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Austere Location Wind Turbine Energy System Analysis

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Abstract

One promising technology to combat an energy shortage in austere locations is wind energy. In combination with battery storage and generator backup, we explore the feasibility of using a hybrid energy system to reduce the volume of diesel fuel required. Modeling the energy demands in austere locations will enable missions in remote settings to optimize their energy costs, increased their energy resiliency and assure their supply. For a modeled time-series energy requirement that varied between 2.4 MW and 5.1 MW, the optimal wind system size was 9.9 MW of installed wind power paired with a 741 kWh battery. Assuming an elevated price of fuel, the cost of operating the base with only fuel was greater than $55 million dollars. The total component and operational cost of the optimized wind, generator and battery system was cost-effective within one year and totaled $48 million dollars.

Keywords: Energy resilience; Energy efficiency; Renewable energy; Wind energy

Introduction

Remote locations require power for communications, security, operational use, and the inhabitant's quality of life; however a large portion of that power is currently generated through liquid fuels, which require overland transport or airlift. Wind turbines may increase the energy resiliency of a location by reducing logistical demand of frequent liquid fuels deliveries.

The Department of Defense stands to benefit from the implementation of wind turbines due to the costs of transporting liquid fuel. This could prevent ground casualties during convoy operations, which account for approximately nine percent of Army casualties in a deployed environment [1].

Literature Review

In general, a successful transition to renewable energy will require addressing several challenges in areas of energy resilience, technology, and corporate culture [2-6]. Specific to this work, factors related to wind as a resource, energy requirements and lifecycle considerations of implementing wind turbines at an austere location will be discussed.

Wind resource

Wind energy is derived from an uneven distribution of solar energy and was first harnessed via wind turbine to generate electricity by James Blyth of Scotland in 1887 [7]. In general, wind turbine systems are composed of a rotor, generator, tower, and control equipment [8]. The rotor converts wind energy into rotational energy. This rotational energy is directed to the generator which produces electricity, the tower provides structural support for the rotor and generator, and the control equipment optimizes the operation, power output, and safety of the system. The minimum air speed required to generate power is called cut-off power. As wind speed increases, the power generated by the turbine increases, and generation ceases to protect the system from damage when the wind becomes too powerful.

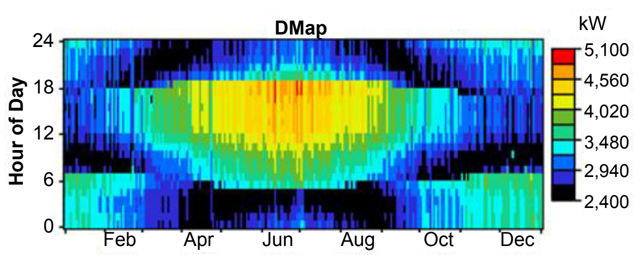

Figure 1: Modeled annual electrical demand by hour.

Wind resource data for a hypothetical location in East Asia is analyzed in this work, and the wind intensity data fits a Weibull distribution marked as a grey curve in Figure 1 [9]. Most wind resource data can be modeled through the Weibull distribution, given as:

$$f(x;\lambda,k)=\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-\left(\frac{x}{\lambda}\right)^{k}} \tag{1}$$

In the equation above, k is a shape parameter greater than zero, and λ is the scale parameter of the distribution. The data fits the Weibull distribution with $\lambda = 5.15$ and $k = 1.88$. The mean speed was 4.56 m/s. This is reasonable since because both in the Weibull distribution and wind data, values less than the mean are more common than extreme values including wind gusts.

Energy requirement

Energy requirements vary with the size, location, and operations of the base. Although it is useful to consider the average daily energy use of a deployed location, peak loads are important to consider when designing a power system. This analysis will utilize wind and electrical demand data modeled for a hypothetical outpost by McCaskey [10].

Figure 2 shows the seasonal variation of energy demand and will be used in conjunction with the base's annual wind data to calculate the optimal number of wind turbines to meet the energy requirement. The electricity demand showed daily and seasonal variation. Summer afternoons exhibited the most intense demands, and the evenings required the lowest electrical load.

