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Computational analysis of deployable wind turbine systems in defense operational energy applications

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ABSTRACT

The U.S. military has been exploring pathways to reduce the logistical burden of fuel on virtually all their missions globally. Energy harvesting of local resources such as wind and solar can help increase the resilience and operational effectiveness of military units, especially at the most forward operating bases where the fuel logistics are most challenging. This report considers the potential benefits of wind energy provided by deployable wind turbines as measured by a reduction in fuel consumption and supply convoys to a hypothetical network of Army Infantry Brigade Combat Team bases. Two modeling and simulation tools are used to represent the bases and their operations and quantify the impacts of system design variables that include wind turbine technologies, battery storage, number of turbines, and wind resource quality. The System of Systems Analysis Toolkit Joint Operational Energy Model serves as a baseline scenario for comparison. The Hybrid Optimization of Multiple Energy Resources simulation tool is used to optimize a single base within the larger Joint Operational Energy Model. The results of both tools show that wind turbines can provide significant benefits to contingency bases in terms of reduced fuel use and number of convoy trips to resupply the base. The match between the turbine design and wind resource, which is statistically low across most of the global land area, is a critical design consideration. The addition of battery storage can enhance the benefits of wind turbines, especially in systems with more wind turbines and higher wind resources. Wind turbines may also provide additional benefits to other metrics such as resilience that may be important but not fully considered in the current analysis.

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EXECUTIVE SUMMARY

The U.S. military conducts a wide range of missions throughout the world, including responding to humanitarian crises. All of these missions currently depend on reliable access to liquid fuel provided through a complex and often vulnerable global logistics system. Generating power on location, whether a contingency base or disaster response coordination point, can reduce risk and enhance mission reach compared to just relying on liquid fuel energy sources. The U.S. military has identified the need for energy alternatives in their strategic planning and investments, however much of the focus on renewable energy thus far has focused on solar photovoltaics with very little consideration for the potential value of energy from wind turbines. This analysis provides a systematic evaluation of the potential benefits of wind energy to contingency bases to provide both technology solution providers and military decision makers with information that is not readily available in public documents.

The analysis in this report is based upon the System of Systems Analysis Toolkit Joint Operation Energy Initiatives Pacific Command Phase IVB, military operations focused on stabilization and restoring services. This baseline scenario simulates a 30-day mission of a hypothetical Army Infantry Brigade Combat Team operating a network of forward deployed contingency bases. The model captures in detail the energy generation, consumption, and resupply convoys to facilitate the comparison of operational energy metrics of alternative scenarios. The alternative scenarios explored in this analysis included adding different quantities of wind turbines, different wind turbine technologies, the inclusion of battery storage systems, and different wind resource profiles. The primary metrics of comparison were the reduction in diesel fuel consumption and the reduction in resupply convoys over the complete mission. Augmenting these results, the Hybrid Optimization of Multiple Energy Resources simulation tool was used to model a single base within the larger network to optimize the number of wind turbines and batteries that lead to the greatest reduction in convoy trips for a variety of wind resource profiles and mission durations.

The characteristics of the wind resource at the base location has a major impact on the benefits of wind energy. Wind resources vary considerably around the world, and also vary seasonally and daily in many locations. Sufficiently detailed information on wind resource is available globally and continues to improve to support energy production estimates for mission planning. Statistically, the average wind speed on most of the land globally is around 4.32 m/s at 50 meters above ground, which is significantly lower than what would typically be considered for a commercial wind turbine deployment. Despite the prevalence of this relatively low wind resource, wind turbines still produce appreciable energy from this lower resource and, more importantly, can produce even more energy with some design changes. The analysis showed that by increasing the blade length by about 27%, wind turbines provided benefits over diesel generator systems in as few as six months at the lowest wind resource and only three months at the higher wind resource. Though such tailored designs do not exist commercially, the development and manufacturing require relatively low-risk research and development.

The overall base power system design and composition is an important driver of wind turbine benefits. The current analyses began with the assumption that the base was networked into two or three separate microgrids with generators sharing loads within each grid. This is not always the case with bases today but is considered a necessary step before the benefits of wind can be fully harvested. Battery storage systems are the other key factor in power system design. Batteries can address any mismatch in generation and load by storing excess wind energy for times of high load or low wind. The addition of batteries increased the fuel savings benefit of wind turbines most in systems with a large number of turbines and at higher wind speeds as wind turbines begin to supply more than 50% of the base load.

The remoteness of the base also impacts the potential benefits of wind energy. This analysis only considered the most forward bases in the modeled network for two reasons. First, the model turbine size of 15 kW was a good match to the scale of the base load such that a reasonable number of turbines (20 – 40) could supply a high percentage of base power. Second, being the most forward bases, the fuel logistics burden is also typically higher. Reducing a gallon of fuel at the more forward bases has compounding benefits all the way back to the port where fuel is delivered in bulk.

Overall, this analysis shows the potential value of deploying wind turbine systems nearly anywhere in the world with considerations of the turbine design and design of the power system. Wind turbines were shown to reduce diesel fuel use between 22% and 83% and reduce the number of required convoy trucks between 5% and 26% over a 30-day mission. The lower end of the benefit generally represents the commercial turbine designs, fewer in number, no battery storage and low wind resource, while increased benefits result from the large-rotor turbine in higher quantities in higher wind speed with battery storage. Optimization studies suggest that from a total transportation burden metric, wind turbines start to break-even on missions lasting longer than about 3 months in this particular mission profile. Additional benefits like resiliency and reliability, not included in this analysis, could enhance the benefits of wind to specific missions.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AC	alternating current
AO	area of operations
AMMPS	advanced medium mobile power source
BCT	brigade combat team
C3T	control and communications tactical
CCI	command and control infrastructure
D3T	Defense and Disaster Deployable Turbine
DC	direct current
DOE	Department of Energy
HEMTT	heavy expanded mobility tactical truck
HOMER	Hybrid Optimization of Multiple Energy Resources
IBD	integrated base defense
ISO	International Standards Organization
JOEI	Joint Operation Energy Initiatives
LHS	load handling system
Li-ion	Lithium-ion
MEP	mobile electric power
MFS	Modular Fuel System
MTBF	mean time between failure
NREL	National Renewable Energy Laboratory
PACOM	Pacific Command
PLS	palletized loading system
SoSAT	System of Systems Analysis Toolkit
XS	extra small

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1. MOTIVATION AND APPROACH

While wind turbines have become a major, new generation source on the domestic grid, providing more than 7% of the energy generated in 2019 [1] including many domestic military installations, they have not been as successful in meeting U.S. military operational energy needs, such as contingency bases overseas. There are a variety of reasons wind has not been incorporated into base planning or operations including logistical and operational barriers or risks, and insufficient experience or training with the technology. However, there are also technical reasons wind turbines have been underutilized, including the difficulty in estimating the wind resource at any particular location globally, and the lack of design specifications for the technology leading to the underperformance of commercial systems. Both of these reasons lead to a poor understanding of the potential value of wind energy in these military applications and where wind can best contribute to a resilient energy system.

The U.S. Department of Energy's (DOE's) Defense and Disaster Deployable Turbine (D3T) project is tasked with evaluating the market potential for rapidly deployable wind energy technologies, developing wind turbine design requirements for operational applications, and assessing commercially available wind technologies against operational design requirements to help identify technology gaps and research and development opportunities. This report is one product of that larger effort and summarizes analysis work using two modeling and simulation tools to attempt to answer the question of how wind energy can provide the most value to a military contingency base. These simulations consider different wind turbine designs, different wind resources, different power system configurations and measure relevant metrics like reduced diesel consumption, and reduction in number of transport trucks and convoys needed to supply bases with power.

The first set of analyses uses the Sandia-developed System of Systems Analysis Toolkit (SoSAT) which has been previously verified and validated and used for U.S. Army Operational Energy Task Force scenario modeling work for the Joint Operational Energy Initiative (JOEI) Program initially sponsored by the Office of the Assistant Secretary of Defense for Operational Energy. Leveraging that prior work as a baseline, which did not previously include renewable generation, provides a credible reference point to assess the potential for wind energy to contribute to the energy resilience of a network of bases operating during a single mission lasting 30 days to 1 year without access to host nation grid-tied power.

Augmenting those results, further detailed analysis uses the Hybrid Optimization of Multiple Energy Resources (HOMER) Pro Microgrid Analysis Tool developed by the National Renewable Energy Laboratory (NREL) and now licensed to a commercial company for further development and technical support. The HOMER software is widely used to optimize microgrid designs for lowest lifecycle cost as the primary metric. While the tool is applied primarily to commercial systems that are designed to operate for many years, it has some powerful capabilities to conduct sensitivity studies that are relevant to considering a single contingency base in more detail. The SoSAT and HOMER models were compared on a few scenarios to ensure they produce consistent results that are complimentary.

