its leadership will have a greater desire to develop alternate sources of energy if they are already searching for ways to improve the security and reliability of their power supply. Sabatowski evaluated all of the major continental USAF installations on several factors, and developed a vulnerability index score for each location. High index scores indicate bases with high vulnerability to power outages.

For the AWE viability decision matrix, the vulnerability index score is then normalized on a 10-point scale by dividing each score by the highest score and then multiplying by 10. Thus, the base with the highest score (e.g. Tinker AFB) receives 10 points, and the rest fall somewhere between 0 and 10.

3.2. Local AWE Power Density

The next score in the AWE viability decision matrix is for the energy available locally in the high altitude winds at each USAF base. The score for this is based on the "Global Assessment of High-Altitude Wind Power," published by Archer and Caldeira.[13] As shown previously in the thesis, Archer developed an atlas with a map showing the average annual wind power density at any location in the world (see Figure 24). (Note: this figure is the same as Figure 5, given in Chapter 2; the figure is again presented below, repeated as Figure 24).

The left side of the figure shows average annual wind power density for an AWE system if it is flown at the optimal altitude. The top box shows the power density available at least 50% of the time; the next box gives the power density available at least 68% of the time; and the bottom box gives the power density available at least 95% of the time. The right portion of the figure illustrates the optimal altitude for an AWE system that would reach those power densities.

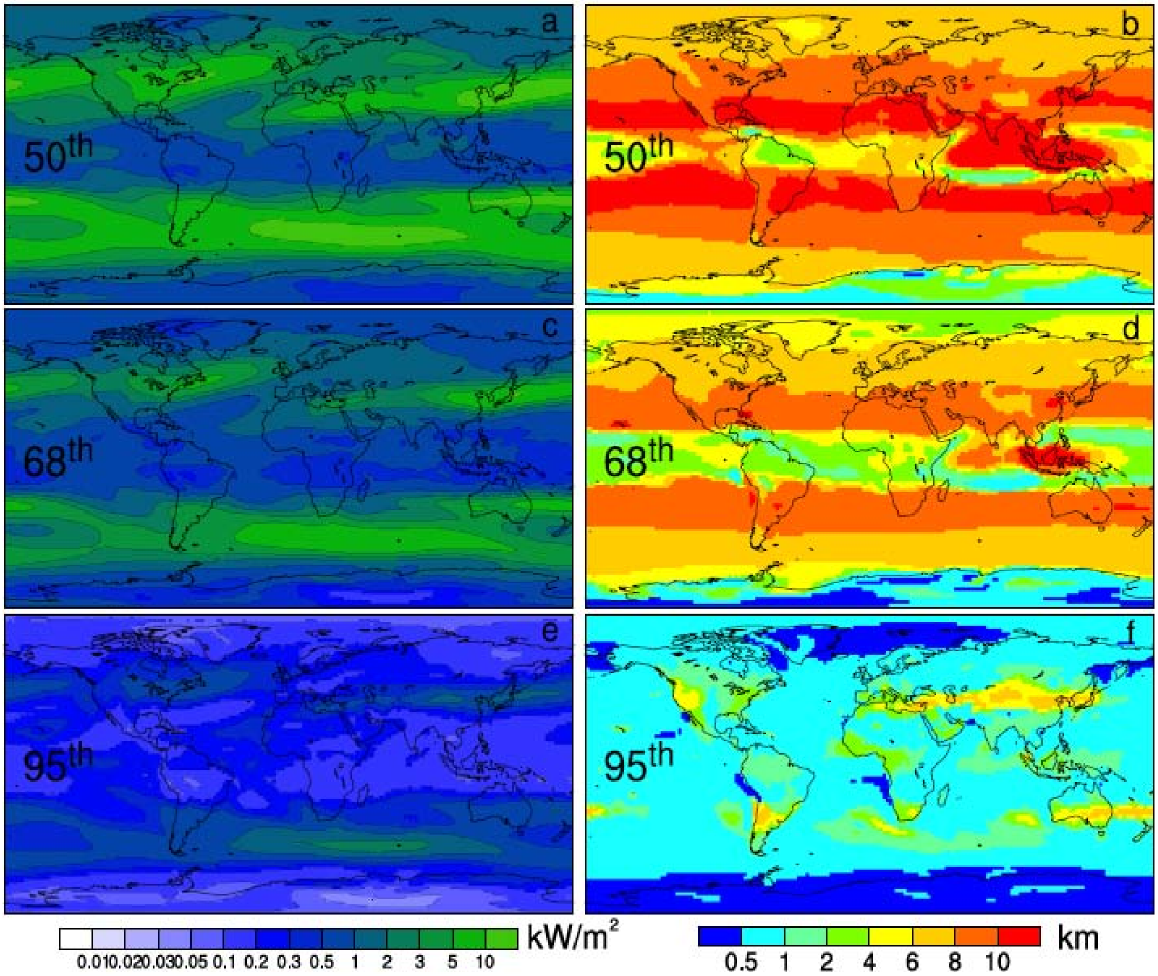


Figure 24. Optimal wind power density (kW/m^2, left panels) and optimal height (km, right panels) that were exceeded 50%, 68%, and 95% of the time during years in 1979-2006[13]

In order to determine the power density available at each USAF base, it was useful to overlay the wind power map covering the U.S. on top of a map of the bases being evaluated. A screen capture of the wind power map, zoomed in upon the U.S., was taken as seen in Figure 25 below.

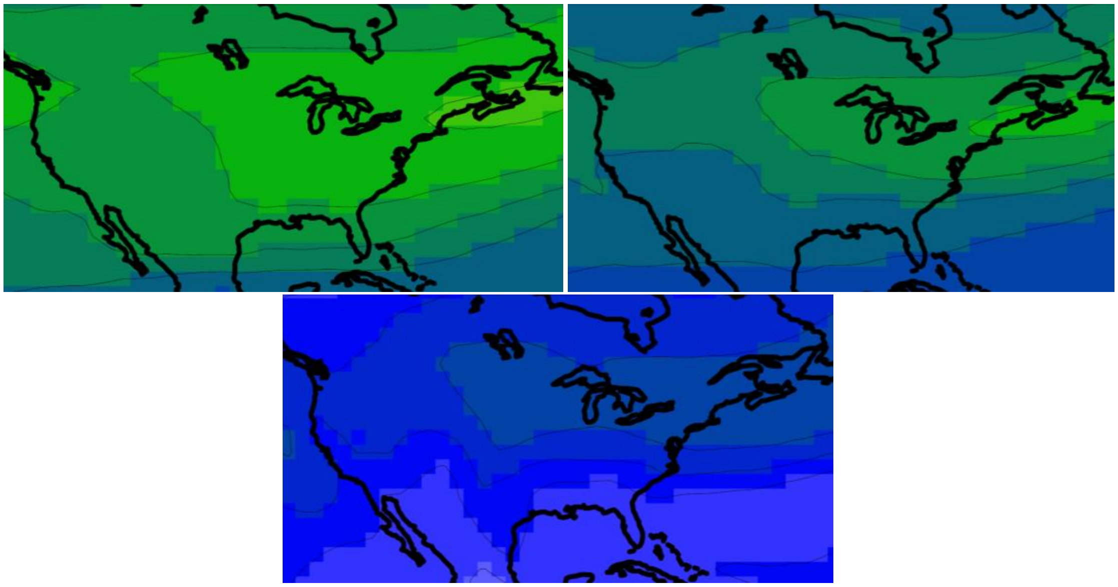


Figure 25. Screen shots from the *High-Altitude Wind Power Atlas*;[13] zoomed in on the U.S. for the 50th (top left), 68th (top right), and 95th (bottom) percentile power densities

Three images were taken, one for each for the 50th, 68th, and 95th percentile power densities. Each image was then overlaid on top of a Google earth map of the U.S., and a pin was placed in the location of each USAF base being evaluated (see Figure 26).

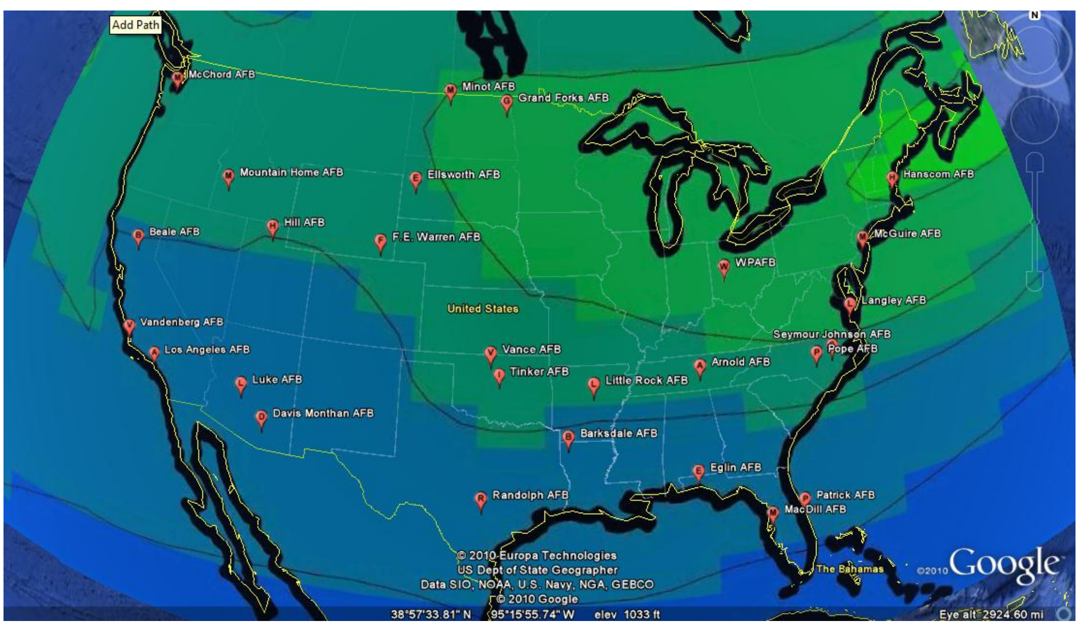


Figure 26. Google Earth view of the U.S., with a High-Altitude Wind Power map overlay; the red paddle icons indicate the locations of the bases being evaluated; the image overlay in this shot is for the 68th percentile wind power density

This method allows an easy way to determine the power density at each base. It also allows other bases or locations to be added easily by doing a search for the base location on Google earth and adding a marker. A good estimate for the wind power density available at a location was determined by comparing the color of the location on the map with the power density key (Figure 27) and observing the base locations proximity to the contour lines.

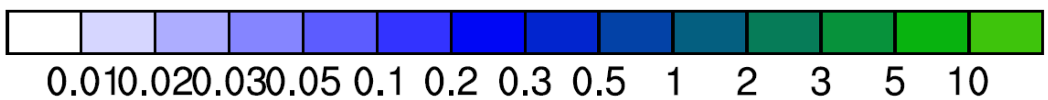


Figure 27. Color key for the High-Altitude Wind Power map in kW/m^2

The power density was recorded for each of the power density percentiles (50th, 68th, and 95th), then the score was obtained by normalizing the data on a 10-point scale, with the highest score receiving 10 points. Thus, each location was given three scores, one for each power density percentile, and each of these scores was weighted equally within the power available score category.

The AWE power density score is important because it will indicate which bases have the strongest and most consistent high-altitude wind energy resource available in their local area. A comparison between the data in Figure 26 and a map of ground-based wind will reveal that the resource is actually excellent all across the U.S. However, the score in this category will give project planners a good idea of how the wind energy potential of one location will compare against other locations. The wind power density trend for the U.S. reveals that the strongest wind power density is in the northeast, and decreases for locations moving toward the south and the west. Higher scores in this category will translate directly to cost savings for an AWE project, since each system will produce more energy per unit in locations with the higher power density score.

3.3. Space Available

The success of an AWE system project at an USAF base is also dependent upon finding space available to install and run the system. This will be particularly important in the early stages of the system development and testing because it will take some time for designers to improve the reliability and safety of the systems. Thus, the pilot program systems will require a larger safety buffer zone.

Some factors to consider are: How much ground space is available next to the base being considered? Is there space available in other locations nearby? How busy is the air space in the area being considered? Answers to these questions were estimated using data for population density maps and air traffic maps. The score for the space available category is composed of three factors: population density in the county where the USAF base is located; population density in a county adjacent to the base; and airline traffic density.

Ideally, an AWE project planner would like to place the system right next to the USAF base (or other location) that they are providing power for. A good indicator to estimate the possibility of finding a suitable location with enough space is the population density of the county where the base is located. Counties with low population densities will have a better chance of having the space available for the project. They will also tend to have lower costs associated with using the land. The bases in counties with very low population densities were given the highest score.

The data for population density came from the 2009 population estimate data given on the census.gov website.[36] The population density for each county was recorded, and then a score was given on a 10-point scale. The scale used is shown in Table 6. A map showing a visual representation of the population data used is shown in Figure 28.

Table 6. Population Density Score key

Persons/mi^2	Score
<10	10
10-49	9
50-99	8
100-199	7
200-299	6
300-399	5
400-499	4
500-699	3
700-999	2
1000-2000	1
>2000	0

In some cases, USAF bases are located in counties where the population density is very high. This can occur if the base is in the same county as a city that is very large, yet it still may be possible to find a location within a reasonable distance that may be suitable. To estimate the likelihood of this, the population density of counties adjacent to the bases' county was also evaluated. The population density of the adjacent county with the lowest population density was recorded, and a score was given for it based on the same scale shown in Table 6.

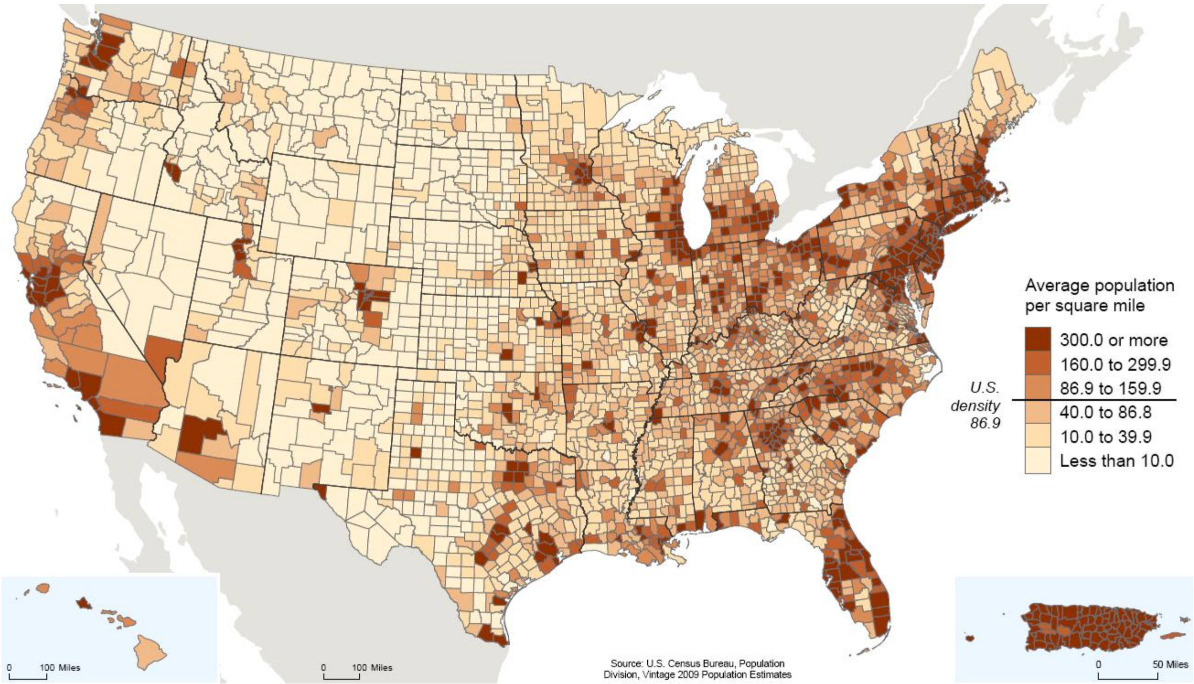


Figure 28. Map of 2009 population density by county for the U.S. (U.S. Census Bureau)[36]

Of course, it is more desirable to have the power system located directly next to the user. So the bases county score is weighted higher within the space available category than the score for adjacent counties. The split used was 40% for the base county, and 20% for the adjacent county. The final 40% of the space available category score is for the local air traffic density.

In order to operate an AWE system, it will be necessary to have sufficient air space available in which to operate. The altitudes that these systems will be most efficient at will be at altitudes that will be competing with other air traffic for space. Therefore, bases in locations with low air traffic density will be more likely to obtain approval to operate.

To compare the air traffic density of the local area for each USAF base, an application tool called Airline Route Mapper was used.[37] The tool shows the airline routes of over 650 airlines worldwide. Screenshots were taken of the airline routes over the U.S., and the images were overlaid on Google Earth in the same manner as the wind power density maps. In order to get a good resolution for the airline routes in the screenshot images, the Airline Route Mapper was zoomed in upon the U.S., dividing the country into approximately 4 even images. The images were then lined up on Google Earth using the contours of the coasts and by matching up the major airports. Below is a screen shot of the images overlaid on Google Earth, with the USAF bases showing (Figure 29).

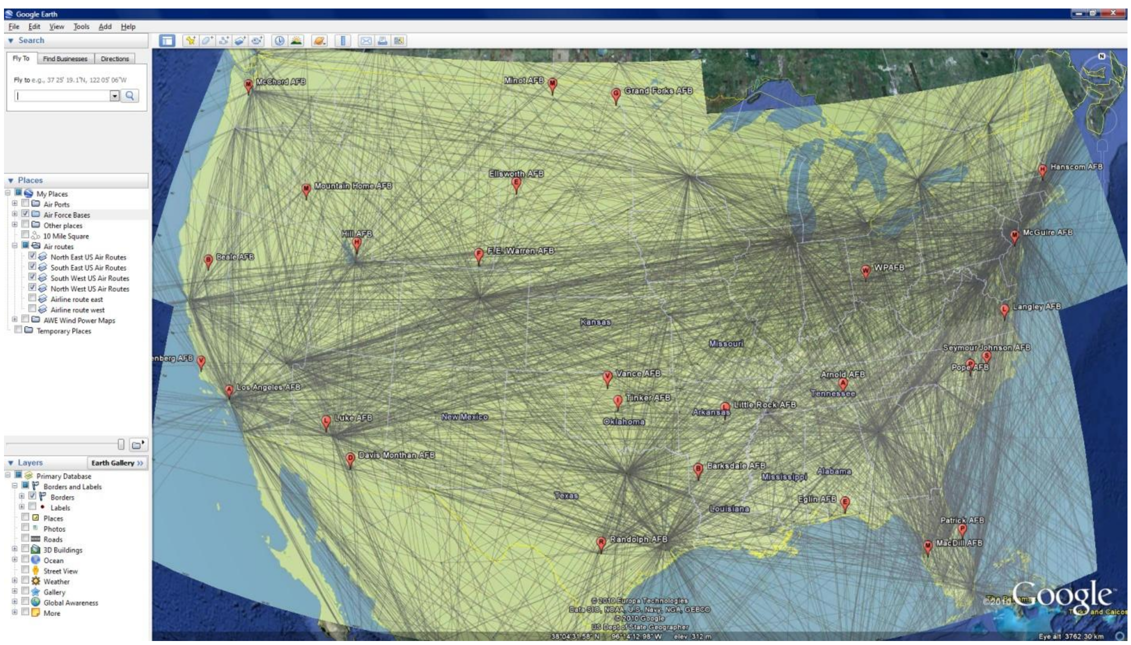


Figure 29. Airline route maps overlaid on a Google Earth map of the U.S.; airline routes shown are from Airline Route Mapper data from December 2010.[37]

To compare the density of the air traffic over each USAF base, Google Earth was zoomed in directly over each base to an eye altitude of 200 miles. A screen shot was taken from this perspective for each USAF base, and the image was saved. Figure 30 below shows two sample images taken this way. The entire set of images can be found in Appendix B.