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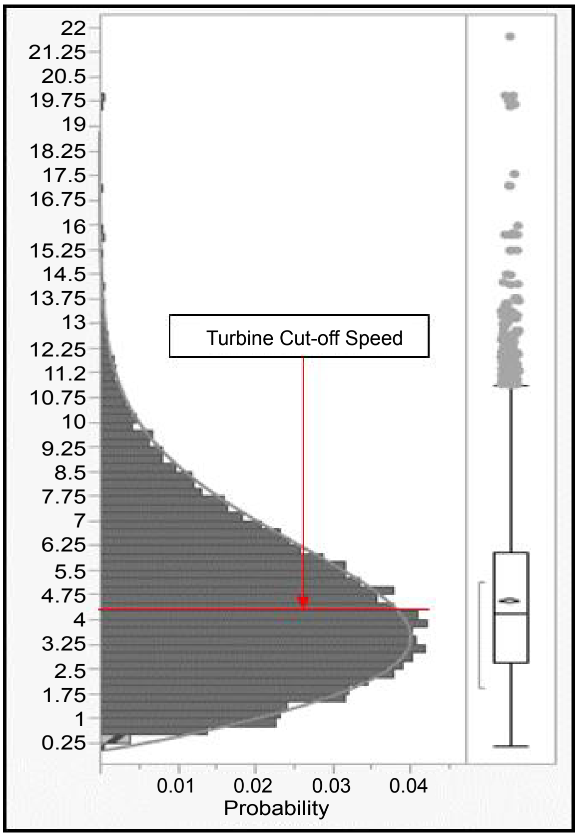

Figure 2: Wind intensity probability density

Table 1 includes costs incorporated into the financial analysis of the wind system. Wind turbine and battery costs were made continuous for optimization. Fuel prices were varied to illustrate its impact on the lifecycle costs of the optimized energy system. The MEP-12 generator was a flat price associated with purchasing and installation.

Item	Cost	References
Wind Turbine Component	$1140/kWh	[10]
Diesel	$3-1000/gal	[1]
MEP-12-Generator	$343 K	[10]
Lithium Ion Batteries	$400/kWh	[10]

Table 1: Cost model.

Table 2 includes the performance of different components in the system. Generator efficiency was held constant, even though its performance can be optimized through varying dispatching methods. Lithium ion batteries were used to model the depth of discharge and power loss of the wind system's battery.

Parameter	Value	Comments
Generator Efficiency (MEP-12)	30%	50 gal/hr at 75 kW (max output) [5]
Battery Depth of Discharge	100%	Lithium Ion Batteries
Battery Loss	8%	Per charge/discharge cycle

Table 2: Performance model.

Figure 3 shows the power produced by the NW100 turbine at various wind speeds. Our model fits the NW100 generation to an R2 value of 0.997. The curve was bounded between 0 kW and 100 kW to ensure the power produced fit the specifications of the generator, while also modeling the "cut-in" effect of wind turbines.

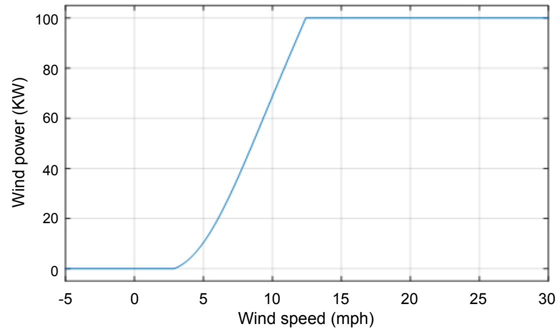

Figure 3: NW100 power produced for various wind speeds.

Lifecycle considerations

Lifecycle considerations for a wind turbine driven power source are initial delivery, setup, and maintenance. Larger and more numerous systems will generate more power, but will incur a higher delivery and maintenance cost. Batteries and generators are also included in the analysis because they serve a crucial role in a consistent delivery of power.

Methods

The model used hourly electrical and wind data gathered by McCaskey. Wind data were fed into a wind power output function to calculate the turbine's output. The turbine's power output was then compared to electrical demand. If the power produced was greater than the power consumed for that hour, excess power "charged" the battery. If power produced was less than the power consumed, it drained the battery. If the battery was at max capacity, extra power was added to a "wasted power" calculation, and the battery remained at maximum charge. If the battery was completely drained and wind turbines could not meet electrical demand, then diesel generators operated to meet the power requirement. This analysis assumed a zero tolerance for power outages. The fuel consumed to meet the need was aggregated for each hour to calculate its total use and costs throughout the year [6-10].

