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Decision Analysis Using Value Focused Thinking to Select Renewable Energy Sources

James S. Duke

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DECISION ANALYSIS USING VALUE-FOCUSED THINKING TO SELECT RENEWABLE ENERGY SOURCES

THESIS

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AFIT/GEM/ENV/04M-09

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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AFIT/GEM/ENV/04M-09

DECISION ANALYSIS USING VALUE-FOCUSED THINKING TO SELECT RENEWABLE ENERGY SOURCES

THESIS

Presented to the Faculty

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In Partial Fulfillment of the Requirements for the

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James S. Duke, BS

Captain, USAF

March 2004

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Abstract

The United States is heavily dependent on fossil fuels to produce electricity. Renewable energy can provide an alternative source of energy for electricity production as well as reduce fossil fuel consumption. The executive agencies in the U.S. must also reduce greenhouse gas emissions by 2010 based on 1990 emission levels as directed by Executive Order. However, there is currently no analysis model to provide guidance toward which renewable energy to select as a course of action.

This research effort used value-focused thinking decision analysis to create a model based on inputs from the Air Force Civil Engineer Support Agency. This model allows a decision-maker to easily alter weights and value functions related to renewable energy sources as needed to correspond to the personal values of that person. These values combined with the objective scores obtained from the generated alternatives results in a suggested course of action. The sensitivity analysis shows the changes of the output based on the alterations of the weighting of each measure. All measures were varied to study their influence on the final outcome. Application of the model at three bases showed this model appears to work based on the influencing weights and values of the decision-maker.

AFIT/GEM/ENV/04M-09

To my parents

Acknowledgments

First, I would like to thank God for giving me the strength and will to meet and overcome any obstacles in life. I would like to express my sincere appreciation to my faculty advisor, Lt Col Ellen England, for her guidance and support throughout the course of this thesis effort. With her knowledge and direction, this thesis resulted in a far more useful product. I would also extend and appreciation to Lt Col Alfred Thal and Maj Jeffrey Weir for the help they've provided during this endeavor. Their insight and experience were certainly appreciated. I would also like to thank my sponsor, Mr. Mike Santoro, from the Air Force Civil Engineering Support Agency for both the support and latitude provided to me in this endeavor.

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James S. Duke

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DECISION ANALYSIS USING VALUE-FOCUSED THINKING TO SELECT RENEWABLE ENERGY SOURCES

1. Introduction

1.1 General Background

Decision-making involves making choices between various alternatives. The choice that is made should rely on the quantitative or qualitative value that is placed on the outcome. Value-focused thinking (VFT) allows a step-by-step approach to achieve an appropriate decision based on what is relevant or important to the decision maker.

This research uses VFT to develop a model to aid a decision maker such as the base commander, Civil Engineer, or base energy manager for evaluation of the use of renewable energy for the main electrical power production on a military installation. Given the measures that are important to the decision maker and the scores those measures receive, a recommendation including a range of values determined using sensitivity analysis are given to aid in choosing which renewable energy source, if any, to utilize for a military installation's needs.

1.2 Specific Background

Executive Order (EO) 13123, signed on June 3, 1999, required executive agencies such as the Department of Defense (DoD) reduce greenhouse gas emissions 30% by the year 2010 when compared to the year 1990 emission levels (Clinton,1999). In addition, each agency was tasked to expand the use of renewable energy sources within its facilities, to include installing 20,000 solar energy systems nation-wide by year 2010 (Clinton, 1999). EO 13123 also directed each agency to reduce energy consumption even if on-site energy needs increase (Clinton, 1999). Recent developments and improvements in renewable energy technology make it possible for the DoD to reach these goals. Over the last 10 years, wind power and photovoltaic cells have become more economically feasible energy sources. Geothermal electrical production is still new but has achieved great success in areas such as the United States Navy's China Lake installation. By identifying viable renewable energy alternatives and employing them, decision makers may save money and reduce greenhouse gas emissions thereby meeting the intent of the EO 13123.

Other recent developments also encourage the use of renewable energy produced on the military installation. With the threat of terrorist attacks and sabotage within the United States increasing, there is a greater need to produce more energy on base. This protected energy source would make the installation more independent from outside energy sources and reduce potential disruptions.

Another benefit to using renewable energy, other than reducing greenhouse emissions, is the possibility of reduced annual maintenance and operating costs. As the price of non-renewable energy steadily increases, it makes sense to transform the nation's energy production infrastructure to renewable energy sources. Although the capital cost may be high, the long term savings may eventually pay for initial costs and the savings can be passed on to the government and eventually back to the American people. With proper contract negotiations with local electrical companies, excess energy produced can be sold outside the military installation increasing the cost effectiveness of the system and potentially generating revenue for the installation.

Finally, renewable energy sources may be used during contingency operations where the energy production and delivery infrastructure may not adequately support Air Force requirements. Again, using renewable energy would allow a base to be self-sufficient and avoid relying on conventional energy sources or off-site power transmission lines. Numerous remote sites could benefit from the use of renewable energy sources. For instance, the radar sites that are located in remote mountain ranges in Alaska currently utilize generators that run constantly and use extensive amounts of fuel oil. If the site were able to utilize wind or solar energy, reliance on the generators would decrease. The generators would still be needed for back up. However, if the runtime for generators were reduced, the greenhouse emissions would decrease accordingly and so would the dependence on outside energy sources.

1.3 Problem Statement

In accordance with Executive Order 13123, the Air Force must reduce greenhouse emissions 30% by year 2010. This reduction mandate requires the Air Force to look at alternative electrical production and rely more on renewable energy resources that do not contribute to greenhouse gas emissions. A reliable method or model to quantify which renewable energy system would be best for any particular base is required. The method employed for evaluating renewable energy sources in this research is value-focused thinking. With this method, objective selection of the best renewable energy alternative and gaining insight into the reasons for the selection are possible.

1.4 Research Objective

The purpose of this thesis is to develop a VFT model to evaluate the best allocation of renewable energy sources at any particular base when given the proper evaluating measures for the installation. These measures will be created by the sponsor to fully capture what is important to make a complete and informed decision.

The particular research questions that must be answered include the following:

1. What methodologies are available for analyzing energy alternatives?
2. What are the appropriate measures that comprise a model to select energy alternatives at a government installation?
3. How do changes in the selected measures affect the outcome of a decision?
4. What are the outcomes of the model at representative installations in differing regions?

1.5 Scope

This research will compare the utility of three different renewable energy resources. The three renewable energy resources are wind, solar, and geothermal. Even though this model is designed for wind, solar, and geothermal energy sources, it can accommodate future energy alternatives as long as the measures remain the same and can be easily scored. Other potential renewable energy sources, such as wave energy and tidal energy for electrical energy, are not included because they are not mature energy sources and are still in their development stage. Perhaps in the future, when these energy sources are further developed, the alternatives can be included in this model. Hydroelectric energy sources were not considered because of cost and environmental concerns. Other energy sources such as fuel cells and compressed natural gas also were not used as they still utilize non-renewable energy for electrical production.

It is hoped that this model can be applied outside the Air Force to virtually any governmental organization with a need for renewable energy production and has the necessary monetary resources to acquire the system. This would further reduce the governmental dependence on outside energy sources and ensure a cleaner environment for future generations.

1.6 Research Approach

This research applies value focused thinking methodology to analyze energy use alternatives. The VFT software that will be used is Logical Decisions (Logical Decisions, 2001). Sensitivity analysis will be completed to determine what factor or factors have the largest impact on the outcome.

In discussion with the sponsor and through a literature review, a series of measures will be developed to evaluate and score the three alternatives. Some examples of those measures could include: initial cost, aesthetics, locations available on base, maintenance cost, force protection, zoning restrictions, energy production fluctuations, base energy requirement, base location, and base line energy usage.

1.7 Significance

Development of a model will give decision makers a tool to help choose the best renewable energy source for their installation. The model also fills a gap in the available literature. No decision models have been found to select energy sources. It is hoped that this research will enable leaders to make knowledgeable and justifiable decisions concerning which renewable energy source to use.

1.8 Review of Chapters

Chapter 2 consists of the literature review of energy sources for the alternatives and explains current civil engineer squadron practices. This chapter also explains how the results of this study can be used by the Air Force corporate structure. In addition, this chapter will compare three various decision analysis methods and why VFT is the proper method for this research. Chapter 3 provides a basic overview of VFT before moving into the methodology that was used. This chapter includes the construction of the value hierarchy. Chapter 4 documents the results of the model along with a sensitivity analysis of the output for various bases selected. Chapter 5 concludes the research project, points out various gaps that are in the model as well as insight into unexpected results. Also, this chapter highlights the benefits of the research and makes recommendations for further research along with potential model modifications.

2. Literature Review

2.1 Overview

This chapter summarizes briefly the history of the three renewable energy production sources: wind, solar, and geothermal. It then explains current civil engineer squadron practices as well as how the results of this study can be used by the Air Force corporate structure. Next, the reason for using Value Focused Thinking in the analysis of renewable energy sources will be explained. Finally, regulations concerning renewable energy sources, potential terrorist threats, and information concerning depletion of natural resources are presented.

2.2 Renewable Energy Resources

Energy production in the United States in 2002 was over 97 quadrillion Btus according to the Department of Energy (DOE, 2004). Of this amount, only 6% of the energy was produced from renewable resources.

Figure 1 shows the sources of energy production in the United States.

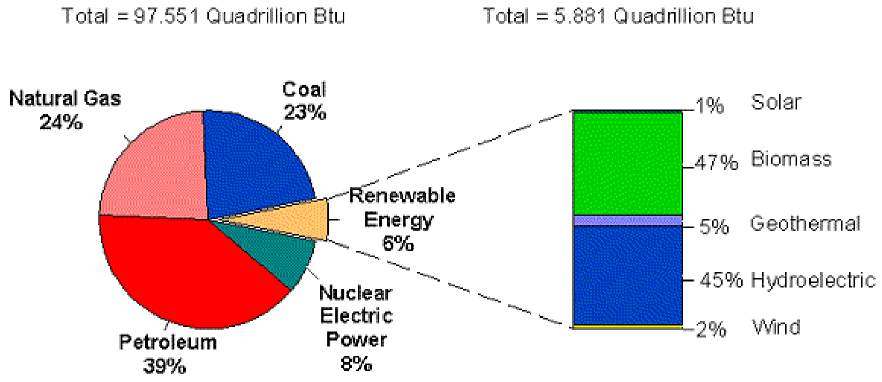


Figure 1. U.S. Energy Production, 2002

(Department of Energy, 2002)

Although there are a number of renewable energy resources available, only a few are considered economically viable based on advances in technology. For this research, wind turbines, photovoltaic, and geothermal energy production resources were utilized for decision-making as they are considered mature technologies.

2.3 Wind Energy

Wind is an ever present resource that is driven by the energy from the sun. As air seeks to achieve a steady state of uniform pressure and uniform temperature, the heat from the sun and the spin of the earth conspire to keep the air from achieving steady state. Wind speed varies greatly with location depending on variables such as topography, time of day, and even time of year. Power from the wind can be represented using a few assumptions and calculations.

2.3.1 Wind Energy History

Wind has been used since the dawn of time to power ships across the seas. Ancient Persians used wind turbines extensively in the seventh century A.D. (Johnson, 1985:2). The first recorded wind turbine in England was in 1191 A.D. (Johnson, 1985:2). Extensive use of turbines in northern Europe rapidly followed. These early crude wind turbines were used mainly to grind and mill grain although they were also used to pump water. The Dutch are credited with the design and use of tapered blades much like what is used in modern turbines. The explosion of turbine use in the United States occurred during the 19th century westward expansion where there was plenty of dry land and water was plentiful underneath the soil (Johnson, 1985:3). Numerous multi-bladed wind turbines were used to draw the water out of the ground for watering farm animals.

In 1890, wind turbines in the Netherlands were used to generate electrical power for the first time (Johnson, 1985:4). The first American electrical wind turbine did not occur until about 35 years later. At that time, the price of electrical production was decreasing due to more conventional generation methods such as the combustion of oil and coal. The result was that wind turbines were relegated to research programs rather than extensive application. Rising electrical prices during the energy crisis of 1973 created a renewed emphasis and funding research for electrical generating wind turbines. Various types of turbines were produced during that time.

2.3.2 Wind Turbine Types

Three major wind turbine types were researched for this study: Horizontal-Axis, Darrius, and Savonius. The horizontal-axis turbine, shown in Figure 2, is easily recognized by the blades that spin much like a propeller on an airplane. This turbine typically stands atop a 60m vertical mount. There are typically three blades, 45m in radius. The variable gearbox and power converter is attached at the hub in a nacelle as shown in Figure 3.

Figure 2. A Horizontal-axis Three-bladed Turbine

(Vision Quest Windelectric, 2003)

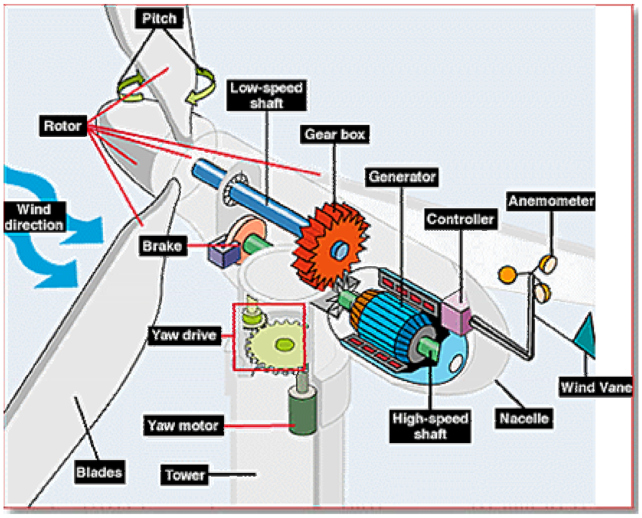


Figure 3. Wind Turbine Gearbox

(DOE, 2003)

The foundation square footage required of the turbine is relatively small but the height is great. The turbines can rotate to face into the wind from any direction and can shut down if the wind is too strong. Computer control allows the movement and shut down to occur. These turbines are used extensively in Europe. A wind farm using over 100 of these machines is currently in use in Egypt (REW, 2003). An advantage of this type of turbine is that there are stronger winds at higher elevations from the ground.

Another widely recognized wind turbine type is the Darrius turbine. Patented in 1931 by G. J. M. Darrius, this turbine has a vertical axis rather than a horizontal axis (Johnson, 1985:13). An advantage of the Darrius type of wind turbine is there is no need to rotate or “face” into the wind. The wind can come from variable directions and there would be minimal loss of energy. Another benefit is that since the blades are being rotated, they are in tension and do not require the thick walled blades as the horizontal–axis turbines require. Finally, since the axis of rotation is vertical, the mechanics of the system can be placed at ground level, making it easier to construct and maintain. A disadvantage to this system is that the turbines are not self starting. If the wind speed decreases to the point that the turbine stops, the Darius needs a motor to initialize the new rotations when wind speed increases. Finally, the efficiency of this turbine is not as high as the horizontal-axis turbines.

Figure 4. Darrius Wind Turbine

(DWIA, 2003)

The third turbine type is the Savonius turbine. This turbine, first identified over fifty years ago, is still experimental and is shown in Figure 5. The benefit of the Savonius turbine is that it has a high starting torque and thus needs no starting motor and can operate in low winds (Johnson, 1985:16). The disadvantages of this turbine include its inability to withstand high winds and its production of variable voltages and frequencies making it incompatible with utility grid applications.

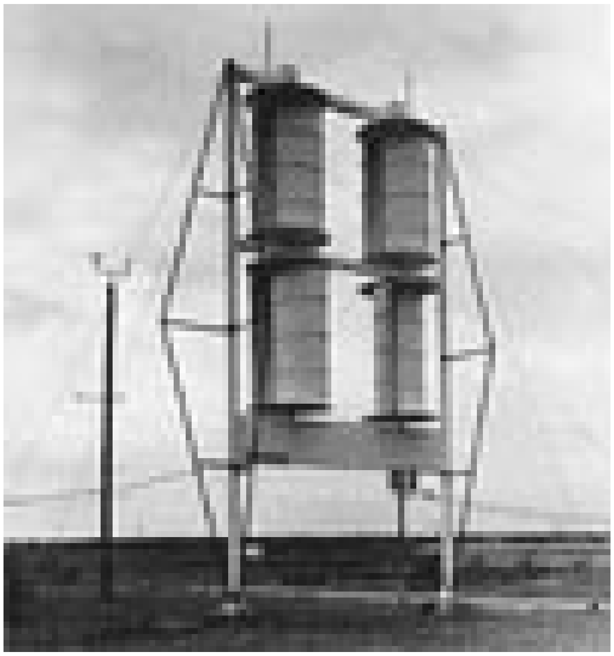


Figure 5. Savonius Wind Turbine

(Pembino, 2003)

Figure 6 (Johnson, 1985:18) shows a comparison of the power coefficients for the various wind turbines discussed. Power coefficients are another name for efficiencies and are derived from dividing the electrical power output by the wind energy input (DWIA, 2003). Figure 6 also shows that for most of the turbines there is an ideal operating tip-to-wind speed ratio. The high-speed two-blade type has the power coefficient which represents the highest efficiency of the types compared. A three-blade mechanism captures more energy but has a higher blade cost and suffers more transmission losses (Johansson, 1993:131). The three blade type is also more stable than the two-blade turbine. Since most wind turbines manufactured today are predominately the high-speed three blade types (Johansson, 1993:131), this system will be the representative wind system of this research. A Vestas-built 1.75 Megawatt wind turbine will be used as the representative system.

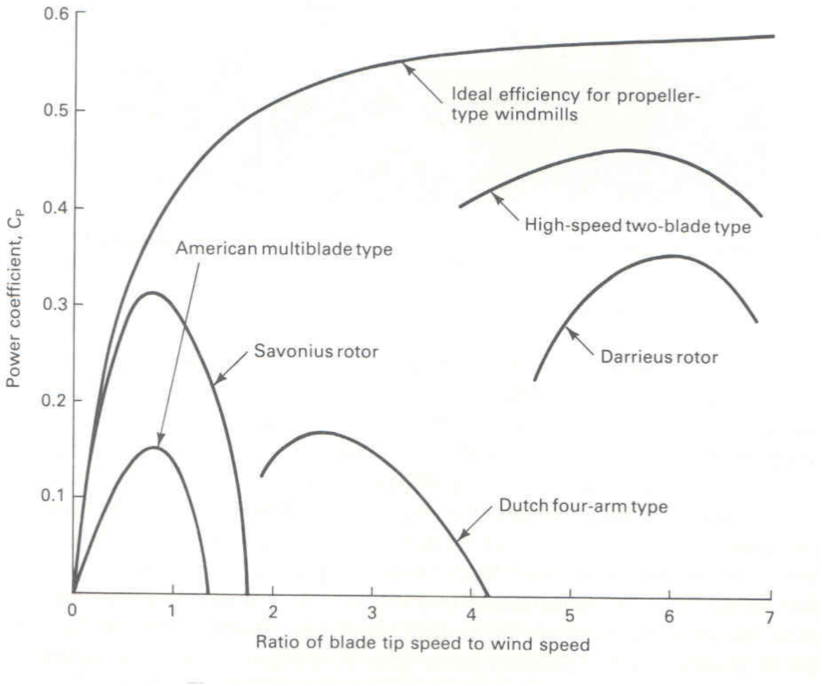


Figure 6. Power Coefficients Comparison

(Johnson, 1985:18)

2.3.3 Wind Energy Production

Many variables must be considered by decision-makers concerning wind energy. Most importantly, an accurate site assessment must be accomplished. For instance, a location near a mountain may have little wind velocity but a selected site located between mountain peaks in a pass may have very consistent high winds that could be harnessed.

Wind velocity is critical to the energy potential of wind turbines. If the wind velocity is too low, no electricity is generated. If the wind velocity is too high, the turbine may be damaged. Wind velocity varies according to elevation above ground and also with surface obstructions. The formula for calculating wind speed at 60m elevation is shown in Equation 1 (DWIA, 2003).

$$v_2 = v_1 \cdot \frac{\ln(h_2 / z_0)}{\ln(h_1 / z_0)} \qquad (1)$$

where

v_2 = wind velocity at height of turbine (ms^{-1})

v_1 = wind velocity at height of 10 m (ms^{-1})

h_1 = the height at which the measurement for site selection is taken, usually corrected to 10 m

h_2 = the height of the hub of the wind turbine

z_0 = roughness corresponding to terrain style

Roughness can be separated into four different classes: z_0 = 0.0002m for Class 0 (water), z_0 = 0.03m for Class 1 (open land with few windbreaks), z_0 = 0.1m for Class 2 (farmland with some windbreaks), z_0 = 0.4m for Class 3 (urban or obstructed rural land).

Another variable that has a large impact on the energy potential of wind turbines is the intermittent nature of the wind. It has been shown that the probability density function of wind velocity can be closely represented by the Raleigh or Weibull function for a given mean velocity (DWIA, 2003). Figure 7 shows an example of the probability distribution at given mean wind speeds. In this case, the mean speed is 6.6 ms^{-1}. The probability function shows a greater chance of wind at a low velocity than at a high velocity. The Weibull distribution is skewed to the right. The highest probability of velocity is at 5 ms^{-1}. The wind velocities at the right are extremes and the probability of seeing such an extreme velocity is low. This distribution allows a close approximation of what type of energy output wind can provide.

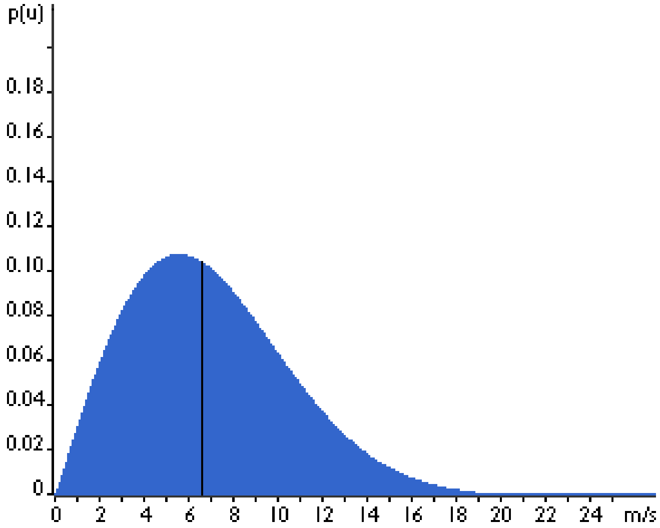


Figure 7. Weibull Distribution of Wind Speed

(DWIA, 2003)

2.3.4 Wind Energy Resources

Wind speed data for over 239 sites throughout the United States has been collected over many years and can be used to evaluate the site of a proposed wind generator. This Total Meteorological Year (TMY) data is standardized to a height of 10 m. The average wind speed for a specific location at a specific hub height can then be interpolated using Equation 1.