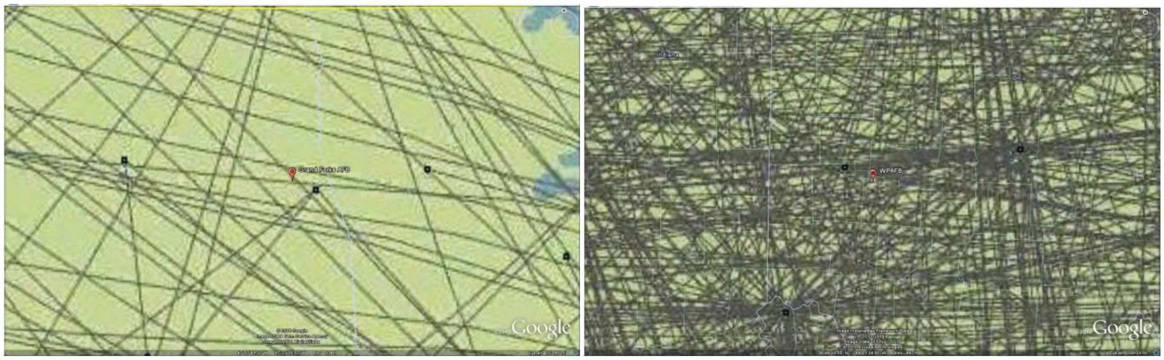


Figure 30. Screen shot of air traffic over two USAF bases, taken at an eye altitude of 200 miles; left is Grand Forks AFB, ND, and on the right is Wright-Patterson AFB, OH

The images were then sorted in order, from least air traffic to most air traffic. This was done with an objective visual inspection, while locations with large airports nearby and a lot of air traffic overhead were ranked lower.

Table 7. Air Traffic Density Score Key

Air Traffic Density	Score
Low	10
Medium Low	8
Medium	6
Medium High	4
High	2
Extreme	0

Once the bases were ranked, they were grouped into one of six categories (shown in Table 7) and scored accordingly. The air traffic ranking and scores, from lowest to highest amount of air traffic, is given in Table 8.

Table 8. Air Force Base Air Traffic Density Ranking and Scores

Rank	AFB	Score	Rank	AFB	Score	Rank	AFB	Score
1	Ellsworth	10	11	Beale	6	21	Seymour Johnson	2
2	Grand Forks	10	12	Tinker	6	22	Pope	2
3	Minot	10	13	Hill	6	23	WPAFB	2
4	Mountain Home	10	14	Little Rock	6	24	Patrick	0
5	Davis Monthan	10	15	FE Warren	6	25	Hanscom	0
6	Vandenberg	8	16	Luke	4	26	Langley	0
7	Eglin	8	17	Barksdale	4	27	McGuire	0
8	Vance	8	18	Arnold	4			
9	Randolph	8	19	Los Angeles	4			
10	McChord	8	20	MacDill	2			

If additional locations need to be evaluated, a screenshot for the additional location can be taken and compared to the rest of the images found in Appendix B. The appendix is used to evaluate and compare new images, identifying which one matches a base the best. Then, the same score is applied to the base that it matches.

3.4. Energy and Cost Savings

The final category for comparison is the USAF base potential cost and energy savings. Two factors were considered that contribute to this metric: base energy requirement and the cost of electricity. Within the energy and cost savings category the factor for cost of electricity was weighted higher at 60% because it contributes more directly to cost savings per kWh of electricity produced. The electricity requirement factor was weighted 40%.

The first factor examined was the base electricity requirement. The amount of energy being used by a base represents how much energy the project can replace with renewables; based on economies of scale, larger projects will tend to be more cost effective per watt-hour produced. Larger projects are also more attractive because they would make a larger contribution to U.S. independence from foreign oil, and directly enhance national security. Therefore, bases that use more electricity annually are given higher scores.

The data used for this evaluation came from the research of Sabatowski.[34, 35] USAF base energy consumption figures were collected directly from the USAF civil engineering energy managers. The data collected included the total annual energy consumption of the base, presented in Mega watt-hours (MWh), for 2007. A table showing the energy consumption data for most of the major USAF installations is displayed in Appendix B.

To obtain the energy savings score, the total annual energy consumption (MWh) was recorded. Then, the base energy consumption was normalized on a 10-point scale, the base with the highest energy consumption receiving a score of 10 points.

The second factor considered was the cost of electricity within the USAF bases local area. Higher local electricity costs would lead directly to higher cost savings for a base implementing an AWE project. Thus, bases in areas with higher electricity prices were also given higher scores.

The average price of electricity for each state is published by the U.S. Energy Information Administration on their website.[38] Below is a map showing the 2009 average price of electricity by state.

The price for each state an USAF base resides in was recorded. Then, the cost of energy score was computed by normalizing the price figures on a 10-point scale, with the base with the most expensive electricity price given a score of 10 points.

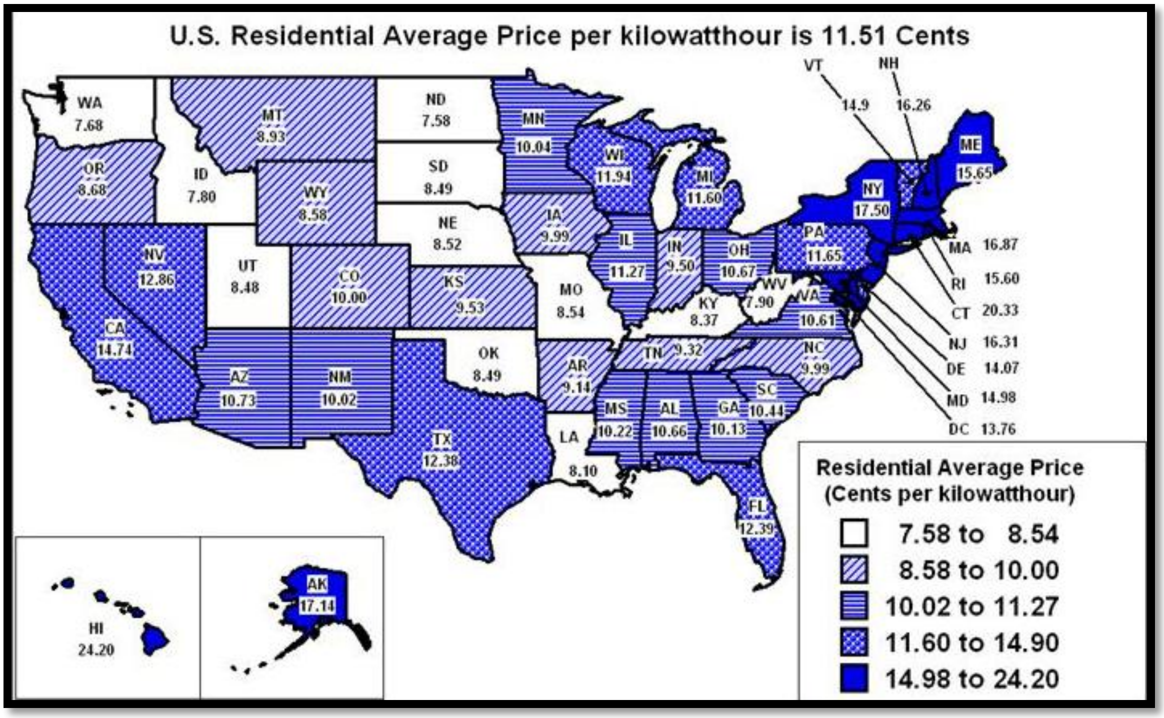


Figure 31. U.S. residential average price of electricity (kWh) for 2009[38]

3.5. Base AWE Feasibility Methodology Summary

The final step for the base AWE decision matrix was to combine the scores from the four categories, with each category being weighted equally. The end results were scores for each base, given on a 100-point scale (0-100 points). These scores were then ranked from highest (best) to lowest. The top six bases were further evaluated, and some preliminary design and estimates for system efficiency, productivity, and cost were outlined. These results, along with the results of the design tool and the AWE feasibility study, will be presented and analyzed in Chapter 4.

IV. Analysis and Results

Chapter 4 is presented in three parts. First, a discussion about the purpose, sample results, analysis and comparisons, and validation of the design tool is communicated. Second, the AWE feasibility study for USAF bases is given. The third and final part of the chapter consists of applying the knowledge learned about AWE performance, efficiency, and design (using the design tool) to the top USAF bases so that a realistic plan for achieving AWE projects will be met. Preliminary design of what an AWE system project would look like at each base, how efficient each system would be, how much power each system would produce, the size of each system, and the potential cost savings and impact of each AWE system are presented.

1. Design Tool for AWE Blade Design

The goals in this first section of Chapter 4 are to: 1) use the design tool to show sample results; 2) compare the results, produced through the design tool for a theoretical AWE system, with three different blade designs operating at three different locations; and 3) validate the design tool results by comparing them to the results of the paper, "Harnessing High-Altitude Wind Power."[10]

It should be emphasized that the design tool was created so that developers would be able to use it to help design and predict the performance of an AWE system for a desired application. The inputs and outputs could be selected by researchers and developers in order to fulfill specific purposes adapted to the individual needs of each USAF base or location. The selection for the sample inputs will first be explained. Then, comparisons to examine trends among AWE sample outputs will be given.

To compare the performance of an AWE system with different blade shapes, and to validate the design tool, a hypothetical AWE system was created. First, several design choices where made which led to the design of this theoretical AWE system. Then, this system was applied to three different USAF base locations. The design tool created several sample outputs for each blade design, and analysis is provided. Three USAF base locations were selected, and the locations pinpointed what local power density and altitude should be used for the calculations.

The two main inputs for each USAF base location were the altitude and the power density. The power density was based on the high-altitude wind power map for the fiftieth percentile power densities.[13] Selected USAF base locations were evaluated at three different altitudes: 1,000 m, 5,000 m, and 9,000 m. These values were chosen because 9,000 m was the altitude where the locations studied had the best power density. 1,000 m was chosen because this range was high enough in altitude to be outside of most of the planetary boundary layer effects, but remained at the lower end of high-altitude wind energy. 5,000 m was chosen because it provided a good idea of what performance to expect when an AWE system would be operated at an intermediate altitude.

The three USAF base locations that were evaluated are: Hanscom, MA; Wright-Patterson, OH; and Ellsworth, SD. Hanscom AFB was selected because this base had the highest power density. WPAFB was selected because of its access to AFIT and to the Air Force Research Labs (AFRL), in addition to having good power density and a high-energy consumption and cost rankings. Ellsworth AFB was selected because it was a top six USAF base (determined by the base feasibility matrix results), and this base had a significant amount of space available, making Ellsworth a good candidate for piloting an early AWE project.

The design tool was used to plot the chord and the twist for an optimal blade design. The analysis, below, will compare the performance of this optimized design to some simplified designs. This was done to study how much impact there was on efficiency and power output performance when the blade design was simplified. The two simplified designs to be compared are: simplified blade A, a no twist and no chord variation; and simplified blade B, a variation with some linear twist and constant chord (Figure 32 and Figure 33).

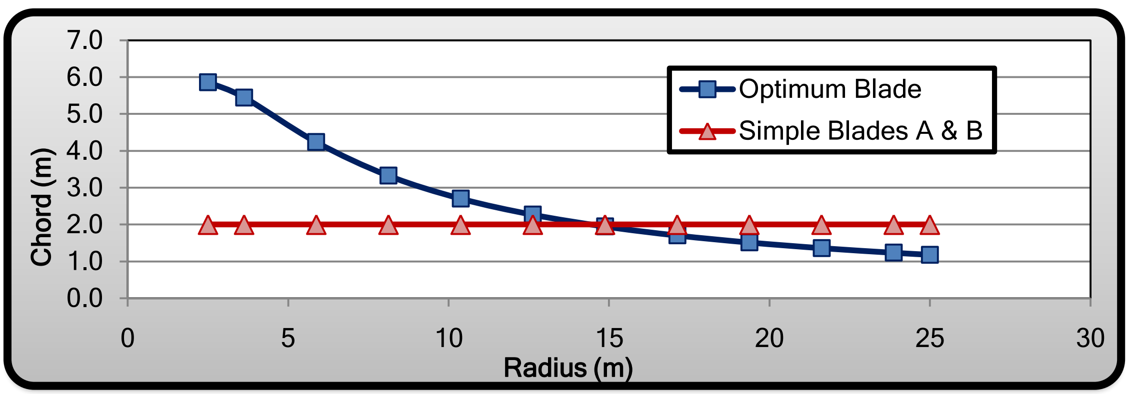


Figure 32. Blade chord shape, as a function of the radius

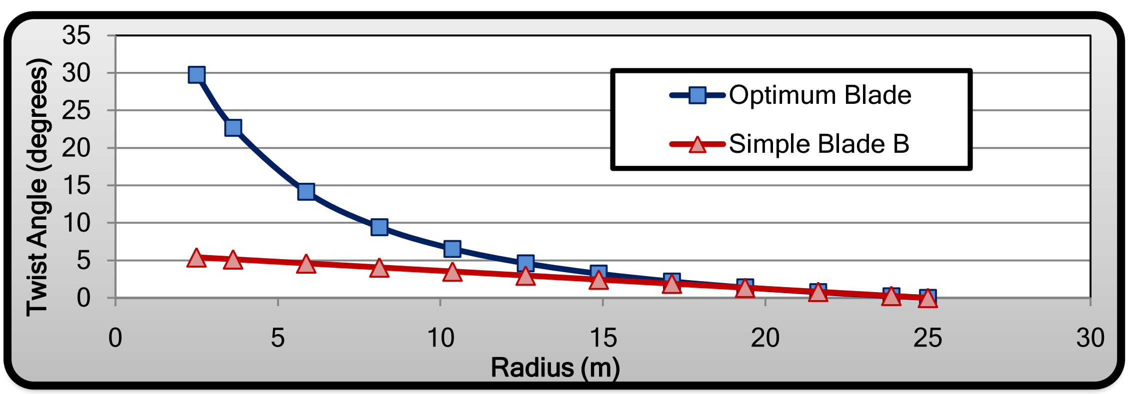


Figure 33. Blade twist angle, as a function of radius

A design choice of a two-meter chord length for the simplified blade was chosen because it was a good approximation of the average chord length, when compared to the optimal blade chord shape (Figure 32). Several values of linear twist for the simplified blade B were tried, and the twist value that provided the best performance, over the range of operating conditions sampled, had 6° of twist (shown in Figure 33). Note that the best twist was small when compared to the optimum blade design that had up to 30° twist at the blade root. However, Figure 33 shows that the twist angle was very similar to the optimized blade twist angle on the outer portions of the blade. Since the outer portions of the blade would rotate at the highest speed and provide most of the power for the system, this relationship between the twist on the optimized blade and the simplified blade B makes sense.

Several more design choices were made for this analysis. One design choice was a 50 m rotor diameter, with a 2.5 m rotor hub radius and a 25 m blade radius. The number of rotor blades was set at two. The number of rotors for the airborne system was another design choice, and for this study, one single rotor was selected. The airfoil used was the Sikorsky SC1095 airfoil because it seemed to perform well at high blade speeds.[33] The system was designed to have a 50% capacity factor, using the annual average power densities of the 50th percentile power densities, given in the *High-Altitude Wind Power Atlas*.[13]

Additionally, a design choice (and variable with significant impact) was the angle of the rotor axis. The angle of the rotor axis was set at 45° above the horizontal for the calculation of maximum vertical lift and lift capacity, but for everything else, it was assumed that the system was facing directly into the wind. The power and efficiency of the system would also be affected when pointing the system upward to create vertical lift. To calculate the loss of power and efficiency, the cosine of the angle would be multiplied by the power output calculated (assuming that the system was facing directly into the wind). This loss of efficiency in an AWE system would vary from somewhere between 10-30%, depending on the steepness of the upward pointing angle of the rotor axis. Stronger winds and a lighter AWE system would allow smaller upward pointing of the rotor axis. Since the thrust vector would be much larger with stronger winds, the vertical component would then be sufficient to keep an AWE system airborne at lower angles.

There is a functional tradeoff between having vertical lift, or having power and thrust, as the rotor points more and more upwards, power and thrust are reduced. However, as more and more of the thrust vector points upward, it results in more vertical lift. This variable is again important to the AWE system because the maximum vertical lift would occur at approximately a 45° angle; however, the best power produced is at an angle of 0°, which has zero vertical lift. Thus, a balance for an AWE system must be struck somewhere between 45° and 0°–this would give enough lift, but maximize the power output of a system.

Table 9, Table 10, and Table 11 show the key results from the design tool for the three locations and the three altitudes studied. Table 9 gives the results for the optimized blade design. The results for the simplified blade A, with no twist or chord variation, are given in Table 10. Finally, Table 11 presents the results for the simplified blade B, with constant chord and 6° of twist.