This report begins with an overview of the SoSAT tool background, structure, prior applications and baseline data and assumptions. The next sections cover the detailed assumptions and modeling approaches used to represent the wind turbines and wind resources in both simulation tools. The following sections present the SoSAT and HOMER modeling scenarios and results. The report concludes with some general observations and suggested areas for further exploration.

2. SYSTEM OF SYSTEMS ANALYSIS TOOKIT

2.1. Motivation

The 2018 National Defense Strategy identifies a goal to build a more lethal force, including "a competitive approach to force development and a consistent, multiyear investment to restore warfighting readiness." [2] The Army is working towards this goal by investing in operational energy systems and processes that extend soldiers' range, endurance, flexibility, mobility, and resilience. Currently, the Army and each of the other military services rely almost exclusively on diesel fuel to power combat operations and the "logistics tail" this requires is a key constraint, especially to the most forward-deployed forces. The Army uses analysis tools to quantify the logistics requirements, constraints, and potential solutions to operational energy scenarios. This D3T project incorporates wind turbine system models into these existing baseline Army scenarios to evaluate the potential benefits of the technology towards meeting Army operational energy goals.

2.2. Background

SoSAT uses established baseline model assumptions for the Joint Operation Energy Initiatives (JOEI) Pacific Command (PACOM) Phase IVB baseline model. The JOEI model was constructed as part of a joint effort with the Army's Operational Energy Analysis Task Force. The initial goal of the project was to develop the baseline model of a 30-day Phase IV, military operations focused on stabilization and restoring services, steady-state operations during the cold winter season and assess the operational energy demand of the Army element in a theater of operations for the defined operations plan. The model is used as a baseline to evaluate the impact of differing technologies, operations, and other vignettes on a variety of energy and other metrics. The objective of the analysis is to reduce the Army's energy dependency and demand, increase existing systems and facility energy efficiency, evaluate alternative energy sources (e.g. wind turbines), and create a culture of energy responsibility while sustaining or enhancing operational capabilities. The baseline model enables analytic assessments across an entire Area of Operations (AO).

2.3. Force Structure

The military force structure comprises the physically distinct contingency basecamps and their support relationships represented graphically in Figure 1. The force structure of this operational scenario is comprised of two divisions with eight brigade combat teams (BCTs), a division headquarters, combat aviation brigades, an engineering brigade, a maneuver enhancement brigade, sustainment brigades, and others. The initial models incorporating wind turbines will consider only a single Infantry BCT (circled in red below) for simplicity. Future models could extend to other BCTs (i.e. Armored and Stryker) if warranted.

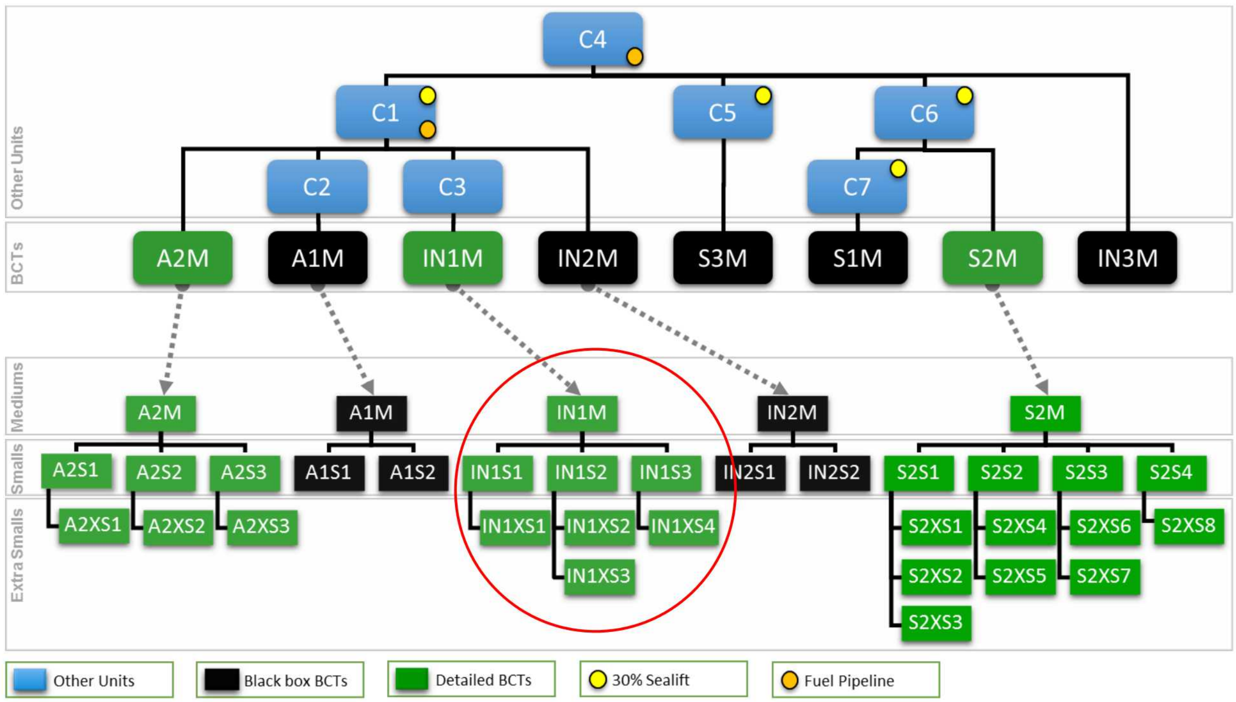

Figure 1. Force Structure and Support Relationships

Detailed BCTs (represented in green) are the highest fidelity model representations of a BCT and include system level details for all vehicles and equipment within each base. Vehicles and equipment that can consume, fail, or impact other systems are modeled. The infantry BCT in this scenario is comprised of three different size basecamps categorized as medium (~4500 personnel), small (~500 personnel) and extra-small (~150 personnel). The medium basecamp provides support to the three small basecamps which then each provide support to one or two extra-small basecamps as shown in the red circle in Figure 1. The distance and time to travel by ground between each base is also specified to model the vehicle convoys required to resupply basecamps to meet their resource consumption based on normal day to day operations. This is commonly referred to the "supply chain" between contingency bases required to provide almost all of the commodities (fuel, water, food, ammo, etc.) to the forward deployed contingency bases.

Each basecamp includes logistic and scenario relevant details about each piece of equipment and vehicle including fuel, electricity, and water consumption rates. There is also the ability to specify utilization rates for each piece of equipment and failure rates. The model runs the operational scenario for the specified length of time, in this case 30 days, with a user-defined time step resolution (generally 1 hour).

2.4. Baseline Energy System Modeling

The SoSAT JOEI model has detailed assumptions for storage, water, power, waste and other consumables for all equipment that use or produces material or energy over time. The focus of this D3T project simulation is electricity generation, so only the power assumptions are discussed here. The baseline power assumptions relevant to the D3T models are as follows:

- Powerplant type generators consist of two identical mobile electric power (MEP) generators (generally 60 kW MEP-1070) operating as primary and back-up. When the primary generator fails, the backup will immediately start without interruption or delay to the power consumers.

- Integrated Base Defense (IBD) is modeled as a single entity that represents a collection of systems. These systems operate 24/7 and are powered by one or more generators that are treated like a microgrid.
- Command and Control Infrastructure (CCI) also operates 24/7.
- Detailed layout of microgrid design for each camp is required to model impact of distribution components.
- Single combined microgrid is modeled to support the entire camp.
- Each mission command, control and communications tactical (C3T) as well as medical operations at each basecamp has its own power plant type generator.

2.4.1. Electricity Load

Each base in the SoSAT scenario has a daily load profile that repeats for the 30-day mission. As an example, the load profile for one of the extra small (XS) bases is show in Figure 2 with a minimum of 191 kW and a peak of 316 kW each day. The peak daily load for each base is tabulated in Table 1 and was used to help size the number of wind turbines in the simulations.