Figure 8 shows the TMY data pictorially and is known as the Department of Energy’s Wind Resource Map (DOE, 2003).

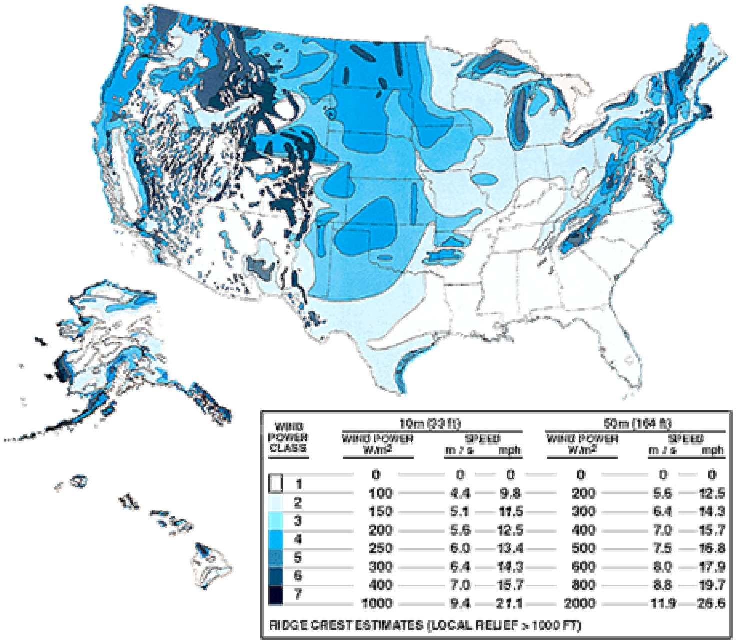


Figure 8. Wind Resource Map

(NREL, 2003)

Although this map may be used as a reference to investigate certain locations, it has to be stated that the site location must be evaluated before construction should begin since there may be local influences that affect the wind to a greater degree. The land acreage needed for one 1.75 Megawatt wind turbine is commensurate with the surrounding area land uses. For instance, crops and pasture land can be used around the base of the turbine with no ill effects (Flowers, 2003). However, for buildings and people, stand-off distances would amount to 15 acres (Renew Wisconsin, 2004). The life span of wind turbines is 25 years (Tauernwind, 2003). The noise generated from wind turbines varies according to wind speed, but can be categorized as 92dB at the base of the wind turbine (Vestas, 2003).

2.3.5 Wind Energy Costs

Due to continuing technological development, the construction and O&M costs of energy are becoming more competitive with conventional methods of electrical production. Currently, the average cost for a wind power system is $750/kW (REW, 2003). The cost may vary according to location and access to the wind turbine site, but the industry average will be used for this model. Currently, the average levelized cost for wind power electricity generating costs is under $0.05/kWh (NREL, 2004). For example, although winds on a mountain peak may be strong and continuous, the cost to construct in an inaccessible site may be exorbitant. Operations and maintenance costs typically run about $0.01/kWh (DWIA, 2003).

2.3.6 Wind Energy Assumptions

Since most wind turbines currently being produced have the three blade configuration, this will be the configuration used for this investigation. Vestas Wind Systems A/S manufactures a 1.75 MW three-bladed turbine that will be used as a representative of the turbines under evaluation. Required capital costs for this Vestas system initially are around $1.3M. Since the cut-in speed required to start rotating the Vestas turbine is 4 ms^{-1} and the mandatory wind stop speed is 25 ms^{-1}, this thesis will evaluate the various regions of wind speed based on the Weibull distribution with the two values as extremes. The first step in finding the mean wind speed was the National

Oceanic and Atmospheric Administration (NOAA) web site (NOAA, 2003). For instance, at Minot AFB, North Dakota, the mean wind speed at 10 m is 4.6 ms^{-1} (NOAA, 2003). Using Equation 1, the mean wind velocity at 60 m is 6 ms^{-1}. This velocity results in a probability that the turbine will turn approximately 73% of the time. Using another example of Maxwell AFB, Alabama, the turbine will turn 52% of the time. Finally, using a selected site of Valdez, Alaska, the probability is 42% that the turbine will turn. If data was not available from NOAA, then ASHRAE's fundamentals book was used (ASHRAE, 1997: 26.6-20).

2.4 Photovoltaic Energy

Photovoltaic cells convert energy from the sun directly into electrical current. While other types of solar energy systems exist, heating water for domestic use and concentrating light to produce intense heat for thermal-electric systems, this research will examine only the standard photovoltaic cell arrays: systems that can be installed onto roofs and over parking areas.

2.4.1 Photovoltaic Energy History

The first photovoltaic device was made in 1876 (Kreider, 1981:24-1). The devices were crude and rudimentary until approximately the last 50 years. By 1958, advances had improved enough to attain an efficiency rating of 14 percent (Kreider, 1981:24-2). With the advent of space flight, the use of photovoltaic cells to provide lightweight and reliable power in space was a driving force in developing the technology. The goal was to attain photovoltaic energy systems that are economically feasible when compared to conventional fossil fuel-fired electrical generation power plants. The space industry drove the photovoltaic industry to research more efficient ways to power satellites until 1974. Then, the price of energy started to increase and made solar power research evolve for other markets such as individual homes, businesses, and utilities. Now, photovoltaic panels are being constructed through various methods and are being incorporated into construction materials that are built into the structure. Photovoltaic panels on a roof are shown in Figure 9. Photovoltaic cells may also provide cover over parking spaces thus shading vehicles while generating electricity as shown in Figure 10.

Figure 9. Photovoltaic Roof

(NREL, 2004)

Figure 10. Photovoltaic Panels over Parking Lots

(NREL, 2003)

2.4.2 Photovoltaic Energy Types

There are a number of photovoltaic panels that can be used to generate electricity: fixed horizontal plate, fixed-tilt, horizontal north/south tracking, horizontal east/west tracking, and two-axis tracking. The fixed-tilt angle is the angle from horizontal that corresponds to the latitude of the site (0° is located at the equator and 90° is at the north or south pole). Fixed horizontal plate systems are stationary and face straight up without any corrections related to time of day, year, or latitude. Fixed-tilt systems are stationary but are tilted based on the site latitude to achieve a higher irradiance from the sun than horizontal mount systems. The degree of tilt for fixed-tilt systems can be increased or decreased depending on what time of year maximum output is required. Horizontal north/south tracking systems rotate on one axis moving north to south. The irradiance (Wm^{-2}) closely matches the irradiance of the fixed horizontal during winter months. The horizontal east/west tracking system also rotates on one axis moving the plate from east to west. The system that achieves the highest irradiance is the two-axis system. The system rotates about two axes, always keeping the face of the plate directly towards the sun. Computer controls direct the motors to turn the non-fixed panels to achieve maximum benefit. Figure 11 and Figure 12 show the differences in irradiance among these systems for the city of Albuquerque, New Mexico. The figures indicate the greatest irradiance over a longer period of time is obtained by the two-axis tracking system during the entire year.

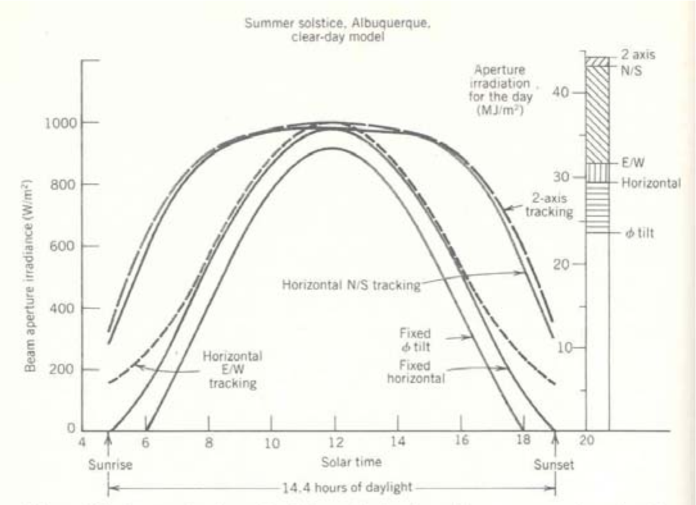


Figure 11. Comparison between Photovoltaic Panel Mounts, June

(Stine, 1985:112)

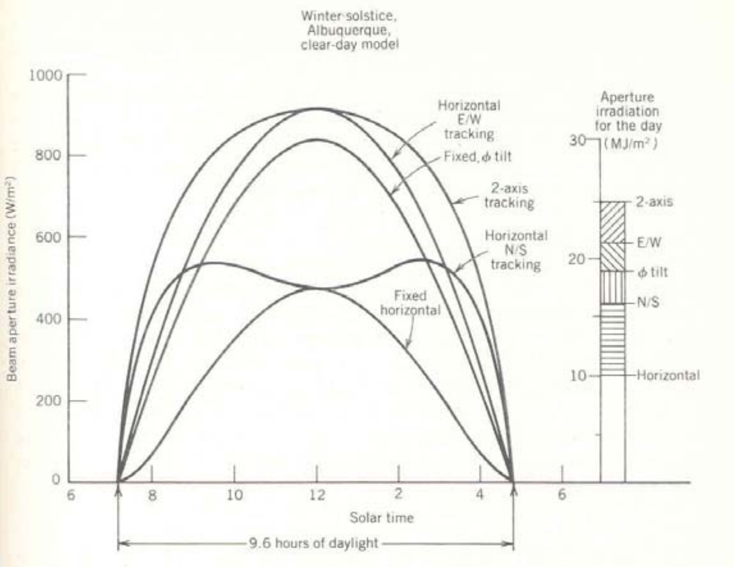


Figure 12. Comparison Between Photovoltaic Panel Mounts, December

(Stine, 1985:113)

Due to the complexity that a rotating system introduces and higher maintenance cost, this research will utilize a fixed-tilt system. National Renewable Energy Laboratory recommends a fixed-tilt system that is tilted at the latitude angle minus 15 degrees if a fixed mount system is to be used for power generation (NREL, 2003).

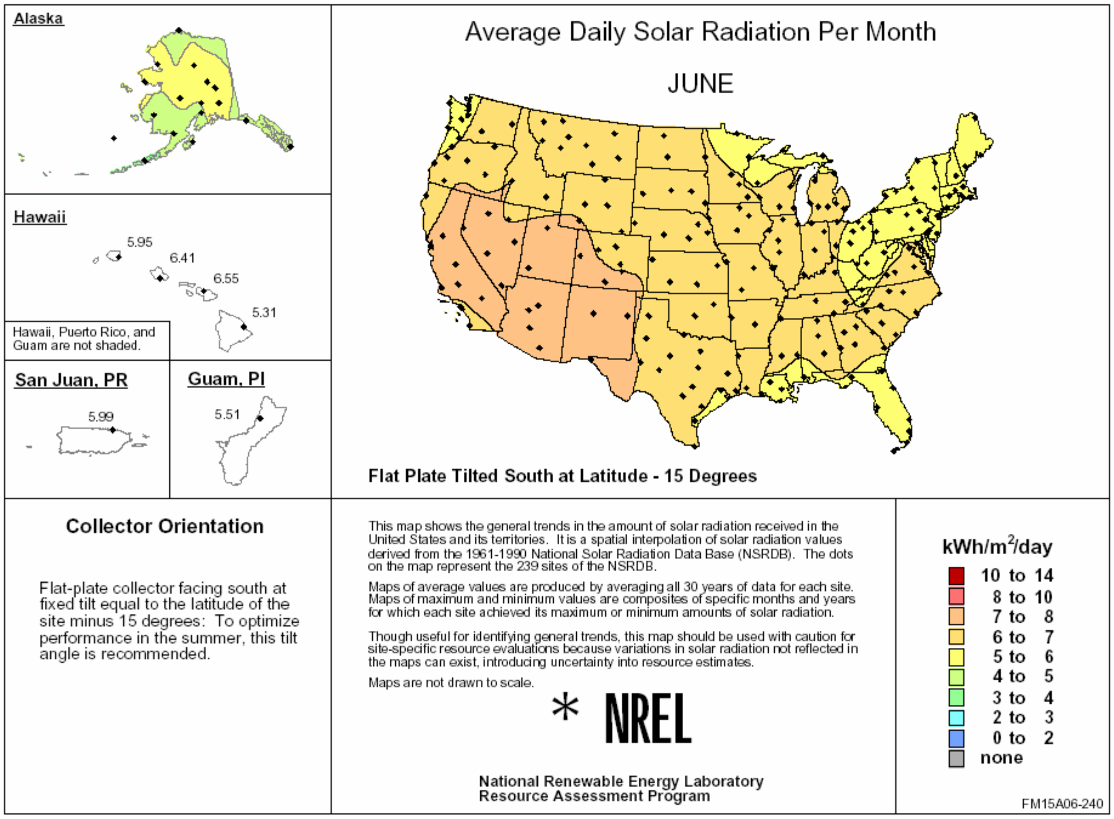
2.4.3 Photovoltaic Energy Production

Solar energy strikes the earth every day. Much of that energy, however, is either absorbed in the atmosphere or reflected back into space. The amount of energy that reaches the upper atmosphere is 1,367 Wm^{-2} (Stine, 1985:84). The percentage of direct energy (insolation) that reaches the surface ranges between 33-88% of this value (Stine, 1985:84). Therefore, the solar irradiance that reaches the surface of the earth ranges from

451 and 1,203 Wm^{-2}. The National Renewable Energy Laboratory offers calculating software (PVWatts) that calculates an output for various photovoltaic mounting types and locations based upon these irradiance values (NREL, 2003). PVWatts calculates the electrical energy produced at a particular location. The program uses data and accounts for photovoltaic system losses due to temperature, soiling, and glass covering. The program allows the selection of the size of system and the tilt of the mounting most appropriate for a particular location. For our model, we will contrast the differing energy sources using the similar output of 1.75 MW.

2.4.4 Photovoltaic Energy Resources

Solar radiation data has been accumulated at the same 239 sites where the wind energy data was collected. Figure 13 is a solar map of the United States and shows the solar radiation striking the earth in June in $kWm^{-2}day^{-1}$. It provides an average snapshot of various points throughout the United States for the month of June using data from 1961-1990. By using the PVWatts calculator and the data received for a fixed plate mounting, an estimate of power production over a year's time period can be made that would be within 10 to 12% of reality (NREL, 2003). The footprint required to produce 1.75 MW is significant. With a 10 square foot panel that produces 120 W, 3.3 acres of panels are required to produce the 1.75 MW of energy. The life span of photovoltaic plates is approximately 20-25 years (CNN, 2003). There is zero noise creation from this source.



Flat-plate collector facing south at fixed tilt equal to the latitude of the site minus 15 degrees: To optimize performance in the summer, this tilt angle is recommended.

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

Figure 13. Solar Irradiation Map for Fixed Plate Mount Minus 15 degrees, June

(NREL, 2003)

2.4.5 Photovoltaic Energy Costs

Because of the high cost of manufacturing, solar panels are still relatively expensive. However, continuing development over the years has lowered the costs rather dramatically. The current crystalline silicon cell installed cost is approximately $9,000/installed kW (Aldous, 2003). The average maintenance costs are negligible but the operating costs average $0.22/kWh (Solarbuzz, 2003).

2.4.6 Solar Energy Assumptions

Due to the decreased maintenance costs associated with a fixed-tilt system, an assumption will be a fixed-tilt panel configuration that is at the same angle as the latitude for the region minus 15 degrees to maximize solar output during the summer months. The highest requirement for electricity is during the summer months and to maximize the use of photovoltaic power during that time period is sensible.

2.5 Geothermal Energy

Geothermal energy captures the heat from the earth and uses it to convert water into steam. The steam pressure drives turbines that convert the potential energy to electricity using generators. The benefit of this system is that it provides a consistent energy source that is not intermittent. Although relatively new, geothermal resources have enjoyed wide spread acceptance when available. Geothermal energy has been used to provide heating in the winter and cooling in the summer throughout the world and is now beginning to find acceptance in providing electrical production.

2.5.1 Geothermal Energy Production History

The first geothermal power plant produced 250 kW in 1913 (Johansson, 1993:554). Italy expanded the use of geothermal energy by reaching an astounding 127 MW in 1944 (Johansson, 1993:555). Geothermal use continuously expanded through the decades and now includes direct heating and other uses. Currently, the world produces over 8,000 MW of power using geothermal power plants (Worldbank, 2004). A main requirement that has hindered the widespread use of geothermal electrical production is that a source of heat above 100 degrees Celsius must be used.

2.5.2 Geothermal Energy Types

There are three main types of geothermal power plants for electrical production. The first is a dry steam power plant as shown in Figure 14. The dry steam plant receives the steam from pipes driven into the earth and channels the steam through a turbine. This turbine then drives a generator to produce electricity. The condensed steam is injected at a location near the well in order for it to be re-heated. The heated water slowly flows along the path of least resistance through the bedrock, up the production well, turns into steam, and drives the turbine.

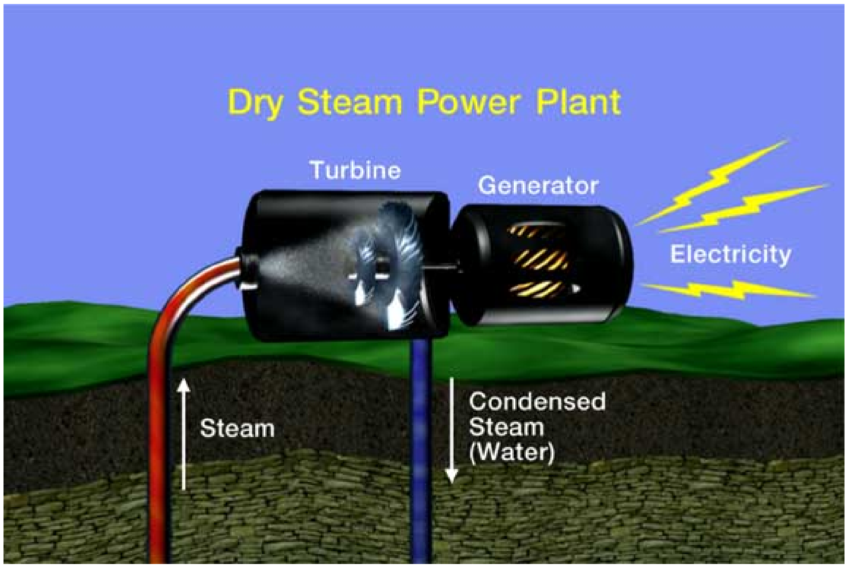


Figure 14. Dry Steam Plant

(Geothermal Education Office, 2003)

The second type of power plant is flash-condensing as shown in Figure 15. The flash-condensing plant receives both the steam and compressed liquid. The hot pressurized water enters a low pressure container. The change of pressure between the liquid and low pressure container causes the liquid to "flash" into steam. This steam then runs through the turbine, thereby increasing the recovered energy and the condensed liquid is injected back into the ground.

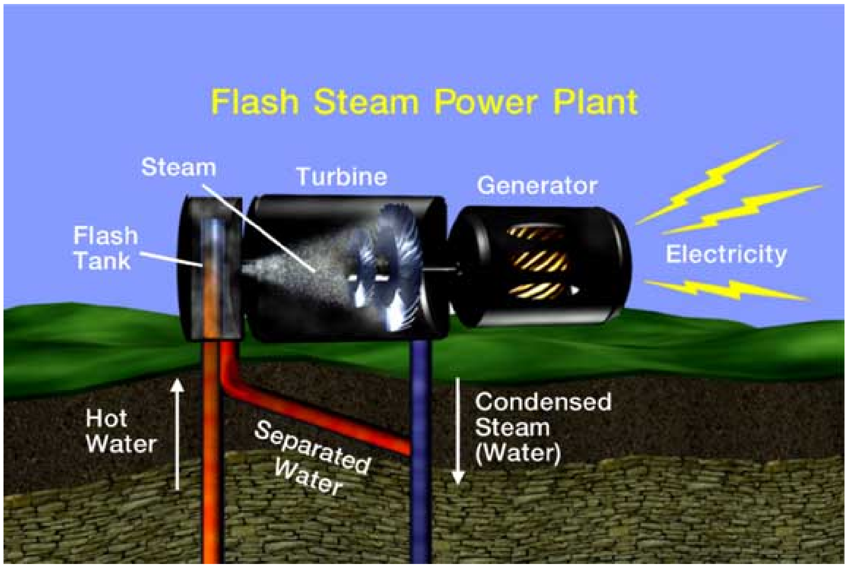


Figure 15. Flash-Condensing Steam Plant

(Geothermal Education Office, 2003)

Another widely used geothermal plant is the binary plant shown in Figure 16. In a binary plant, the heated liquid is passed through a heat exchanger to another liquid. This liquid is heated and passed to the turbine where it is flashed into steam. It is then condensed and passed through the heat exchanger again. The original liquid from the earth is cooled by passing through the heat exchanger and is injected back down into the earth to be re-heated.

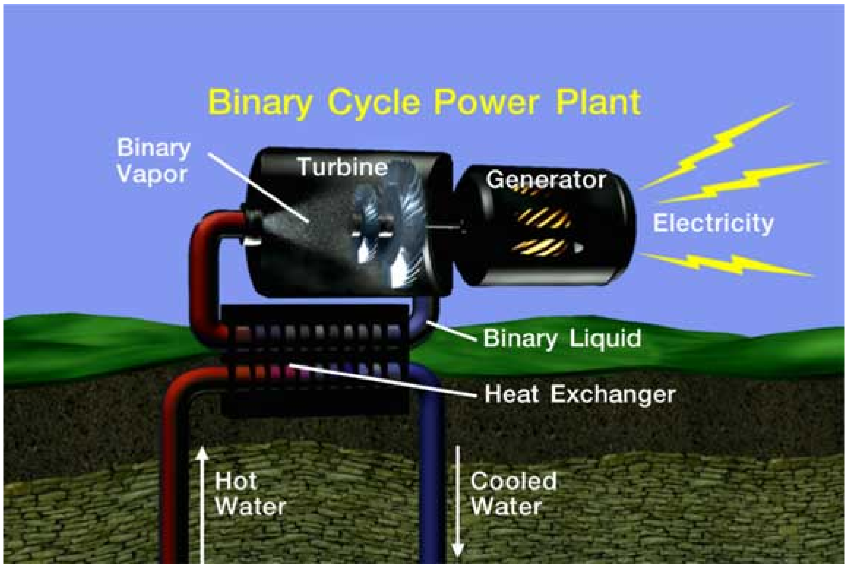


Figure 16. Binary Cycle Plant

(Geothermal Education Office, 2003)

2.5.3 Geothermal Energy Production

Although, theoretically, geothermal plants are possible in every region, some heat reservoirs lie very far below the surface that makes them economically unviable. Ground temperatures 10-15 feet (3-4.5 meters) below the surface vary seasonally but eventually reach a stable temperature at about 28 feet (8.5 meters) as shown in Figure 17. Figure 18 shows the mean soil temperature at 15 feet varies throughout the United States.