Table 9. Optimized blade shape performance

Altitude	Power density	Power coeff	Efficiency	Power out	Thrust	Max vertical lift	Lift capacity
9,000 m	kW/m^2			W	N	N	kg
Hanscom	10	0.489	48.9%	9,683,311	495,738	247,869	25,276
WPAFB	7	0.489	48.9%	6,735,715	389,188	194,594	19,843
Ellsworth	4	0.489	48.9%	3,845,578	267,841	133,921	13,656
5,000 m							
Hanscom	3	0.489	48.9%	2,913,320	259,163	129,582	13,214
WPAFB	2	0.489	48.9%	1,926,957	196,741	98,371	10,031
Ellsworth	1.6	0.489	48.9%	1,559,070	170,827	85,414	8,710
1,000 m							
Hanscom	0.45	0.489	48.9%	443,336	84,750	42,375	4,321
WPAFB	0.3	0.489	48.9%	294,300	64,493	32,247	3,288
Ellsworth	0.3	0.489	48.9%	294,300	64,493	32,247	3,288

Table 10. Constant chord, no twist blade performance

Altitude	Power density	Power coeff	Efficiency	Power out	Thrust	Max vertical lift	Lift capacity
9,000 m	kW/m^2			W	N	N	kg
Hanscom	10	0.304	30.4%	6,026,561	321,294	160,647	16,381
WPAFB	7	0.354	35.4%	4,873,262	246,536	123,268	12,570
Ellsworth	4	0.388	38.8%	3,050,965	201,606	100,803	10,279
5,000 m							
Hanscom	3	0.385	38.5%	2,291,787	228,215	114,108	11,636
WPAFB	2	0.375	37.5%	1,478,350	178,358	89,179	9,094
Ellsworth	1.6	0.381	38.1%	1,213,082	154,441	77,221	7,874
1,000 m							
Hanscom	0.45	0.380	38.0%	344,593	76,630	38,315	3,907
WPAFB	0.3	0.381	38.1%	228,966	58,309	29,155	2,973
Ellsworth	0.3	0.380	38.0%	228,710	58,314	29,157	2,973

Table 11. Constant chord, 6° linear twist blade performance

Altitude	Power density	Power coeff	Efficiency	Power out	Thrust	Max vertical lift	Lift capacity
9,000 m	kW/m^2			W	N	N	kg
Hanscom	10	0.289	28.9%	5,561,599	290,436	145,218	14,808
WPAFB	7	0.331	33.1%	4,562,816	223,148	111,574	11,377
Ellsworth	4	0.403	40.3%	3,168,419	217,801	108,901	11,105
5,000 m							
Hanscom	3	0.399	39.9%	2,375,009	212,147	106,074	10,816
WPAFB	2	0.396	39.6%	1,558,982	162,469	81,235	8,284
Ellsworth	1.6	0.402	40.2%	1,281,321	138,553	69,277	7,064
1,000 m							
Hanscom	0.45	0.402	40.2%	364,355	68,738	34,369	3,505
WPAFB	0.3	0.402	40.2%	242,005	52,308	26,154	2,667
Ellsworth	0.3	0.402	40.2%	242,014	52,306	26,153	2,667

In each of the tables, the first two columns were design choices that were inputs to the design tool. The power density used was the annual average for the location at each altitude, referenced in the *High-Altitude Wind Power Atlas*.[13]

The biggest findings to see from this data are the high potential of the power that could be generated from these systems. For example, at Hanscom AFB, all three of the blade designs generated over 5.5 MW from a single 50 m diameter AWE system, at an altitude of 9,000 m. Even Wright-Patterson and Ellsworth would generate over 4.5 and 3.5 MW, respectively.

Figure 34, from *Wind Power Explained*, illustrates that a ground-based wind turbine with a 50 m diameter would only be rated for 660 kW. In order to achieve capacities similar to an AWE turbine (also 50 m in diameter), a ground-based turbine would need to be at least 126 m in diameter (nearly three times in diameter, and over six times the area).[5]

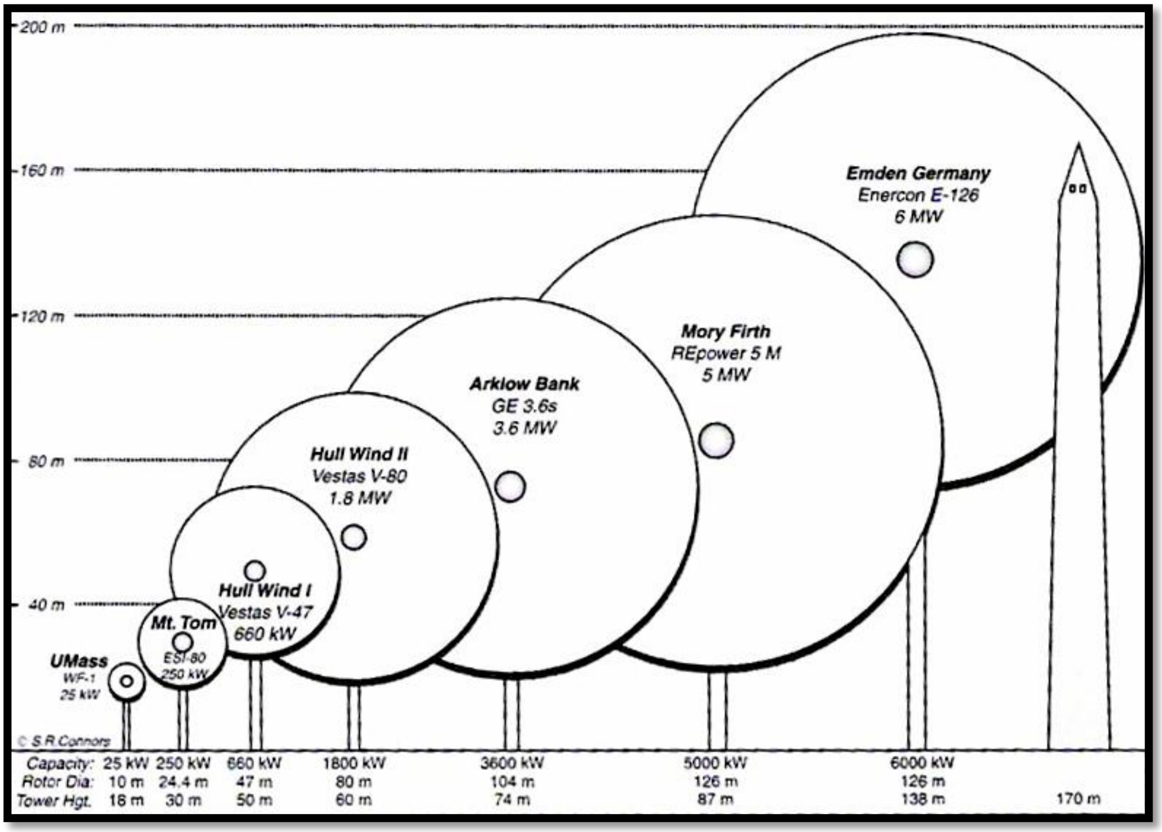


Figure 34. Sample size, diameter, and rated power for ground-based wind turbines[5]

Another observation from the sample blade performance tables was that the optimized blade design calculator, for the scenarios used, predicted an efficiency of 48.9%. At lower wind speeds, this was a reasonable estimate if a good airfoil design would be used with a high lift-to-drag ratio. The estimates for efficiency and power were higher than they should be for the higher wind power densities at Hanscom and Wright-Patterson (at 9,000 m). This was because the optimal blade design calculations did not take into account the decrease in lift-to-drag when the blade would operate at higher Mach numbers in the transonic region (in the range of Mach 0.7 to 1). Notice that the efficiencies calculated for the simplified blades at Hanscom and Wright-Patterson (at 9,000 m) were much lower than the optimal blade estimated efficiency. This was because the calculator for the simplified blade design *did* include the effects of increased drag as the blade speed approaches Mach 1. One way to avoid this increased drag from operating in the transonic region would be to increase the number of blades on an AWE system. This would allow the system to operate at a lower rotational speed, meaning the blades could be kept at a speed under the transonic region.

Additionally, another important note when comparing the three different blade designs were the efficiency differences between each of them. For the simplified blade A, with constant chord and no twist, the efficiency across almost all of the operating conditions was about 10% less than what was predicted for the optimized blade design. With the exception of the high-altitude Wright-Patterson and Hanscom locations, the efficiency drop was larger because of the increased drag effects as the blade wind speed approached Mach 1, as mentioned above.

For simplified blade B, with constant chord and 6° of twist, the efficiency loss was about 8%. A 2% increase over blade A, improvement came because it was closer to the optimal shape than the non-twist version. Yet, it was not as much of an improvement as a designer could hope for: an 8% loss in power generation, over the lifetime of a system, would have tremendous cost impact. Therefore, the simplified blade would need to have a *very* large cost savings in the form of being less expensive to manufacture and/or having higher reliability in order to compensate for this loss.

An important trend to observe was the large difference in power generated at the varying altitudes. The power generated at 1,000 m tended to be less than $1/10^{th}$ of the power, generated at the same location, at 9,000 m. The power available at 1,000 m would still be significantly greater, and a lot more consistent, than what would be available at ground level. However, an AWE system operator would only want to operate at the lower altitudes if it was necessary. On the other hand, at 5,000 m, the power that could be generated was significantly lower than at 9,000 m. This option could still be attractive because the resulting power generating predictions were significant.

The thrust and lift capacity numbers were also revelatory, because they showed that for the lower altitudes, there was a lift capacity of 2,500-4,000 kg for a system. For the higher altitudes, the lift capacity ranged from 10,000-25,000 kg per system. This was remarkable, since 9,000 m of system cable would have significant weight.

From these results, a recommendation for blade design would be best satisfied by using the design tool to tweak an AWE system design until satisfactory compromise between efficiency needs and ease of manufacturing and reliability are met. The actual structural analysis will be left for future work; however, the data presented using the design tool will give AWE system designers accurate expectations of where to begin.

To validate the design tool, the tool was used to duplicate the calculations of similar research in “Harnessing High-Altitude Wind Power.”[10] The researchers developed a four-rotor, Flying Electric Generator (FEG) designed to generate 240,000 W (see Figure 19). The specifications for the FEG rotors were entered into the design tool, and the results calculated by the design tool were compared to the results given in this paper to see if both came up with similar performance predictions.

The FEG used four, two-bladed rotors, each having a diameter of 10.7 m. The rated wind speed was set at 18.4 m/s, and the operating altitude was designed for 4,600

m. These operating conditions would produce a wind power density of about 2.4 kW/m^2. The blade used for the design comparison had a constant chord with no twist, comparable to the simplified blade A studied earlier in the chapter. For these inputs, the design tool calculated a coefficient of power of .395 (39.5% efficiency). This result was very close to the estimated value, given in "Harnessing High-Altitude Wind Power," of .4 (40% efficiency). After combining the calculated result for four rotors and accounting for an electrical transmission efficiency of 90%, the design tool predicted a power output of 306 kW. Assuming a rotor axis angle of 45°, this resulted in a calculated power output of 216 kW. This result was extremely close to the paper's predicted performance of 240 kW. The small difference could be accounted for by assuming a slightly different rotor axis angle. Thus, the design tool was validated.[10]

2. USAF Base AWE System Feasibility

When considering the development and use of a new technology like AWE, it was important to select a location for the project that would provide the best chance for success. Therefore, the goal of this evaluation was to provide a standardized method to compare USAF bases (or other sites) to see which locations would be the best for a pilot AWE project. A good score on this evaluation does not necessarily guarantee success, nor does a bad score mean an AWE project would not provide great benefit to that location. Each location would have various needs and challenges that will have to be worked out in order to implement an AWE project of such scale and complexity. This section of the research will identify and highlight key factors that should be considered in order to pick the best base locations. Twenty-seven major continental USAF installations were evaluated, based on these factors: base vulnerability to power outages; wind energy available locally in the higher-altitude winds; space available; and energy and cost savings. The top bases in each category were then identified, and six USAF bases with top overall scores (as well as Hanscom, for comparison) are presented and discussed.

The information below presents the results of the USAF base feasibility matrix, and provides analysis and discussion. The data used for the evaluation, and the results, are shown in the subsequent table and figure (Table 12 and Figure 35).

2.1. USAF Base AWE Feasibility Category Results

The results of the U.S. Air Force base AWE evaluation are displayed in Table 12. The final scores are visually represented in Figure 35. The techniques used for this standard method of comparison were described in Chapter 3. Each of the four AWE feasibility evaluation categories was color-coded; the blue columns in Table 12, and the blue portions of the bar graph in Figure 35, represent the category for power outage vulnerability. Red corresponds to the AWE power density available within the local area. Green illustrates the space available category. The purple color code relates the cost and energy savings category.

The first column in each category gives the overall category score. The following columns contain the raw data for each of the category sub factors. The last columns in each category show the normalized scores for the sub factors, on a 10-point scale.

The four highest scoring USAF bases in the category of vulnerability to power outages are (in order): Tinker, OK; Vance, OK; Little Rock, AR; and McDill, FL. The first three of these four are all within the same general region of the U.S. (each in one of two neighboring states, Oklahoma or Arkansas). This category of vulnerability score was based upon the vulnerability index developed by Sabatowski.[35] These areas have had a history of large power outages, each lasting a long amount of time. The leadership at these USAF bases may be interested in an AWE project in order to help improve the security of their energy supplies.

In the category of local AWE power density, the bases in the best locations for power generation are: Hanscom, MA; McGuire, NJ; Wright-Patterson, OH; and Grand Forks, ND. The best AWE power density in the U.S. is in the New England area, and the wind strength gradually reduces for locations farther south and west (see Figure 26). AWE power was particularly applicable for these locations because a high score here could directly translate into cost efficiency for a system. Each AWE system operating in these locations would produce significantly more power per generating system than at other locations, because of their high scores in this category. The results at these USAF bases would include lower costs for the required upfront infrastructure, as well as lower rates for operating and maintenance costs per MWh of electricity produced.

The USAF bases that received the top scores for the space available category are: Ellsworth, ND; Mt Home, ID; Grand Forks, ND; and Minot, ND. These locations would have a high probability of finding a suitable location on the ground to base an AWE system at, and they would provide a more reasonably sized safety zone than some of the bases in more densely populated areas. These USAF bases would also be more likely to obtain approval to use airspace and to operate at the ideal altitude for power generation. The remoteness and land available at these locations would also contribute to lower costs associated with using the land.

Table 12. Airborne Wind Energy (AWE) USAF base feasibility decision matrix

Air Force Base	State	County	Adjacent County	Power Outage Vulnerability: Category Score	Vulnerability	Vulnerability: Normalized	Local AWE Power Density: Category Score	50th: kW/m²	68th: kW/m²	95th: kW/m²	50th: Normalized	68th: Normalized	95th: Normalized	Space Available: Category Score	County Population Density: persons/mi²	Lowest Adjacent County Density: persons/mi²	Air Traffic Density	County Population Density: Normalized	Lowest Adjacent County Density: Normalized	Air Traffic Density: Normalized	Energy & Cost Savings: Category Score	Energy Requirement: MWh	Cost of Electricity: ¢/KWh	Energy Requirement: Normalized	Cost of Electricity: Normalized	Total	Rank
Arnold	TN	Coffee	Grundy	8.5	0.39	3.4	13.3	7.0	2.5	0.3	7	5	4.0	15.5	122.4	39.2	Medium High	7	9	4	18.3	564,132	9.32	10.0	5.5	55.6	4
Barksdale	LA	Bossier	Webster	12.8	0.59	5.1	10.3	5.5	2.0	0.2	5.5	4	2.9	15	133.0	68.0	Medium High	7	8	4	9.1	108,208	8.10	1.9	4.8	47.2	11
Beale	CA	Yuba	Sierra	2.2	0.10	0.9	9.9	4.0	1.8	0.3	4	3.6	4.3	18	115.4	3.3	Medium	7	10	6	14.8	96,954	14.70	1.7	8.7	44.9	15
Davis Mon.	AZ	Pima	Graham	0.7	0.03	0.3	8.2	4.0	1.5	0.2	4	3	2.9	22	111.0	8.0	Low	7	10	10	11.4	104,520	10.73	1.9	6.4	42.3	19
Eglin	FL	Okaloosa	Covington AL	6.1	0.28	2.4	8.7	5.0	1.5	0.2	5	3	2.4	19.5	191.9	35.6	Medium Low	7	9	8	16.4	301,744	12.39	5.3	7.3	50.6	9
Ellsworth	SD	Meade	Perkins	6.7	0.31	2.7	15.1	5.0	3.0	0.5	5	6	7.1	25	6.9	1.0	Low	10	10	10	8.5	54,442	8.49	1.0	5.0	55.4	5
F.E. Warren	WY	Laramie	Platte	4.1	0.19	1.7	12.7	4.5	2.5	0.4	4.5	5	5.7	20	33.0	4.0	Medium	9	10	6	9.7	114,214	8.58	2.0	5.1	46.5	14
Grand Forks	ND	Grand Forks	Steele	3.9	0.18	1.6	18.8	7.0	3.5	0.6	7	7	8.6	24	46.2	2.5	Low	9	10	10	8.3	87,578	7.58	1.6	4.5	55.0	6
Hanscom	MA	Middlesex	Hillsborough NH	3.3	0.15	1.3	25.0	10.0	5.0	0.7	10	10	10.0	3	1839.0	463.0	Extreme	1	4	0	15.8	46,586	16.87	0.8	10.0	47.1	12
Hill	UT	Davis	Morgan	7.0	0.32	2.8	11.8	4.5	2.0	0.4	4.5	4	5.7	11.5	1007.0	15.0	Medium	1	9	6	12.3	269,049	8.48	4.8	5.0	42.6	18
Langley	VA	Hampton	York	4.6	0.21	1.8	17.2	7.5	3.0	0.5	7.5	6	7.1	1.5	2805.0	583.5	Extreme	0	3	0	12.4	169,034	10.61	3.0	6.3	35.7	25
Little Rock	AR	Pulaski	Lonoke	16.5	0.76	6.6	11.7	6.5	2.0	0.3	6.5	4	3.6	13	502.0	87.0	Medium	3	8	6	9.5	77,529	9.14	1.4	5.4	50.7	8
Los Angeles	CA	Los Angeles	Kern	13.5	0.62	5.4	8.0	3.0	1.5	0.3	3	3	3.6	8	2427.0	99.0	Medium High	0	8	4	13.6	32,495	14.70	0.6	8.7	43.1	17
Luke	AZ	Maricopa	Gila	2.2	0.10	0.9	8.8	4.0	1.5	0.3	4	3	3.6	12.5	437.0	11.0	Medium High	4	9	4	11.1	89,948	10.73	1.6	6.4	34.6	26
McChord	WA	Pierce	Lewis	3.9	0.18	1.6	11.9	5.0	2.5	0.3	5	5	4.3	16.5	477.2	31.0	Medium Low	4	9	8	8.4	87,355	7.68	1.5	4.6	40.7	20
McDill	FL	Hillsborough	Polk	15.0	0.69	6.0	6.8	3.0	1.5	0.2	3	3	2.1	5.5	1173.0	325.0	High	1	5	2	13.4	133,851	12.39	2.4	7.3	40.7	21
McGuire	NJ	Burlington	Atlantic	1.5	0.07	0.6	20.9	8.5	4.0	0.6	8.5	8	8.6	5	558.6	489.0	Extreme	3	4	0	15.9	80,796	16.31	1.4	9.7	43.3	16
Minot	ND	Ward	Burke	5.0	0.23	2.0	17.0	6.5	3.0	0.6	6.5	6	7.9	24	28.3	1.7	Low	9	10	10	7.9	64,168	7.58	1.1	4.5	53.8	7
Mt Home	ID	Elmore	Camas	1.3	0.06	0.5	12.7	4.5	2.5	0.4	4.5	5	5.7	25	9.4	1.0	Low	10	10	10	7.8	46,237	7.80	0.8	4.6	46.7	13
Patrick	FL	Brevard	Osceola	7.2	0.33	2.9	7.2	3.5	1.5	0.2	3.5	3	2.1	6	527.8	203.8	Extreme	3	6	0	12.3	70,355	12.39	1.2	7.3	32.6	27
Pope	NC	Cumberland	Bladen	4.8	0.22	1.9	13.6	7.0	2.5	0.3	7	5	4.3	10.5	483.4	37.0	High	4	9	2	9.4	30,959	9.99	0.5	5.9	38.3	23
Randolph	TX	Bexar	Bandera	3.0	0.14	1.2	8.8	4.0	1.5	0.3	4	3	3.6	13.5	1332.0	26.0	Medium Low	1	9	8	12.6	92,208	12.38	1.6	7.3	38.0	24
Seymour J.	NC	Wayne	Duplin	3.9	0.18	1.6	13.6	7.0	2.5	0.3	7	5	4.3	12	205.8	65.2	High	6	8	2	10.1	70,730	9.99	1.3	5.9	39.6	22
Tinker	OK	Oklahoma	Lincoln	25.0	1.15	10.0	13.9	6.0	2.5	0.4	6	5	5.7	11.5	1011.0	34.0	Medium	1	9	6	15.7	460,255	8.49	8.2	5.0	66.1	1
Vance	OK	Garfield	Grant	19.6	0.90	7.8	13.9	6.0	2.5	0.4	6	5	5.7	21	55.0	4.0	Medium Low	8	10	8	8.0	27,523	8.49	0.5	5.0	62.5	2
Vandenberg	CA	Santa	San Luis Obispo	4.6	0.21	1.8	9.5	3.5	1.8	0.3	3.5	3.6	4.3	19	148.8	80.9	Medium Low	7	8	8	17.3	241,241	14.70	4.3	8.7	50.4	10
Wright Patt	OH	Greene	Fayette	7.4	0.34	3.0	19.3	8.0	4.0	0.5	8	8	7.1	11	386.3	69.2	High	5	8	2	18.1	488,081	10.67	8.7	6.3	55.8	3
Category Weight				25			25							25							25					100	
Sub Factor Weight						100					33.3	33.3	33.3					40	20	40				40	60		