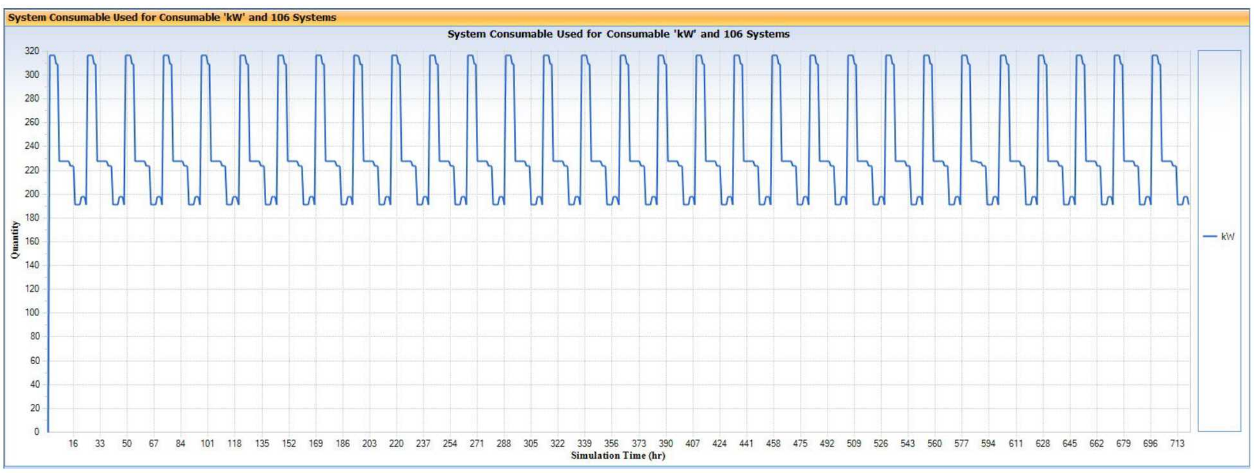

Figure 2. A 30-Day Load Profile for One of the XS Bases in the SoSAT Baseline Scenario

Table 1. Electricity Load and Personnel for Each Base in the SoSAT Model

Base description	Personnel	Peak daily load (kW)	Average daily energy use (kWh)
Medium	5,489	9,334.79	169,224
Small 1	461	1,046.65	18,350
Small 2	724	1,526.1	26,934
Small 3	941	1,867.83	31,879
XS1	120	316.4	5,697
XS2	163	437.46	7,785
XS3	163	437.46	7,785

Base description	Personnel	Peak daily load (kW)	Average daily energy use (kWh)
XS4	163	437.46	7,785

2.4.2. *Electricity Generation*

In the baseline scenario all electrical power comes from diesel spot generators. Generally, there is a backup generator for each generator in operation, so total capacity is double the peak load. There are two (XS) or three (medium and small) independent microgrids at each base to support critical loads at Mission Command and Medical and a microgrid to serve all remaining base loads. Table 2 shows how many of each generator type support each area on a base along with the total rated capacity for those bases.

Table 2. Number and Type of Advanced Medium Mobile Power Source (AMMPS) Generators at Each Base Assigned to a Specific Microgrid

Microgrid	Medium	Small	XS
Mission Command	45 x 60 kW AMMPS	8 x 60 kW AMMPS	1 x 60 kW AMMPS
Medical	20 x 60 kW AMMPS	1 x 15 kW AMMPS	N/A
Microgrid for general base loads	4 x 60 kW AMMPS 21 x 840 kW DPGDS	1 x 10 kW AMMPS 28 x 60 kW AMMPS (42 at S2, 53 at S3)	1 x 30 kW AMMPS 9 x 60 kW AMMPS (7 at XS1)
Total rated capacity	21,780 kW	2,185 kW	510 kW

2.5. SoSAT Wind Turbine Input Requirements

In order to integrate wind turbine systems into the existing baseline SoSAT contingency base models several inputs are required. These inputs include, but are not limited to, the wind resource profile and the turbine design models. SoSAT requires a wind resource profile that is a 30-day time series of wind speed with an hourly resolution. Turbine model design parameters are required to determine the hourly energy production of a turbine system corresponding to the turbine specific power for the wind resource. This can then be scaled to the number of turbines present at a base supplying electrical energy to a microgrid. Section 3 describes how the wind resources were defined as an input to the wind turbine models described in Section 4 This enabled the new scenarios explored with SoSAT as described in Section 5.

The baseline SoSAT scenario does not include wind turbines or any other power generators beyond the standard MEP generators. Section 3 describes how the wind resources were defined as an input to the wind turbine models described in Section 4. This enabled the new scenarios explored with SoSAT as described in Section 5.

3. WIND RESOURCE PROFILES

The baseline SoSAT scenario does not define a wind resource profile, therefore wind speed profiles had to be developed as an input to the wind turbine models. The local wind resource is the most critical variable in determining the viability of wind energy systems to provide value to a contingency base. The power available in the wind resource scales with the third power of the wind speed, so small changes in wind speed have a large impact on system performance. A wind resource can be represented as a Weibull function which statistically captures both an average wind speed and the variability of that wind speed in a probability distribution. The two-parameter Weibull distribution function is defined as:

$$f(v) = \frac{k}{A} * \left(\frac{v}{A}\right)^{k-1} * e^{-\left(\frac{v}{A}\right)^{k}}$$

where v is the wind speed in m/s, A is a scaling parameter in m/s and k is a dimensionless shape factor that captures how variable the resource is. The wind resource is highly location dependent, but for the purposes of the current analysis, a representative "Low" and "Good" wind resource were defined. These two resource classifications represent the range of wind resources than occur globally (Figure 3) or alternatively the range in a single location that experiences seasonal differences in wind resource quality.

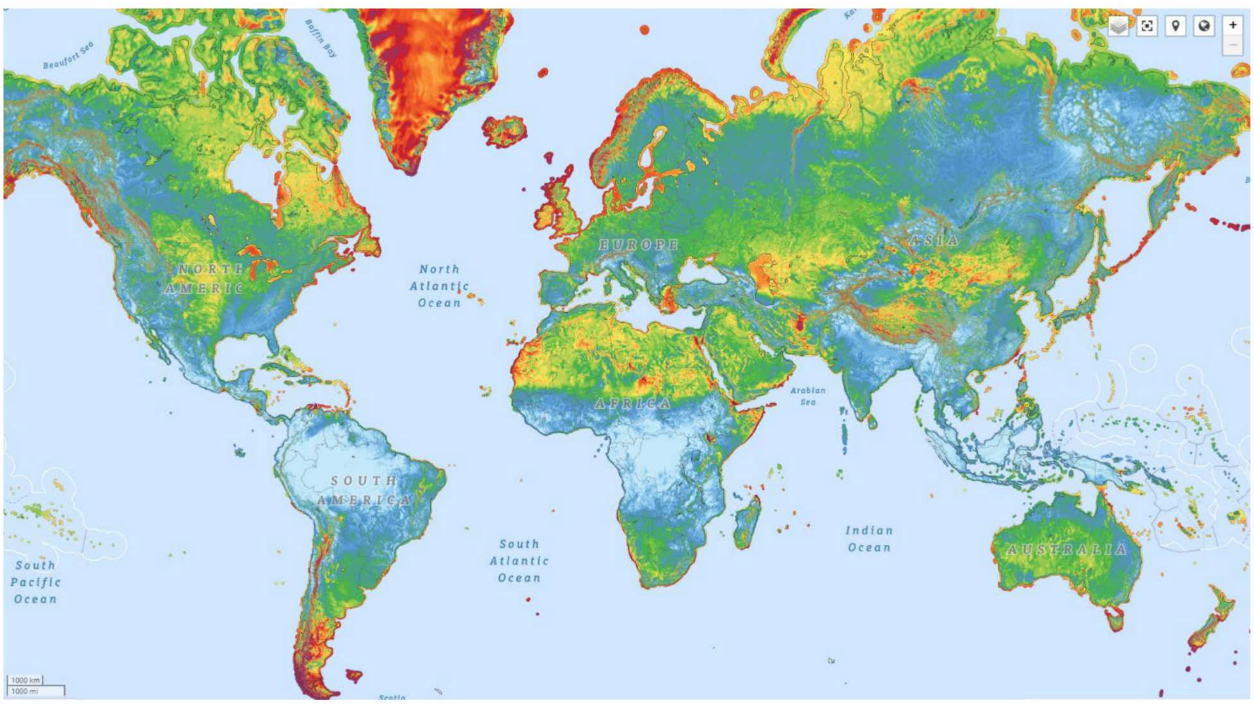

Figure 3. Global Wind Resource Map at 50 m Above Ground from Global Wind Atlas [3]. Average Wind Speed Varies from High (Red) to Low (Blue) Across the Globe.

3.1. Definition of Wind Profiles

The same data used to generate the wind speed map at 50m above ground in Figure 3 was used to populate the data in Table 3 showing the minimum average wind speed for different percentiles of the global land area. Using these data, the "Low" wind resource is defined as the average wind speed on at least 90% of the land globally, or 4.32 m/s. This is intended as a bounding case for a deployable wind system that could theoretically be quickly installed anywhere on land to support defense or disaster response efforts where detailed data on a specific deployment site is most likely unavailable.

Table 3. Wind Resource Averages as a Function of Land Area [3]

Land area	Global average wind speed at 50m
90th percentile	4.32
75th percentile	4.39
50th percentile	4.50
25th percentile	4.70
10th percentile	4.87

The "Good" wind resource was selected as an average of 6.22 m/s. While it is a somewhat arbitrary selection, it does represent what would be qualitatively considered an economically viable resource to deploy a commercial wind turbine. Also, because wind power scales with the third power of the wind speed, it contains approximately three times the potential power as the "Low" wind profile. These two resources provide a wide range of resources to assess the performance of a wind turbine to cover a lot of potential locations and seasons without having to run many scenarios.