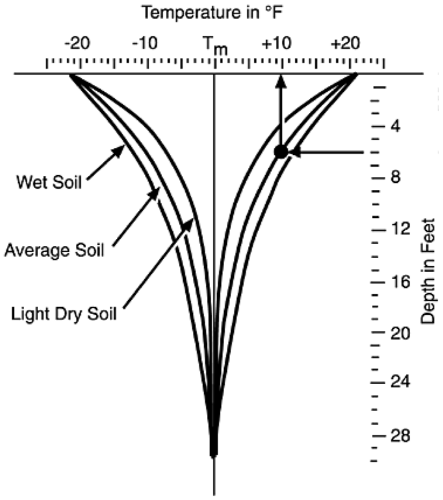


Figure 17. Soil Temperature Variations by Depth

(DOE, 1995)

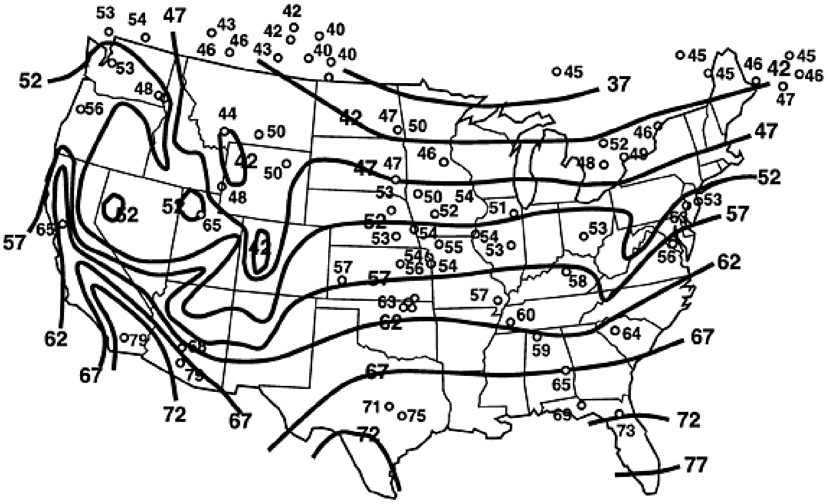


Figure 18. Mean Ground Temperature (°F) at 15 Feet below the Surface

(DOE, 1995)

Figure 19 is a map of the United States showing the thermal gradient of the United States. As the depth of a well increases, the temperature increases. This temperature gradient is represented for various locations by the scale to the right. Starting with the mean ground temperature in Figure 18 and using the thermal gradient from Figure 19, a depth can be calculated to reach 150°C. With a beginning temperature based on Figure 18, the best locations for geothermal plants can be determined. By combining the mean ground temperature with the gradient, we can get an idea on how deep the appropriate heat reservoir is. For instance, using the middle of Missouri as an example, the mean soil temperature is 57 °F (14 °C). With a thermal gradient of 15 °C/km, then a temperature of 150 °C should be reached at (150-14) °C/ 15 °C/km or 9.1 km.

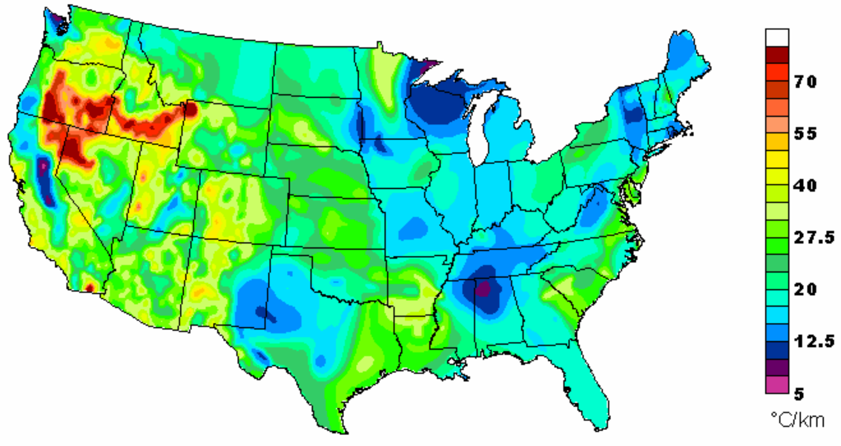


Figure 19. Thermal Gradient of the United States

(Blackwell et al., 1997)

2.5.4 Geothermal Energy Resources

Using Figures 18 and 19, and a heat reservoir temperature of 150 °C, a general assumption can be made on the costs of a geothermal power plant since the cost is based on the plant as well as the depth of the production well. The resource is continuous and abundant. The China Lake geothermal plant has an on-line availability of over 98% (US Navy, 2003). The space required for a 30 MW geothermal plant is approximately 1-8 acre (Shibaki, 2003). The life span of geothermal plants is approximately 45-50 years (Geo-Heat Center, 2003). The noise generated by running a binary geothermal plant is typically in the 55 dBA range. Efficiency of a binary plant for various heat source temperatures is given in Figure 20.

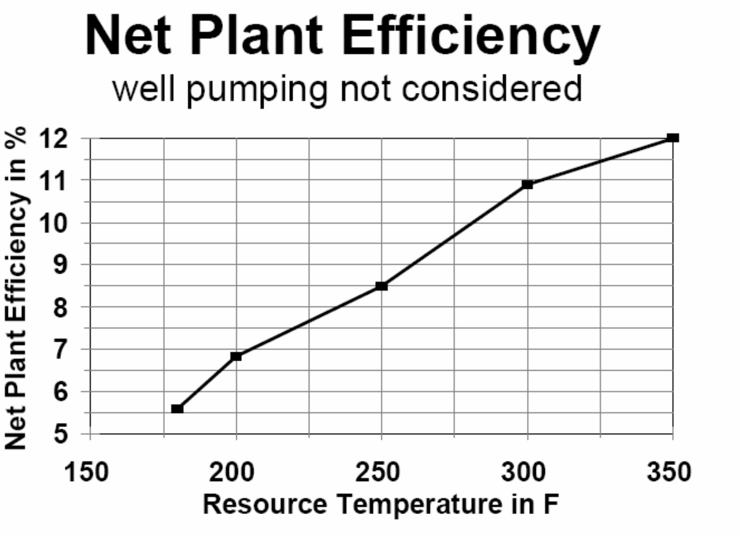


Figure 20. Plant Efficiency for Binary Cycle Geothermal Plant

(Rafferty, 2000)

2.5.5 Geothermal Energy Costs

The plant cost for a binary system is approximately $3,500/kW. This cost is reflective of the plant itself, not the drilling and preparing the injection and production well sites. The costs associated with the well drilling and piping are approximately $1,000/m. This shows the advantages of finding heat reservoirs nearer the surface of the earth. Additionally, the Operations & Maintenance (O&M) costs have been found to be a percentage of the total plant value. Typically this percentage is 4% of plant value (Gawlik & Kutscher, 2000). A 1.75 MW geothermal plant may cost approximately \$6.1M (\$3500/kW x 1750 kW) and the plant maintains a continuous production of 98% of the theoretical production of 15,340,500 kWh (24 hrs/day x 365.25 days x 1750 kW). By dividing the plant cost over the yearly production (15,340,500 x 0.98), the cost/kWh is roughly \$.016/kWh.

2.5.6 Geothermal Energy Assumptions

This research will be based on a binary system with a maximum depth of 10 kilometers and a reservoir temperature target of 150 °C. With a heat reservoir located closer to the surface, the initial costs will be less since the injection and production well depth will be less. In keeping with the previous comparisons, the energy produced will be the same as the other renewable energy sources at 1.75 MW. The depth is kept to a maximum of 10 km in order for the costs not to become to exorbitant.

2.6 Civil Engineer Squadron

How can the Air Force incorporate using renewable energy for electrical production? A major issue with any new technology is how to convert the new technology to application and spend the necessary funds to achieve a desired result. It is hoped that this VFT model will enable the decision makers to see for themselves the process used and the insight gained towards a renewable energy decision. As an example of power usage on an Air Force installation, Barksdale AFB, Louisiana, requires a peak load of 20 MW while the emergency generating capacity is 2 MW (Cost, 2003). With enough power produced on-site, a base can reduce or eliminate the need for off-site power generation and be totally independent from outside energy sources.

2.6.1 Current Practices

On January 1, 2003, Dyess AFB, Texas, contracted with TXU energy to provide 100% of the base's energy requirements (Rosine, 2003). This contract alone helped Air Combat Command fulfill its requirements under EO 13123 (Rosine, 2003). Although the Dyess contract was big and meets many requirements from the federal government, it still allows for the potential disruption of electrical energy since the source is located outside the base.

Vandenberg AFB, California, embarked on an ambitious plan in 2001 to evaluate four sites for possible wind turbines. After collecting data for 1 year, 2 of the sites were deemed economically viable and a plan is in place to construct two 1.5 MW wind turbines on base. Further locations on Vandenberg AFB are being evaluated as well as off-shore based wind farms. Ken Padilla, (base energy manager at Vandenberg AFB) along with other people looked at the available resources and chose wind energy since they believed it was more promising than other developed energy sources (Padilla, 2003). Wave energy was their number one choice due to the predictability and the energy density of waves. However, wave energy was not chosen because it was still in the development stage and there was a question of who was the governing authority for off-shore resources (Padilla, 2003).

Additionally, Lajes AB is currently funded to construct a 2.6 million Euro wind turbine off base in the Azores. The purpose of this construction is to lower costs and to abide by E.O. 13123. The contracting method calls for the United States to pay for the construction, but the local Portuguese power company to run and maintain the equipment (Golart, 2004). The work has been under negotiation for years and there is no supportable documentation as to why they chose wind turbines over geothermal or solar.

2.6.2 Contracting Methods

Although an in-house workforce may seem to be the desired method for operating an electrical plant, that may not be the case. As the military draws down, many functions that were performed by Air Force personnel have been converted to civilians or replaced by contracted workers. Since there are no Air Force Specialty Codes for any electrical production other than generators, then some form of contracting is the preferred method. The Navy's China Lake geothermal plant is based on a land-lease program where a private company constructed and operates the plant. California Energy Co, Inc. was awarded the contract and built a 270 MW geothermal plant in stages (U.S. Navy, 2003). While the company owns and operates the site and sells the electricity to the local community, the Navy reaps monetary awards from the sales and offsets electrical costs. From 1987 to 1993, the Navy reduced their electric bill by $24.2 million (U.S. Navy, 2003). Utilizing experts in the business world outside of the military seems to be an easier and more efficient way to support the construction of these power plants. Another method may be a contractor-operated plant. The Unites States funds the construction and lets a contractor operate for a set fee. In this way, the entire electrical production can be used on base before it is sent to the local power grid to generate funds.

2.7 Decision Analysis

Which decision model is the best to apply in this decision? In order to gain support for a suggested course of action, the best decision model requires the cooperation and involvement of the decision-maker. There are three major decision model types: descriptive, predictive, and prescriptive. Descriptive models include simulation and involve queuing or inventory models. Predictive models use regression or time series techniques to predict an outcome in the future. Prescriptive models provide an insight for making better decisions and specify a course of action for the decision-maker. Prescriptive models are comprised of mathematical programming and decision analysis. Within decision analysis, most models are thought of as either using alternative-focused thinking or value-focused thinking. Since this model is designed to provide insight to the decision maker and recommend a course of action, the prescriptive model is the preferred method.

2.7.1 Alternative-Focused Thinking

Alternative-focused thinking models rely on preconceived notions and comparisons before any evaluation measures are made. With knowledge of what will be evaluated, measures and the weights of those measures can be skewed to provide an outcome that the decision-maker prefers. The alternatives are then compared to one another when scoring the measures. It's this comparison of one alternative to another that drives this model away from what is required in this research. Instead, this model examines the overall benefit to the decision-maker, not to each alternative. This different approach is called value-focused thinking.

2.7.2 Value-Focused Thinking

The value-focused thinking model begins with identifying the decision-maker or proxy decision-maker. This person decides what measures are important and the weight of importance of each measure before any alternatives are generated. This way a multi-objective analysis can be made and insight can be given as to what is most important to the decision-maker first and foremost. With the weighting of the various parameters performed before applying any alternatives, the decision-maker hopefully will not bias the decision one way or another.

2.8 Driving Forces for Research

There are a few driving forces for this thesis. Along with the regulatory requirement created in 1999 to reduce greenhouse emissions, recent events cause the military to look at ways of becoming self sufficient due to possible terrorist actions. The national energy supply is one way for terrorists to create problems. Finally, with a dwindling non-renewable energy reserve, it becomes ever more pressing to utilize existing forms of renewable energy when possible.

2.8.1 Regulations

President William Clinton signed EO 13123 on June 3, 1999, requiring executive agencies such as the DoD to reduce greenhouse gas emissions 30% by year 2010 when compared to 1990 levels (Clinton, 1999). In addition, each agency was tasked to expand the use of renewable energy sources within its facilities, to include installing 20,000 solar energy systems nation-wide by year 2010 (Clinton, 1999). EO 13123 also directed each agency to reduce energy consumption even if on-site energy requirements increase (Clinton, 1999). By incorporating renewable energy production on an installation, the military can achieve the objectives set forth in EO 13123.

2.8.2 Terrorist Threats

In February 2003, President Bush released his national strategy on infrastructure protection (Bush, 2003). Part of this strategy is to ensure energy producers examine their own assets for vulnerabilities and correct them as needed. With the potential of terrorist actions being able to diminish our military readiness levels, continuous energy supply to a base is an urgent requirement.

2.8.3 Depleting Natural Resources

The last reason for this research is that the continuous use of non-renewable resources continues unabated. The major fuel source for electrical production is coal which provides for over 56% of the world fuel needs (DOE, 2002). If the world population growth continues at a 5% annual rate, then the worldwide recoverable reserves will only last 86 years. Even the Department of Energy estimates that coal will last only another 230 years (DOE, 2003)

3. Methodology

3.1 Overview

This research effort evaluates three specific renewable energy sources for providing the primary electrical power for a military base. Value-focused thinking (VFT) was chosen as the tool to select the best energy source. Using VFT allows the decision-maker to evaluate how the energy sources compare against the decision makers overall goal of implementing a renewable energy source. By creating a model with identifiable measurements that can be evaluated, the decision-maker can gain insight into what is important in the decision analysis process. Fortunately, there have been previous researchers in the field of VFT who have developed a roadmap for the evaluation of various alternatives to decision making. Shoviak and Chambal (2001) pioneered a ten-step process that will be utilized for model development. The ten-step process carefully guides an evaluator to construct a working usable decision analysis model. This chapter will explain the process and show the development of the working model for evaluating energy sources. Steps 1 through 7 will be conducted in this chapter while steps 8 through 10 will be conducted in Chapter 4 of this thesis.

3.2 Step 1: Problem Identification

This step identifies the reason for building a model to begin with. In order to create the VFT model, the model developer and the decision maker must work closely to ensure the model will accurately reflect the question that is posed. Otherwise, the effort will have been wasted and the research results cannot be used properly. Also, prolonging the time for problem identification may cause the decision maker to lose sight of the original intent and change the scope of the effort. This change in direction would cause undo effort and may result in wasted time. By keeping the problem identification time to a minimum, it will ensure the outcome is useful for all parties involved. Once the problem is clearly identified, the value hierarchy can be constructed. In this case, the problem is that the DoD must reduce greenhouse gas emissions 30% by year 2010 when compared to 1990 levels (Clinton, 1999). By identifying viable renewable energy alternatives and employing them, decision makers may save money and reduce greenhouse gas emissions as required. Along with encouraging the use of renewable energy, recent threats of attacks on military installations emphasize the need to generate much of the installation's electrical energy on site. Power loss on a base during national or local emergencies may prevent the installation from providing support to the local community and be detrimental to the national defense mission. The recent blackout event of 2003 throughout the northeast United States illustrates the need to have power generating capabilities on a base. If a base is dependant on outside energy sources, their ability to perform their mission or help the local populace is diminished if the power on the base is also non-existent.

The purpose of this model is to allow a decision maker to use the values and weights given to various measures to select which renewable energy source is the best choice for a given location. This model will illustrate the step-by-step method so that it can be easily recreated and changed to suit newer technologies. VFT allows the development of newer technologies to be easily added to the model without having to adjust and develop a new model every time (Keeney, 1992:38-39).

3.3 Step 2: Constructing the Value Hierarchy

The value hierarchy is a graphical representation of what is important to the decision-maker with respect to the decision being made. Kirkwood identifies two different methods to develop this hierarchy (Kirkwood, 1997:19-23). They include a top-down method and a bottom-up method. The top-down method starts by asking the decision-maker what is most important in a broad sense (cost, location). Then, these broad categories (the first tier) are further broken down into smaller, particular components that help define the category. Finally, the end result is a series of smaller components or measures that can be quantified and scored. These measures align within the broad categories in the higher tier of the hierarchy. The bottom-up method starts with a series of measures and then an attempt is made to define groups for these measures. The top-down method was used in this research and is the preferred method by instructors of VFT at the Air Force Institute of Technology (AFIT). By creating this hierarchy, the decision-maker can determine if the measures are complete enough for an accurate assessment.

Ultimately, the decision-maker determines what measures go into the final value hierarchy. With the limited amount of time that a typical executive has, there are suggestions to further shorten the time needed for developing the value hierarchy by using various techniques. One method used for creating the measures of the hierarchy is called the “gold standard” (Weir, 2003). The “gold standard” technique utilizes published mission statements or objectives to establish the evaluation measures of the decision-maker or organization. A benefit of the “gold standard” is that a proposed hierarchy can be created and can be brought to the decision-maker. Determining evaluation measures can be a long arduous process when starting from scratch. Using the “gold standard” methodology allows the decision-maker to look at the initial measures and determine whether they are appropriate for the decision at hand. This helps to ensure the time spent with the decision-maker is short and productive. In this case, EO 13123 requires increased use of renewable energy at federal agencies but has little further guidance.

Because there were no published mission statements or objectives, measures were suggested to the decision-maker according to the lesser “platinum standard”. This standard relies on interviews with senior leaders and key technical personnel. After review, the decision-maker requested to include more measures to more accurately reflect the decision-making inputs. Once all the measures were identified, they were then sorted into categories. These measures are arranged in a hierarchical, or tree-like, structure. At the top of the structure is the fundamental objective. Below the fundamental objective, the lower tier measures “branch out” to define the complete set of values. A tier represents measures on the same level of importance in the value hierarchy. There can be multiple tiers or a single tier in a value hierarchy depending on the complexity of the fundamental objective and supporting measures. As one moves down the hierarchy, the lower-level tiers in the hierarchy continue to refine the prior measures into more detailed ones.

Figure 21 shows the value hierarchy based on discussions with the decision-maker. The first tier shows what the decision-maker considers the most important goals are when looking at renewable energy. These goals are resources, location, and operation. The resources category includes those measures that directly affect the monetary outlays and personnel resources. The location category is concerned mainly with how the construction affects the base and whether it interferes in some way. The operation category gives voice to efficiency and how steady the power source creates energy. Each first-tier goal was further decomposed into the second-tier goals shown in Figure 21.

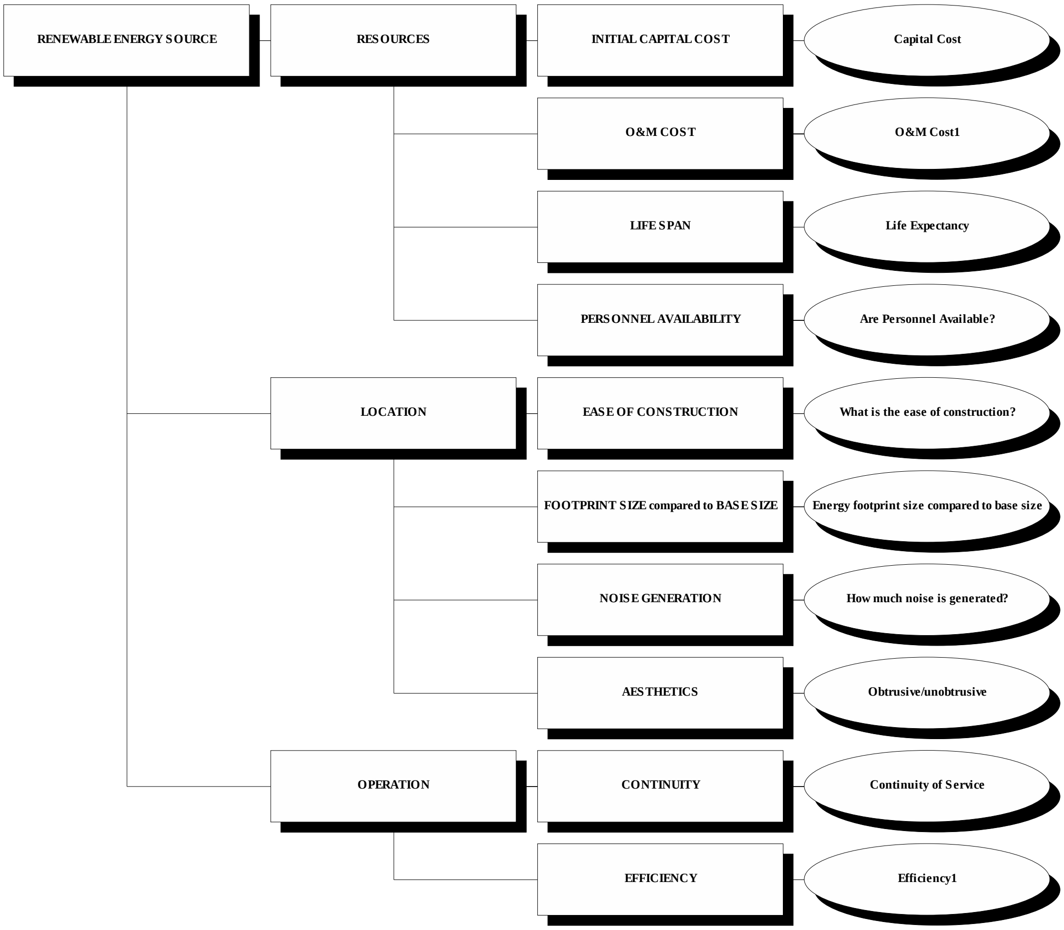


Figure 21. 1st and 2nd Tier Value Hierarchy for Selecting Renewable Energy

Desirable properties in a value hierarchy include: completeness, non-redundancy, independence, operability, and small size (Kirkwood, 1997:16-18). A value hierarchy is considered complete when the evaluation criteria from each tier, taken as a group, adequately cover all concerns necessary to evaluate the overall objective of the decision (Kirkwood, 1997:16). Additionally, the value hierarchy must be non-redundant. If two or more measures were similar in their measurement, then additional weight is given to these measures collectively than would otherwise be given. For instance, consider the value of Quality of Life. This might be measured from the standpoint of a child and a spouse. If the measurement unit is in years between household moves (a quality of life issue) for both, then the weight given each individually is compounded and has more weight than otherwise intended. Yet another criterion of the value hierarchy is that there needs to be independence. Independence is defined as the preference level for one measure is not dependent on the level of another measure. Kirkwood uses an example of a potential job seeker to illustrate this criterion (Kirkwood, 1997:17-18). Although a job seeker may have stated salary, pension benefits, and medical coverage as non-redundant measures in a value hierarchy, they are not necessarily independent. With great pension benefits and medical coverage, the job seeker may place less value on salary.   The operability of a value hierarchy is based on the user. It is the ease with which a user can understand the hierarchy and follow the paths to the evaluating measures. If the hierarchy is too complicated, it may not be useful to the decision-maker. Finally, the size of the hierarchy determines the complexity and ease of understanding. Having too big of a hierarchy will undoubtedly lead to confusion and distrust of the model. There is a tendency to continue adding measures until the hierarchy is too large to comprehend and any insight that can be gained will be difficult to understand (Kirkwood, 1997:19). This model retains the necessary measures to evaluate the current and future renewable energy sources.