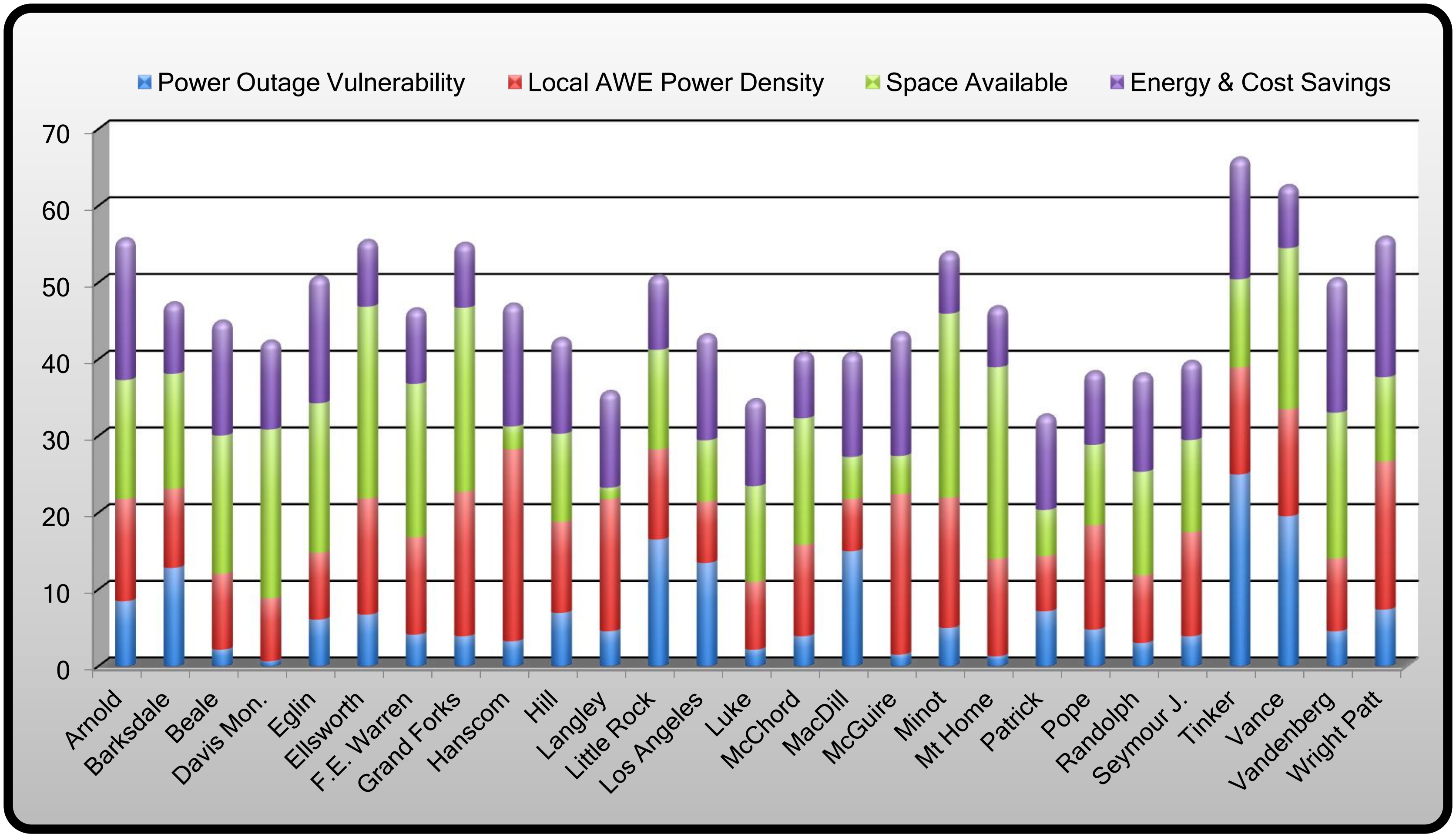


Figure 35. USAF base AWE feasibility study results

Because space available is so important for operating an AWE system, some of the bases with the lowest scores in this category could face some very strong resistance to operating AWE systems in their area. Because of this, it is significant to note which USAF bases received the lowest scores in this category. The worst scores in this category were given to: Langley, VA; Hanscom, MA; McGuire, NJ; and McDill, FL. Some options that these locations would have to consider, in order to operate AWE systems, are listed below.

- Find a hole in the existing air traffic patterns
- Have the FAA create a space where AWE systems can operate
- Find a location (away from large airports) that may have air traffic in the higher altitudes, and operate a system at lower altitudes
- Deploy a sea-worthy version of an AWE system off the coast

Each of these options could present difficult challenges, as well as high additional costs and risks. Note that two of the bases with the worst space available (Hanscom and McGuire) are locations that have the best power density available, as well as having the highest electricity costs. These factors make it tempting to try to implement an AWE system, despite the additional challenges.

Energy and cost savings were accounted for in the final category that was evaluated. The USAF bases with the best score are: Arnold, TN; Wright-Patterson, OH; Vandenberg, CA; and Eglin, FL. Each of these locations have reasonably high electricity prices, and also have *very* high levels of energy consumption that dwarf the consumption of some of the smaller installations. In some cases, these bases consume 10 times more energy than smaller USAF bases. Even though the cost of electricity factor was weighted more than the energy requirement factor, the latter still had a very strong impact on the score for this category. It would be most beneficial to place an AWE project at the USAF bases that scored well in the energy and cost savings category, because this would provide a much larger impact on renewable energy use and cost savings (even if these bases only utilized a single project) than other locations would.

2.2. Results: Overall Best USAF Base AWE Feasibility Scores

The bases that received the top six overall combined scores are (in order, beginning with the highest ranking): Tinker, OK; Vance, OK; Wright-Patterson, OH; Arnold, TN; Ellsworth, SD; and Grand Forks, ND. Figure 36, below, shows the score for the top six bases, as well as Hanscom, MA, for comparison.

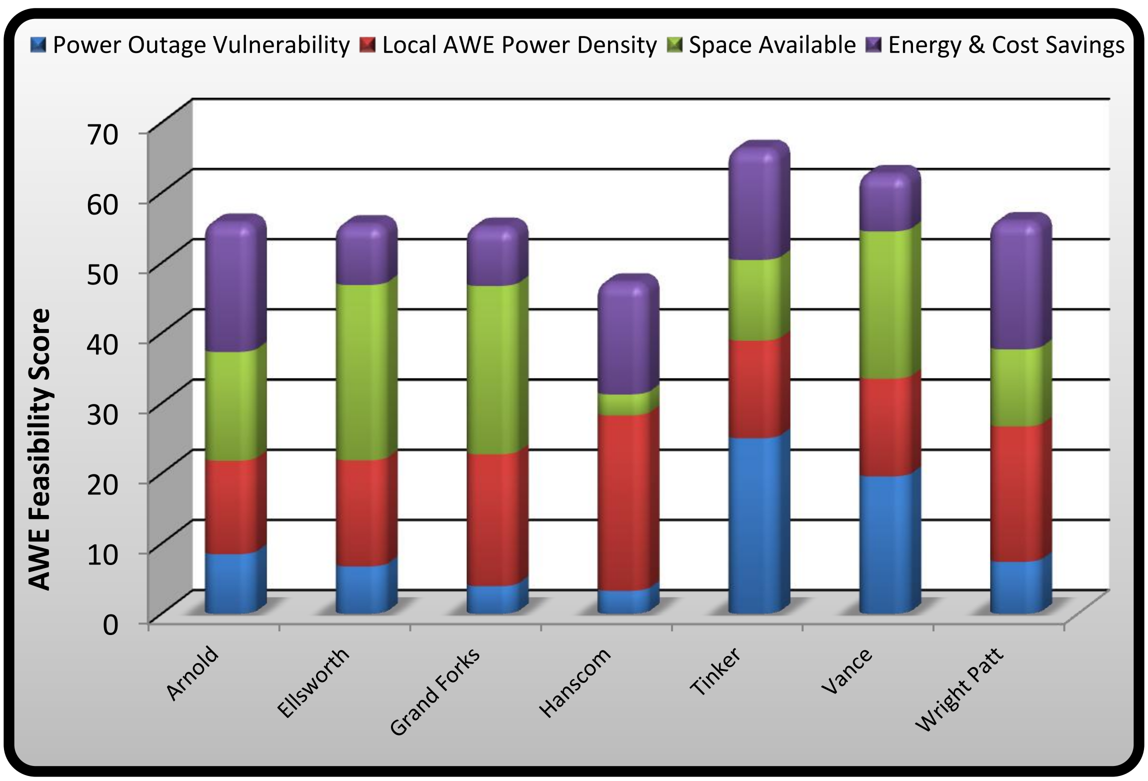


Figure 36. AWE feasibility scores for the top six USAF bases; Hanscom (ranked 12th overall) was also added for comparison, since it had the highest power density score

All of the top six bases scored as a top four base in either one or two categories. For the most part, none of these bases scored poorly in any of the four categories, which could make them balanced options for an AWE project. These top six stand in contrast with Hanscom, which scored very well in two categories, but had very low scores in the space available and vulnerability categories. This imbalance contributed to its relatively lower 12th place overall ranking, and addressed the possibility of some serious implementation difficulties. The low power outage vulnerability for a base means that USAF leadership could have a reduced motivation for the project, and the low space available could cause location difficulties already discussed.

Tinker AFB was given the highest overall score because this base scored fairly well in each category, but additionally had a high vulnerability score. It received the top vulnerability score, which was significantly higher than the number two vulnerability score for Vance AFB. Tinker also has had very large energy consumption, at about 460,000 MWh per year, which is the third highest for energy consumption of the bases studied. Tinker's only weakness was a high county population density; however, there is a county nearby with a low population density, and the air traffic around Tinker is average. An AWE project could need to be some distance from this base, increasing the project costs, but the overall combination of good scores in all categories made this base the best initial choice for an AWE pilot system.

Vance AFB had the next highest overall score. Vance came in second in the vulnerability score, and it had more space available than Tinker. Vance is located close to Tinker, so they both had the same average score for AWE power density available. The biggest weakness for Vance was that this base has had a somewhat low price for electricity, combined with a small energy consumption of only 28,000 MWh. Vance's other high scores suggested that if beginning with a small AWE project is desirable, then this USAF base would be a good place to start.

Wright Patterson Air Force base was third overall. WPAFB received the second highest energy and cost savings score, and the third highest AWE power density score. The combination of these two scores made WPAFB a very exciting location for an AWE project, since it could produce enormous benefits in the form of cost efficiency per MWh produced, as well as provide overall impact and considerable energy benefits through a single project. The challenge at WPAFB was finding available airspace.

Arnold AFB was ranked fourth overall, getting the top score in cost and energy savings. The base has consumed a whopping 564,000 MWh each year. Arnold gets slightly above average scores in the rest of the categories, suggesting that this base would be a well-rounded location for putting an AWE project at; Arnold also has had a high potential to make a large difference in renewable energy use and cost savings.

Ellsworth and Grand Forks Air Force bases had nearly identical overall scores, ranking fifth and sixth respectively. Both bases were in the top four of the space available category (first and third, respectively). Ellsworth and Grand Forks also had good AWE power density scores (seventh and fourth, respectively). However, these bases' vulnerability scores were average, and their energy and cost savings scores were well below average, so the impact of an AWE project would be limited in size. The biggest advantage to these locations would be that they would be relatively easy to site, and they would provide efficient power.

These top six ranked USAF bases comprised the best balance of factors that would contribute to a successful AWE project. The next section will apply some of the data (compiled using the design tool), about AWE performance and design, to the energy requirements of these top ranked bases. Then, projections about what an AWE system at these locations would look like and how it would perform are presented.

3. Preliminary USAF Base AWE System Design and Performance

This final section of Chapter 4 used the design tool and the top six USAF bases (as well as Hanscom) to output an estimated design for an AWE system that would meet each bases' needs. Preliminary design of each base AWE system project, the efficiency of each system, the power output of each system, and the size of each system were proposed. From these factors, the performance of the system, the potential cost savings, and the impact for each base location could be predicted. Overall impact for the DoD is then put forward.

Table 13. Base AWE project design

AFB	Arnold	Ellsworth	Grand Forks	Hanscom	Tinker	Vance	Wright Patt
State	TN	SD	ND	MA	OK	OK	OH
Ranking	4	5	6	12	1	2	3
Power requirement (MWh)	564,132	54,442	87,578	46,586	460,255	27,523	488,081
Annual energy /AWE system (MWh)	24,409	19,054	25,793	36,737	21,448	21,448	29,348
Number of systems to meet demand	29	4	5	2	27	2	21
Annual energy generated (MWh)	566,281	60,971	103,170	58,779	463,273	34,317	493,044
Cost of energy (¢/kWh)	9.32	8.49	7.58	16.87	8.49	8.49	10.67
Value of energy generated (Million)	$52.8	$5.2	$7.8	$9.9	$39.3	$2.9	$52.6
Cost of AWE @ 2 ¢/kWh (Million)	$11.3	$1.2	$2.1	$1.2	$9.3	$0.7	$9.9
Cost savings (Million)	$41.5	$4.0	$5.8	$8.7	$30.1	$2.2	$42.7
% Cost savings	79%	76%	74%	88%	76%	76%	81%

Table 13 shows some projected system design, performance, and cost figures for an AWE project applied to the top six USAF bases, and Hanscom. The table gives an idea of what it would take to meet the needs of an USAF base using an AWE project.

The table shows several aspects of what a projected AWE design would look like. The power requirement for each base, how much energy a single theoretical AWE system would provide annually, and the number of systems needed to meet the demands of each USAF base were presented. Next, the total commercial value of the energy generated for each base (based on current electricity prices) was calculated. Based on the estimated cost of energy to produce AWE power, when compared to current electricity rates, a projection of potential cost savings was made. The cost used for this assessment was 2¢/kWh (see Figure 37).[9, 10] Finally, the total cost savings and percentage of cost savings was determined. The numbers of potential savings using this AWE technology were impressive. Imagine if the USAF's electricity bill could be reduced by 70-80%! *Just these seven combined AWE projects could save the USAF $135 million, annually.*

Source	Average Estimated ¢/kWh
Coal	3.4
Gas	4.7
Nuclear	2.9
Ground Based Wind	5.7
Solar	32.5
AWE	2.0

Figure 37. Comparison of the projected average cost of energy from several sources, based on data from the "High-Altitude Wind Power Generation"[9, 10]

There were several design choices and assumptions used to calculate these figures. First, the same theoretical 50 m diameter AWE system, developed in the design tool section of this chapter, was used. It was assumed that the AWE system would be operated at the altitude with the best power density, which would be at about 9,000 m most of the time. Figure 38 shows the assumed operating power density that an AWE system would use for each USAF base location.