3.2. HOMER Synthetic Wind Data Generation

The SoSAT simulations require a time-series of wind speeds with 1-hour resolution for a minimum of 30 days. If a specific location was identified, the wind speed time series could be generated from actual measurements in the field. This analysis is considering generic locations and therefore requires a time-series to be generated synthetically. Two different wind resource profiles were generated using the HOMER Pro v3.13 microgrid analysis software, labeled "Low" and "Good" as defined in the previous section. The parameters used to quantify the wind resources within the HOMER software are listed in Table 4. Most of the values other than the average wind speed and Weibull parameters are default values offered by the HOMER software, but are based on statistical analyses of historical data from hundreds of meteorological stations across the United States [4]. The HOMER software uses a five-step algorithm based on an autocorrelation method to generate one year of 1-hour time step wind speed values. Additional details about the data synthesis method can be found in the HOMER user manual. [5]

The objective of this analysis was to assess the performance of wind turbines operating in two generic locations with a generally low wind resource and a generally good wind resource. A more detailed and accurate analysis of a particular system would require data to be measured at an actual geographic location of interest.

Table 4. Wind Resource Parameters Used to Generate Two Different Wind Speed Time-Series

HOMER parameters	Low Wind Resource	Good Wind Resource
Monthly average (m/s)	4.32 (April)	6.22 (June)
Weibull k	2.021	2.017
Weibull A	4.876	7.02
1-hour autocorrelation factor	0.85	0.85
Diurnal pattern strength	0.25	0.25
Hour of peak wind speed	15	15
Altitude above sea level (m)	0	0
Anemometer height (m)	30	30
Surface Roughness	.01 (rough pasture)	.01
Scaling with height above ground	Logarithmic	Logarithmic

The HOMER software automatically generates a full year of 1-hour time series wind speed data that meets the statistical parameters selected. For the 30-day SoSAT analysis, 30 concurrent days had to be selected that best matched the same annual statistics. For the low wind resource that happened to be the month of April, while for the good resource June was a better match. These 30 days were then statistically fit to a Weibull distribution which varied slightly from the initial parameters used to generate the time series. Table 4 represents the final parameters for the selected 30-day time series.

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4. WIND TURBINE MODELS

Two different wind turbine models were developed for the SoSAT simulation scenarios. The first turbine model approximates a commercially available 15 kW-rated wind turbine. The second model represents a hypothetical design iteration of the commercial turbine using a larger rotor diameter with the same power rating (15 kW). The result of this design choice is that the larger rotor produces more power at the lower wind speeds which would be well-suited for the low wind speed resource described in the previous section. The intent with these two models is to explore the primary design driver for wind turbine performance which is the rotor swept area. While other design parameters are very important, they are also increasingly specific to a particular wind system design and are outside the scope of this report. The remainder of this section describes the design choices and modeling approach for the wind turbine models used in both the SoSAT and HOMER simulations.

4.1. Transportation Logistics

The constraints for a deployable wind turbine design are going to be driven primarily by the transportation logistics, though other factors regarding the turbine installation and operation are important to consider in a detailed design. While the U.S. military can accomplish just about anything logistically, there exist preferred or standard equipment to move and handle materiel. The wind turbine blade length determines the rotor diameter, and the longest blade that can be commonly transported by the types of units that require deployable power systems will be considered the bounding case. The U.S. Army will be used as the reference force because it is the largest user of mobile electric power systems.

4.1.1. Heavy Expanded Mobility Tactical Truck

The U.S. Army primarily uses the Heavy Expanded Mobility Tactical Truck (HEMTT) platform to move materiel around in theater. The HEMTT consists of a family of 4-axle, 8-wheel drive tactical vehicles that come in multiple configurations to support different missions, including fuel and cargo transport and recovery of broken-down vehicles [6]. The HEMTT M1120 Load Handling System (LHS) variant is capable of transporting two 2,500-gallon Modular Fuel System (MFS) tank racks of liquid fuel with the addition of a trailer (Figure 4). The M1120 with MFS is modeled in the SoSAT simulation to transport fuel between the bases.

Figure 4. M1120 Load Handling System HEMTT with Trailer Transporting Two 2,500-Gallon MFS Tank Racks

The Palletized Loading System (PLS) M1075A1 with M1076 trailer is capable of loading, transporting and unloading various payloads including 8 x 8 x 20-foot International Standards Organization (ISO) containers (Figure 5). The PLS and trailer each have a payload capacity of 16.5 tons for a total of 33 tons [6]. This system is not explicitly modeled in the SoSAT scenario but is used as a proxy for what could be used to deploy wind turbines that are packed into 20-foot ISO containers. From a logistics burden perspective, the M1120 with trailer carrying 5,000 gallons of fuel is assumed equivalent to the M1075A with trailer carrying two 20-foot ISO containers.

Figure 5. M1075A1 PLS unloading a 20-foot ISO Shipping Container

4.1.2. Shipping Container Dimensions

The Army Container Operations Field Manual FM 55-80 [7] states that unit equipment and initial deployment of sustainment operations primarily use 20-foot shipping containers. As mentioned, the HEMMT vehicles are equipped to handle this size of container. Internal dimensions of a standard 20 ft ISO container are 5.9 m length, 2.35 m width, 2.39 m height. For the analysis in this report, these internal ISO container dimensions are used as the constraints on the size of the wind turbine components, most notably the blade length which is limited to 5.9 m (19.35 ft). The tower is assumed to be constructed from multiple 5.9 m pieces (e.g. telescoping) to achieve the desired overall height of 30 m in this analysis.

4.2. Wind Turbine Design Parameters

Given the general logistics constraints presented in the previous section, the design parameters were selected for two model wind turbine designs as summarized in Table 5. The baseline turbine is based on a typical 3-bladed commercially available and modern 15-kW wind turbine. The parameters were chosen to approximate the dimensions and performance of that turbine. The rotor diameter is 9.6 m, making each blade slightly less than half (4.8 m) of that with the remainder coming from the hub. The large-rotor turbine design is simply an iteration on the commercial turbine where the only difference is that the blade length is increased to the maximum ISO container dimension of 5.9 m. With the hub, this results in a rotor diameter of 12.2 m. This is not intended to represent an optimal blade length selection, rather just to demonstrate the impacts to the power system design by having the option of a longer blade. The other parameters in Table 5 are either typical design specifications or calculated values based on the rotor diameter and wind resource.

Table 5. Parameters Used to Develop the Two Wind Turbine Models

Parameter	Commercial Turbine	Large-rotor Turbine
Coefficient of Performance (max)	0.45	0.45
Air density (kg/m3)	1.225	1.225
Rotor diameter (m)	9.6	12.2
Rotor area (m2)	72.4	116.9
Cut-in wind speed (m/s)	3	3
Rated Power (kW)	15	15
Cut-out wind speed (m/s)	25	25
Specific power at rated (W/m2)	207	128
Maximum rotor thrust (N)	2,812	3,300
Maximum blade root bending moment (N-m)	2,838	4,231
Number of blades	3	3
Hub height (m)	30	30
Annual Energy Production at low (4.32 m/s) average resource (kWh)	24,520	35,787
Capacity Factor at 4.32 m/s	18.7%	29.5%
Annual Energy Production at good (6.22 m/s) average resource (kWh)	53,425	67,205
Capacity Factor at 6.22 m/s	40.7%	51.1%

The parameters above were used to build computational models of the rotors based on the aerodynamic design process described by Jamieson [8]. The primary outputs of the design tool are the calculated power curves shown in **Error! Reference source not found.**. The power curves provide the relationship between the wind speed and the power output of the turbine. In reality, the power curve is more variable due to turbulence in the wind, controller settings, and other real-world uncertainties, but this simplified assumption is appropriate for the level of analysis in this study.