Ultimately, the bottom tier of the value hierarchy contains the measures upon which the entire decision is based. After analysis and consultation with the decision-maker, the current model appears to meets the criteria of non-redundancy, independence, operability, completeness, and limited complexity. Therefore, the next step is the evaluation criteria of the measures.

3.4 Step 3: Developing Evaluation Measures

Evaluation measures are used to quantify the values on the bottom tier of the value hierarchy. These evaluation measures are created to define how the value will be assessed. According to Kirkwood, there are four classifications of evaluation measures. They are either natural or constructed, and either direct or proxy (Kirkwood, 1997:24). A natural scale is one that means the same to everyone who views it. Natural scales are typically easily quantified and are readily available. On the other hand, a constructed scale is useful when a natural scale cannot be attained and must be constructed in some fashion. These typically have levels associated with the measure rather than actual numbers. A direct scale measures the degree of attainment of the objective. Finally, a proxy scale is useful when there is no real method to quantify a measure, but rather allows a measure to be scored based on other criteria. Student grades are an example of a constructed, proxy measure. Since some children are smart but do not test well, using grades as a measure of how bright the child is a proxy since actual student learning is not quantifiable. Due to the fact that the grades are based on levels, this also is a constructed measure.

An evaluation measure can have any of the four combinations of natural, constructed, direct, and proxy. These combinations are shown in Table 1 with associated examples. Kirkwood proposes that the ideal scales are those that pass the clairvoyance test (Kirkwood, 1997:28). If a clairvoyant were to know the future, would the clairvoyant be able to assign a score to the outcome of each alternative. The natural scales easily pass the clairvoyance test, but the constructed measurements do not pass as easily. The order of preference for scales is natural-direct, constructed-direct, natural-proxy, constructed-proxy (Parnell, 2002).

Table 1. Evaluation Measure Examples

	Natural	Constructed
Direct	Net Present Value Time to Accomplish Cost to Accomplish	Olympic Diving Scoring Weather Prediction Categories R&D Project Categories
Proxy	Gross National Product (Economic Growth) Number of Subsystems (System Reliability)	Performance Evaluation Categories (Promotion Potential) Student Grades (Student Learning)

(Weir, 2003)

The model that was developed for this research utilizes all four classifications, but the majority of measures fall under the natural, direct classification.

3.4.1 Initial Capital Cost

This measure represents the initial capital cost of the alternative. The capital costs are measured based on the prevailing industry average cost to develop 1.75 MW of power. The reason for selecting a specific amount is to compare similar amounts of power. It would be inappropriate to compare a generating source producing 1.5 MW of power with one that is producing 200 MW of power. Another factor in determining the initial cost is that some renewable energy sources have life spans of varying lengths. Whereas the lifespan of wind turbines and solar panels are between 20 and 25 years, the life span for geothermal plants is between 40 and 50 years. For this reason, the net present value must be calculated for having to construct another wind turbine or install newer solar panels in 20 to 25 years. With construction costs continuously declining and more efficient panels being manufactured, this initially is difficult to estimate and bring to present day values. However, by looking at the projected costs developed by Renewable Energy World, the future costs per kW can be estimated and by discounting the future dollars by 3% per year to present dollars (Kujawa, 2003). These costs can then be used to compare like amounts. The limits for this measure are $0 and $40 million. This is a natural-direct measurement type.

3.4.2 Operation & Maintenance Cost

This measure is also based on current industry standards. The price is based on a $/kW rather then total costs. This enables the model to be used for many configurations and new alternatives. The extremes are $0.01/kWh to $0.3/kWh so as to capture the full range of O&M costs in this model. As new alternatives are discovered, these values can be re-examined with the new energy source. This is a natural-direct measurement type.

3.4.3 Lifespan

One of the measures that the decision maker considers important is the lifespan of the machinery that is harnessing the energy source. While the cheaper alternative initially may seem better, the lifespan may be that a replacement alternative would have to be purchased new equipment after a short time period. This may make the final purchase price too high. The fact that geothermal plants have twice the life span of both wind turbines and the photovoltaic systems have been incorporated into the initial cost discussed in section 3.4.1. The extremes used in this are a low of 20 years to a high of 50 years. This type of measure is natural-direct.

3.4.4 Personnel Availability

Whether or not there are skilled workers with the required expertise are readily available in the local area is another measure that is incorporated into this model. Local area is defined as within 100 miles. If a company builds an electrical generator but has no one in the local area to service it, this may affect whether this particular source should be chosen. As long as there is a contractor within 100 miles able to service the energy producer, then the personnel are considered to be available. More value is given to having someone readily available.

3.4.5 Ease of Construction

This measure is a type of correction factor for construction in terrain that may be unsuitable to normal estimating. Since the industry averages are used for the building of the plant, a different factor must be incorporated to adjust for the difficulty of the terrain. This measure uses a percentage of construction cost and is based on the terrain. In this case, a score of standard will be applied if the terrain allows costs to be less than or equal to 5% increase of total initial industry average cost. A score of moderate will result if the terrain results in a greater than 5% or less than or equal to 15% increase over industry cost. Finally, a score of expensive will result if the terrain results in greater than 15% increase in costs. Based upon the history of construction in the local area, the base engineer can identify the areas of base that would result in the above findings. A detailed cost analysis of potential sites cannot be made due to the lack of historical construction data for these generation sources. This model is used to evaluate many potential renewable energy sources to narrow the field and concentrate on viable options. Only then, would the request for bids go out and accurate construction costs be tabulated.

For instance, if a mountain top radar site is being evaluated for geothermal, solar, and wind energy sources, the construction costs would be unknown due to the lack of knowledge about that particular area. A bid would be required for each type of energy source. However, if this model were to be used to reduce the field of choices to just wind turbines, then bids could be requested from multiple wind turbine companies who would then review the site for construction costs. This type of measure is constructed-proxy.

3.4.6 Footprint Size Compared to Base Open Space

When dealing with military installations, thought has to be given to the amount of open space that is made off limits due to constraints or construction. This measure captures those thoughts. When a potential energy source is being evaluated or scored, measurement is taken as to how much of the open land is being used or rather how much of the open land is being placed off limits to future construction due to either safety zones, actual land use, or Air Installation Compatibility Use Zone (AICUZ) noise levels. The extremes are 0% (this is theoretically possible given that solar panels could in fact be incorporated into existing building construction or over hanging parking lots) to 100%. This type of measure is constructed-direct.

3.4.7 Noise Generation

This measure captures the value of noise in generating power. A high value is placed on having a quiet operation. If the noise generated is over 85 dB, then actions must be taken to limit exposure to people in that vicinity. Therefore, the extremes are 0 dB for the most desired and 100 dB being the least desired. The value function drops to zero at 85dB. This measure is a natural, direct.

3.4.8 Aesthetics

One of the possible constraints on an energy source is the ability of the base populace to see the apparatus. If the base commander does not care that there may be a large amount of solar panels or some wind turbines on base, this weighting may be very low. On the other hand, the commander may feel a need to hide everything; in this case the weighting will be higher. The purpose of this measure is to incorporate the commander's acceptance of whichever energy source is utilized. The possible scores for this measure are obtrusive or unobtrusive based on input from the base commander. This type of measure is constructed, proxy.

3.4.9 Continuity

When dealing with renewable energy sources, there may be times when the production is zero. In the case of photovoltaic cells, the power is zero when the sun goes down. In cases when the power is not being produced, energy is obtained from the local energy supplier as before. This measure captures the estimated amount of continuous power for any region. Wind has an average velocity that can be utilized to determine how often the wind will create power between the cut-in and stopping speeds of the particular wind turbine. Appendix A shows the continuity for varying wind velocity averages for the different classifications. This table can be altered as newer technology becomes available and allows higher mounts than 60 m.

Photovoltaic continuity can be represented by comparing the theoretical production against the calculated production using PVWATTS software at the National Renewable Energy Laboratory (NREL, 2003). This continuity takes into account the latitude and configuration of the solar panel system. It has been shown that the calculated power is within 10 to 12% of reality over a year's period.

Geothermal sources produce electricity at a steady rate and typically are affected only by annual maintenance shut downs. The industry average is around 98% of continuous service with 2% down time being used for annual maintenance (USN, 2003). This makes the geothermal options a continuous and desirable source of electrical production. This type of measure is natural, direct.

3.4.10 Efficiency

Efficiency is defined as percentage conversion of potential energy to electrical energy. For photovoltaic cells, the efficiency is currently around 17% for crystalline-silicon plates. Efficiencies for photovoltaic cells have been steadily increasing with newer manufacturing techniques. Wind power efficiencies can be defined as the percentage of potential wind energy that can be converted to electrical energy. This is based on the velocity and density of the air along with the total square footage of the blades, the sweep of the blade angle, and the number of blades. For three-bladed wind turbines, the efficiency, or co-efficiency as it is sometimes referred to, is around 40%. At low resource temperatures, geothermal plants achieve an efficiency of around 11% (Rafferty, 2000:7). With all things being equal, more efficient systems are desired due to the lower cost and greater energy captured. This is in addition to the continuity measure which is based on the amount of time that an energy source can provide power. This measure is a natural, proxy type.

3.5 Step 4: Single Dimension Value Function

Standardizing the various measurements is the purpose of the single dimension value function. Kirkwood uses two types of functions: piecewise linear and exponential (Kirkwood, 1997: 61). Although they can be used interchangeably, the piecewise linear function is used when the number of different scoring levels in a measurement is quite small. This is the case when the score has a few options such as yes/no and easy/medium/hard. Otherwise, the exponential function is better to use. Equation 2 shows the formula for the exponential function for a monotonically increasing value function (Kirkwood 1997:65):

$$V(x) = \frac{1 - \exp\left[-\left(x - Low\right)/\rho\right]}{1 - \exp\left[-\left(High - Low\right)/\rho\right]} \tag{2}$$

where

x = the scored amount of the alternative in that measure

High = the upper extreme of the measure

Low = the lower extreme of the measure

ρ = strength value that is set by the decision-maker that changes the shape of the value function

Equation 2 shows how the value decreases or increases with respect to ρ. In the first measurement of initial capital cost, the extremes of the measure are the boundaries used in the formula. Figure 22 shows a monotonically decreasing function. The low value is \$0M and the high value is \$40M. The Logical Decision software that was used requires the values to be within the boundary.

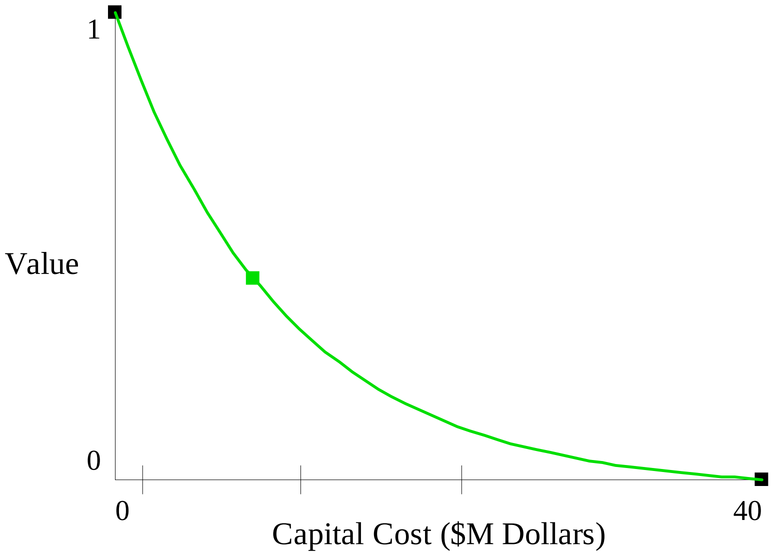


Figure 22. Monotonically Decreasing Exponential SDVF

The degree to which ρ increases or decreases are dependent upon the decision-maker and how that person feels the shape of the function should be. For instance, there is a greater value loss in going from $2M to $3M than there is going from $30M to $40M. This is relative to the decision-maker and his/her personal preferences. The decision-maker for this research is also the sponsor and his preferences were used throughout to create this model. Once established, this model can be easily adapted by a base or unit commander. The function can assume any shape in order to present an accurate portrayal of the value of the measurement. The monotonicity of the function refers to the shape of the function. In other words, the monotonicity of the function determines whether it is increasing or decreasing in value but only one direction. There are no monotonistic SDVFs that are both increasing and decreasing. It can be a straight line, increasing, decreasing, S-curve, or any other myriad representation of the decision maker's values. In the above case, the lower levels of the measure are preferred to the higher levels and quickly decrease in value. The entire series of single dimension value functions can be found in Appendix B.

3.6 Step 5: Value Hierarchy Weighting

After the measures of the decision maker are clearly identified and value functions are applied to those measures, then it is time to apply weights to the measures. There are two ways to apply the weights. The first is local weights, which are calculated across a tier for a particular branch and sum to one within that branch. The second method is using global weights, which sum to 1 and are done across an entire tier. Weighting the various goals and eventually the measures allow the decision maker to assign weights when compared to the other measures and determine what has greater significance to the result.

There are three major methods to determine local weights: assessments by the decision maker, swing weighting, and 100-point method (Kirkwood, 1997: 68-72). In this case, the decision-maker understood the concept and created a local weighting that was incorporated into the model. Figure 23 shows the local weighting that was created by the decision maker.

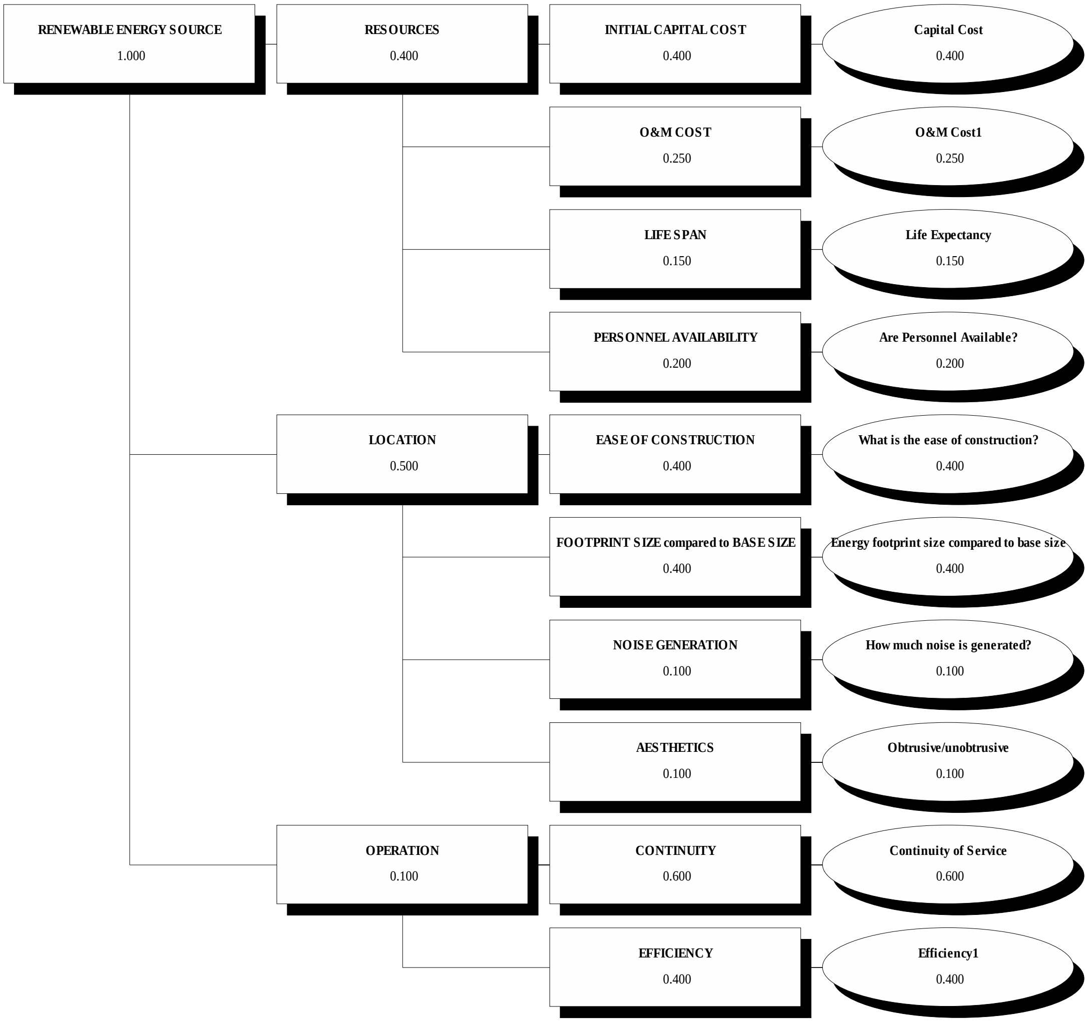


Figure 23. Value Hierarchy with Local Weights

The second step is to look at the implied global weighting of the model. This is easily done by multiplying the local weights to the successive tiers below each branch. Using aesthetics as an example, the local weight for “Location” (0.5) would be multiplied by the local weight of “Aesthetics” (0.1) to obtain the global weight of 0.05. Global weights essentially show how much weight a particular measure contributes to the overall model when compared to the other measures. Figure 24 shows the model’s global weights. The decision-maker can alter the weights at any time to reflect possible changes in focus in the future.

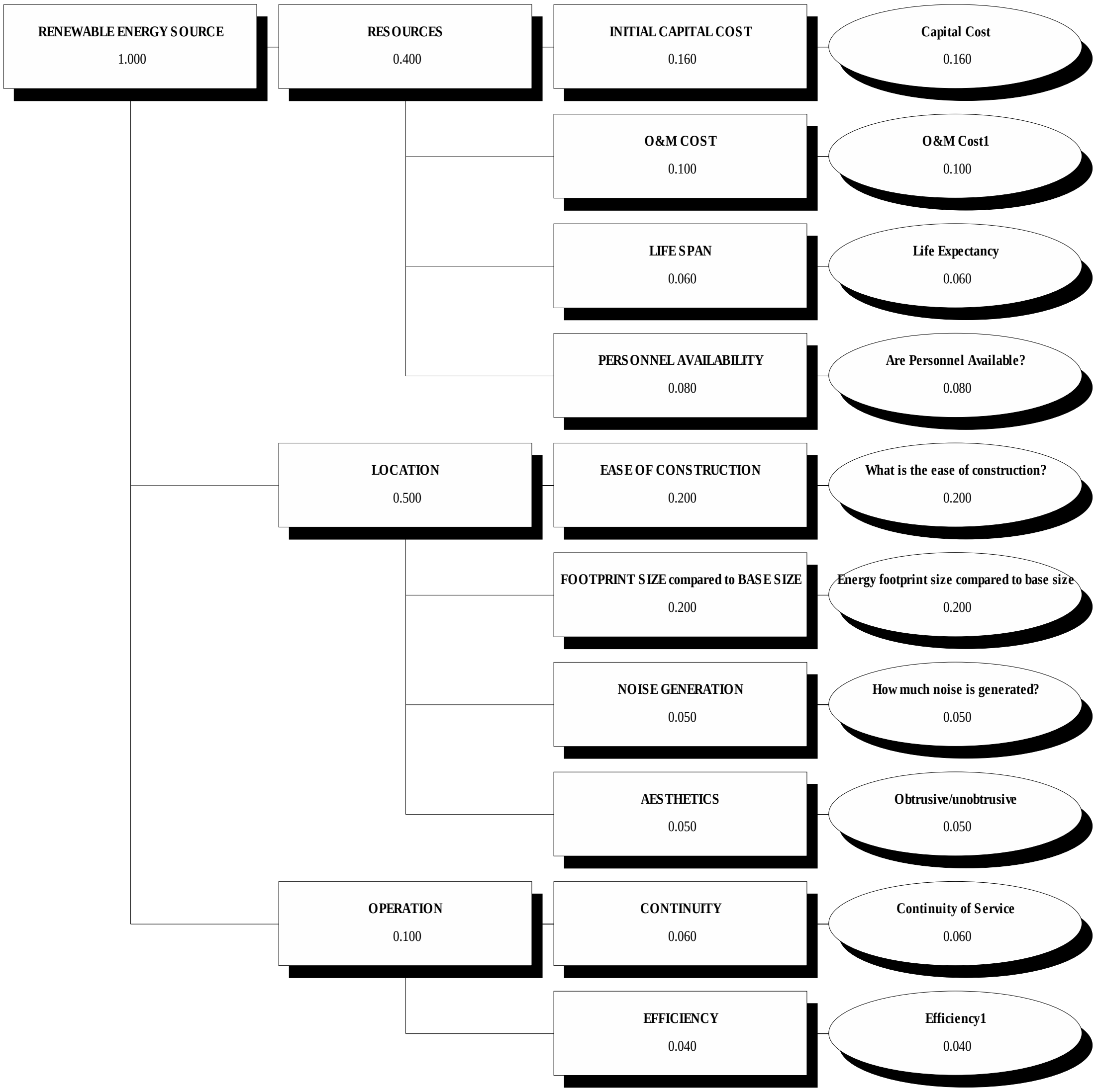


Figure 24. Value Hierarchy with Global Weights

3.7 Step 6: Alternative Generation

Once the hierarchy has been created, measures have been weighted, and value functions have been created, alternatives are finally generated. This model is designed to incorporate newer renewable technology as it is being made economically viable.