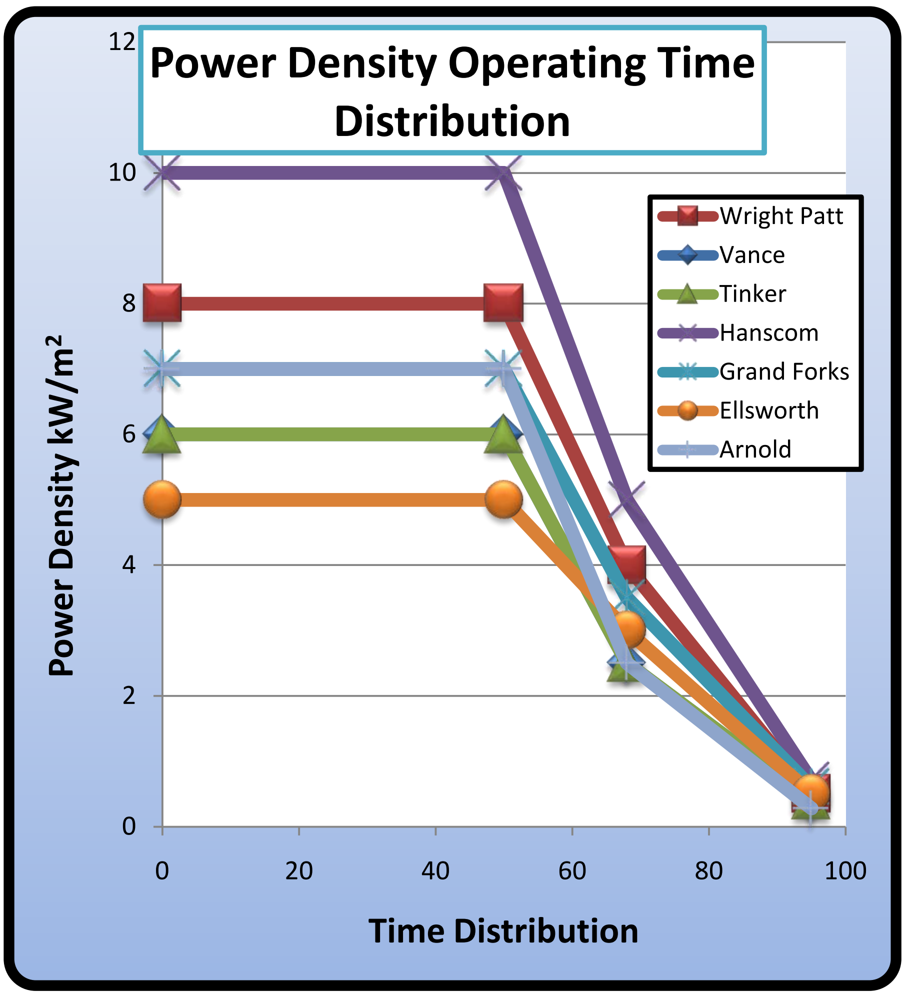


Figure 38. Estimated power density operating time distribution

Figure 38 shows the assumption that 50% of the time, the system operated at its peak (in the 50th percentile power density). For the next percentage of time, it was assumed to operate on a distribution spread linearly between the 50^{th} and 68^{th} percentile power density, and then the 68^{th} to 95^{th} power density. At least 5% of the time, no power would be produced. An aerodynamic efficiency of 30%, and 20% of electrical losses, were also assumed.[10]

The culmination of this information *is* a strategy for future AWE project planners to use in designing and fielding AWE systems. The feasibility of AWE systems at these top six USAF bases is promising. Utilizing AWE systems in other locations can then become more viable, too, as AWE system use is honed and broadened. The design tool has provided a method to analyze and predict the performance of an individual AWE system. The feasibility study provided a method by which a good location could be selected for an AWE project. With this information, users can now plan for and project the benefits that an AWE system could provide for any USAF base, and other energy applications. The examples given in this chapter have helped to demonstrate that there are great benefits in the form of cost savings, energy security, and renewable and clean energy available from the AWE resource.

Based on current technologies, the research has shown how dramatic the impact of AWE systems can be for the DoD. But if battery technologies continue to improve and vehicle fleets transition to electric and hybrid vehicles, electricity consumption will continue to rise over the next several years. It is even likely that many aircraft developed in the future will be electric or hybrid. As this transformation in energy consumption for the U.S. economy and for the DoD occurs, USAF AWE systems would magnify the redeeming impact that the development of AWE technology could have.

V. Conclusions and Recommendations

1. Conclusions of Research

Tapping into higher altitude winds will have many advantages and challenges. For example, one advantage involves the effects that the planetary boundary layer and the jet streams have on power density as altitude increases. These effects lead to wind speeds that are up to 10 times faster than those near the ground, resulting in much higher power density. Another advantage of AWE is that there are more consistent winds, reducing the intermittency and energy storage requirements typically experienced by other renewable energy sources. Also, the energy source comes to the AWE system so that the system can work in isolated locations without importing fuel or being dependent on the local utilities and infrastructure. A major advantage of AWE is the global availability of the high-altitude wind, with a plentiful supply available domestically in the U.S.

The AWE technology does face some significant challenges that need to be overcome. One challenge is the increased complexity of an airborne system. The airborne nature of AWE systems requires the use of lighter and more expensive materials. An airborne system will also require the development of flight controls. The long tether is also a significant design challenge. An additional obstacle to AWE implementation is the issue of allocating air space for the AWE systems to use and share with other aircraft. Despite the challenges of AWE technology, no obstacles appear to be insurmountable.

AWE could be very beneficial for supporting military energy needs. AWE can be used in remote areas, wartime areas, on bases, and in certain areas of civilian populations (where air traffic does not travel). From a civil engineering perspective, AWE can be one of the tools that will be in place first as the military sets up new installations, especially in areas without electricity or other energy sources.

AWE can have great impact on the security, economics, and environment for the USAF, and for the country. Supporting security and national energy independence, AWE can provide a stable and consistent source of domestic energy that is renewable. This will allow the USAF to meet the goals of the National Security Strategy[2] and the Air Force Energy Plan 2010.[39] Economically, researchers estimate that the cost of fully developed AWE technology will produce energy that will be less expensive than any other current source of energy at around 2¢/kWh (see Figure 37).[9, 10] AWE energy can tremendously benefit the USAF, since energy costs the USAF $9 billion per year (8% of the total USAF budget).[39]

If renewables are to be massively adopted by the USAF or the population, the key is that the cost of renewables (such as AWE) must be lower than fossil fuels. Renewables need to be cheaper than fossil fuels and become the go-to source of energy, leaving the fossil fuels as the backup when the availability of the preferred renewable source is not available.

The design tool developed in this research will be beneficial for the future development of AWE systems because it has the adaptability to analyze the blade/rotor performance at any altitude and at any operating condition. The design tool will allow an optimum blade design to be chosen that meets the criteria of having a good combination of efficiency, while being easily and inexpensively manufactured. Key results from the blade design comparisons are that the optimal blade design had 48.9% projected efficiency, while the simplified blade A (with no chord or twist variations) had 30-38%

predicted efficiencies, and the simplified blade B (with constant chord and 6° twist) had predicted efficiencies of 28-40%. The efficiency numbers that the design tool realized are promising. Through the design tool, analysis is ongoing. Changes in the design have a large affect on the performance of the blade, therefore, it is important to use a good tool to design the best AWE system blade for an application.

The design tool is an invaluable instrument for analyzing trends of and coming up with recommendations for blade designs for AWE systems to be used at USAF bases. USAF bases with high vulnerability to utility power disruptions have an increased need for an alternate source of energy to improve the security of their energy.[34, 35] Using the base feasibility decision matrix, bases with a high vulnerability were scored higher because of their greater motivation to acquire an alternate energy source. The higher the power density, the more power a particular-sized system can output. Therefore, the cost of a system at a location with a high power density will be cheaper, so USAF bases with a high power density were scored higher in that category. The AWE system will need adequate air and ground space as a safety zone for testing and implementation; thus, bases with low population densities were scored higher, since finding a suitable location is more likely. In addition, bases that have a low population density in an adjacent county were also scored higher. USAF bases that consume a high amount of energy, and have higher electricity rates, would benefit more by having a larger decrease in their electric bill. These bases were scored highest in that specific category. Each category was weighted based upon its relative importance.

The highest scoring USAF bases of those sampled in the decision matrix were Tinker, Vance, Wright-Patterson, Arnold, Ellsworth, and Grand Forks (Hanscom was also scored), with scores ranging between 40-60 out of 100. USAF bases beyond what Figure 35 shows can additionally be scored in a similar manner, so that planners can decide the viability of their particular base. Once any base has been selected, the design tool can then be used to design, prototype, and manufacture an AWE system tailored to the energy needs of each selected USAF base.

Key results, from applying a preliminary AWE system design to the top USAF bases, showed a potential for 75-80% in cost savings for electricity. Applying airborne wind energy to just these seven bases studied could provide up to $135 million in annual savings for the USAF.

2. Recommendations for Future Research

The results presented in this thesis show that AWE is viable for supplying USAF base energy needs. It is important to continue analysis of energy conversion on different blade designs, because what is most efficient and most cost-effective for the design of an AWE system can then be determined and made into a functioning system for use by the USAF and DoD.

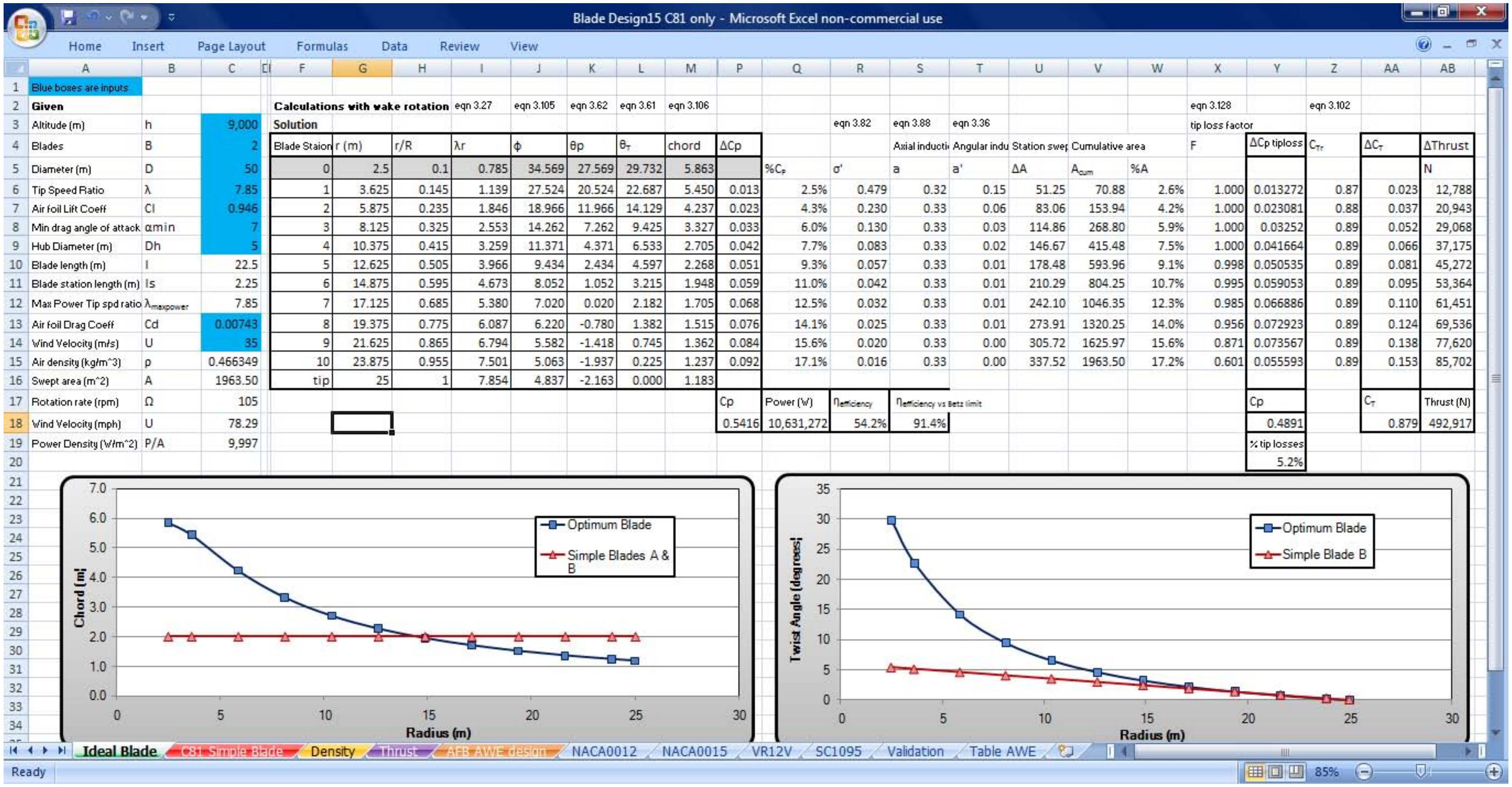
It is also recommended that a follow-on cost analysis for the blades of different designs be done. This analysis would compare how much total energy is produced over the lifetime of an AWE system rotor blade, and project how much longer one blade would last than the other. Then, a final comparison on which blades would win out in lifetime costs would help AWE technology be affordable from the get-go of USAF use.

Future research should be conducted to develop the flight controls of an AWE system. A Finite Element Model should be constructed, in order to optimize the structures used for the AWE system. Additional analysis to optimize the number of rotors used in a single AWE system should also be conducted.

Because AWE technology has the potential to transform the energy dynamics within the USAF, it is recommended that the Air Force immediately begin a program to develop and field an AWE system. Major companies and research offices should compete for bids in an effort to rapidly advance, improve, and employ AWE technology.

Ken Caldeira, Professor of Global Ecology, has said, "There is enough energy in high-altitude winds to power civilization 100 times over. Sooner or later, we're going to learn to harness that vast resource and use it to run civilization."[7] This thesis recommends continued research and active development of harnessing high-altitude wind power, or AWE, for the use of the USAF.

Appendix A: Design Tool Screen Shots



Blue boxes are inputs		
Given		
Altitude (m)	h	9,000
Blades	B	2
Diameter (m)	D	50
Tip Speed Ratio	λ	7.85
Air foil Lift Coeff	Cl	0.946
Min drag angle of attack	αmin	7
Hub Diameter (m)	Dh	5
Blade length (m)	l	22.5
Blade station length (m)	ls	2.25
Max Power Tip spd ratio	$\lambda_{maxpower}$	7.85
Air foil Drag Coeff	Cd	0.00743
Wind Velocity (m/s)	U	35
Air density (kg/m^3)	ρ	0.466349
Swept area (m^2)	A	1963.50
Rotation rate (rpm)	Ω	105
Wind Velocity (mph)	U	78.29
Power Density (W/m^2)	P/A	9,997

Calculations with wake rotation

Solution

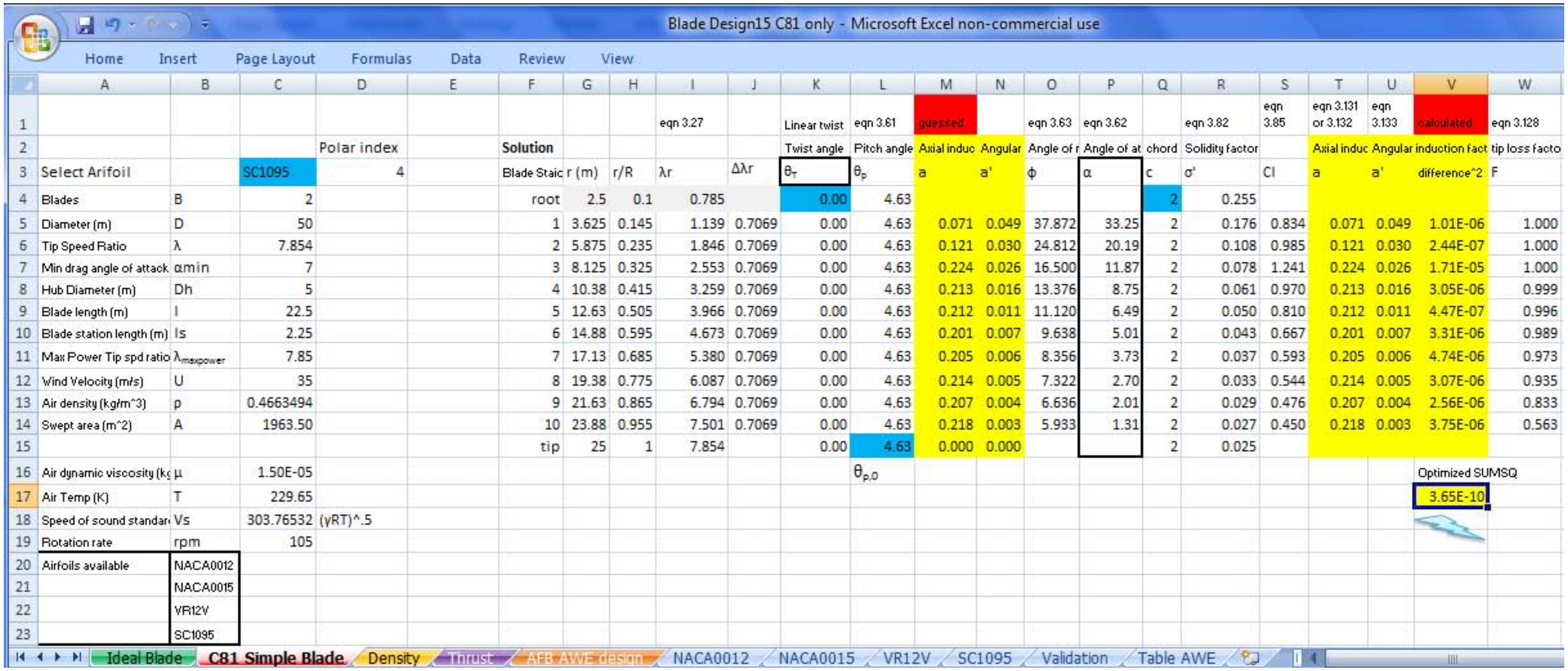
Blade Staion	r (m)	r/R	λr (eqn 3.27)	ϕ (eqn 3.105)	θp (eqn 3.62)	θ_T (eqn 3.61)	chord (eqn 3.106)	ΔCp	$\%C_P$	σ' (eqn 3.82)	Axial inducti a (eqn 3.88)	Angular indu a' (eqn 3.36)
0	2.5	0.1	0.785	34.569	27.569	29.732	5.863					
1	3.625	0.145	1.139	27.524	20.524	22.687	5.450	0.013	2.5%	0.479	0.32	0.15
2	5.875	0.235	1.846	18.966	11.966	14.129	4.237	0.023	4.3%	0.230	0.33	0.06
3	8.125	0.325	2.553	14.262	7.262	9.425	3.327	0.033	6.0%	0.130	0.33	0.03
4	10.375	0.415	3.259	11.371	4.371	6.533	2.705	0.042	7.7%	0.083	0.33	0.02
5	12.625	0.505	3.966	9.434	2.434	4.597	2.268	0.051	9.3%	0.057	0.33	0.01
6	14.875	0.595	4.673	8.052	1.052	3.215	1.948	0.059	11.0%	0.042	0.33	0.01
7	17.125	0.685	5.380	7.020	0.020	2.182	1.705	0.068	12.5%	0.032	0.33	0.01
8	19.375	0.775	6.087	6.220	-0.780	1.382	1.515	0.076	14.1%	0.025	0.33	0.01
9	21.625	0.865	6.794	5.582	-1.418	0.745	1.362	0.084	15.6%	0.020	0.33	0.00
10	23.875	0.955	7.501	5.063	-1.937	0.225	1.237	0.092	17.1%	0.016	0.33	0.00
tip	25	1	7.854	4.837	-2.163	0.000	1.183					