The optimized number of wind turbines was calculated by running the wind system model using McCaskey electric loads and wind availability for a year. The optimum amount of turbines for a given fully burdened cost of fuel and battery capacity was the value which produced the minimum cost. The optimal battery capacity was calculated using a similar method, but held wind turbines constant while modeling the system for a year.

For each fuel price, we optimized the wind turbines required starting with a 50 MW battery. The optimized wind turbine output was then fed into a battery optimization function. The battery optimization function calculated the optimal capacity of batteries for a given amount of wind turbines. The optimized battery capacity was then fed back as an input for the wind turbine optimization function. The wind optimization and battery optimization loop continued until both formulas agreed on an optimal wind turbine and battery size, or the change between iterations was less than 1%.

Analysis

As shown in Figures 4 and 5, for fuel costs of $2.00/kWh, the optimal number of wind turbines was 99 and the optimal battery capacity was 741 kWh.

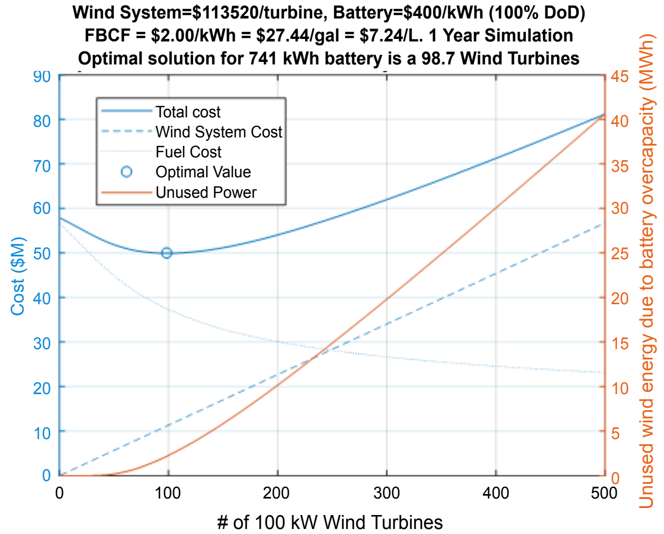

Figure 4: Optimal wind system size for FBCF=$2.00.

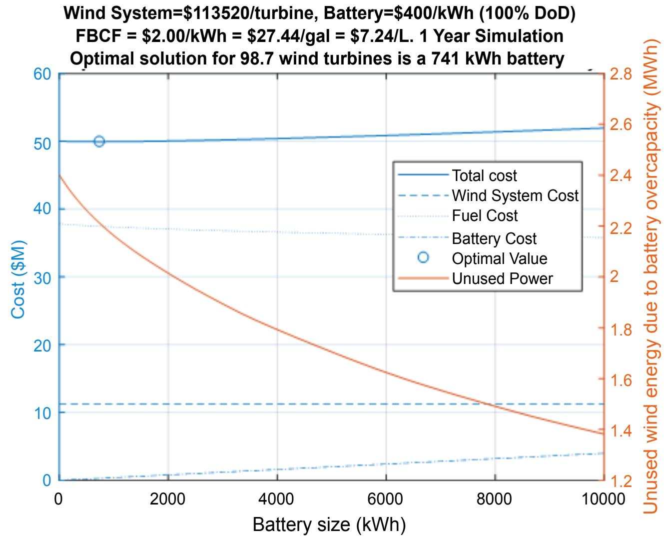

Figure 5: Optimal battery size for FBCF=$2.00.

In the wind system size optimization, the total cost had a steep decline when the wind system was implemented. This was due to a sharp decline in fuel consumption to meet power demands. The total price of the system increased gradually after the optimal point because the power produced was outpacing the battery.

However, as the battery grows larger, the cost of fuel saved is lower than the costs of each kilowatt of battery. Unused power also decreases, but installing enough battery to capture all wind power was cost prohibitive in the model. The battery system size optimization showed that at lower fuel costs, it was beneficial to have a relatively small to zero battery capacity.

Fully burdened costs of fuel were varied to see the effect of fuel price on the optimal wind and battery size. In general, as the FBCF of a location increases, the optimal size for wind and batteries increase.

Figure 6 illustrates the cost of implanting the wind system or using diesel exclusively for one year. Wind systems have a large installation cost, but still outperformed diesel use within one year.