Hopefully, in the process of creating the value hierarchy, new ideas or new alternatives can be generated that were not originally considered. Sometimes, so many alternatives can be generated that the decision-maker would have to limit the amount of alternatives based on some screening criteria. Wind turbines and solar panels can be used as an example of how multiple alternatives from one renewable energy source can be generated. Wind turbines are made by many manufacturers and come in a myriad of sizes. For the purpose of this model, only one specific wind generator model from one manufacturer was used. Solar panels are also created by many manufacturers, but some of the major differences that a base may generate involve the space saving installation on roofs and parking lots as opposed to taking away the usefulness of open land. Keeney stated that "alternatives should be created that best achieve the values specified for the decision situation" (Keeney, 1992:198).

3.8 Step 7: Alternative Scoring

Data must now be collected from each alternative. This data must be gathered using the measure units described earlier. This can be very cumbersome if there are many measures or if the data is hard to find. Therefore, the data should be easily researched or accessible. Another aspect of the measures is that the data must be ambiguous. For this research, three bases (Base X, Y, and Z) were examined using the model. These are real bases but will not be identified. The purpose of using these real bases is to get an accurate portrayal of how well the model will work. The alternatives will be scored for each of the three bases and three sets of outputs will be created. The data from each of the bases was placed into a matrix in Logical Decision software for evaluation.

3.8.1 Base X Information

Base X is located in a windswept area of the Midwest. The land is open farmland. From the National Oceanic and Atmospheric Association (NOAA) web site, the mean wind speed is 11.3 mph (NOAA, 2004) and the latitude is 44.03°N. The mean ground temperature is 47°F from Figure 18. From Figure 19, the thermal gradient is 27.5°C/km. The reservoir should be at a depth of 5.1 km. The location allows easy construction. The size of base X is 5,000 acres. Table 2 is the scoring for the renewable energy for Base X.

Table 2. Scoring of Renewable Energy for Base X

	Energy footprint size compared to base size	How much noise is generated?	What is the ease of construction?	Continuity of Service	Efficiency1	Capital Cost	Life Expectancy	O&M Cost1	Are Personnel Available?	Obtrusive/ unobtrusive
Geothermal	0.0002	55	Standard	0.98	0.11	11.2	50	0.016	No	No
Solar	0.00066	0	Standard	0.2	0.17	21.5	25	0.22	Yes	No
Wind	0.0002	92	Standard	0.78	0.4	1.73	25	0.01	Yes	No

3.8.2 Base Y Information

Base Y is located in a desert terrain that is bounded by a few low mountains. The mean wind speed is 9 mph. The latitude is 36.23°N. The mean ground temperature is 57°F from Figure 18. From Figure 19, we get the gradient of 25°C/km. The heat reservoir should be at a depth of 5.4 km. The location allows easy construction. The size of the base is 2.9 million acres. Table 3 is the scoring for the renewable energy sources for Base Y.

Table 3. Scoring of Renewable Energy for Base Y

	Energy footprint size compared to base size	How much noise is generated?	What is the ease of construction?	Continuity of Service	Efficiency1	Capital Cost	Life Expectancy	O&M Cost1	Are Personnel Available?	Obtrusive/ unobtrusive
Geothermal	0.0	55	Standard	0.98	0.11	11.5	50	0.016	Yes	No
Solar	0.0	0	Standard	0.23	0.17	21.5	25	0.22	Yes	No
Wind	0.0	92	Standard	0.67	0.4	1.73	25	0.01	Yes	No

3.8.3 Base Z Information

Base Z is located in a high desert terrain that is relatively flat. The mean wind speed is 4.3 mph. The latitude is 34.38°N. The mean ground temperature is 62°F and the temperature gradient is 13°C/km. From this data the heat reservoir should be 10.2 km in depth. Because this depth surpasses our imposed limit of 10 km in depth, the geothermal energy source is not included in this round of analysis. The location allows easy construction. The size of the base is 92,000 acres. Table 4 shows the scoring for the renewable energy for Base Z.

Table 4. Scoring of Renewable Energy for Base Z

	Energy footprint size compared to base size	How much noise is generated?	What is the ease of construction?	Continuity of Service	Efficiency1	Capital Cost	Life Expectancy	O&M Cost1	Are Personnel Available?	Obtrusive/ unobtrusive
Solar	0.0	0	Standard	0.22	0.17	21.5	25	0.22	Yes	No
Wind	0.0	92	Standard	0.17	0.4	1.73	25	0.01	Yes	No

3.9 Summary

This is the basic framework of the model. At any step of the way, a different decision-maker using this model can alter the measures, weights, values, and scores to accurately reflect that person’s requirements. The next chapter will deal with the analysis of the three bases and how the renewable energy compares among them.

4. Analysis

4.1 Overview

This chapter presents steps 8 and 9 in the Value-Focused Thinking (VFT) process. Using the data described in Chapter 3, real in-put data was used from three bases to evaluate the properties of this model. These bases are referred to as Bases X, Y, and Z. Results of the output were based on the output from Logical Decision software. Steps 8 and 9 will be presented for each base in order. The deterministic analysis is shown first and then highlights from the sensitivity analysis will be presented.

4.2 Base X Evaluation

Using the data for Base X and incorporating the values of the decision maker, an analysis was made concerning which renewable energy source would be most advantageous for this particular region. The next step in this process is the deterministic analysis.

4.2.1 Step 8: Deterministic Analysis

The mathematical equation shown in Equation 3 is used to calculate the total value of this analysis. A score is calculated for each alternative by summing up the scores from each value function and the corresponding weights for each measure. The scores are then combined to give a summation for each alternative and thus are used to rank them. This is called the additive value function (Kirkwood, 1997:230). In order to use this function, each measure has a SDVF with values that are typically between 0 and

1. Also, the combined weights must equal 1. If these conditions are met, then the function is as follows:

$$v(x)=\sum_{i=1}^{n}\lambda_i\cdot v(x_i) \tag{3}$$

where

$v(x)$ = multi-objective value function,

$v_i(x_i)$ = individual measure value determined by using the SDVF to convert the measure's x-axis score, and

λ_i = global weight on each respective measure.

For Base X, the stacked bar ranking or deterministic analysis is shown in Figure 25. This shows the combined weight and value for each of the measures for the alternatives evaluated.

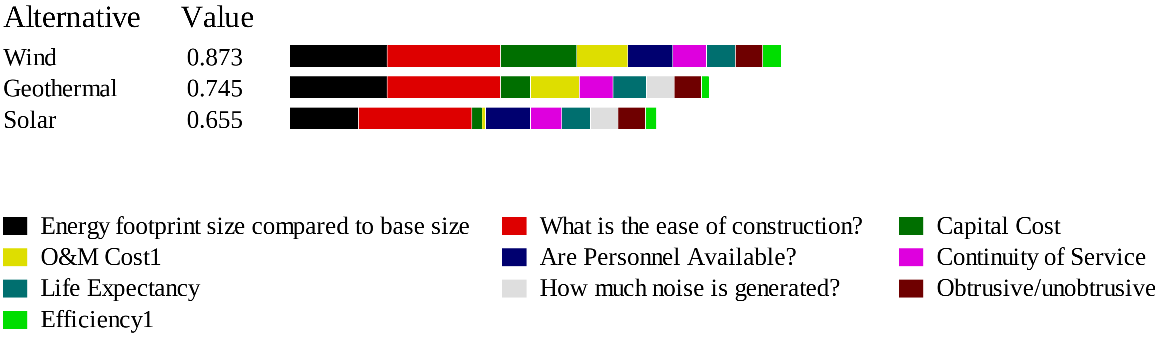


Figure 25. Deterministic Analysis of Alternatives for Base X

The colors represent the measures that were used to evaluate the potential energy sources. For instance, the capital cost portion of the figure shows a larger amount for wind turbines than for geothermal or solar. This is because the wind capital cost is lower and the value placed on a lower cost is greater. Therefore, the final impact to the analysis is a larger final value given to wind turbines. Just the opposite occurs in noise generation. Although wind turbines create more noise than the other systems, a higher value is placed on quieter systems. Therefore, the final impact is more value given to solar systems.

4.2.2 Step 9: Sensitivity Analysis

Additional insight into why wind power has the most value for Base X may provide further assistance to the decision maker. Sensitivity analysis is a method that can be used to “determine the impact on the ranking of alternatives of changes in various model assumptions” (Kirkwood, 1997:92). The easiest and most common area of change that can be examined is in the weighting of the measures. Since the weightings are reflective of the decision-maker’s importance, the sensitivity analysis can show how the ranking may be affected if the weights were altered even a little. These changes may also be affected by future breakthroughs in technology that would affect the alternative’s value for a measure and thus the ranking. Figure 26 shows the sensitivity of the noise generation measure.

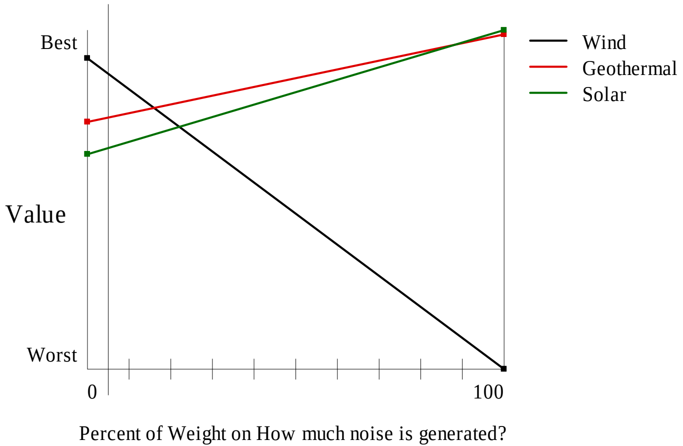


Figure 26. Sensitivity Graph for Noise Generation Measure

Figure 26 illustrates what happens when the global weight the decision-maker places on noise generation increases from the current 5% to 15.2%. By changing this measure's weight and altering the other weights proportionally, the recommended alternative changes from wind to geothermal. This phenomenon occurs again in the life expectancy measure. If the decision-maker increases the global weight on life expectancy from 6% to 50% and holds the other weights proportional, then the recommended alternative energy power sources also switches from wind to geothermal as shown in

Figure 27.

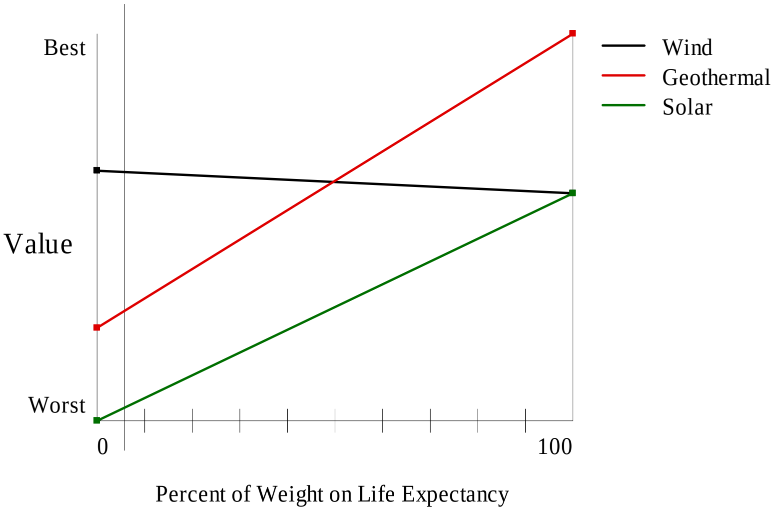


Figure 27. Sensitivity Graph for Life Expectancy Measure

Figure 28 shows the lack of sensitivity of the initial capital cost and represents the lack of sensitivity found in the other measures. This lack of sensitivity may also provide valuable insight into the decision-maker's process depending on how far removed from affecting the outcome it is.

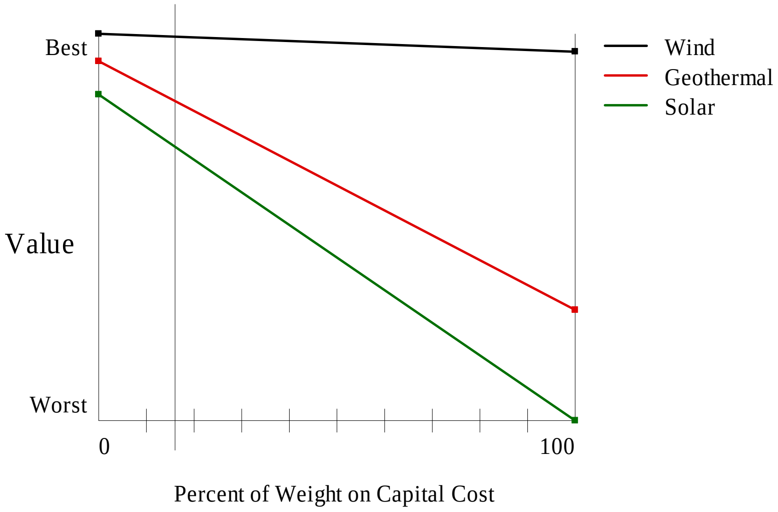


Figure 28. Sensitivity Graph for Initial Capital Cost Measure

This lack of sensitivity doesn't alter the ranking of the alternatives if the weight of the measure is reduced or increased. This insensitivity occurred in the following measures: initial capital cost, O&M cost, personnel availability, construction ease, footprint size, aesthetics, continuity of service, and efficiency. Sensitivity graphs for all measures are presented in Appendix C. The other graphs tend to show insensitivity as opposed to having any ability to alter the outcome given the weights and proportions in this model.

4.3 Base Y Evaluation

The same analysis was applied to Base Y. This analysis covers the same measures but of a very different environment in an attempt to validate the model in various locales.

4.3.1 Step 8: Deterministic Analysis

In performing the analysis for Base Y, the result may or may not have similar outcomes. Since the weights are the same, then any similarity is a result of the additive function and the variations in the SDVF. Figure 29 shows the deterministic analysis for Base Y.

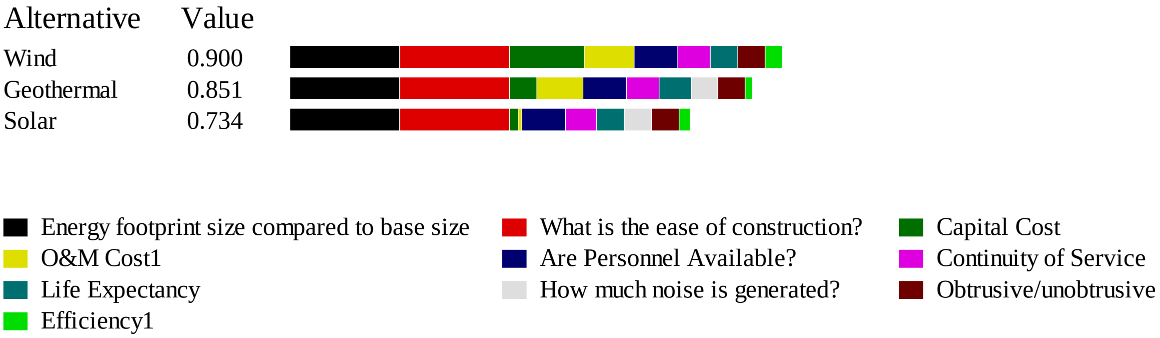


Figure 29. Deterministic Analysis of Alternatives for Base Y

Since Base Y is quite large and the energy footprint for all three has minimal impact, therefore, they each received full value. O&M Cost (in yellow) causes a large disparity among the alternatives as does capital costs.

Although this ranking shows the wind turbine as being the preferred alternative energy source, the value scores are closer than that of Base X. By performing the sensitivity analysis, a relationship may be found that is more of concern to the decision maker than previously thought.

4.3.2 Step 9: Sensitivity Analysis

As with the analysis of Base X, Base Y has many measures that when weighted differently alter the outcome of the function. For example, the suggested outcome changes from wind to geothermal to solar when the weight of the noise measure increases from 5% to 100% as shown in Figure 30. First, the recommendation changes from wind to geothermal when the weight is approximately 9.5%. Finally, the recommendation changes from geothermal to solar when the weight is increased to approximately 92%,

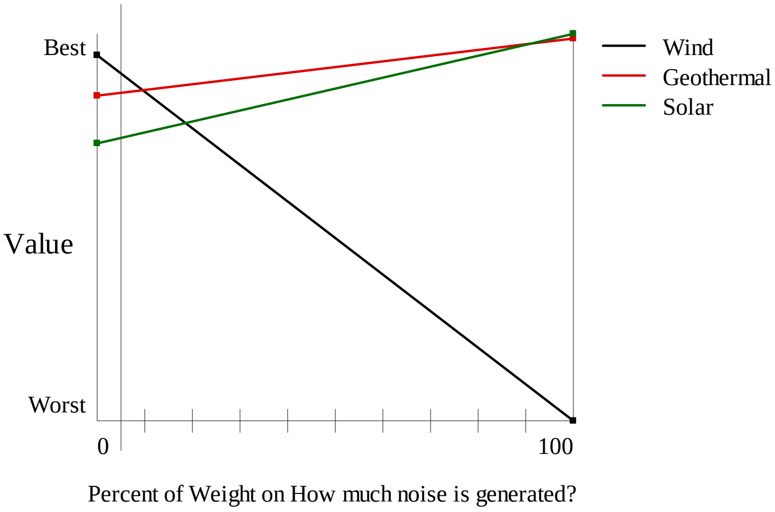


Figure 30. Sensitivity Graph for Noise Generation Measure

Another measure that is also affected by altering weights is the life expectancy measure as seen in Figure 31. As the weight increases from 6% to approximately 30%, the recommendation changes to geothermal energy.

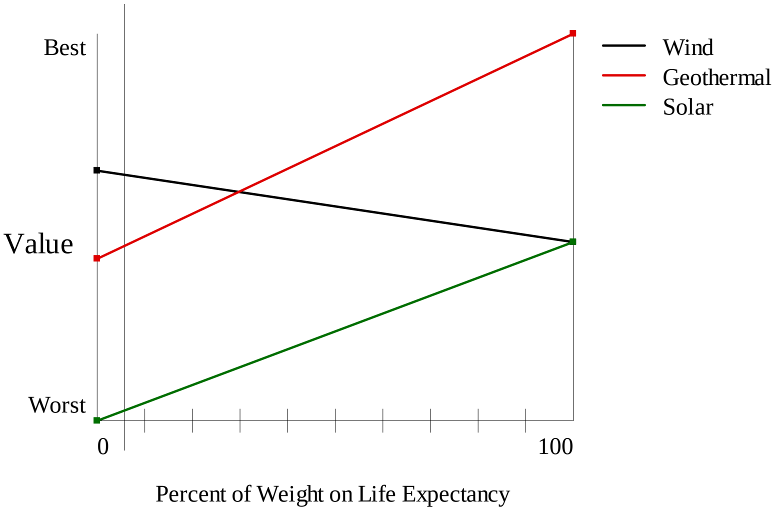


Figure 31. Sensitivity Graph for Life Expectancy Measure

Using the different environment found at Base Y caused one major difference in the model. Initial cost became another measure that, when weighted differently, alters the outcome of the function and suggests a different alternative. Figure 32 shows the life expectancy sensitivity graph.

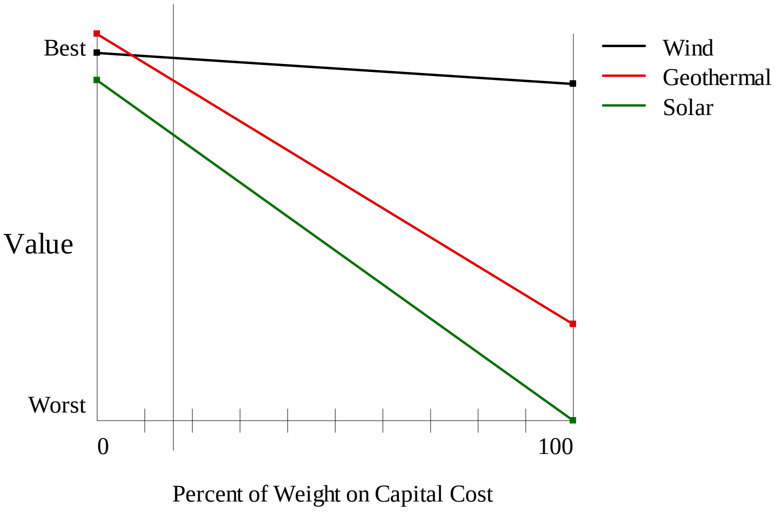


Figure 32. Sensitivity Graph for Initial Cost Measure

If the weight for capital cost were to bear less importance to the decision-maker than the current 16%, then the outcome would suggest geothermal energy. This switch occurs when the weight is approximately 7%.

The model remained insensitive to the other measures in the model as before. All measures can be found in Appendix C. Finally, this model examined a third location unlike Base X or Y.

4.4 Base Z Evaluation

The same type of analysis was applied to Base Z. However, using a screening criterion that a geothermal reservoir must have a reservoir depth of less than 10 Km, a geothermal alternative was not evaluated. This analysis covers the same measures but for a slightly different environment in an attempt to validate the model in various locales.

4.4.1 Step 8: Deterministic Analysis

The deterministic analysis for Base Z is shown in Figure 33. Capital costs and O&M costs make up a large part of the disparity between the wind option and the photovoltaic option. Given future technological breakthroughs, these values may achieve parity and photovoltaic energy may be the recommended decision. Wind remains the suggested energy source for this location. However, without the geothermal alternative, the sensitivity analysis reveals an interesting phenomenon.