Cp	Power (W)	$\eta_{efficiency}$	$\eta_{efficiency}$ vs Betz limit
0.5416	10,631,272	54.2%	91.4%

Blade Staion	Station swep ΔA	Cumulative area A_{cum}	%A	tip loss factor F (eqn 3.128)	ΔCp tiploss	C_{Tr} (eqn 3.102)	ΔC_T	ΔThrust N
1	51.25	70.88	2.6%	1.000	0.013272	0.87	0.023	12,788
2	83.06	153.94	4.2%	1.000	0.023081	0.88	0.037	20,943
3	114.86	268.80	5.9%	1.000	0.03252	0.89	0.052	29,068
4	146.67	415.48	7.5%	1.000	0.041664	0.89	0.066	37,175
5	178.48	593.96	9.1%	0.998	0.050535	0.89	0.081	45,272
6	210.29	804.25	10.7%	0.995	0.059053	0.89	0.095	53,364
7	242.10	1046.35	12.3%	0.985	0.066886	0.89	0.110	61,451
8	273.91	1320.25	14.0%	0.956	0.072923	0.89	0.124	69,536
9	305.72	1625.97	15.6%	0.871	0.073567	0.89	0.138	77,620
10	337.52	1963.50	17.2%	0.601	0.055593	0.89	0.153	85,702

Cp	% tip losses	C_T	Thrust (N)
0.4891	5.2%	0.879	492,917

Figure 39. Design tool screen shot of optimal blade design calculations



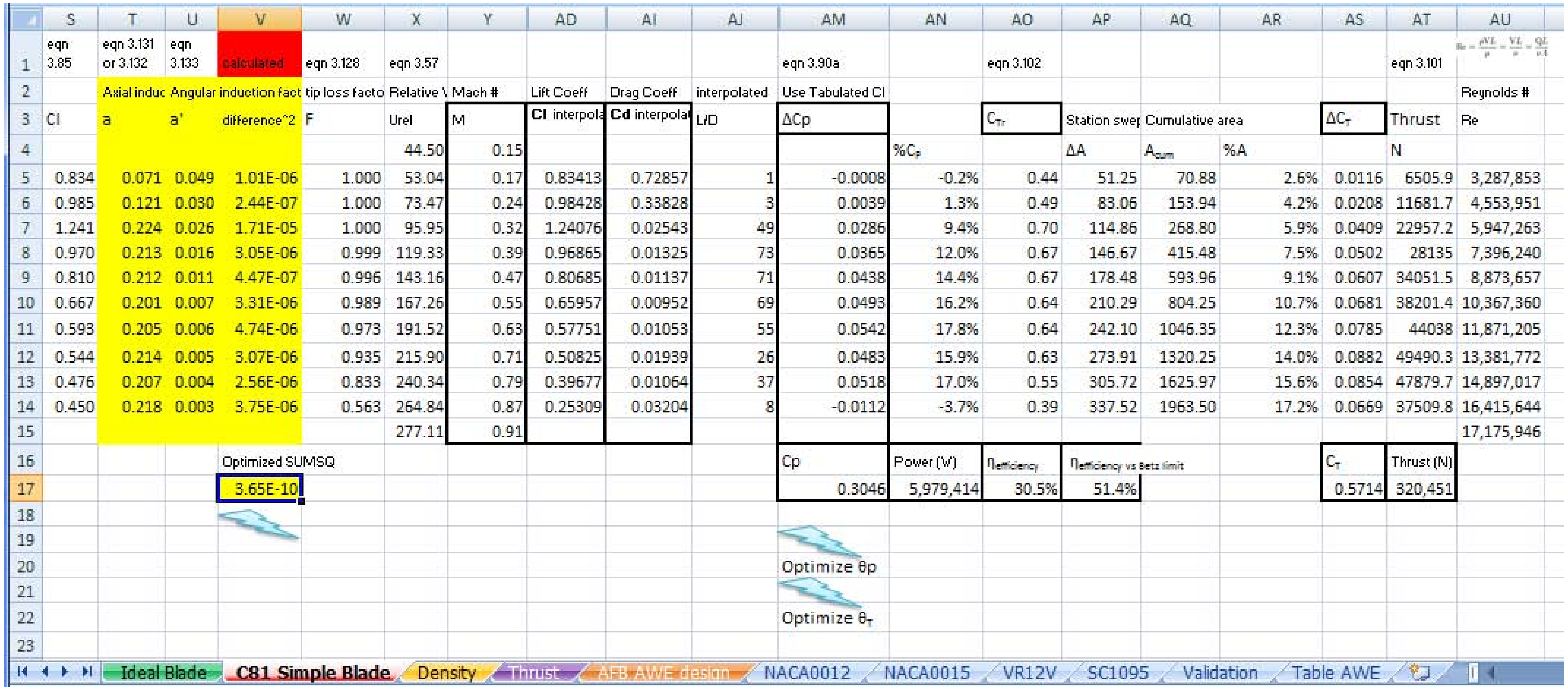
Blade Design15 C81 only - Microsoft Excel non-commercial use

Home Insert Page Layout Formulas Data Review View

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1									eqn 3.27		Linear twist	eqn 3.61	guessed		eqn 3.63	eqn 3.62		eqn 3.82	eqn 3.85	eqn 3.131 or 3.132	eqn 3.133	calculated	eqn 3.128
2				Polar index		**Solution**					Twist angle	Pitch angle	Axial induc	Angular	Angle of r	Angle of at	chord	Solidity factor		Axial induc	Angular	induction fact	tip loss facto
3	Select Arifoil		SC1095	4		Blade Staic	r (m)	r/R	λr	Δλr	θ_T	θ_p	a	a'	ϕ	α	c	σ'	Cl	a	a'	difference^2	F
4	Blades	B	2			root	2.5	0.1	0.785		0.00	4.63					2	0.255					
5	Diameter (m)	D	50			1	3.625	0.145	1.139	0.7069	0.00	4.63	0.071	0.049	37.872	33.25	2	0.176	0.834	0.071	0.049	1.01E-06	1.000
6	Tip Speed Ratio	λ	7.854			2	5.875	0.235	1.846	0.7069	0.00	4.63	0.121	0.030	24.812	20.19	2	0.108	0.985	0.121	0.030	2.44E-07	1.000
7	Min drag angle of attack	αmin	7			3	8.125	0.325	2.553	0.7069	0.00	4.63	0.224	0.026	16.500	11.87	2	0.078	1.241	0.224	0.026	1.71E-05	1.000
8	Hub Diameter (m)	Dh	5			4	10.38	0.415	3.259	0.7069	0.00	4.63	0.213	0.016	13.376	8.75	2	0.061	0.970	0.213	0.016	3.05E-06	0.999
9	Blade length (m)	l	22.5			5	12.63	0.505	3.966	0.7069	0.00	4.63	0.212	0.011	11.120	6.49	2	0.050	0.810	0.212	0.011	4.47E-07	0.996
10	Blade station length (m)	ls	2.25			6	14.88	0.595	4.673	0.7069	0.00	4.63	0.201	0.007	9.638	5.01	2	0.043	0.667	0.201	0.007	3.31E-06	0.989
11	Max Power Tip spd ratio	$\lambda_{maxpower}$	7.85			7	17.13	0.685	5.380	0.7069	0.00	4.63	0.205	0.006	8.356	3.73	2	0.037	0.593	0.205	0.006	4.74E-06	0.973
12	Wind Velocity (m/s)	U	35			8	19.38	0.775	6.087	0.7069	0.00	4.63	0.214	0.005	7.322	2.70	2	0.033	0.544	0.214	0.005	3.07E-06	0.935
13	Air density (kg/m^3)	ρ	0.4663494			9	21.63	0.865	6.794	0.7069	0.00	4.63	0.207	0.004	6.636	2.01	2	0.029	0.476	0.207	0.004	2.56E-06	0.833
14	Swept area (m^2)	A	1963.50			10	23.88	0.955	7.501	0.7069	0.00	4.63	0.218	0.003	5.933	1.31	2	0.027	0.450	0.218	0.003	3.75E-06	0.563
15						tip	25	1	7.854		0.00	4.63	0.000	0.000			2	0.025					
16	Air dynamic viscosity (kg	µ	1.50E-05									$\theta_{p,0}$										Optimized SUMSQ	
17	Air Temp (K)	T	229.65																			3.65E-10	
18	Speed of sound standar	Vs	303.76532	(γRT)^.5																			
19	Rotation rate	rpm	105																				
20	Airfoils available	NACA0012																					
21		NACA0015																					
22		VR12V																					
23		SC1095																					

Ideal Blade / C81 Simple Blade / Density / Thrust / AFB AWE design / NACA0012 / NACA0015 / VR12V / SC1095 / Validation / Table AWE

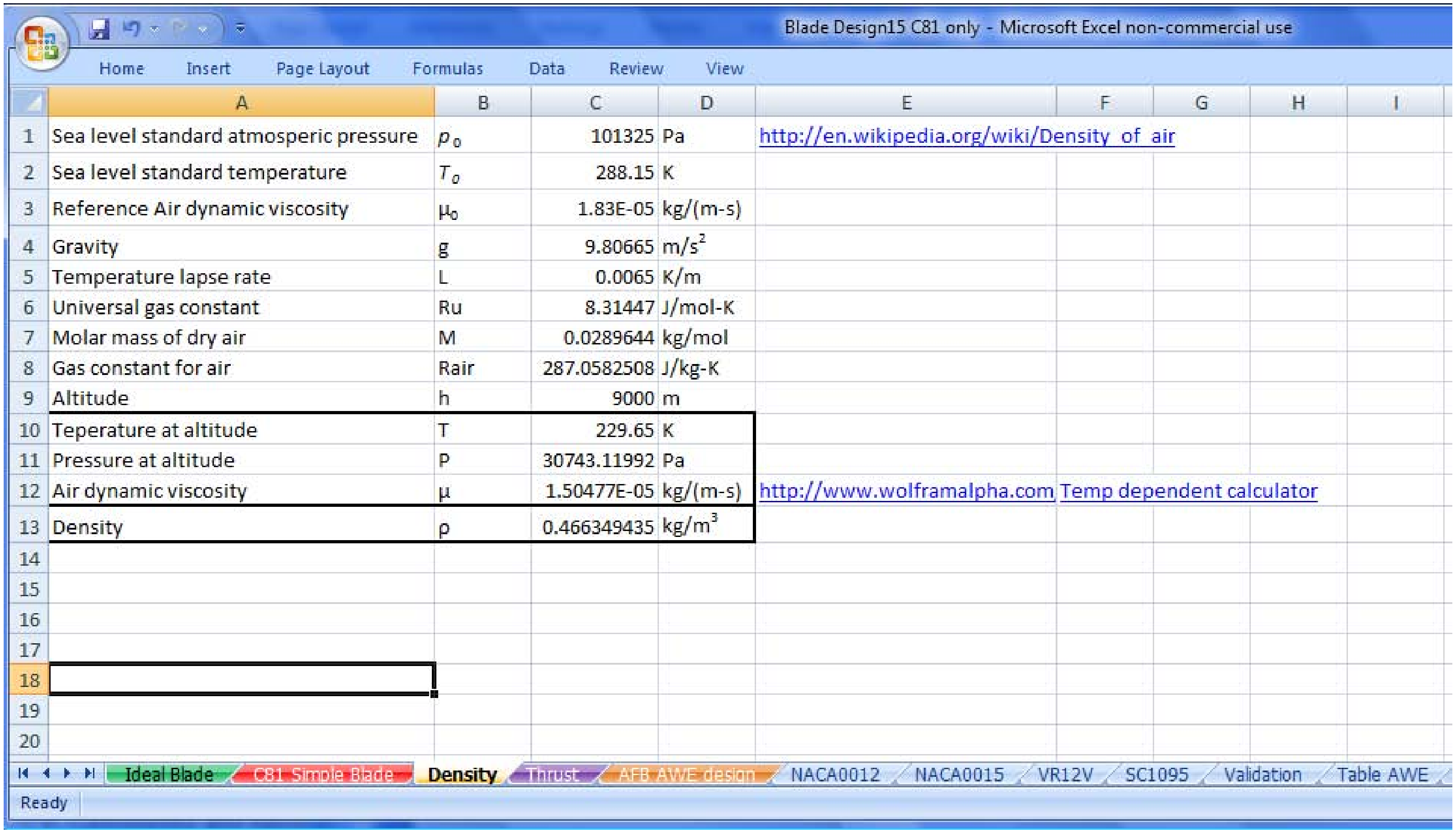
Figure 40. Design tool screen shot of simplified blade design calculations (Part 1)



	S	T	U	V	W	X	Y	AD	AI	AJ
1	eqn 3.85	eqn 3.131 or 3.132	eqn 3.133	calculated	eqn 3.128	eqn 3.57				
2		Axial induc	Angular induction fact		tip loss facto	Relative \	Mach #	Lift Coeff	Drag Coeff	interpolated
3	Cl	a	a'	difference^2	F	Urel	M	**Cl** interpola	**Cd** interpolat	L/D
4						44.50	0.15			
5	0.834	0.071	0.049	1.01E-06	1.000	53.04	0.17	0.83413	0.72857	1
6	0.985	0.121	0.030	2.44E-07	1.000	73.47	0.24	0.98428	0.33828	3
7	1.241	0.224	0.026	1.71E-05	1.000	95.95	0.32	1.24076	0.02543	49
8	0.970	0.213	0.016	3.05E-06	0.999	119.33	0.39	0.96865	0.01325	73
9	0.810	0.212	0.011	4.47E-07	0.996	143.16	0.47	0.80685	0.01137	71
10	0.667	0.201	0.007	3.31E-06	0.989	167.26	0.55	0.65957	0.00952	69
11	0.593	0.205	0.006	4.74E-06	0.973	191.52	0.63	0.57751	0.01053	55
12	0.544	0.214	0.005	3.07E-06	0.935	215.90	0.71	0.50825	0.01939	26
13	0.476	0.207	0.004	2.56E-06	0.833	240.34	0.79	0.39677	0.01064	37
14	0.450	0.218	0.003	3.75E-06	0.563	264.84	0.87	0.25309	0.03204	8
15						277.11	0.91			
16				Optimized SUMSQ						
17				3.65E-10						
18										
19										
20										
21										
22										
23										

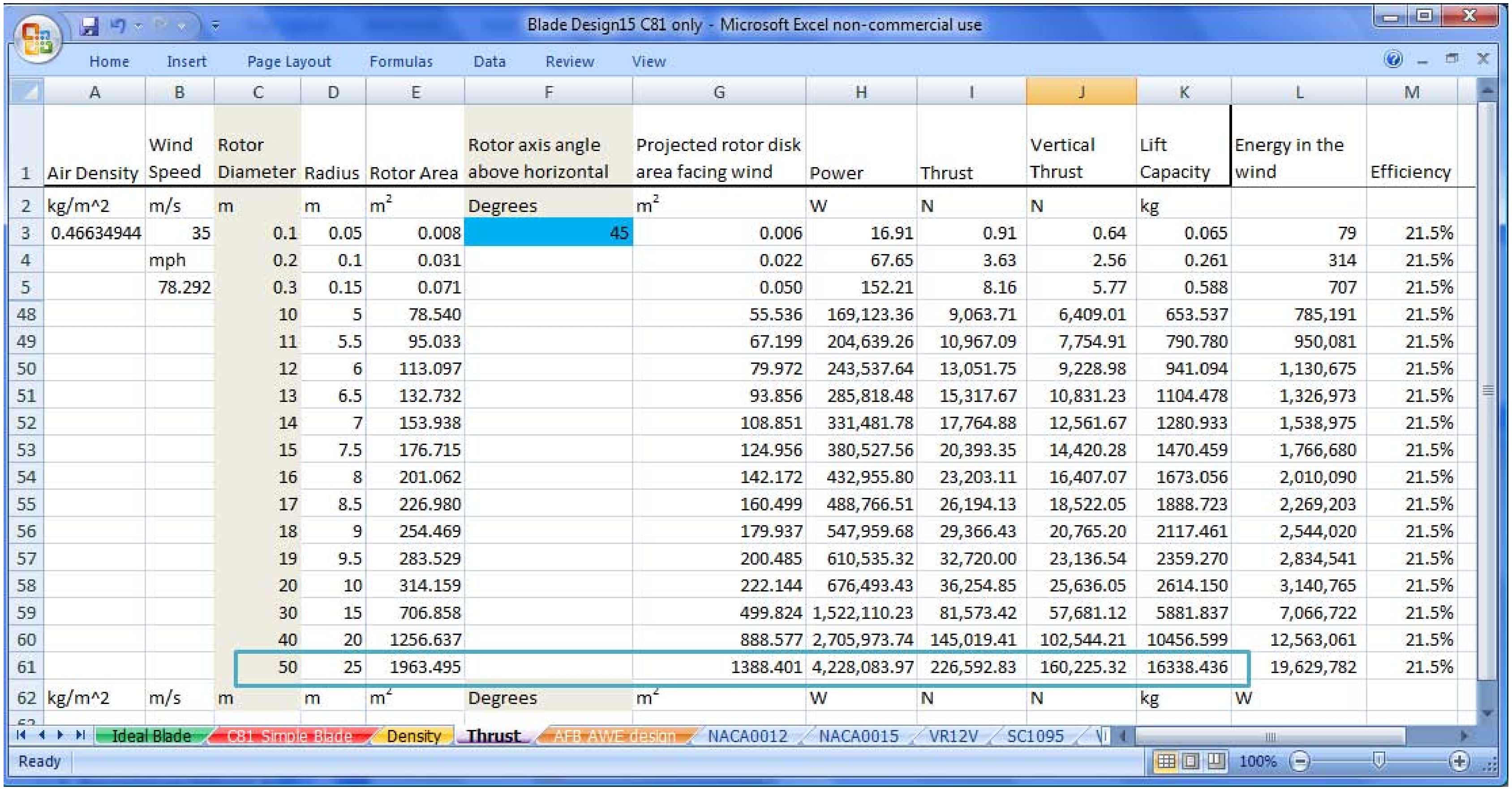
	AM	AN	AO	AP	AQ	AR	AS	AT	AU
1	eqn 3.90a		eqn 3.102					eqn 3.101	$Re = \frac{\rho VL}{\mu} = \frac{VL}{\nu} = \frac{QL}{\nu A}$
2	Use Tabulated Cl								Reynolds #
3	ΔCp		C_{Tr}	Station swe|	Cumulative area		ΔC_T	Thrust	Re
4		$\%C_P$		ΔA	A_{cum}	%A		N	
5	-0.0008	-0.2%	0.44	51.25	70.88	2.6%	0.0116	6505.9	3,287,853
6	0.0039	1.3%	0.49	83.06	153.94	4.2%	0.0208	11681.7	4,553,951
7	0.0286	9.4%	0.70	114.86	268.80	5.9%	0.0409	22957.2	5,947,263
8	0.0365	12.0%	0.67	146.67	415.48	7.5%	0.0502	28135	7,396,240
9	0.0438	14.4%	0.67	178.48	593.96	9.1%	0.0607	34051.5	8,873,657
10	0.0493	16.2%	0.64	210.29	804.25	10.7%	0.0681	38201.4	10,367,360
11	0.0542	17.8%	0.64	242.10	1046.35	12.3%	0.0785	44038	11,871,205
12	0.0483	15.9%	0.63	273.91	1320.25	14.0%	0.0882	49490.3	13,381,772
13	0.0518	17.0%	0.55	305.72	1625.97	15.6%	0.0854	47879.7	14,897,017
14	-0.0112	-3.7%	0.39	337.52	1963.50	17.2%	0.0669	37509.8	16,415,644
15									17,175,946
16	Cp	Power (W)	$\eta_{efficiency}$	$\eta_{efficiency}$ vs Betz limit			C_T	Thrust (N)	
17	0.3046	5,979,414	30.5%	51.4%			0.5714	320,451	
18									
19									
20	Optimize θp								
21									
22	Optimize θ_T								
23									