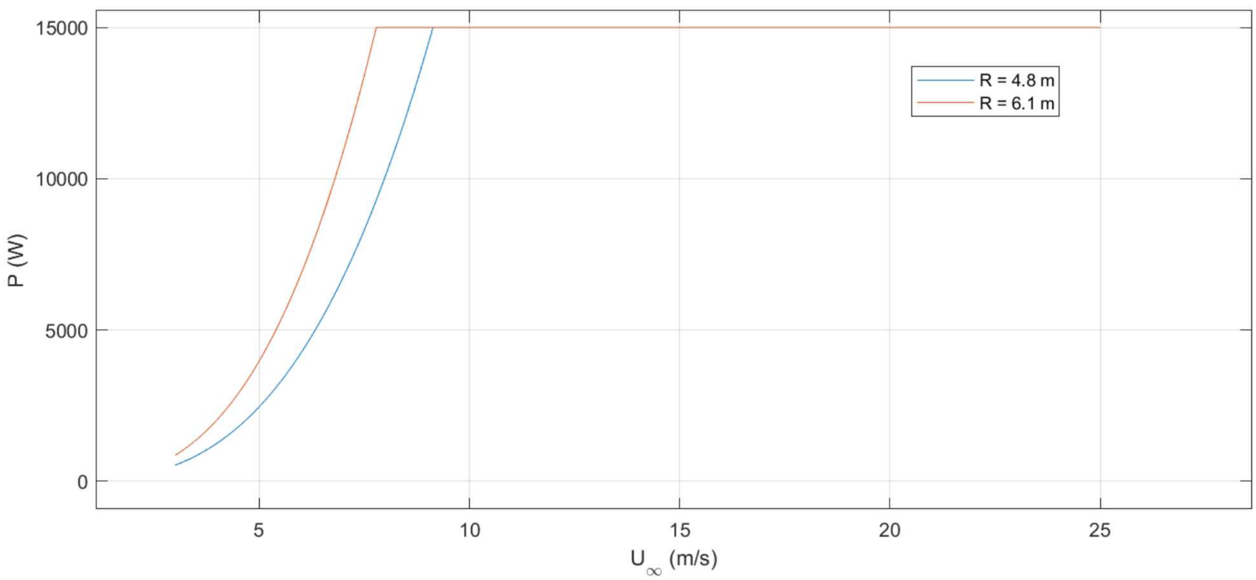

Figure 6. Power Curves for the Two Modeled Wind Turbines, Commercial (Blue) and Large-rotor (Red), Showing the Relationship Between the Wind Speed (U) and the Power Output (P) in Watts.

The differences between the power curves are evident at the more frequent, lower wind speeds where the large-rotor turbine produces more power than the commercial turbine for any given wind speed until they both achieve the same rated power of 15 kW at higher wind speeds. There are trade-offs to the increased power generation of the larger rotor design, and the primary impact is that the loads on the turbine increase due to the increased thrust of the rotor. Table 5 tabulates the increase in both rotor thrust and the bending moment at the root of the blades where they connect to the hub. Thrust increases from 2,812 N to 3,300 N, or about 17%. The blade root bending moment increases from 2,838 N m to 4,231 N m, or nearly 50%. The thrust and root bending moment would have increased even further if the generator size had increased because the rated wind speed would have been higher than in the low specific power design. The implication for this increase in loads is that the components, namely the blades and tower, will need to be reinforced for added strength. This can be accomplished through various design choices, but generally result in added weight and cost. A more detailed study would be required to fully understand these tradeoffs, but for the purposes of this study, it is assumed that the added cost of the large-rotor turbine is not a significant factor in the choice of technology. Additional details on the impact of rotor size on a variety of turbine parameters can be found in Appendix A.

4.3. Incorporating Wind Turbine Models into the Simulation Tools

The two wind turbine models are incorporated into the SoSAT and HOMER tools using slightly different methods. The power curves and wind speed time-series used to develop a wind turbine power output time-series were confirmed to be the same in both tools. SoSAT does not have the ability to incorporate renewable resources like wind and solar directly in the simulation. Therefore, in SoSAT, a wind turbine was represented as a renewable generator with a power output that is an hourly variable utilization percentage of the rated power. This hourly variable utilization percentage is a function of the turbine's rated power and the wind resource. External to the SoSAT model, a wind resource time series was applied to a wind turbine power curve (Figure 6) to produce a power output that can then be represented in the SoSAT model as a utilization percent of rated power.

Additionally, the wind turbine was set up as a primary energy source and with a diesel generator as back-up, such that the generator will meet the remaining demand that the turbine cannot. In the HOMER tool, there exists the ability to define a wind turbine generator by a few different parameters but namely the power curve is entered in a tabular form. In this study, the power curve was discretized in increments of 0.05 m/s. The wind resource data in HOMER were synthesized in the tool itself as described in Section 3.2. HOMER then computes the power output as part of a turbine based on the power curve and wind speed time series.

4.4. Contingency Base Footprints

Renewable energy systems generally require more space than a diesel generator system to produce the same power due to the much lower energy density of the solar and wind resource as compared to diesel fuel. This could be a potential constraint on the total potential capacity of wind systems at a given base location due to the required footprint. Wind turbines cannot be closer together than a single rotor diameter otherwise they would physically impact each other. Even at distances of seven rotor diameters apart they can impact each other through wakes produced by the rotors. Table 6, extracted from the Army Techniques Publication on Base Camps, provides some general planning factors for the physical footprint of various sized bases [9]. The company-sized base camp roughly corresponds to the extra small (XS) bases that were modeled in HOMER and SoSAT (Table 1).

Table 6. Physical Dimensions of Different Sized U.S. Army Contingency Bases

Base Camp Size	Approximate Population	Dimension (m)	Surface area (not including standoff) m2	Length of Perimeter (nominal) m
Platoon	50	150 x 250	37,500	800
Company	300	300 x 450	135,000	1,500
Battalion	1,000	500 x 1,200	600,000	3,400
Brigade	3,000	TBD by planners	TBD by planners	TBD by planners
Support area	6,000+	TBD by planners	TBD by planners	TBD by planners

The footprint required per turbine based on the separation distance is provided in Table 7. As mentioned, a one-rotor diameter (1x) is a physical minimum dictated by the blades not striking each other on neighboring turbines, and the 10x separation is likely conservative, so those are reasonable bounding limits. For the simulation cases in SoSAT, either 20 or 40 turbines were modeled for each of the XS bases and in HOMER, up to 60 turbines were modeled.

Table 7. Footprint Required per Turbine for Different Separation Distances

Rotor diameter separation	Commercial Turbine area required per turbine (m2)	Large-rotor Turbine area required per turbine (m2)
1x	72	117
3x	652	1,052
5x	1,810	2,923
10x	7,240	11,690

Table 8 shows the minimum (1 rotor diameter offset) area required for each quantity of turbines. When comparing that to the overall Company base surface area of 135,000 m^2, the largest percent area occupied by the 60 large-rotor turbines is just above 5%. This is just the minimum distance, and a more realistic offset would be 3 rotor diameters as a fairly dense yet viable placement. Table 9 shows the footprint required for this larger 3x offset for the two turbine designs and the different quantities of turbines. Given the same 135,000 m^2 base footprint as a reference the space required now ranges from almost 10% up to nearly 47%. While 10% may be feasible, it's much less likely that 47% of a base area would be occupied by turbines. Of course, there could be special designs where the base perimeter is extended to make room for the additional turbines, but this comes at a cost of protection and may make that choice less appealing from a cost-benefit perspective.

Table 8. Footprint Required for Different Quantities of Turbines at Minimum (1X) Offset Distance

Number of turbines	Commercial Turbine minimum area required (m2)	Large-rotor Turbine minimum area required (m2)
20	1,440	2,340
40	2,880	4,680
60	4,320	7,020

Table 9. Footprint Required for Different Quantities of Turbines at 3X Rotor Offset Distance

Number of turbines	Commercial Turbine minimum area required (m2)	Large-rotor Turbine minimum area required (m2)
20	13,040	21,040
40	26,080	42,080
60	39,120	63,120

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5. SOSAT WIND POWER SCENARIO SIMULATIONS AND RESULTS

With the wind resource profiles and wind turbine models properly defined and adapted to work in the SoSAT tool, the next step in the analysis was to explore the impact of different wind energy systems on the baseline SoSAT JOEI model in terms of energy and transportation metrics. The details of the selected scenarios and results of the simulations are presented in this section.

5.1. Model and Variable Overview

The SoSAT JOEI model was modified to run a series of scenarios measuring the impacts of wind systems on the 30-day contingency base mission. Wind turbines were added to XS bases under various conditions. The variables explored in detail were turbine design, wind resource, turbine count, and the inclusion/exclusion of battery systems. The results of the analyses focused on fuel savings and the resulting reduction in transportation required for base resupply. Both of these result metrics are relevant to measuring the benefits of wind turbines, and SoSAT captures and stores this information.

During the modeling process, several key decisions were made which led to the final set of models. Turbines were only added to the XS bases because the total quantity of turbines was reasonable (20-40 rather than 1,000) and could provide significant benefits to the XS base microgrids. Wind power was only used to support the base microgrids with the larger but less critical electrical needs, while both base medical and command loads continued to be supplied by diesel generators only. Initial models were built where turbines would turn off when demand was sufficiently met to avoid producing excess energy; however, without modeling failure rates for turbine systems and with the goal of understanding the benefits of batteries, these models were not pursued further. Additionally, the SoSAT software has a battery system model which could not represent the desired use case. Therefore, all battery models had recharge, storage, and discharge time series data for battery systems calculated external to SoSAT, then incorporated to achieve the desired functionality.

5.1.1. *Turbine Design Specific Power*

Two different turbine designs with unique rotor specific power were explored including a commercial 15kW turbine and a large-rotor 15kW turbine design. See section 4.2 for more details on why these turbine designs were selected and how their power profiles were produced.

5.1.2. *Wind Resource*

Two wind resources were also explored as part of the modeling process: a low wind resource and a good-wind resource. See section 3.2 for more details on how these time series were determined and generated. Wind resource modeling reflected the impact of base location on the benefits of incorporating wind turbines as an energy source.