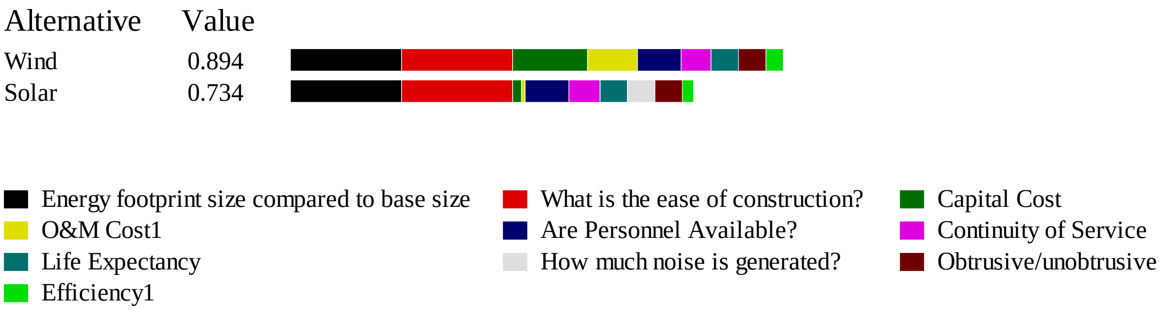


Figure 33. Deterministic Analysis of Alternatives for Base Z

4.4.2 Step 9: Sensitivity Analysis

There are only two measures that alter the outcome of the analysis. The first measure to affect the suggested course of action is the noise measure. Figure 34 illustrates that when the weight increases from 5% to approximately 18.5%, the suggested course of action is to choose solar energy.

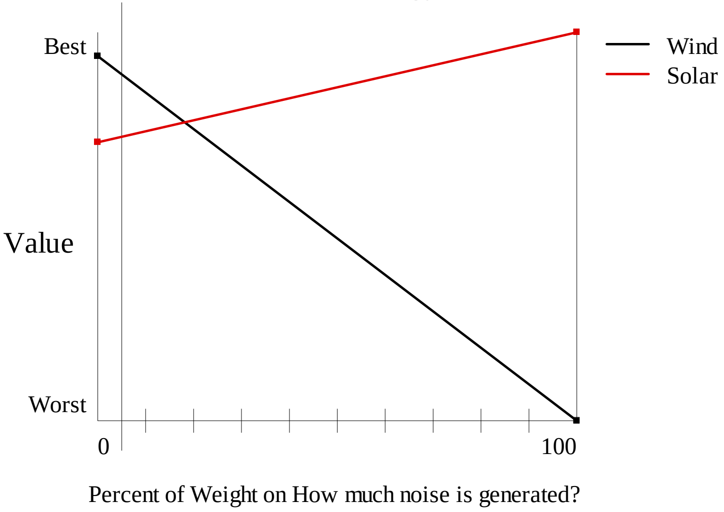


Figure 34. Sensitivity Graph for Noise Generation Measure

The other measure that affects the outcome for Base Z evaluation is the continuity measure. This continuity measure is shown in Figure 35.

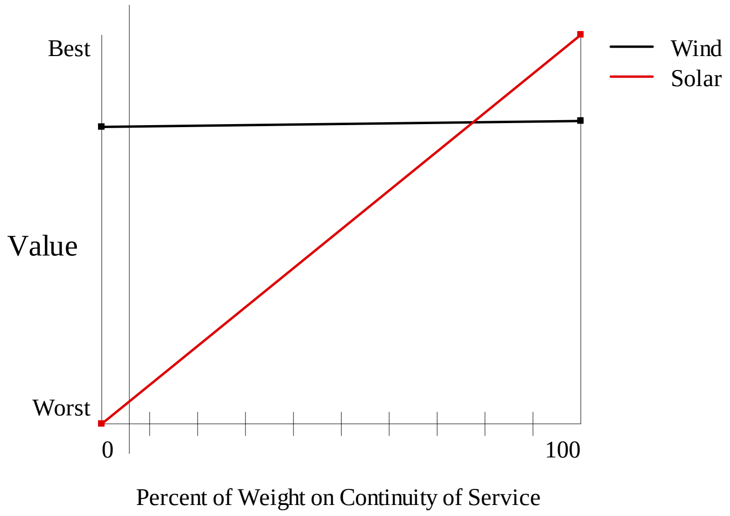


Figure 35. Sensitivity Graph for Continuity of Service Measure

If the decision-maker desires more continuous service and adds weight accordingly, the suggested outcome changes from wind to solar energy. This change occurs if the weight given to continuity of service is approximately 77%. A possible reason why this measure alters the final outcome for Base Z and not the other bases is likely due to the lower wind production at this site than the other two bases.

4.5 Summary

The purpose of using VFT is not to make the choice for the decision maker, but rather let the decision maker know what is recommended based on his or her particular desires. VFT provides a systematic method of examining an issue requiring a decision. For this model and analysis, the results imply wind energy is the preferred choice of renewable energy at each of the three locations, bases X, Y, and Z. Hopefully, this analysis will give the decision maker greater insight into why wind energy was recommended over the others. During the analysis, altering the weights of the following measures changed the recommendation: noise generation, life expectancy, initial capital cost, and continuity of service. A common thread occurred among the three locations in that altering the weight of the noise generation measure changes the recommendation. The model was insensitive to the rest of the measures and the output remained the same. The decision-maker can see what impact these had on the model and decide if the weights applied to the model were still appropriate. This model is flexible and can be used and adapted to provide insight for other decision makers in the future.

As new renewable energy sources become viable for construction, they can be added as another alternative to this model.   Although this analysis compared 3 distinct sources, multiple versions of the same renewable source can be added to the same model. For instance, solar panels that are mounted on the ground as well as those panels that are incorporated into the roofing tile can be evaluated. Differing wind turbine manufacturers and turbine sizes can be evaluated. Finally, differing types of geothermal plants such as dry steam and flash steam can also be investigated.

5. Conclusion

5.1 Overview

Chapter 5 provides a brief review of this research endeavor while answering the initial questions presented in Chapter 1. This review is followed by the main conclusion obtained from this effort. Then, the strengths and limitations of the model are presented. Finally, suggested follow-on research areas are included for continuation of this topic in future endeavors.

5.2 Review

Although there are many decision analysis tools available for research, many limit the ability to weight the factors that affect the result in favor of the objectives of the decision-maker. Alternative-focused thinking is a comparison decision tool but can fail to include what is important to the decision-maker. The value-focused thinking decision analysis methodology was used to evaluate various renewable energy sources for electrical production on an installation. Using the sponsor as the decision-maker, a model was created by combining various evaluation measures into a value hierarchy. That hierarchy represents what is most desired for completing a comparative analysis between possible energy sources.

Then, the sponsor created single dimension value functions (SDVFs) for each measure to convert the scores into value units as well as assigned weights to each of the measures. Alternatives were identified and scored in each measurement. The weights and value scores were then combined using the additive value function to obtain a ranking. This ranking was the deterministic analysis and resulted in the wind turbines as the most desired outcome in the cases examined. Sensitivity analysis was then applied to each measure. This provided insight into how sensitive the model's results were to changing weights in the model. One of the measures that affected the final outcome the most was noise generation. Increasing the weight of this one measure caused wind turbines to fall from the most desired status. If wind turbine manufacturers worked to lower the noise these turbines make, then the model would become more insensitive to changing the weights of this measure.

Additional insight was made by applying this model to three locations around the United States. By analyzing the outcome and realizing which measures were sensitive and which measures were insensitive, it is hoped the decision-maker can make a better informed decision. The results in each of the three location resulted in wind turbines being top choice.

Based on the history of the few wind turbines currently in contracting negotiation, it appears the beginning is in sight for producing energy using renewable resources. It is hoped this model will help in analyzing which energy source offers the best potential for a renewable energy source in the respective location, when decision-makers desires are considered.

5.3 Conclusion

The purpose of this effort was to assist the United States Air Forces in selecting renewable energy sources for electrical power production using a quantifiable, multi-objective decision analysis methodology. In producing power on-site, the government can reduce outside power dependency and mitigate the affects of sabotage on an installation. Using this model allows an unbiased and objective analysis for the base commander to decide what the most important qualities are for a renewable energy source. The model then takes those qualities and provides a suggested course of action. This model aids the decision-maker in that process.

5.4 Strengths

The model created in this research effort demonstrates that using the values from a base commander and incorporating those values into the model, a best course of action can be selected. A base commander typically has a limited time for explanations of complex issues. When time is limited, a decision-making committee or even a proxy decision-maker can be consulted. By having fewer measures and a simpler explanation, the base commander may be more interested and may become engaged for the short time that is necessary to create a personalized model using the same measures.

Additionally, whereas more complex models can create trust issues, this model remains simple so as to be understandable and easily defendable. If the model is too cumbersome and unwieldy, then people may distrust it. The model chosen for use must be simple enough that its concepts can be easily grasped and appreciated.

The simplicity of this model is also evident when performing a sensitivity analysis. With a limited number of measures in this model, the sensitivity analysis is also simple and understandable. When a measure is examined for sensitivity, each of the weights has a relatively high value compared to a model with many measures. As the weighting increases or decreases, the other weightings change correspondingly. However, in more complicated models, when a measure has its weight shifted but is one of over 20 measures; it can be difficult to understand what is occurring in the model.

5.5 Limitations

The biggest limitation in the model is potential bias by the decision-maker. In this case, the decision-maker knew which renewable energy sources were to be examined. The decision-maker was told not to let the knowledge of the energy sources skew his weighting or valuation functions, however, that potential bias can never be totally removed from the model. The best method would be to use this model and present it to the decision-maker without mentioning which types of energy sources are being evaluated. Only by keeping the decision-maker in the dark would this model become truly unbiased.

Although, the values used for determining the scores were based on various data (NOAA, 2003; ASHREA, 1997; Blackwell, 2003), it must be noted that existing site conditions should be the primary source of data for scoring. Wind may be strong and consistent in one area and weak and inconsistent a short distance away. For this research, area averages were used since no site specific data were available. Before construction a study would need to be accomplished to generate site specific data. Another potential weakness is the measures and values associated with the measures may change with time and decision-makers.

5.6 Future Research

The obvious follow-on research is to go directly to a base and ask if they would be interested in having this analysis performed. Whereas this research effort was focused on developing the model, the next step is for the model to be applied repetitively to real world situations. This research could set the stage for an avalanche of renewable energy projects throughout the United States Air Force.

A potentially greater benefit may be from applying this model to the United States Army bases. Many of their bases may have fewer restrictions for high elevation constructions than the Air Force does. It is hoped this model can be applied throughout the Department of Defense and the US government.

Other governmental agencies may be able to use this model to save energy and money as well. The Department of Interior has many buildings located inside national parks that must either produce their own electrically with generators or bring power lines across great distances. By applying this model, national parks may have the potential of being energy self-sufficient.

Finally, a last benefit may be for extreme locations. The Alaskan radar stations are located in a myriad of hard to reach places and must run on diesel generators. If this model was applied and renewable energy was harnessed for many of those areas, fuel consumption could be cut dramatically and the money spent over time would decrease accordingly. Deployment sites could also be evaluated for portable renewable energy sources and reduce our dependence on large generators or unreliable local power sources.

5.7 Final Thoughts

Our nation and our defense department have become increasingly dependent upon non-renewable energy sources such as foreign crude oil. The use of renewable energy sources such as wind, solar and geothermal power for electricity production can partially off-set that dependence while increasing the security of those base utilities. The model developed here aides in the selection of the best renewable energy source for electrical power generation at any select base or location. The wide-spread acceptance and use of this model could potentially generate great monetary savings while enhancing the security and self-sufficiency of the Department of Defense and reducing the deleterious emissions associated with conventional power sources.

Appendix A. Continuity Tables Based on Multiple Wind Speeds

The following four tables were created to allow quick interpretation of existing mean wind speeds for a location. The following four tables are based on the roughness classes defined in Chapter 2. By knowing the mean wind speed (MWS) at 10m above ground level and the roughness of the terrain, one can determine the expected continuity of the wind turbine by using the Weibull distribution and the limits of the wind turbine. The continuity of the turbine is defined as how long the power is produced and is the ratio of produced over theoretical production. In this case, the Vestas V66 1.75 MW wind turbine is used. Table 5 shows the continuity table for open water terrain for up to a MWS of 40 mph at 10m height.

Table 5. Continuity Table for Class 0 (Open Water)

MWS(mph)	Continuity	MWS(mph)	Continuity
1	0.00	21	0.89
2	0.00	22	0.88
3	0.01	23	0.88
4	0.08	24	0.87
5	0.20	25	0.86
6	0.32	26	0.85
7	0.43	27	0.83
8	0.53	28	0.82
9	0.60	29	0.80
10	0.66	30	0.79
11	0.71	31	0.77
12	0.75	32	0.75
13	0.79	33	0.73
14	0.81	34	0.71
15	0.83	35	0.70
16	0.85	36	0.68
17	0.86	37	0.66
18	0.87	38	0.64
19	0.88	39	0.62
20	0.88	40	0.61

Table 6 shows another continuity table for open land with few windbreaks. This is primarily the open desert or the Great Plains area where the wind still has somewhat of a laminar flow.

Table 6. Continuity Table for Class 1 (Open Land w/ Few Windbreaks)

MWS(mph)	Continuity	MWS(mph)	Continuity
1	0.00	21	0.87
2	0.00	22	0.86
3	0.03	23	0.85
4	0.13	24	0.83
5	0.27	25	0.82
6	0.41	26	0.80
7	0.52	27	0.78
8	0.60	28	0.76
9	0.67	29	0.74
10	0.72	30	0.72
11	0.77	31	0.70
12	0.80	32	0.68
13	0.83	33	0.66
14	0.85	34	0.64
15	0.86	35	0.62
16	0.87	36	0.60
17	0.88	37	0.58
18	0.89	38	0.56
19	0.88	39	0.54
20	0.88	40	0.53

Table 7 shows the continuity for farmland with some wind breaks. As the wind flows around trees and valleys, there is a larger disparity between upper and lower winds. For the same 10m high wind speed, the 60m wind speed for open water is closer to the ground level wind speed, whereas for the farmland the 60m is higher thus causing a greater continuity of wind.

Table 7. Continuity Table for Class 2 (Farmland w/ Some Windbreaks)

MWS(mph)	Continuity	MWS(mph)	Continuity
1	0.00	21	0.86
2	0.00	22	0.84
3	0.04	23	0.83
4	0.17	24	0.81
5	0.32	25	0.79
6	0.45	26	0.77
7	0.56	27	0.75
8	0.64	28	0.73
9	0.70	29	0.70
10	0.75	30	0.68
11	0.79	31	0.66
12	0.82	32	0.64
13	0.84	33	0.62
14	0.86	34	0.60
15	0.87	35	0.58
16	0.88	36	0.56
17	0.89	37	0.54
18	0.88	38	0.52
19	0.88	39	0.50
20	0.87	40	0.49

Table 8 shows the continuity for urban or obstructed rural areas. The blockage that occurs at lower altitudes is more prevalent and therefore the winds at 60m are actually more than if there were no blockage and the same surface wind velocity.

Table 8. Continuity Table for Class 3 (Urban or Obstructed Rural)

MWS(mph)	Continuity	MWS(mph)	Continuity
1	0.00	21	0.82
2	0.00	22	0.80
3	0.08	23	0.77
4	0.24	24	0.75
5	0.40	25	0.73
6	0.53	26	0.70
7	0.63	27	0.68
8	0.70	28	0.65
9	0.75	29	0.63
10	0.80	30	0.61
11	0.83	31	0.58
12	0.85	32	0.56
13	0.87	33	0.54
14	0.88	34	0.52
15	0.88	35	0.50
16	0.88	36	0.48
17	0.88	37	0.46
18	0.87	38	0.45
19	0.86	39	0.43
20	0.84	40	0.41

Appendix B. Single Dimension Value Functions

The following Value Functions were generated with the help of the sponsor and the software, Logical Decisions (Santoro, 2003). The graphs represent the value of each measure to the decision maker. This appendix will illustrate the ten measures by presenting the figures used in the model. When applying this model to future assessments, the new decision maker should review the value function and determine whether he or she agrees with the functions. Figure 36 shows the SDVF for Initial Capital Cost. The decision maker places more value on the change at a lower cost than at the higher cost region. An example point is shown in Figure 36, representing a capital cost of 8 million dollars and a value of 0.49.

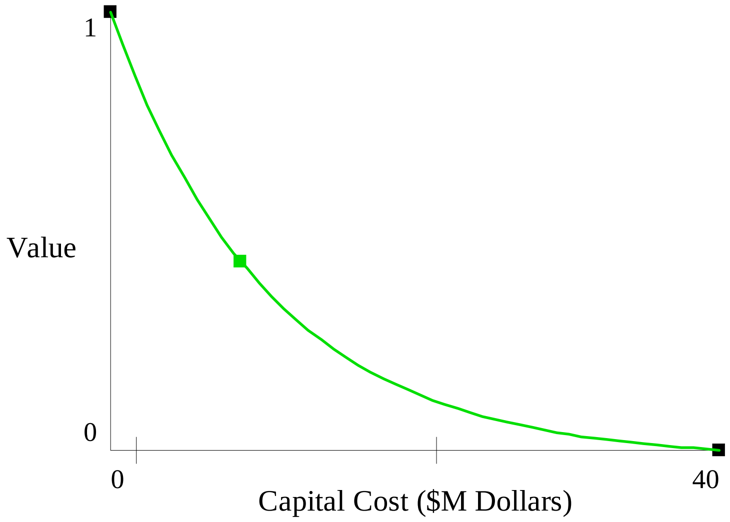


Figure 36. SDVF for Capital Cost

Figure 37 shows the SDVF for the O&M Costs. The value function indicates as costs increase values decline; however, not as rapidly as seen with the capital cost value function. These values can be easily incorporated or changed by the decision maker in the Logical Decision software. An example point is shown indicating a value of approximately 0.29 for an O&M cost of $0.12/kWh.

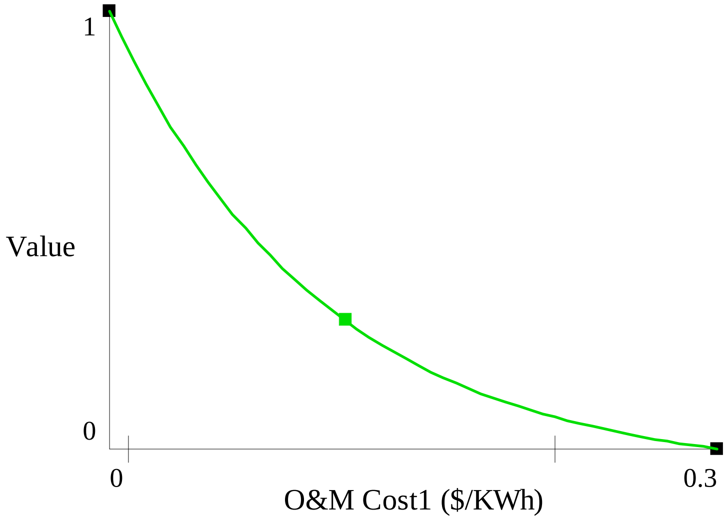


Figure 37. SDVF for Operations & Maintenance Costs

Figure 38 shows the value the decision maker placed on the life span of the equipment used to harness the renewable energy source. A selected point on the graph is represented by a life expectancy of 18 years and a corresponding value of 0.74.

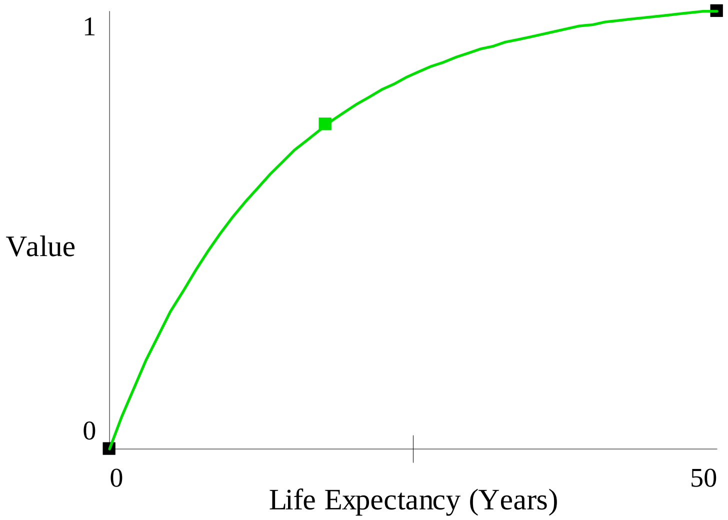


Figure 38. SDVF for Life Expectancy

Figure 39 shows a categorical relationship, the measure is answered with a yes or no. The question posed to develop the value function is whether there are skilled personnel available in the local area to maintain on the equipment. An exponential function is not required as this can be valued in “steps”. In this case, it’s either full value or no value.

Figure 39. SDVF for Personnel Availability

Figure 40 is also categorical and has no exponential function. The question posed to develop the value function is to what degree the construction site allows easy construction. The value assigned would be based on the approximate percentage of decrease or increase from industry standard cost the site location would cause.

Figure 40. SDVF for Ease of Construction

Figure 41 shows the SDVF for the ratio of Footprint Size compared to Base Open Space. This is just the ratio of the space used to capture the energy source and may equal zero if, for instance, only roofs were used to capture solar energy. This exponential function places more value on smaller footprint size. A selection point is shown of a ratio of approximate 0.0009 and a corresponding value of 0.50.

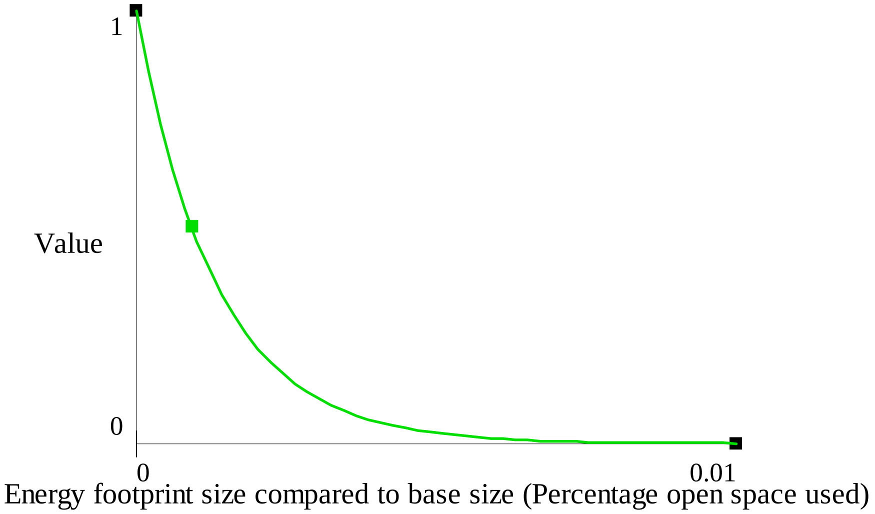


Figure 41. SDVF for Footprint Size Compared to Base Open Space

Figure 42 highlights the value function of noise generation from an energy generation system. There is no value in having noise generated above 85 dB since certain measures must be done to protect base personnel above that sound level.