Figure 41. Design tool screen shot of simplified blade design calculations (Part 2)



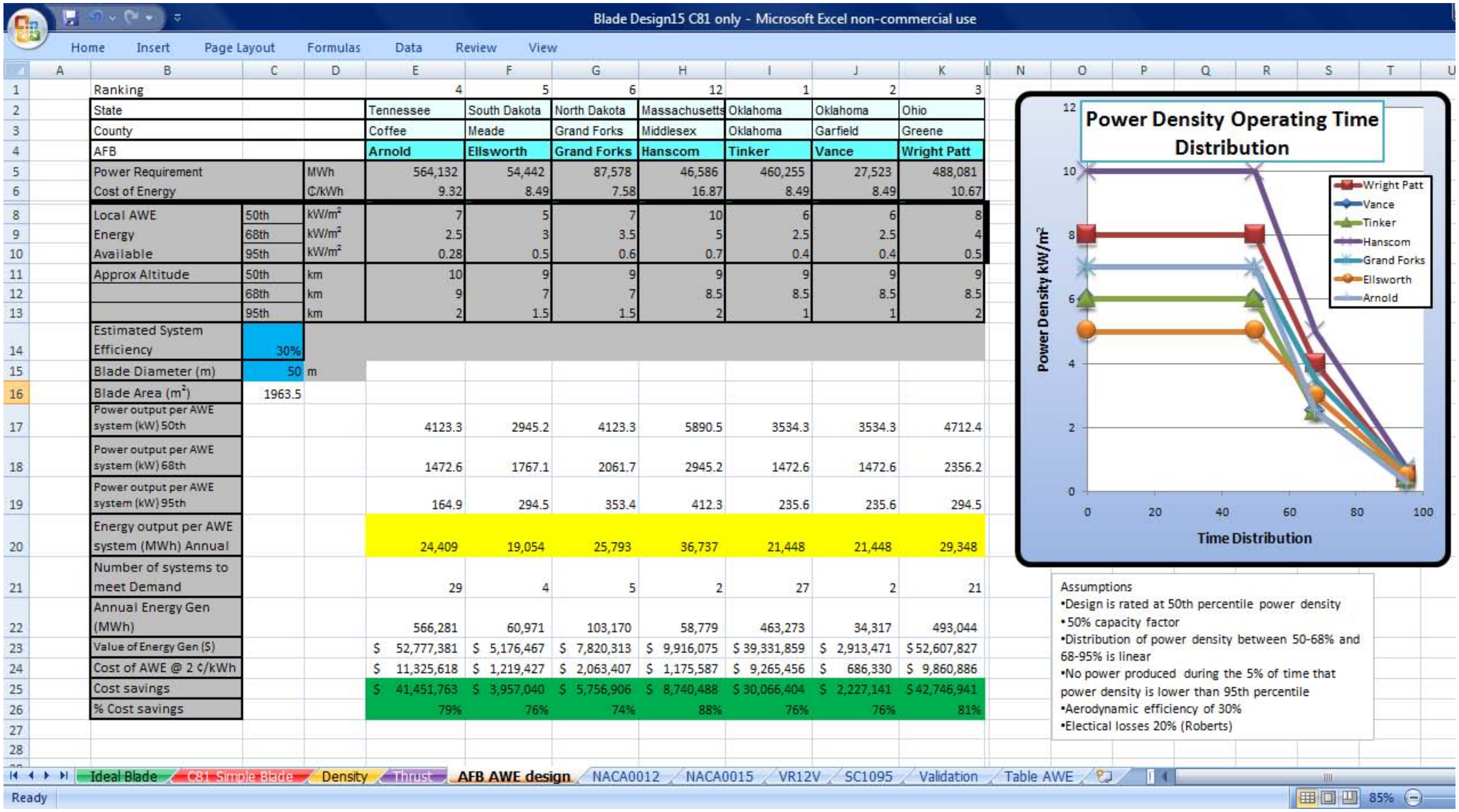
Sea level standard atmosperic pressure	p_0	101325	Pa	http://en.wikipedia.org/wiki/Density_of_air
Sea level standard temperature	T_0	288.15	K	
Reference Air dynamic viscosity	μ_0	1.83E-05	kg/(m-s)	
Gravity	g	9.80665	m/s^2	
Temperature lapse rate	L	0.0065	K/m	
Universal gas constant	Ru	8.31447	J/mol-K	
Molar mass of dry air	M	0.0289644	kg/mol	
Gas constant for air	Rair	287.0582508	J/kg-K	
Altitude	h	9000	m	
Teperature at altitude	T	229.65	K	
Pressure at altitude	P	30743.11992	Pa	
Air dynamic viscosity	μ	1.50477E-05	kg/(m-s)	http://www.wolframalpha.com Temp dependent calculator
Density	ρ	0.466349435	kg/m^3	

Figure 42. Design tool screen shot of atmosphere density calculations



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Air Density	Wind Speed	Rotor Diameter	Radius	Rotor Area	Rotor axis angle above horizontal	Projected rotor disk area facing wind	Power	Thrust	Vertical Thrust	Lift Capacity	Energy in the wind	Efficiency
2	kg/m^2	m/s	m	m	m²	Degrees	m²	W	N	N	kg		
3	0.46634944	35	0.1	0.05	0.008	45	0.006	16.91	0.91	0.64	0.065	79	21.5%
4		mph	0.2	0.1	0.031		0.022	67.65	3.63	2.56	0.261	314	21.5%
5		78.292	0.3	0.15	0.071		0.050	152.21	8.16	5.77	0.588	707	21.5%
48			10	5	78.540		55.536	169,123.36	9,063.71	6,409.01	653.537	785,191	21.5%
49			11	5.5	95.033		67.199	204,639.26	10,967.09	7,754.91	790.780	950,081	21.5%
50			12	6	113.097		79.972	243,537.64	13,051.75	9,228.98	941.094	1,130,675	21.5%
51			13	6.5	132.732		93.856	285,818.48	15,317.67	10,831.23	1104.478	1,326,973	21.5%
52			14	7	153.938		108.851	331,481.78	17,764.88	12,561.67	1280.933	1,538,975	21.5%
53			15	7.5	176.715		124.956	380,527.56	20,393.35	14,420.28	1470.459	1,766,680	21.5%
54			16	8	201.062		142.172	432,955.80	23,203.11	16,407.07	1673.056	2,010,090	21.5%
55			17	8.5	226.980		160.499	488,766.51	26,194.13	18,522.05	1888.723	2,269,203	21.5%
56			18	9	254.469		179.937	547,959.68	29,366.43	20,765.20	2117.461	2,544,020	21.5%
57			19	9.5	283.529		200.485	610,535.32	32,720.00	23,136.54	2359.270	2,834,541	21.5%
58			20	10	314.159		222.144	676,493.43	36,254.85	25,636.05	2614.150	3,140,765	21.5%
59			30	15	706.858		499.824	1,522,110.23	81,573.42	57,681.12	5881.837	7,066,722	21.5%
60			40	20	1256.637		888.577	2,705,973.74	145,019.41	102,544.21	10456.599	12,563,061	21.5%
61			50	25	1963.495		1388.401	4,228,083.97	226,592.83	160,225.32	16338.436	19,629,782	21.5%
62	kg/m^2	m/s	m	m	m²	Degrees	m²	W	N	N	kg	W	

Figure 43. Design tool screen shot of thrust and lift capacity calculations



	B	C	D	E	F	G	H	I	J	K
1	Ranking			4	5	6	12	1	2	3
2	State			Tennessee	South Dakota	North Dakota	Massachusetts	Oklahoma	Oklahoma	Ohio
3	County			Coffee	Meade	Grand Forks	Middlesex	Oklahoma	Garfield	Greene
4	AFB			Arnold	Ellsworth	Grand Forks	Hanscom	Tinker	Vance	Wright Patt
5	Power Requirement		MWh	564,132	54,442	87,578	46,586	460,255	27,523	488,081
6	Cost of Energy		C/kWh	9.32	8.49	7.58	16.87	8.49	8.49	10.67
8	Local AWE	50th	kW/m^2	7	5	7	10	6	6	8
9	Energy	68th	kW/m^2	2.5	3	3.5	5	2.5	2.5	4
10	Available	95th	kW/m^2	0.28	0.5	0.6	0.7	0.4	0.4	0.5
11	Approx Altitude	50th	km	10	9	9	9	9	9	9
12		68th	km	9	7	7	8.5	8.5	8.5	8.5
13		95th	km	2	1.5	1.5	2	1	1	2
14	Estimated System Efficiency	30%								
15	Blade Diameter (m)	50	m							
16	Blade Area (m^2)	1963.5								
17	Power output per AWE system (kW) 50th			4123.3	2945.2	4123.3	5890.5	3534.3	3534.3	4712.4
18	Power output per AWE system (kW) 68th			1472.6	1767.1	2061.7	2945.2	1472.6	1472.6	2356.2
19	Power output per AWE system (kW) 95th			164.9	294.5	353.4	412.3	235.6	235.6	294.5
20	Energy output per AWE system (MWh) Annual			24,409	19,054	25,793	36,737	21,448	21,448	29,348
21	Number of systems to meet Demand			29	4	5	2	27	2	21
22	Annual Energy Gen (MWh)			566,281	60,971	103,170	58,779	463,273	34,317	493,044
23	Value of Energy Gen ($)			$ 52,777,381	$ 5,176,467	$ 7,820,313	$ 9,916,075	$ 39,331,859	$ 2,913,471	$ 52,607,827
24	Cost of AWE @ 2 ¢/kWh			$ 11,325,618	$ 1,219,427	$ 2,063,407	$ 1,175,587	$ 9,265,456	$ 686,330	$ 9,860,886
25	Cost savings			$ 41,451,763	$ 3,957,040	$ 5,756,906	$ 8,740,488	$ 30,066,404	$ 2,227,141	$ 42,746,941
26	% Cost savings			79%	76%	74%	88%	76%	76%	81%

Figure 44. Design tool screen shot of USAF base AWE cost and energy savings calculations

Appendix B: USAF Base Feasibility Study Data

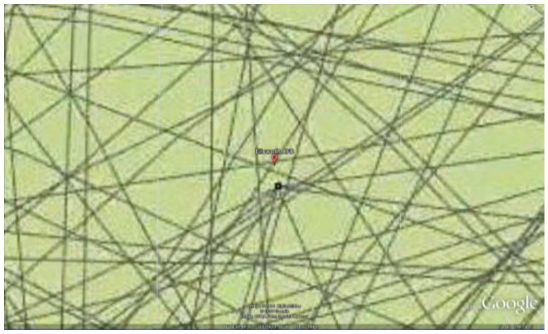
Table 14. USAF base electricity consumption data for 2007

Air Force Bases	Utility	FY07 Consumption (MWH)	States	Air Force Bases	Utility	FY07 Consumption (MWH)	States
ASCENSION ISLAND		3,479	N/A	LACKLAND AFB (incl. Wilford Hall)	City Public Serv-SA	286,317	Texas
AF ACADEMY	City of Colo Spgs, WAPA	123,454	Colorado	LANGLEY AFB	Virginia Elect Pwr Co/PJM	169,034	Virginia
ALTUS AFB	Western Farmers Electric	64,175	Oklahoma	LAUGHLIN AFB	AEP Texas Central	43,721	Texas
ANDERSEN AFB	Navy/ Guam Power Authority	74,388	Guam	LITTLE ROCK AFB	Entergy	77,529	Arkansas
ANDREWS AFB	PEPCO/PJM	88,415	Maryland	LOS ANGELES AFB	So Cal Edison	32,495	California
ARNOLD AFB	TVA	564,132	Tennessee	LUKE AFB	Arizona Public Service, WAPA	89,948	Arizona
BARKSDALE AFB	SWEPCO	108,208	Louisiana	MacDILL AFB	Tampa Electric Co.	133,851	Florida
BEALE AFB	PG&E, WAPA (100%)	96,954	California	MALMSTROM AFB	Montana Power Co	78,356	Montana
BOLLING AFB	PEPCO/PJM	83,259	D.C.	MARCH ARB	So Cal Edison	38,878	California
BUCKLEY AFB	Public Serv Colorado	103,175	Colorado	MAXWELL AFB	Ala. Power Co.	109,828	Alabama
CANNON AFB	SW Public Serv, WAPA	40,182	New Mexico	McCHORD AFB	City of Seattle	87,355	Washington
CAPE CANAVERAL AFS	FP&L	129,775	Florida	McCONNELL AFB	Kansas Gas & Elect	39,349	Kansas
CHARLESTON AFB	Santee Cooper	61,131	South Carolina	McGUIRE AFB	Jersey Central P&L	80,796	New Jersey
CHEYENNE MTN AFB	Colorado Spgs Util, WAPA	32,608	Colorado	MINOT AFB	Verendrye Elect	64,168	North Dakota
COLUMBUS AFB	TVA	47,717	Mississippi	MOODY AFB	Colquitt EMC	48,535	Georgia
DAVIS-MONTHAN AFB	Tucson Elect Pwr	104,520	Arizona	MT HOME AFB	Idaho Electric	46,237	Idaho
DOBBINS ARB	Georgia Pwr Co.	21,625	Georgia	NELLIS AFB	Nevada Power, WAPA	114,032	Nevada
DOVER AFB	City of Dover/Delaware	60,342	Delaware	CREECH (Part of Nellis AFB)	Nevada Power, WAPA	10,815	Nevada
DYESS AFB	AEP Texas North	69,368	Texas	OFFUTT AFB	Omaha Public Power/ WAPA (100%)	154,128	Nebraska
EDWARDS AFB	So Cal Edison, LADWP, WAPA	180,621	California	PATRICK AFB	Fla. Power & Light	70,355	Florida
EGLIN AFB	Gulf Power Co.	301,744	Florida	PETERSON AFB	City of Colo Spgs, WAPA	128,599	Colorado
EIELSON AFB	Golden Valley Electric Assoc./ Self-Gen	1,162	Alaska	POPE AFB	Ft. Bragg (Carolina P&L)	30,959	North Carolina
ELLSWORTH AFB	WAPA (Basin Elect)	54,442	South Dakota	RANDOLPH AFB	City Public Serv-SA	92,208	Texas
ELMENDORF AFB	ML&P	147,801	Alaska	ROBINS AFB	Georgia Pwr Co.	392,612	Georgia
F E WARREN AFB	Rocky Mtn Gen., WAPA	114,214	Wyoming	SCHRIEVER (FALCON) AFB	Mtn View Elect / WAPA	79,099	Colorado
FAIRCHILD AFB	BPA	90,206	Washington	SCOTT AFB	Illinois Power Co.	171,974	Illinois
GOODFELLOW AFB	AEP Texas North	47,791	Texas	SEYMOUR-JOHNSON AFB	Carolina P&L	70,730	North Carolina
GRAND FORKS AFB	Nodak Co-op/WAPA	87,578	North Dakota	SHAW AFB	S. Carolina Elect & Gas	87,955	South Carolina
GUNTER AFB	Ala. Power Co.	53,838	Alabama	SHEPPARD AFB	TXO	137,082	Texas
HANSCOM AFB	Boston Edison/ NEPOOL	46,586	Massachusetts	TINKER AFB	OG&E	460,255	Oklahoma
HICKAM AFB	HECO	129,943	Hawaii	TRAVIS AFB	PG&E, WAPA (100%)	127,856	California
HILL AFB	Utah Pwr & Light, WAPA	269,049	Utah	TYNDALL AFB	Gulf Power Co.	99,288	Florida
HOLLOMAN AFB	El Paso Electric, WAPA, Otero Co-op	118,155	New Mexico	VANCE AFB	SWAPA	27,532	Oklahoma
HURLBURT FLD	Gulf Power Co.	110,704	Florida	VANDENBERG AFB	PG&E	241,241	California
KEESLER AFB	Miss. Power Co.	138,597	Mississippi	WHITEMAN AFB	Energy One	72,938	Missouri
KIRTLAND AFB	Public Serv New Mex/ WAPA	112,134	New Mexico	WRIGHT-PATTERSON AFB	Dayton P&L/PJM	488,081	Ohio

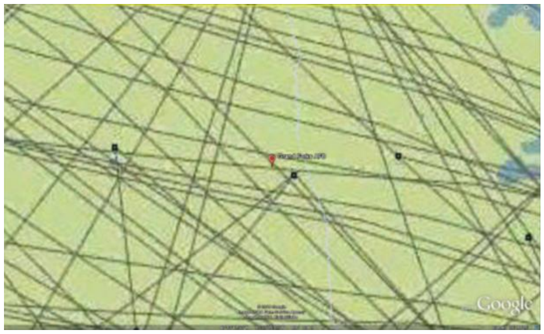
Air traffic ranking lowest

to highest density

1. Ellsworth
2. Grand Forks
3. Minot
4. Mountain Home
5. Davis-Monthan
6. Vandenberg
7. Eglin
8. Vance
9. Randolph
10. McChord
11. Beale
12. Tinker
13. Hill
14. Little Rock
15. F.E. Warren
16. Luke
17. Barksdale
18. Arnold
19. Los Angeles
20. MacDill
21. Seymour Johnson
22. Pope
23. Wright-Patterson
24. Patrick
25. Hanscom
26. Langley
27. McGuire