5.1.3. *Turbine Count*

Initial model exploration determined that with the low wind speed resource, roughly 40 turbines would result in average power production being equivalent to average power demand. Subsequently, as a decision variable, both 20 and 40 turbine counts were modeled to better explore the space with the aim of determining the potential diminishing benefits of additional turbines, as well as the interaction between turbine count and other model decision variables. Additionally, 20 turbines seemed to be a more feasible count from a base footprint and transportation standpoint. This variable was explored in more detail using the HOMER tool as described in Section 6.

5.1.4. *Battery Systems*

While exploring the initial wind turbine models, it was observed that there was significant energy lost in excess renewable production caused by the variability and temporal mismatch of the wind resource and the load. This is a challenge for many renewable resources as supply is based on something external to demand (i.e. wind). Battery systems can be used to capture this excess production of energy and release it back into the base when renewable production cannot meet demand. For modeling purposes, it was assumed that batteries could capture all excess energy produced by the wind turbines and output any required energy into the microgrid with 100% efficiency. It was also assumed that the battery systems would fit within the same shipping container as the wind turbine, and thus not incur any additional transportation cost. While these assumptions were generally reasonable, there were a few scenarios as noted that resulted in some batteries which were quite large and would likely require additional transportation capacity. More realistic and optimum battery parameters were explored in more detail using the HOMER tool in Section 6.

Table 10. Summary SoSAT Simulation Scenarios for Each Turbine Design

Wind Resource	Turbine Count	Battery Inclusion
Good	20	No
		Yes
	40	No
		Yes*
Low	20	No
		Yes
	40	No
		Yes

*Batteries for this scenario are likely not feasible to transport with turbines in the same ISO containers, and require additional transportation.

The total number of SoSAT wind turbine scenarios run to determine the potential benefits of wind power and importance of decision variables was 16 (8 for each turbine model). Table 10 summarizes the scenarios that were run for each turbine design: two wind resources, turbine count, with or without a battery. This large set of scenarios was used to both determine the potential benefits of wind power by comparing many model results to the baseline scenario, as well as understanding the relative importance of and interaction between decision variables relating to wind power.

5.2. Transportation Reduction Results

Monthly vehicle reduction is a metric that represents the reduction in transportation vehicles and trailers required to transport fuel from small to XS bases within the JOEI SoSAT model. Table 11 summarizes the impact on this transportation metric from the variables of all 16 scenarios. The large-rotor turbine design offers improved power generation versus the commercial design especially at lower wind speeds, resulting in significantly fewer monthly transportation vehicle resupply trips. This difference in vehicle reductions between turbine designs becomes most evident as the turbine count increases and battery systems are added.

Table 11. Mission Transportation Reduction Results Summary

Wind Resource	Base Turbine Count	Battery Inclusion	Commercial Turbine Monthly Vehicle Reduction		Large-rotor Turbine Monthly Vehicle Reduction	
			Count	%	Count	%
Good	20	No	14	8.3	17	10.1
		Yes	16	9.5	19	11.2
	40	No	20	11.8	27	16
		Yes*	36	21.3	44	26
Low	20	No	8	4.7	12	7.1
		Yes	10	5.9	14	8.3
	40	No	12	7.1	14	8.3
		Yes	14	8.3	25	14.8

*Batteries at this scale are likely not feasible to transport with turbines in ISO containers, and require additional transportation.

In addition to the reduction of vehicles required to transport fuel from the small to the XS bases, there is also a cascading network effect which results in reduced vehicles transporting fuel from the medium to the small bases. The reduction in fuel demands in one part of the supply chain (XS bases) results in reduced transportation burden throughout the whole supply chain that is connected to that node. Also, because the extra small bases generally represent the most forward locations, the reduction of a gallon of fuel at these locations is generally more impactful logistically than a reduction of a gallon of fuel further up the logistics tail.

The "Months for Transportation Offset" metric shown in Figure 7 are the months of operation for the wind turbine to have a lower overall transportation burden than the baseline model. This is calculated by dividing the total turbine count (at all bases) by the monthly vehicle savings. This metric represents the transportation breakeven point, beyond which transporting turbines at a rate of one per standard military ISO container requires less transportation than transporting fuel to operate the diesel generators powering the base microgrids. Refer to Section 4.1 on transportation logistics for more information on transportation assumptions for fuel and turbines. A lower value indicates an earlier breakeven point and better performance and feasibility of wind turbines models from strictly a transportation logistics standpoint.

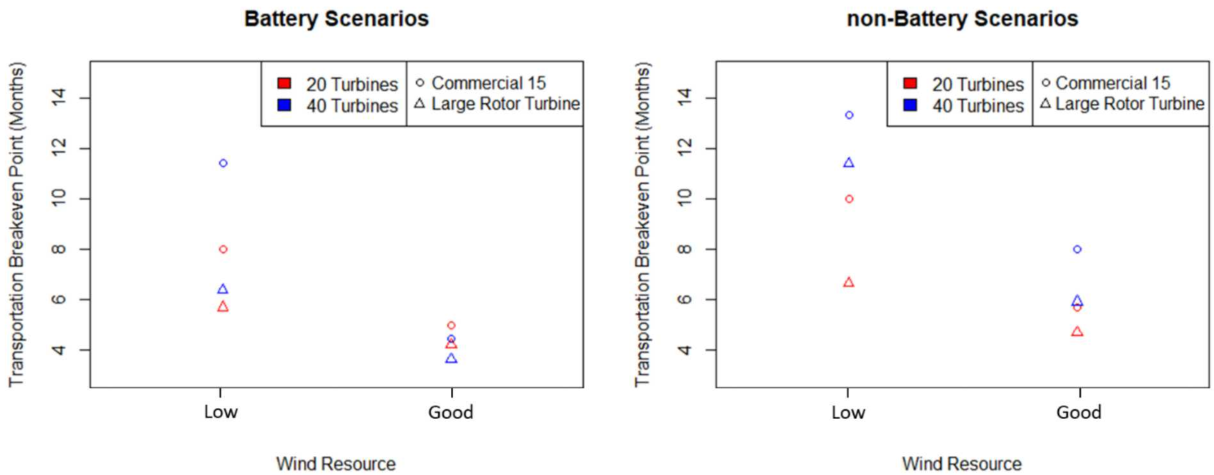

Figure 7. Mission Months for Transportation Offset Summary Results

From a transportation equivalence standpoint, some scenarios seem to be infeasible because of longer time required for transportation offset, particularly models with a low wind resource (4.32 m/s avg.) and 40 commercial turbines at each of the four XS bases. When less wind is available it seems reasonable to reduce the number of turbines supplied at a base because it is challenging to produce enough energy to offset the burden of transporting the turbines. The two strategies which seem optimal with regards to transportation burden are either deploying a small turbine count without batteries if there is a low wind resource or a large turbine count with batteries if there is a high-wind resource. A more detailed study was conducted to identify optimal system configurations using HOMER as presented in Section 6.4 .

5.3. Fuel Savings Results

The inclusion of wind turbines at bases results in a significant reduction in use of diesel generators. Table 12 displays the overall operating hours for the 38 diesel generators supplying the four base microgrids during the 30-day mission. Additionally, the percentage reduction in operating hours compared to the baseline model is displayed.

Table 12. Mission Generator Demand Reduction Results Compared to Zero Wind Turbine Baseline Scenario

Wind Resource	Base Turbine Count	Battery Inclusion	Commercial Turbine		Large-rotor Turbine	
			Generator Operating Hours	Percent Reduction Compared to Baseline (%)	Generator Operating Hours	Percent Reduction Compared to Baseline (%)
Good	20	No	15,642	41	13,486	49
		Yes	15,047	44	12,567	53
	40	No	12,424	53	10,401	61
		Yes*	7,079	73	4,404	83

Wind Resource	Base Turbine Count	Battery Inclusion	Commercial Turbine		Large-rotor Turbine	
Low	20	No	20,769	22	18,264	31
		Yes	20,651	22	18,021	32
	40	No	17,425	35	15,133	43
		Yes	16,048	40	12,189	54

*Batteries at this scale are likely not feasible to transport with turbines in ISO containers, and require additional transportation.

This is the most direct and measurable benefit of including wind turbines at bases, a reduction in the operational demand on diesel generators to meet the power demand at base microgrids. The SoSAT turbine scenarios result in 22% up to 83% reductions in generator usage compared to baseline. The large-rotor turbine offers approximately an additional 10% reduction in generator demand compared to the commercial turbine during the 30-day mission across all scenarios. This reduction in diesel generator demand caused by the inclusion of wind turbines results in significant fuel savings at XS bases.