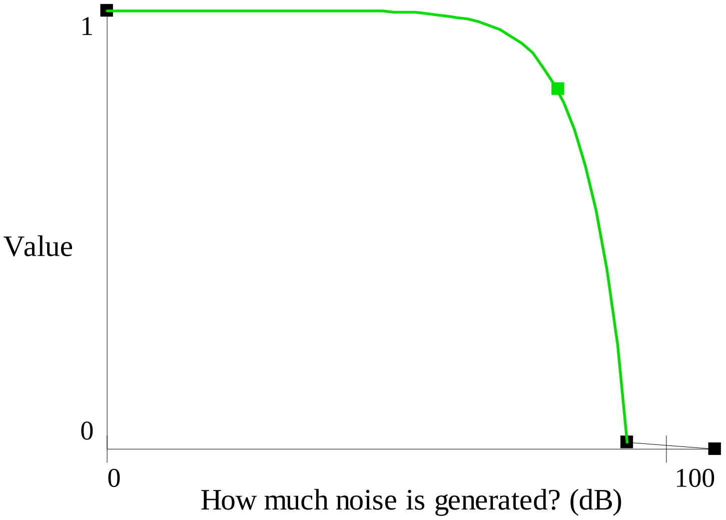


Figure 42. SDVF for Noise Generation

Figure 43 shows the SDVF for how much Aesthetics has value in this model. A base commander may have differing views concerning various renewable energy resources. This measure is categorical and the question is whether the equipment is obtrusive or unobtrusive.

Figure 43. SDVF for Aesthetics

Figure 44 shows the SDVF for continuity. The decision maker places greater emphasis on a longer continuous power production than on shorter length. A selected point on the graph is represented by a continuity of service of 10.6% which translates to a value of 0.76.

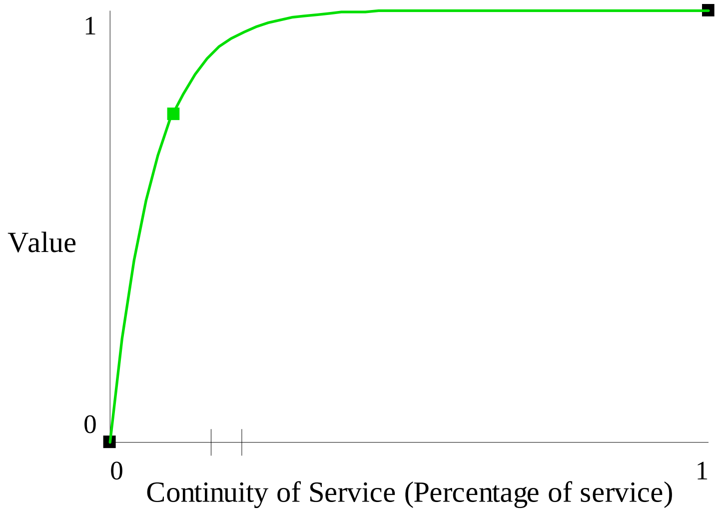


Figure 44. SDVF for Continuity of Service

The last SDVF in this model is for efficiency. This is a measure of efficiencies between systems. Although they may not make a large difference between major energy systems, they may make a difference between the same energy systems. Along with comparing different renewable energies, this model can also be used between like entities. This model can compare self-standing solar panels along with roof mounted solar panels. Manufacturers may have differing efficiencies of photovoltaic systems. All things being equal, the more efficient system might be selected. The SDVF in Figure 45 rewards higher efficiencies. A selected point on the graph is represented by an efficiency of 29.3% which translates to a value of 0.73.

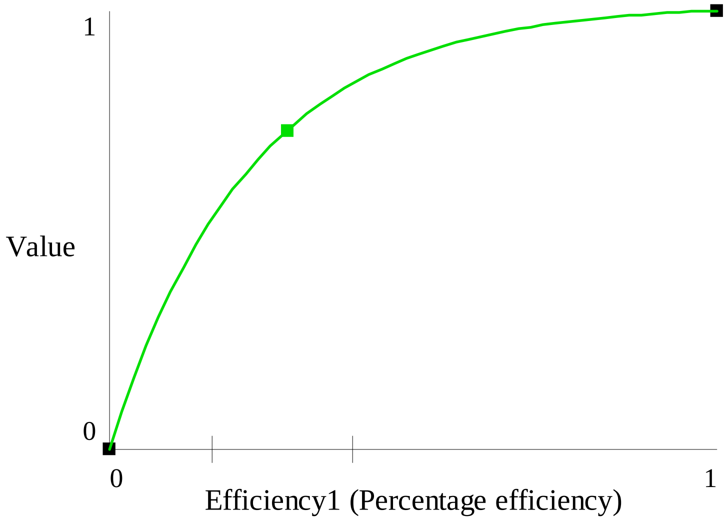


Figure 45. SDVF for Efficiency

Appendix C. Sensitivity Graphs

This appendix provides the graphical representation of the results of performing sensitivity analysis on each of the ten measures for the three bases evaluated. For each measure the graph represents the swing weighting that may or may not affect the suggested energy source for that particular base. As the weighting of that particular measure increases or decreases, the other measures' weights are proportionally decreased or increased correspondingly. The affect on the outcome is shown as the energy source either rises or falls accordingly.