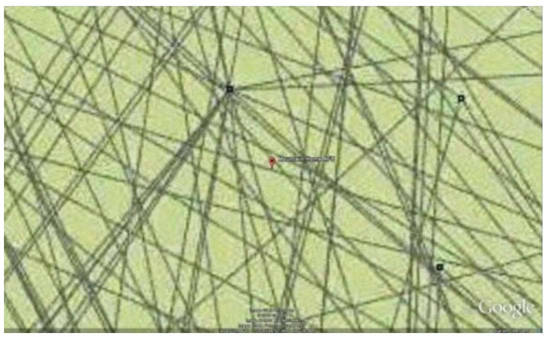


(1) Ellsworth

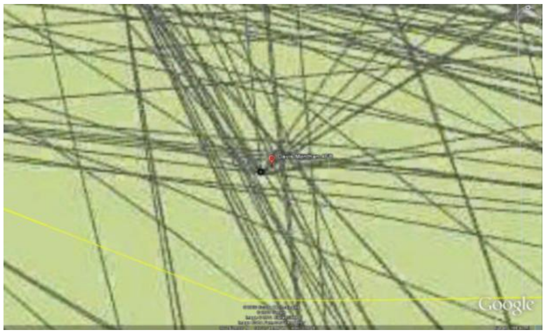


(2) Grand Forks

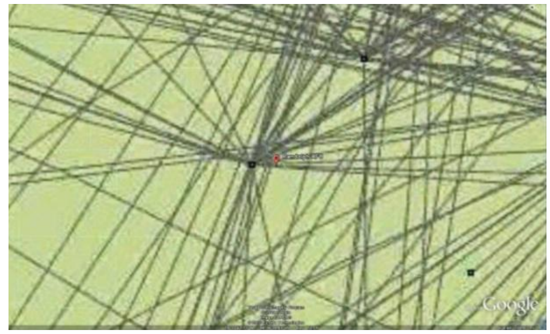
(3) Minot



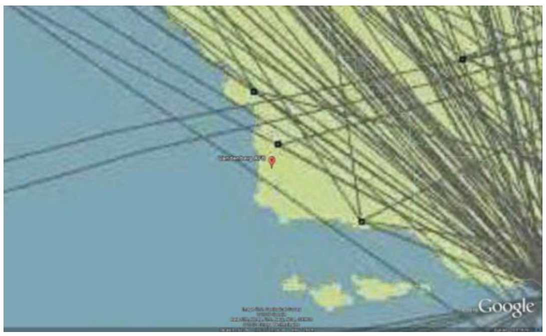
(4) Mountain Home



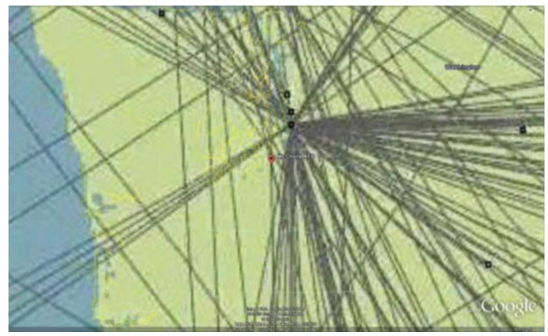
(5) Davis-Monthan



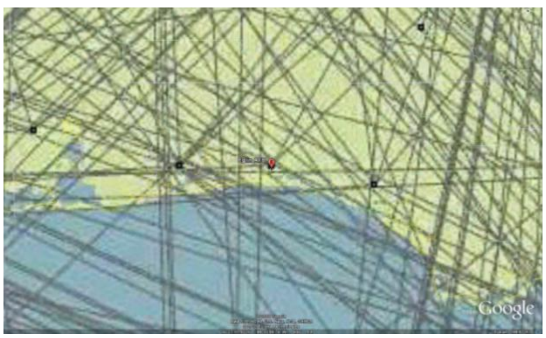
(9) Randolph



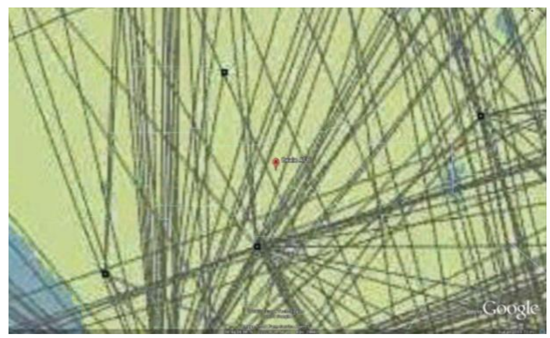
(6) Vandenberg



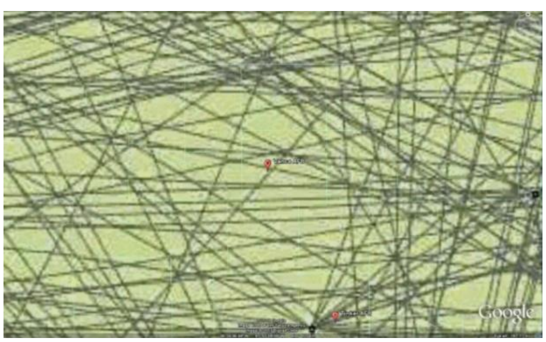
(10) McChord



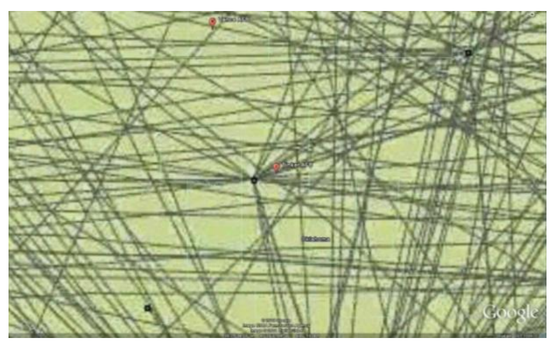
(7) Eglin



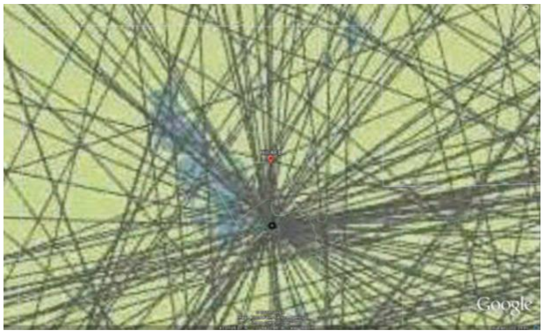
(11) Beale



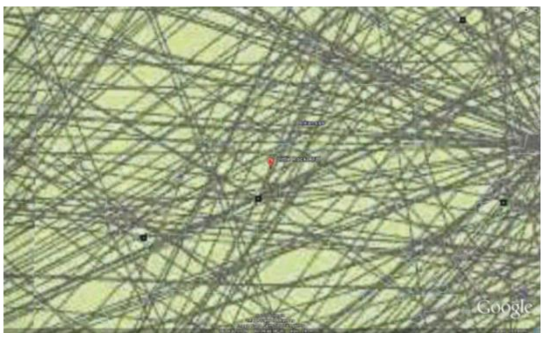
(8) Vance



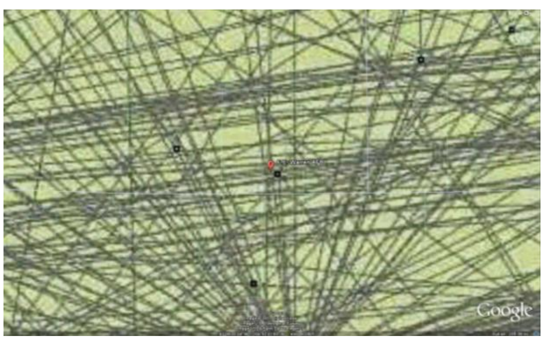
(12) Tinker



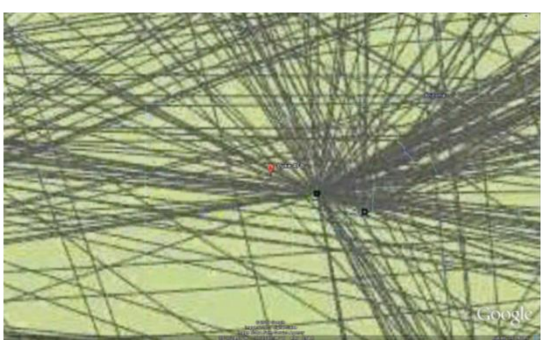
(13) Hill



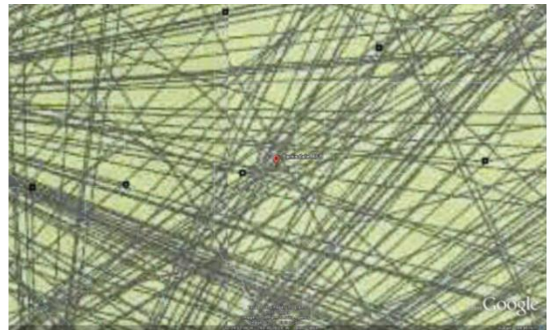
(14) Little Rock



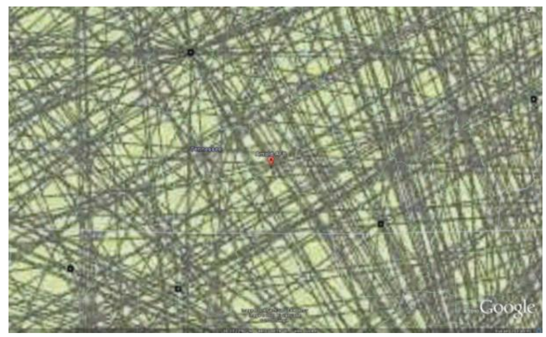
(15) F.E. Warren



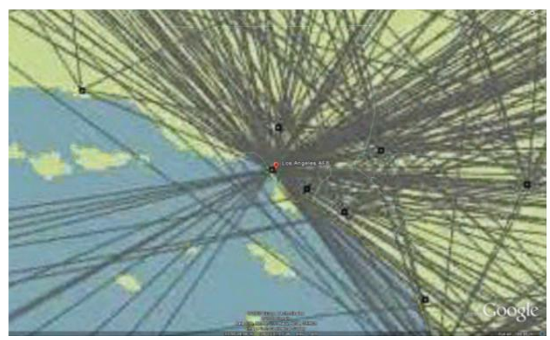
(16) Luke



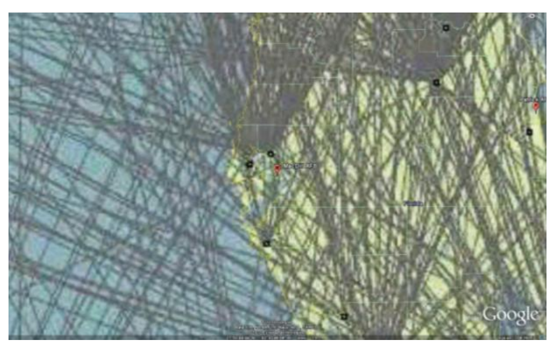
(17) Barksdale



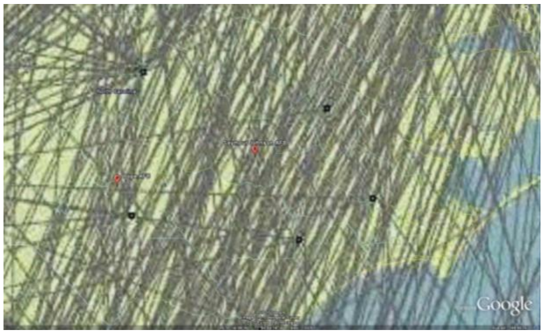
(18) Arnold



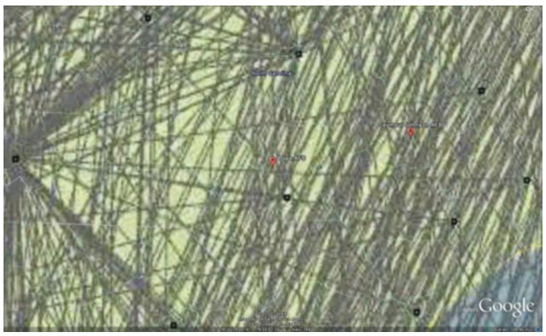
(19) Los Angeles



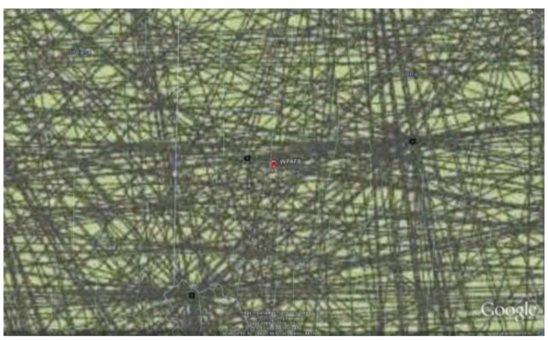
(20) MacDill



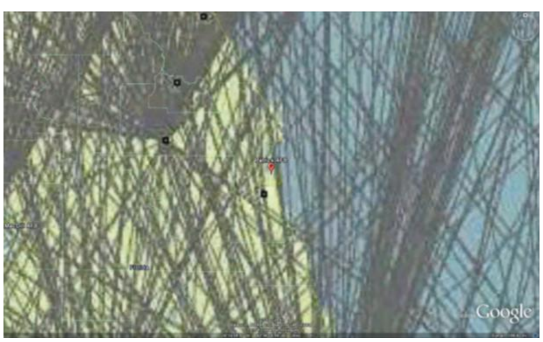
(21) Seymour Johnson



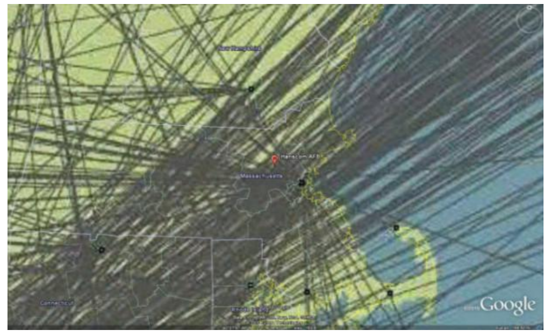
(22) Pope



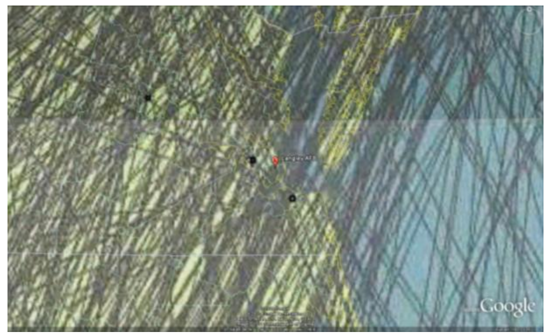
(23) Wright-Patterson



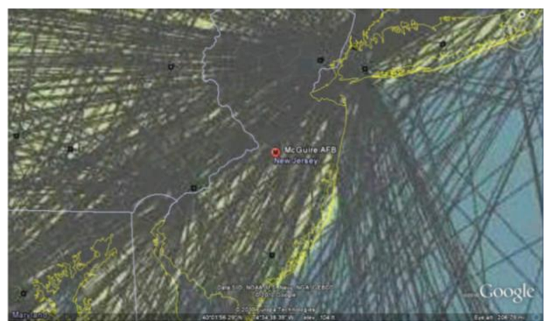
(24) Patrick



(25) Hanscom



(26) Langley



(27) McGuire

Table 15. USAF base AWE feasibility study category rankings

USAF Base	State	Overall Rank	Vulnerability Rank	Power Density Rank	Space Available Rank	Energy & Cost Savings Rank
Arnold	TN	4	7	12	12	1
Barksdale	LA	11	6	18	13	21
Beale	CA	15	23	19	10	8
Davis Mon.	AZ	19	27	24	5	15
Eglin	FL	9	12	23	8	4
Ellsworth	SD	5	11	7	1	22
F.E. Warren	WY	14	17	13	7	18
Grand Forks	ND	6	18	4	3	24
Hanscom	MA	12	21	1	26	6
Hill	UT	18	10	16	18	13
Langley	VA	25	15	5	27	12
Little Rock	AR	8	3	17	15	19
Los Angeles	CA	17	5	25	22	9
Luke	AZ	26	23	21	16	16
McChord	WA	20	18	15	11	23
McDill	FL	21	4	27	24	10
McGuire	NJ	16	25	2	25	5
Minot	ND	7	13	6	3	26
Mt Home	ID	13	26	13	1	27
Patrick	FL	27	9	26	23	14
Pope	NC	23	14	10	21	20
Randolph	TX	24	22	21	14	11
Seymour J.	NC	22	18	10	17	17
Tinker	OK	1	1	8	18	7
Vance	OK	2	2	8	6	25
Vandenberg	CA	10	15	20	9	3
Wright Patt	OH	3	8	3	20	2

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Biography

Captain Troy L. Cahoon graduated from Cardston High School in Cardston, Alberta, Canada in 1994. He completed his Bachelor of Science in Mechanical Engineering at Brigham Young University (BYU), UT, in 2003. He received his United States Air Force commission on April 28, 2003, after completing Reserve Officer Training at BYU.

The first USAF assignment for Captain Cahoon was at Wright-Patterson AFB, Ohio. He worked as an electronic warfare engineer and program manager for the Special Ops Systems Group of the Aerospace Systems Center, providing upgrades for the AC-130 Gunship and other Special Ops aircraft. Starting in May 2006, he was assigned to Hill AFB, Utah, as a test engineer, and then program manager, for the Range Threats Squadron of the 84th Combat Sustainment Wing. In June 2008, Captain Cahoon moved to the Range Squadron of the 388th Fighter Wing, also at Hill AFB. There he worked as a range instrumentation engineer on the Utah Test and Training Range (UTTR). In August 2009, Captain Cahoon entered the Graduate School of Engineering and Management at the Air Force Institute of Technology (AFIT), where he graduated in March 2011 with a Master's degree in Aeronautical Engineering. Captain Cahoon's current assignment is at Edwards AFB, California, where he is working in the Air Force Research Laboratory (AFRL), Propulsion Directorate.

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14. ABSTRACT
Excitement among researchers about Airborne Wind Energy (AWE) technology matches DoD aims to advance and employ renewable energy. AWE seeks to cost-effectively tap the vast supply of wind energy available at altitudes high above the reach of conventional, ground-based wind turbines (e.g. 500-12,000m). This paper explores viability and implementation of AWE technology for fulfilling USAF energy needs. Characteristics, potential, and developmental status of the AWE resource are presented. A design tool for a rotor-based AWE system is developed, facilitating the analysis of blade performance to simplify design and provide the best efficiencies for a range of conditions. USAF bases are evaluated upon energy needs, design requirements, and other factors to determine which bases could benefit most from AWE. Bases most viable for an AWE project, with 75% potential savings on energy costs/base (up to $40M annually for larger bases), are: Tinker, Vance, Wright-Patt, Arnold, Ellsworth, and Grand Forks. Key results reveal it is possible to achieve notable benefits for the USAF using AWE technology.

15. SUBJECT TERMS
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