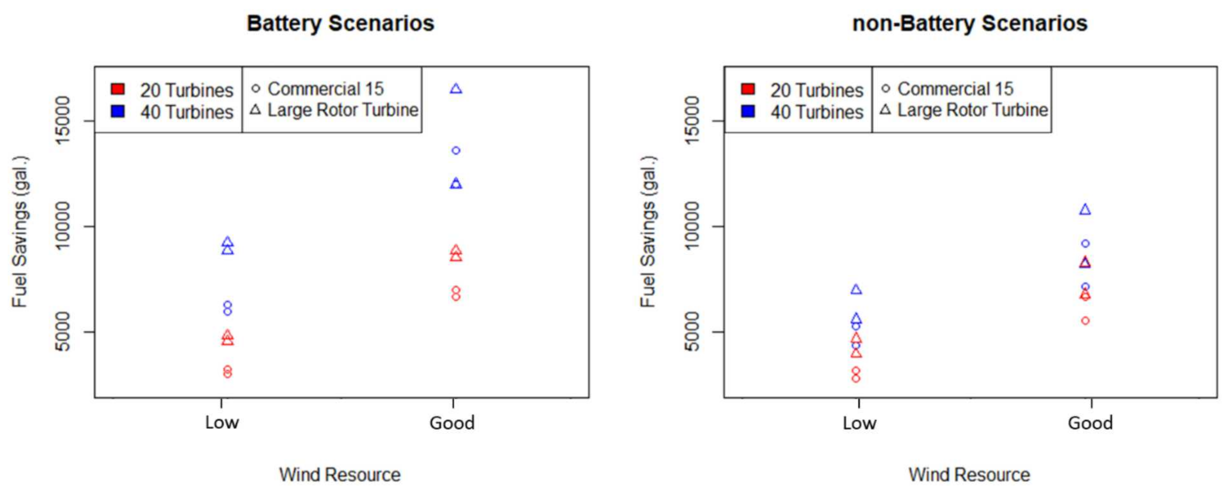

Figure 8. XS Base Monthly Fuel Savings Results

The low wind speed turbine results in significantly higher fuel savings across all scenarios compared to the commercial turbine. In Figure 8, the triangles representing large-rotor turbine model scenarios are higher along the vertical fuel savings axis than the commercial 15 kW turbines. The differences in fuel savings between turbine designs appear to be most pronounced in the battery scenarios as the batteries can capture the excess energy produced by the large-rotor turbines during high wind speed and low load demand periods. The primary result here is that with a good wind resource, a large-rotor turbine can produce more energy than the commercial turbine. However, this only results in significant benefits to bases if excess renewable energy can be captured and stored in some manner. Without the inclusion of battery systems within the microgrid there is little additional benefit to designing a large-rotor turbine compared to a commercial 15 kW turbine.

5.4. Battery Systems Feasibility and Results

Some of the wind turbine models produce significantly more energy than is required at the microgrid at times of high wind speed. The inclusion of a battery system at the bases can capture this excess energy and increase the benefits of wind turbines to base microgrids. In the SoSAT scenarios, battery systems are assumed to be ideal. That is, they capture all excess energy produced by the wind turbine and return 100% of that energy when needed. Real batteries have a less than 100% roundtrip efficiency and a minimum state of charge as well as charge and discharge rate limits. Regardless, this simplified analysis enables the metrics associated with battery performance (max charge rate, max capacity and max discharge rate) to be determined and explored in more detail to verify that there are systems available that can meet these requirements.

Table 13. Mission Battery System Summary Results

Wind Resource	Base Turbine Count	Extra Small Base	Commercial Turbine		Large-rotor Turbine	
			Max Battery Capacity (kW*h)	Max Battery Capacity Per Turbine (kW*h)	Max Battery Capacity (kW*h)	Max Battery Capacity Per Turbine (kW*h)
Good	20	XS1	1,746	87	2,497	125
		XS2	646	32	646	32
	40	XS1	19,493*	487*	65,665*	1,642*
		XS2	10,259*	256*	17,935*	448*
Low	20	XS1	555	28	916	46
		XS2	212	11	398	20
	40	XS1	2,836	71	4,332	108
		XS2	2,152	54	2,981	75

*Batteries at this scale are likely not feasible to transport with turbines in ISO containers, and requires additional transportation.

Summarized above in Table 13 are the maximum capacity metrics for the battery systems in all the SoSAT models. These values are the maximum capacity of energy that the batteries would need to store in order to capture all the excess energy produced under the assumption of perfect efficiency. Only two of the four bases are listed here, because the operational scenario for the XS2 is the same as XS3 and XS4 bases, therefore the battery results for the XS2 is representative of all three.

Table 14. Mission Battery Inclusion Fuel Savings Results

Wind Resource	Base Turbine Count	Battery Inclusion	Commercial Turbine Monthly fuel savings (gal.)	Commercial Turbine Monthly Transportation Reduction	Large-rotor Turbine Monthly fuel savings (gal.)	Large-rotor Turbine Monthly Transportation Reduction
Low	20	No	12,421	8	18,229	12
		Yes	12,877	10	19,211	14

The inclusion of battery systems for the model scenarios based on a low wind resource and 20 turbines at each of the XS bases results in additional benefits. The additional fuel savings are the result of the battery systems capturing excess energy produced from the turbines to be later released back into the microgrid, therefore further reducing the operational demand for diesel generators. For the commercial turbine model an additional 4% or 456 gallons of fuel are saved every month when battery systems are included with wind turbine systems. For the large-rotor turbine these savings are even greater, with the inclusion of battery systems, resulting in an additional 5% or 982 gallons of fuel savings every month.

For both turbine models there is an additional two transportation vehicle reduction during the mission as compared to the same scenarios without batteries. This reduction in vehicles is per month and these benefits would grow as base operational durations grow. The large-rotor turbine benefits more from the inclusion of battery systems because it produces more excess energy during the 30-day mission.

Additional battery analysis incorporating more realistic parameters and optimization on a single extra small base was completed using the HOMER tool as described in Section 6.4.

5.5. Summary of SoSAT Results

The supplemental use of wind turbines at XS base microgrids results in significant fuel savings and subsequent transportation reduction. Sixteen unique wind turbine models were run using SoSAT and all produced favorable results in terms of reducing fuel requirements compared to the baseline, no wind turbine scenario. Depending on scenario, anywhere between 5,000 and 15,000 gallons of fuel can be saved per month at each XS base (Figure 8), with the greater savings associated with better wind resources and more turbines. These fuel savings result in a significant reduction in transportation burden within the SoSAT JOEI model Infantry BCT supply chain. The wind turbine scenarios reduce vehicles required to transport fuel along the supply chain from small to XS bases by between 8 and 44 transportation vehicles and trailers per month (Figure 11). Again, the savings increases with better wind resources and more turbines. The turbines themselves do need to be initially transported to bases. However, over time there is a breakeven point where less transportation is required for turbines than is required for fuel to support base microgrid energy demands (Figure 7). This reduction in monthly vehicles transporting fuel not only lessens the logistical burden of resupplying a base, but also significantly reduces the number of vehicles, and therefore soldiers, traveling through potentially hostile regions to resupply military contingency bases.

The large number of wind turbine models run in SoSAT also enables the comparison of key decision variables associated with wind turbine deployment. These decision variables included wind resource, turbine count, turbine design, and the inclusion of battery systems. The main effects of these variables were fairly straightforward, i.e., a better wind resource resulted in more power provided by turbines and more fuel offset. The most interesting results based on an examination of these decision variables were the interaction between them, and what appeared to be the optimal decisions given a wind resource. Increasing turbine count or improving turbine design results in additional fuel savings if a battery system is also added to capture excess renewable energy (Figure 8). Based on these interactions and overall model results, the two optimal solutions appear to be dependent on the available wind resource. If the wind resource is low, then strategies which use a smaller turbine count appear to be most beneficial, with battery inclusion and turbine design being less important factors (Figure 7). If the wind resource is good, then a strategy which takes full advantage of this appears optimal, utilizing a high turbine count and battery systems to capture all the excess renewable energy produced by the turbines (Figure 7). These two strategies indicate that prior knowledge of base location and wind resource determine the potential benefits of wind power and can support mission planning regarding how wind turbines are most effectively deployed at military contingency bases.

5.6. Future SoSAT Analysis

The currently modeled battery systems are designed to be perfect, capable of capturing all excess energy produced by the wind turbines and releasing it back into the system with 100% efficiency. This was intentional in order to both measure the potential benefits of battery systems to the models and determine what scale of battery would be required. Realistic systems to meet these requirements could be determined either via subject matter expert elicitation or using more detailed microgrid modeling tools like HOMER. SoSAT models could be updated based on these realistic battery systems to more accurately measure the benefits of including batteries at bases to capture the excess energy produced by the wind turbines.

The current set of SoSAT models only include wind turbine systems at the XS contingency bases. These bases were selected for modeling wind power since a reasonable number of turbines could offset a significant portion of the base's energy requirements. Turbines could be added on a similar scale to the small and medium bases, resulting in roughly equivalent absolute benefits with much lower relative benefits to the bases. For example, adding 20 wind turbines to a small base microgrid would result in roughly the same absolute benefits as adding 20 wind turbines to the extra small base, but would result in a much smaller portion of energy offset for that base. Additionally, these larger bases have the benefit of operating for longer durations and therefore would be good candidates for wind power.