Figure 7 breaks down the total wind system costs into component costs for the first year. Fuel costs were kept below $50 million for all fully burdened costs of fuel. This means that in later years, the operating costs of the wind system will outperform diesel use because the system will already be installed. However, this assumes that maintenance costs are negligible. International journal of renewable energy research.

Conclusions

The optimizations performed support the use of wind turbines in remote locations, even when only one year of operation is anticipated. The optimal wind system size was 99 turbines with a 741 kWh battery. The total cost of this system was roughly $48 million dollars over one year. The cost of operating the base with only fuel was greater than $55 million dollars.

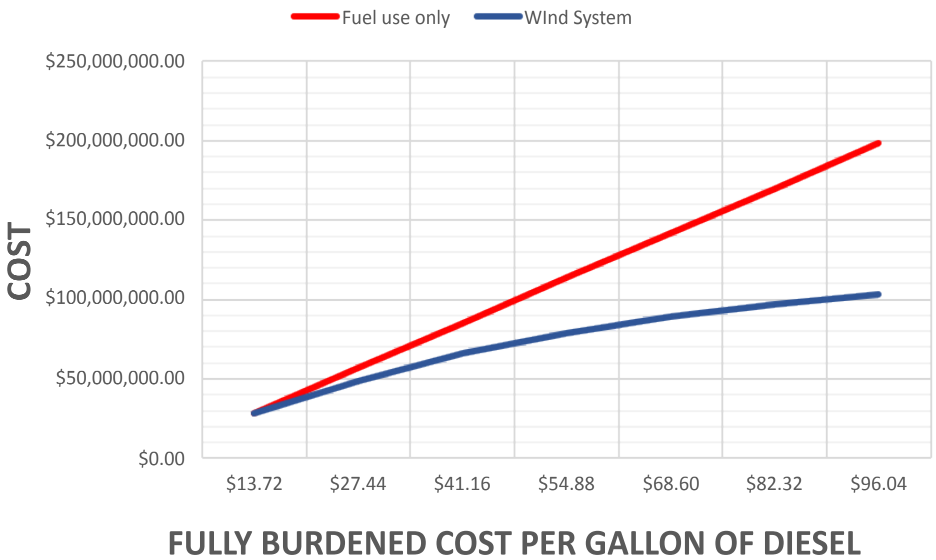

Figure 6: Wind system costs vs. fuel only costs for one year.

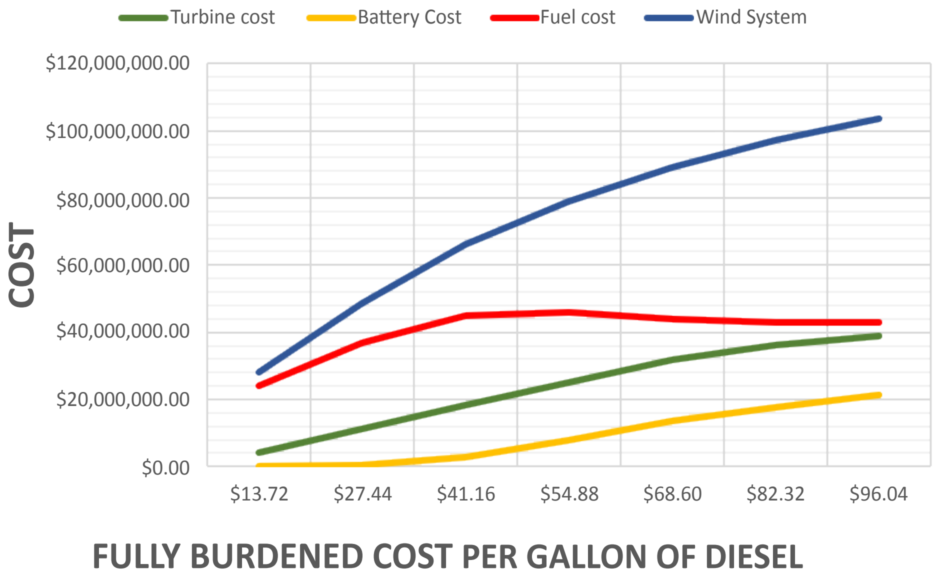

Figure 7: Component cost breakdown of optimized wind systems.

In further research, it would be beneficial to optimize dispatching methods between the batteries and generator. This would optimize the generator's performance along with the wind system. It would also be prudent to use a smaller turbine to model the analysis. Smaller turbines would be easier to ship and install, and may be able to capture lower wind speeds.

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