Base X Sensitivity Graphs

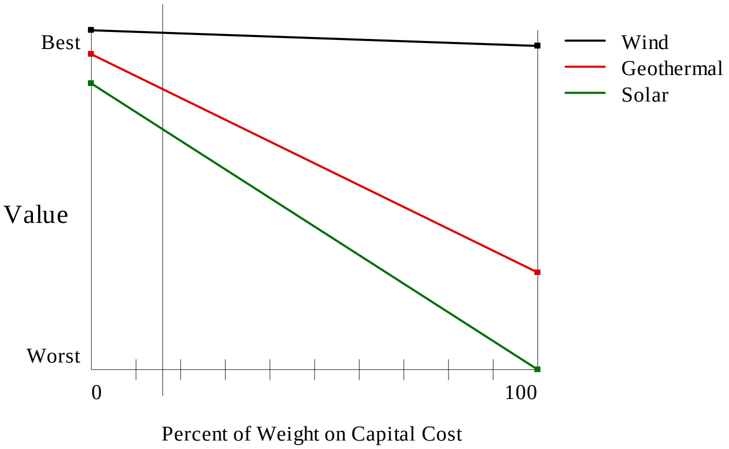


Figure 46. Sensitivity Analysis on Capital Cost, Base X

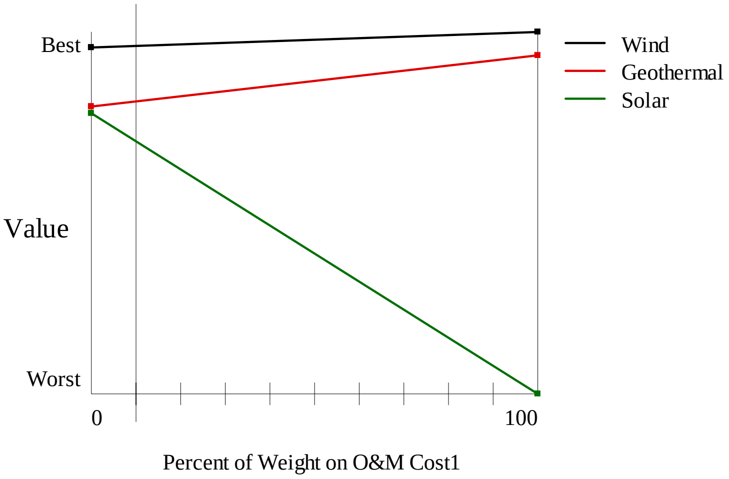


Figure 47. Sensitivity Analysis on Operations and Maintenance Cost, Base X

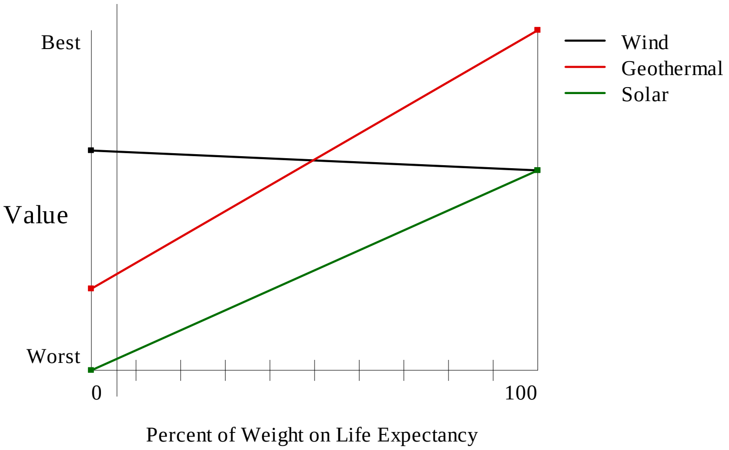


Figure 48. Sensitivity Analysis on Life Expectancy, Base X

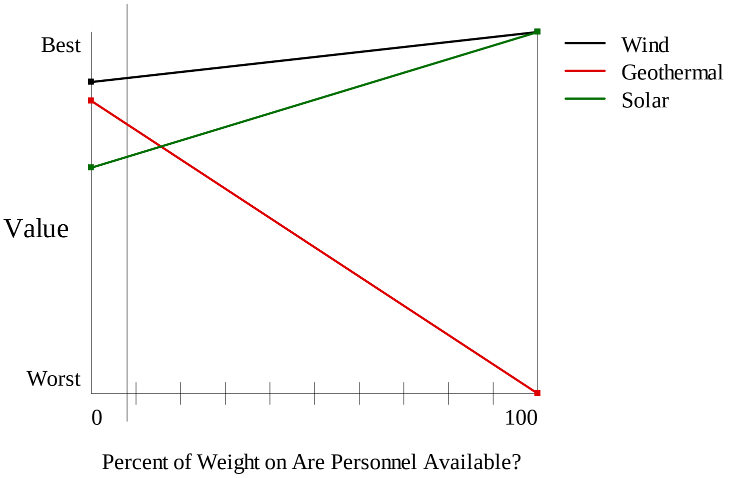


Figure 49. Sensitivity Analysis on Personnel Availability, Base X

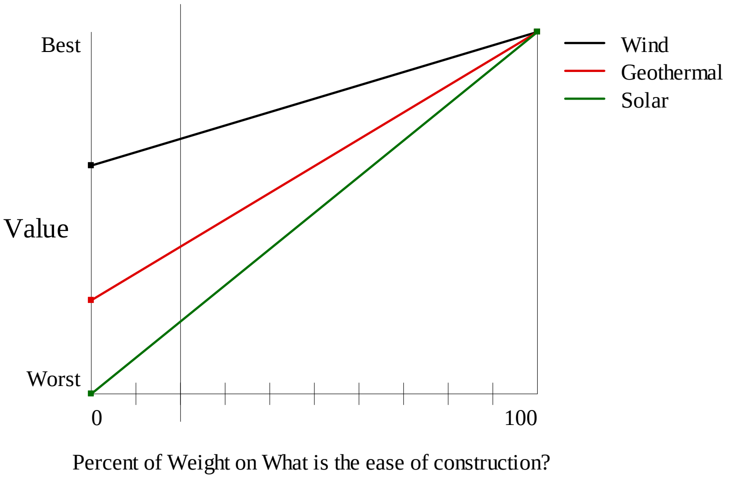


Figure 50. Sensitivity Analysis on Ease of Construction, Base X

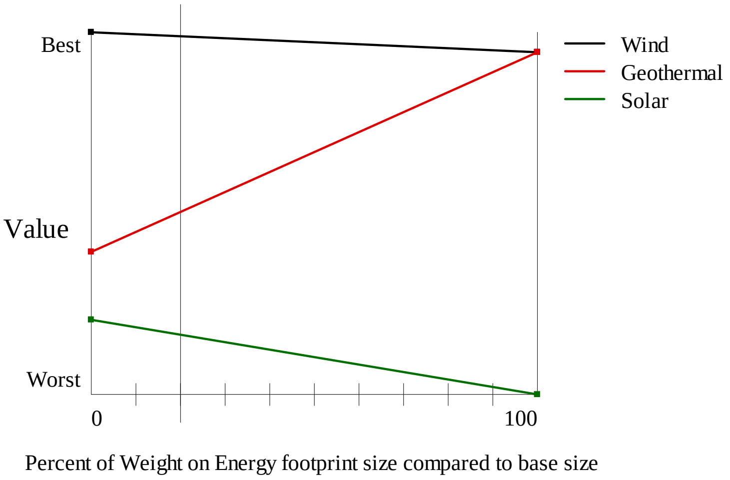


Figure 51. Sensitivity Analysis on Footprint Size Compared to Base Size, Base X

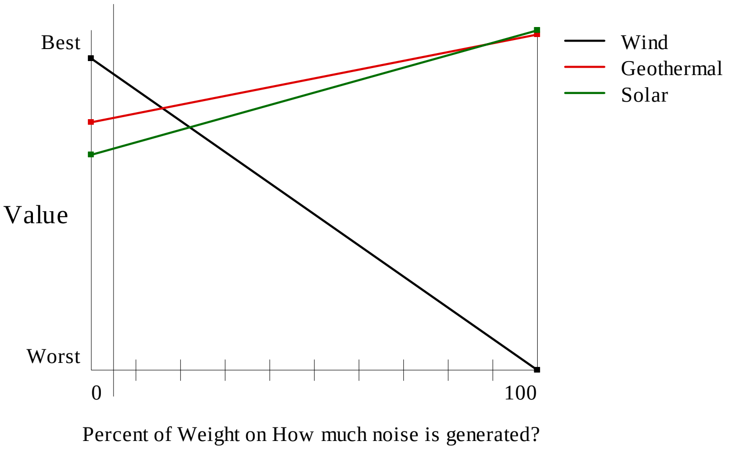


Figure 52. Sensitivity Analysis on Noise Generation, Base X

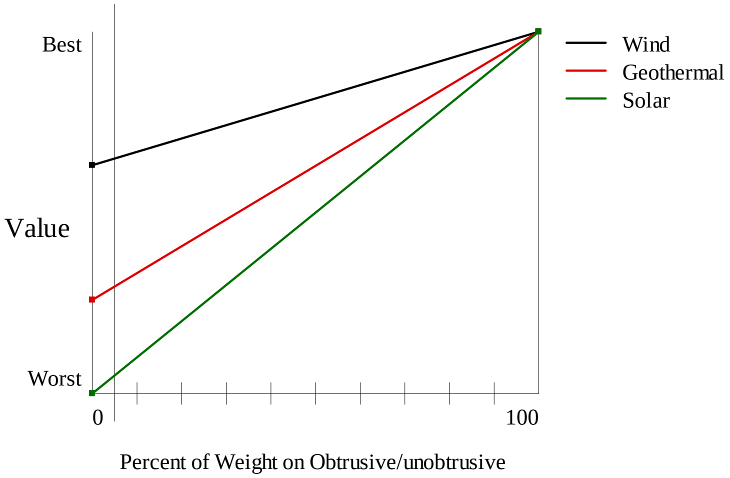


Figure 53. Sensitivity Analysis on Obtrusiveness, Base X

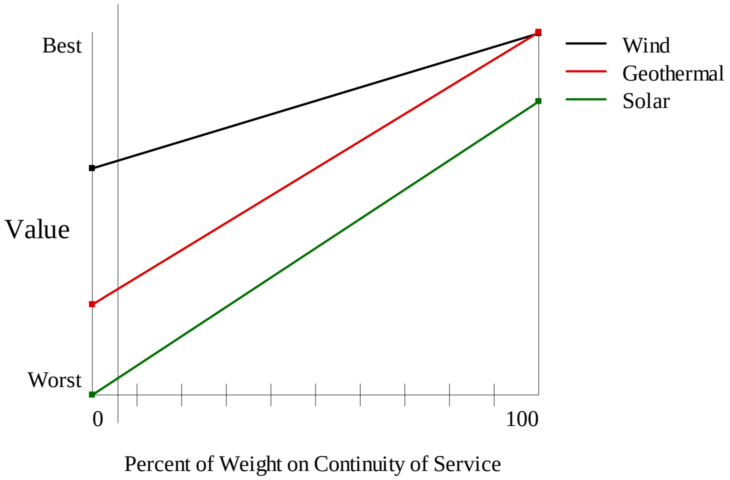


Figure 54. Sensitivity Analysis on Continuity of Service, Base X

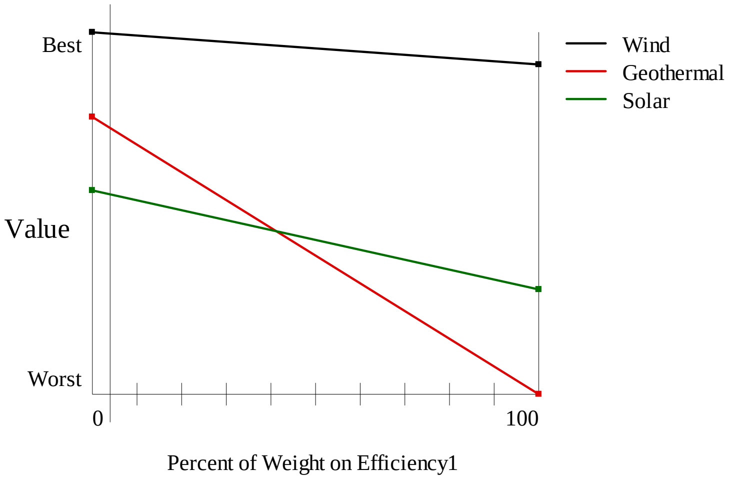


Figure 55. Sensitivity Analysis on Efficiency, Base X

Base Y Sensitivity Graphs

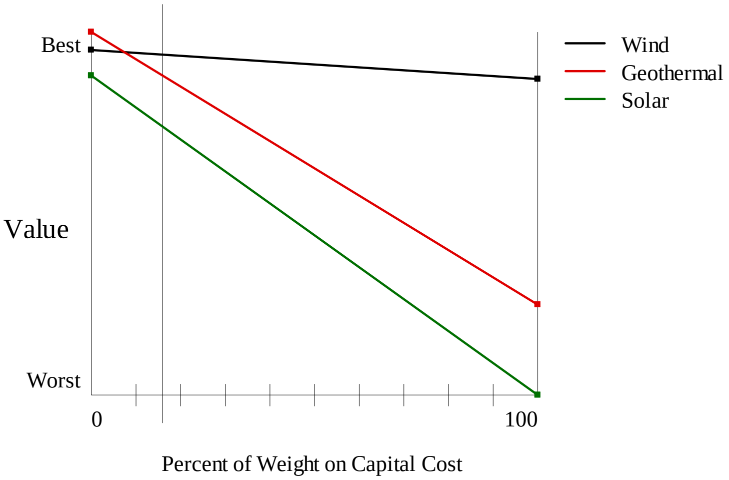


Figure 56. Sensitivity Analysis on Capital Cost, Base Y

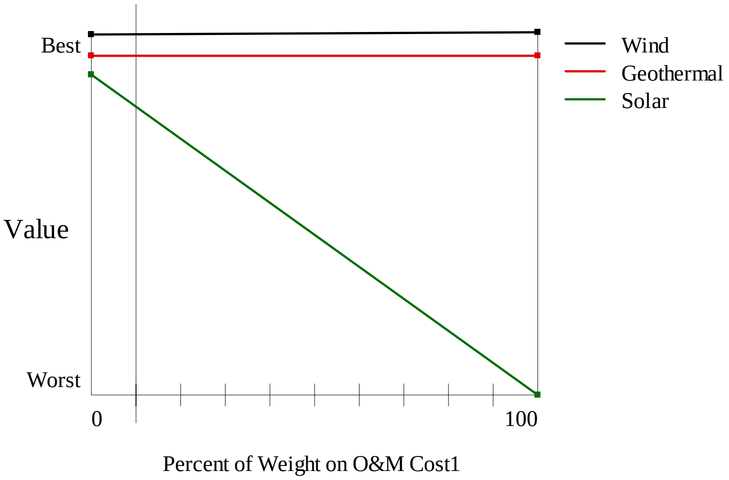


Figure 57. Sensitivity Analysis on Operations & Maintenance Cost, Base Y

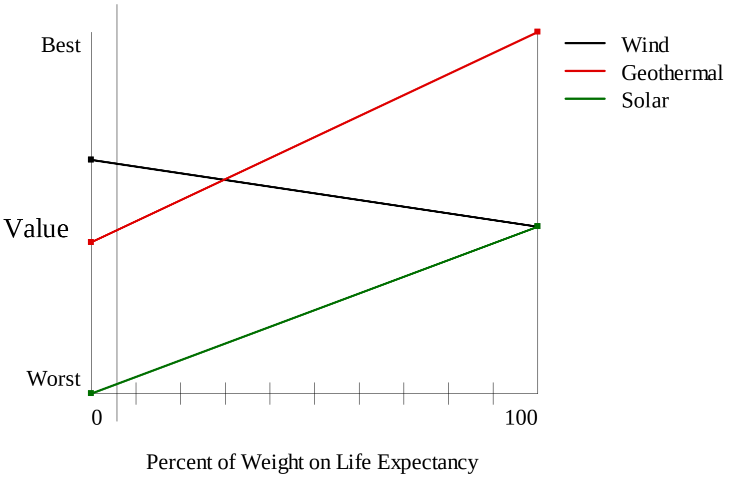


Figure 58. Sensitivity Analysis on Life Expectancy, Base Y

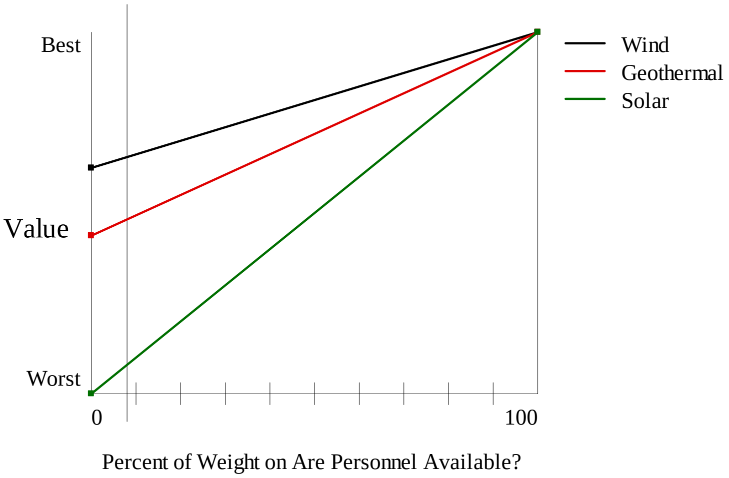


Figure 59. Sensitivity Analysis on Personnel Availability, Base Y

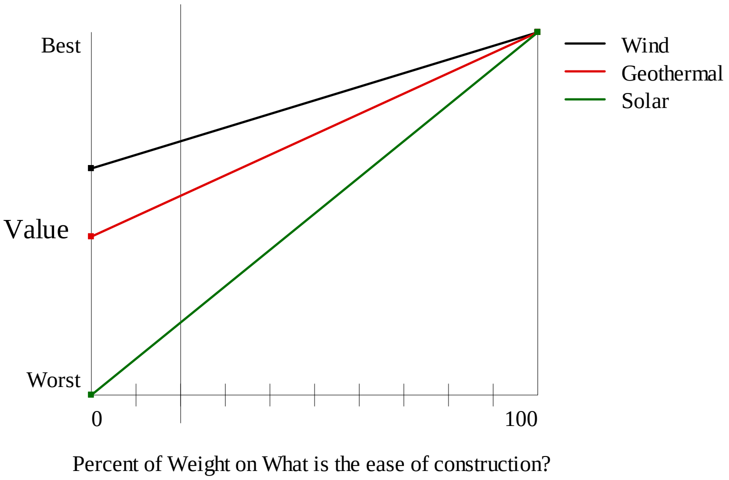


Figure 60. Sensitivity Analysis on Ease of Construction, Base Y

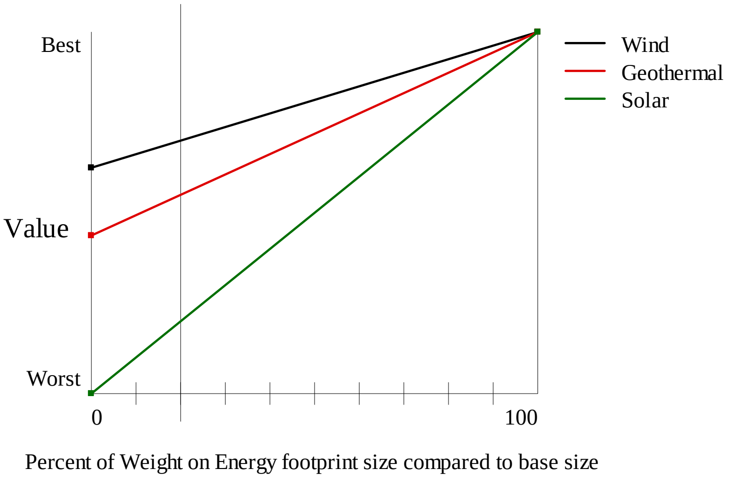


Figure 61. Sensitivity Analysis on Footprint Size Compared to Base Size, Base Y

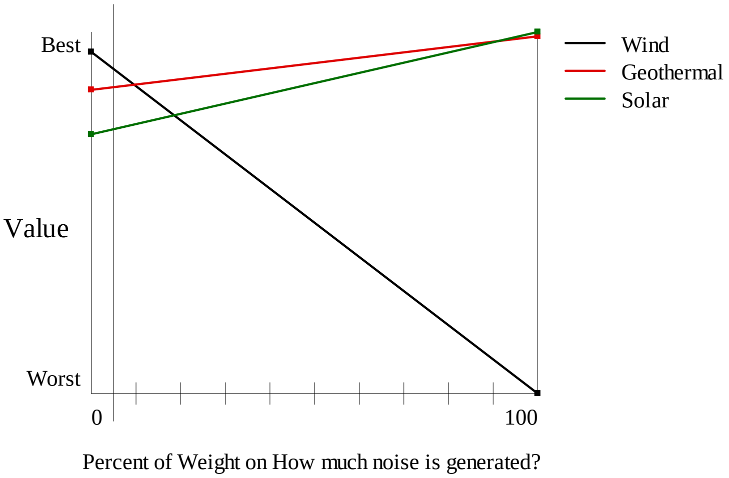


Figure 62. Sensitivity Analysis on Noise Generation, Base Y

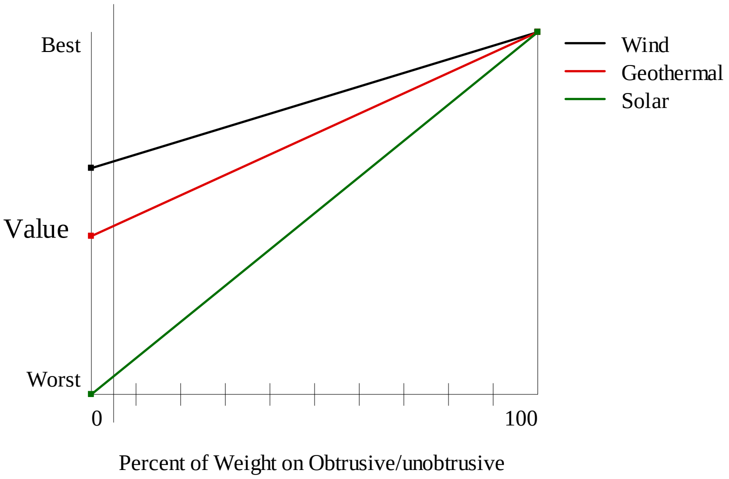


Figure 63. Sensitivity Analysis on Obtrusiveness, Base Y

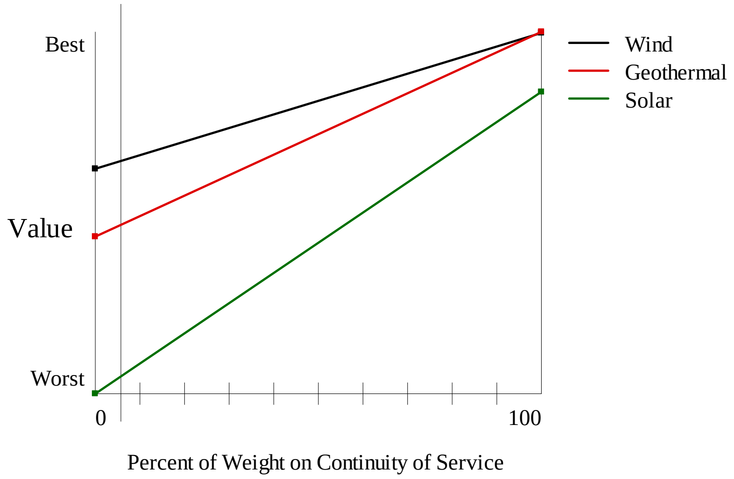


Figure 64. Sensitivity Analysis on Continuity of Service, Base Y

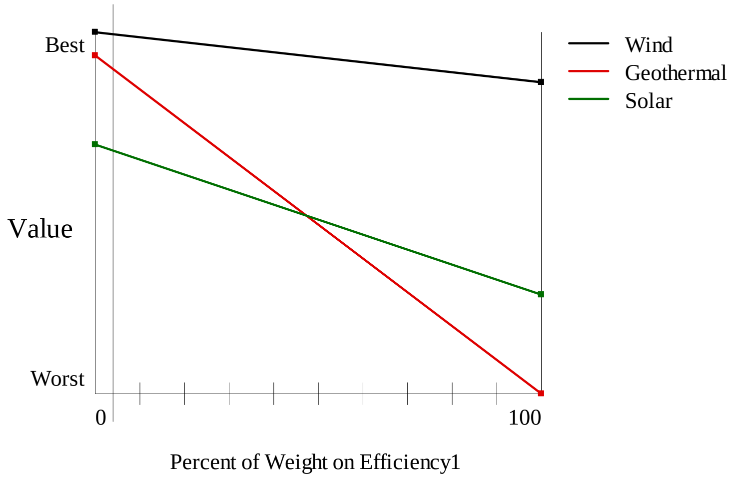


Figure 65. Sensitivity Analysis on Efficiency, Base Y

Base Z Sensitivity Graphs

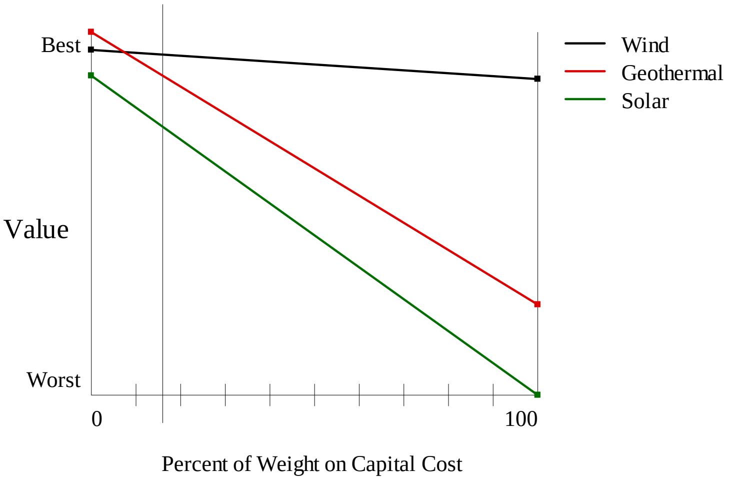


Figure 66. Sensitivity Analysis on Capital Cost, Base Z

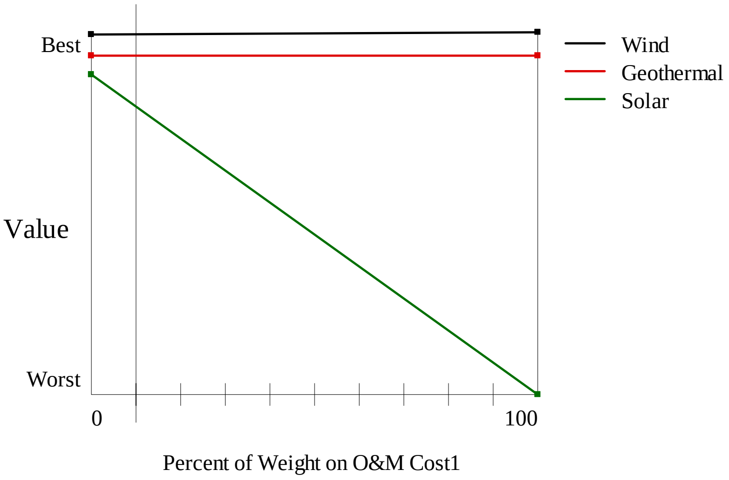


Figure 67. Sensitivity Analysis on Operations and Maintenance Cost, Base Z

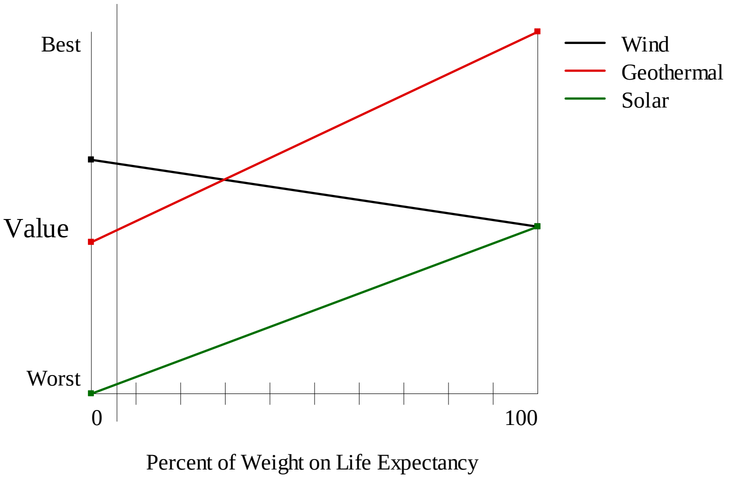


Figure 68. Sensitivity Analysis on Life Expectancy, Base Z

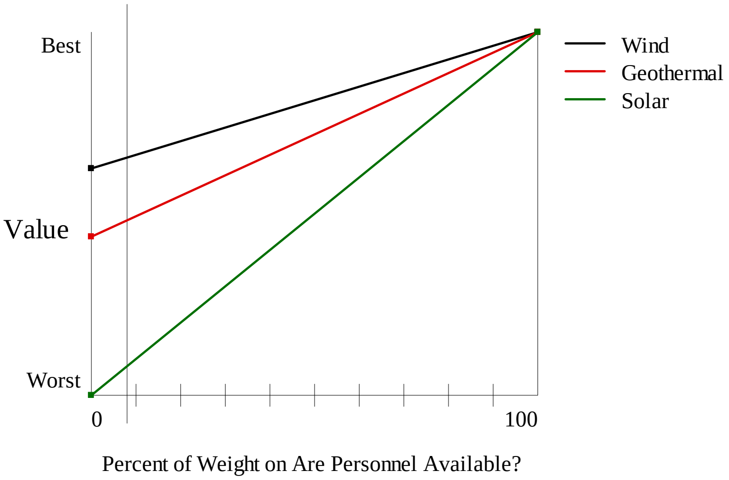


Figure 69. Sensitivity Analysis on Personnel Availability, Base Z

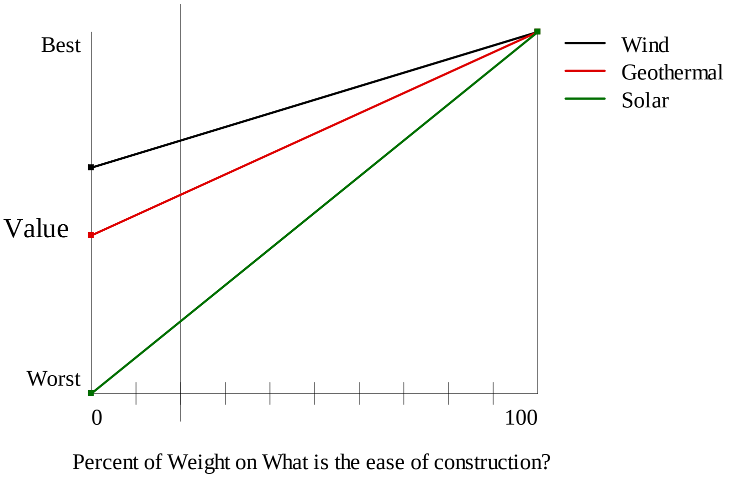


Figure 70. Sensitivity Analysis on Ease of Construction, Base Z

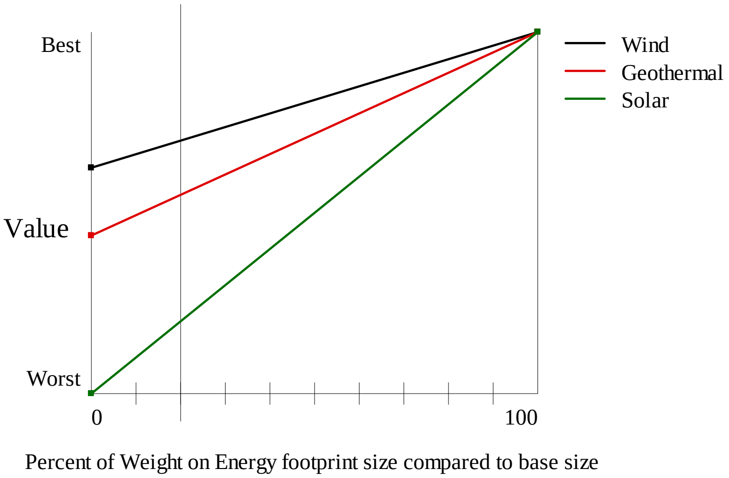


Figure 71. Sensitivity Analysis on Footprint Size Compared to Base Size, Base Z

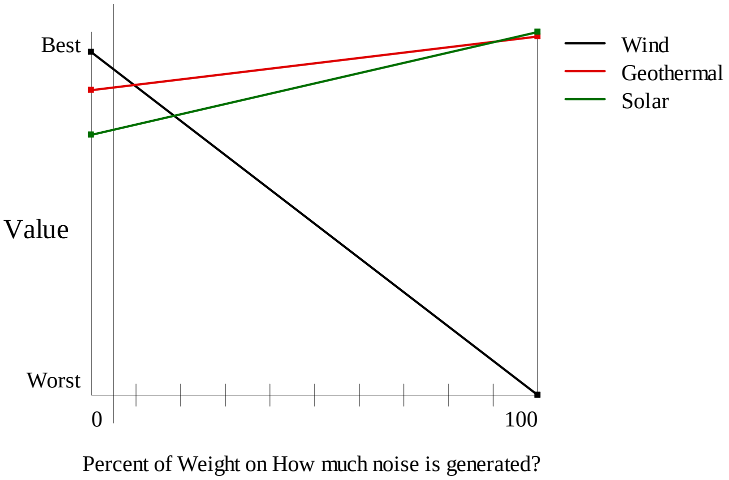


Figure 72. Sensitivity Analysis on Noise Generation, Base Z

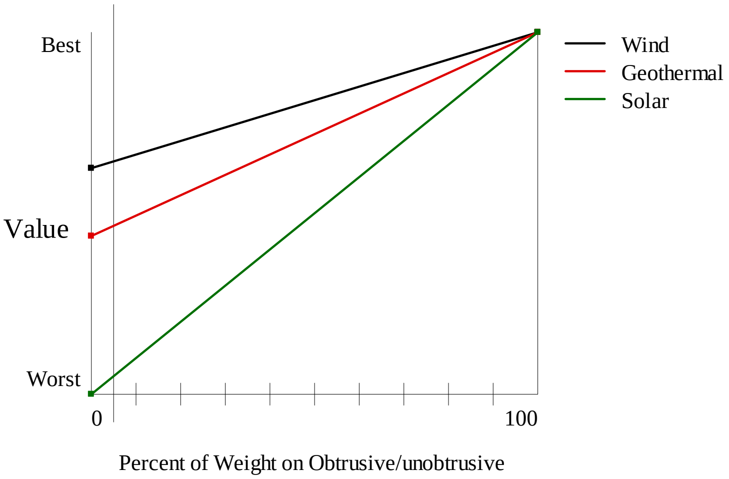


Figure 73. Sensitivity Analysis on Obtrusiveness, Base Z

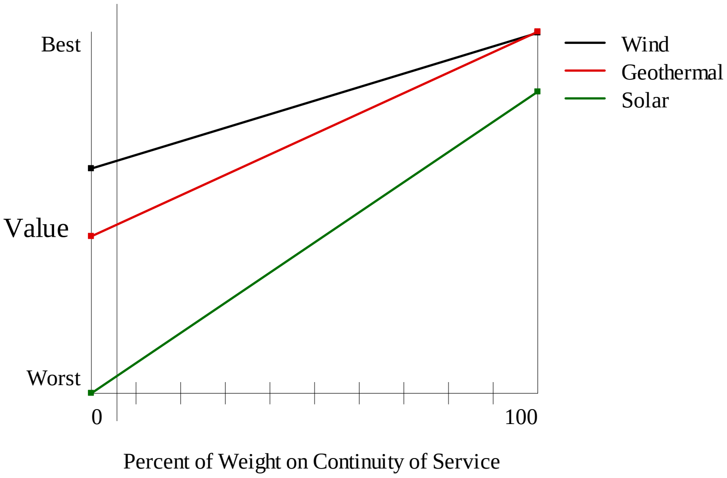


Figure 74. Sensitivity Analysis on Continuity of Service, Base Z

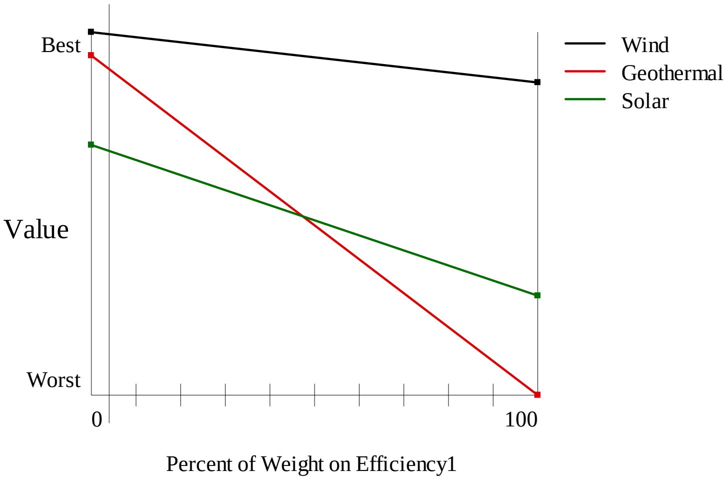


Figure 75. Sensitivity Analysis on Efficiency, Base Z

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Vita

Captain James Steven Duke was born in Nurnberg, Germany. In 1987, he graduated from J.O. Johnson High School in Huntsville, Alabama and entered the University of Alabama in Huntsville that same year. He earned a Bachelor of Science degree in Mechanical Engineering in May 1992. He was accepted to Officer Training School and was commissioned in May 1996.

His first assignment was to Barksdale AFB, Louisiana. While there, he served as an engineering project manager and squadron section commander for the 2nd Civil Engineer Squadron. His next assignment was to Kunsan AB, Republic of Korea, where he served as Commander, Housing Flight in the 8th Civil Engineer Squadron. In March 2000, he reported to Ramstein AB, Germany, and served as Design Team Chief and Chief of Base Development. In August 2002, he entered the Engineering and Environmental Management Program, Graduate School of Engineering and Management, Air Force Institute of Technology. Following graduation, Captain Duke will be assigned to Headquarters, United States Air Forces in Europe, Ramstein AB, Germany.

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14. ABSTRACT

The United States is heavily dependent on fossil fuels to produce electricity. Renewable energy can provide an alternative source of energy for electricity production as well as reduce fossil fuel consumption. The executive agencies in the U.S. must also reduce greenhouse gas emissions by 2010 based on 1990 emission levels as directed by Executive Order. However, there is currently no analysis model to provide guidance toward which renewable energy to select as a course of action.

This research effort used value-focused thinking decision analysis to create a model based on inputs from the Air Force Civil Engineer Support Agency. This model allows a decision-maker to easily alter weights and value functions related to renewable energy sources as needed to correspond to the personal values of that person. These values combined with the objective scores obtained from the generated alternatives results in a suggested course of action. The sensitivity analysis shows the changes of the output based on the alterations of the weighting of each measure. All measures were varied to study their influence on the final outcome. Application of the model at three bases showed this model appears to work based on the influencing weights and values of the decision-maker.

15. SUBJECT TERMS

Value-Focused Thinking, VFT, Decision Analysis, Renewable Energy, Geothermal, Wind, Solar, Photovoltaic

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