One of the benefits of having an energy harvesting capability at a base is that it increases the bases resilience to interrupted supply and reduces the frequency of required resupply. Both could be modeled in SoSAT to determine the additional resiliency of bases with wind turbines versus bases without wind turbines, but this would require significant modification and evaluation of the baseline SoSAT JOEI scenario. These models would provide additional military scenario simulation results that support the benefits of having renewable generation at military contingency bases.

6. HOMER SIMULATION CASES AND RESULTS

HOMER Pro v3.13 (HOMER) is a simulation tool for the design and optimization of microgrid power systems for a broad range of applications including military bases. The HOMER software was used to compliment the prior SoSAT analysis by examining in more detail a single XS base with a wider range of design variables to help answer some of the remaining questions resulting from the SoSAT analysis. This section provides an overview of the model definition and assumptions in HOMER and discussion of the results with comparisons to SoSAT where relevant.

6.1. HOMER Model Component Definition

The HOMER simulation tool has the capability to represent a wide range of generation types, energy resources, loads, microgrid controllers and optimization parameters for a single microgrid power system. For this analysis, the microgrid was defined by a custom hourly load profile, two custom wind turbine models, a generic diesel generator, a generic Lithium-ion (Li-ion) battery, a generic power converter to go between AC and DC, and a microgrid controller. One of the primary limitations of the HOMER tool is the requirement to simulate at least one full year, whereas SoSAT can do arbitrary time durations and in the case of this analysis, a 30-day simulation. This discrepancy is addressed as described in the load profile and wind resource sections below.

6.1.1. Load Profile

The baseline SoSAT model described in Section 5 has detailed load profiles for many sizes and types of bases constructed from specific mission profiles and equipment located at each contingency base. For the HOMER analysis, only the load profile for one of the XS bases (XS2) in the Infantry BCT is modeled. This particular load profile (Figure 2) has a repeating 24-hour pattern for the duration of the simulation with a maximum electrical load of 409 kW and a minimum load of 230 kW. As mentioned, the baseline SoSAT simulation is only 30 days in duration, but HOMER requires a full year of load data. This was handled by simply repeating the same 24-hour profile for a full 365 days. This profile is incorporated into HOMER as an hourly time series.

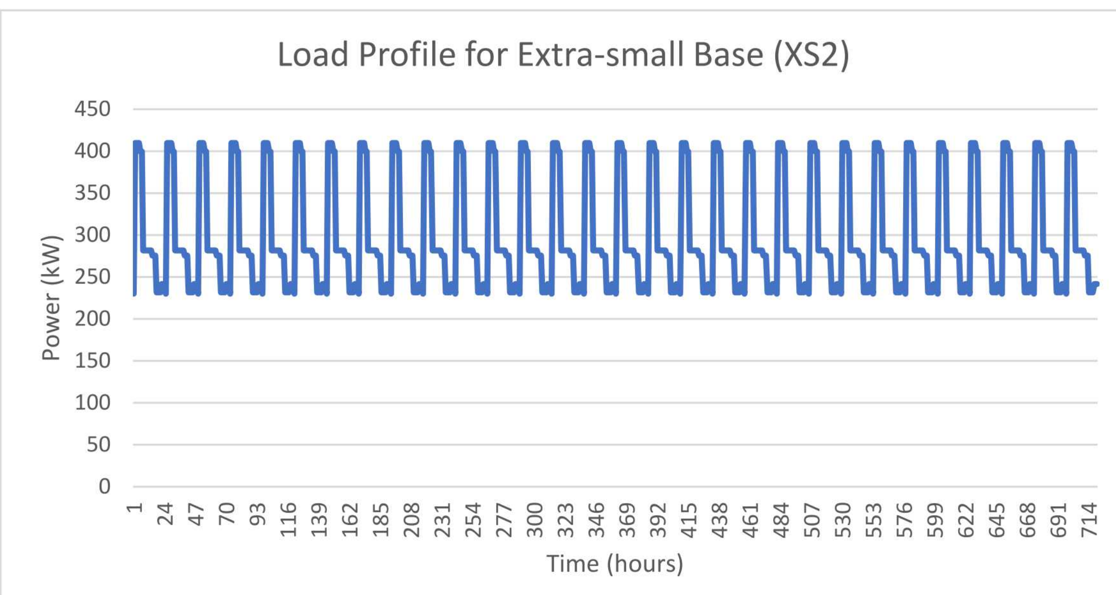

Figure 9. 30-Day Load Profile for the XS2 Base from the SoSAT Model

6.1.2. Wind Resource

HOMER includes the capability of synthesizing an hourly wind speed time series from input statistics as described in section 3.2. An entire year of hourly wind speed is generated in the tool but only a specific 30-day range was exported for use in SoSAT to fit the simulation duration. Two bounding wind resource profiles were simulated in HOMER, a "low wind" resource that averaged 4.32 m/s and a "good wind" resource that averaged 6.22 m/s. These were the two profiles that were also used in SoSAT as described previously. Additionally, three additional wind resource profiles (4.8, 5.27, 5.75 m/s average) between those two bounding cases were explored in HOMER as part of an additional parameter sensitivity study.

6.1.3. Wind Turbines

Models of two custom turbines were defined by their respective power curves as described in Section 4.2. The commercial turbine is intended to approximate a 15-kW turbine that is currently available for purchase whereas the large-rotor turbine represents a hypothetical turbine that incorporates a larger blade design to capture more wind energy at lower wind speeds. The size of the blade was selected to be the longest single structure that could fit in a typical 20-foot ISO shipping container per the logistical constraints described in Section 4.1. This is not intended to represent an optimal blade length selection, rather just to demonstrate the impacts to the power system design by having the option of a longer blade. In general, the ~15 kW size class of turbine is a reasonably good fit for the XS base as defined in the model, but smaller or larger power rating turbines could also be considered.

6.1.4. Diesel Generator

The SoSAT model for the XS base includes eight spot generators rated at 30 kW or 60 kW to power the microgrid portion of the base (Table 2). HOMER is limited to a single diesel generator in the simulation, so instead of multiple spot generators that share load, a single generic medium genset (460 kW) diesel generator is represented with a minimum load ratio of 25%. The generator is the baseline model in the HOMER library and does not exactly match a specific model like an AMMPS generator commonly used by the military. However, initial comparisons of fuel consumption results from the SoSAT and HOMER baseline models compared well with a deviation of less than 1%. Diesel generators were included in all scenarios for both SoSAT and HOMER because the assumption was that the wind turbines are primarily offsetting diesel fuel use rather than entirely replacing diesel generators.

6.1.5. Battery Storage

For the HOMER simulations, a generic 1 kWh capacity Li-ion battery model was used from the HOMER component library with the default specifications as listed in Table 15. Battery storage capacity was explored as part of the optimization routine in HOMER, so using a small unit of storage as a cell that could be stacked into a larger battery of arbitrary capacity provided the most design range. Li-ion was selected because it is commercially developed and has numerous performance advantages over other common technologies like lead-acid batteries.

Table 15. Battery Parameters Used in the HOMER Simulation

Li-ion Battery Parameter	Value
Nominal Voltage (V)	6
Nominal Capacity (kWh)	1
Nominal Capacity (Ah)	167
Roundtrip efficiency (%)	90
Maximum Charge Current (A)	167
Maximum Discharge Current (A)	500
Minimum State of Charge (%)	20

6.1.6. Power Converter

HOMER requires a power converter model to be represented in the model when there is a mix of AC and DC devices. Because the power converter specifications depend on the battery storage and because it was not considered a critical component to optimize as part of this particular analysis, HOMER enables an option for an "unlimited free power converter". This device will automatically convert any amount of power back and forth from AC to DC and cost nothing.

6.1.7. Microgrid Controller

HOMER includes multiple microgrid controller options depending on the particular system objectives. The Cycle Charging controller strategy charges the battery using diesel, thus adding more energy to the battery and making it more likely that the generator can be turned off in periods of low load. In the Load Following strategy, the generator does not charge the battery and therefore ensures that the generator can continue to be used during future periods of high load. Each of these strategies work well when the future load and generation are well characterized; however, that is rarely the case especially when renewable generators are included. Therefore, the Combined Dispatch strategy was selected as it uses the current net load to determine whether to charge the battery using the generator or not. It uses the Cycle Charging dispatch strategy when the net load is low, and the Load Following dispatch strategy when the net load is high. By Cycle Charging during periods of low net load, the Combined Dispatch helps avoid using the generator at low loads. By Load Following during periods of high net load, the Combined Dispatch allows the continued use of the generator. More information on the microgrid controller strategies can be found in the HOMER user manual. [5]

6.2. HOMER Transportation Analysis Metrics

HOMER is programmed to optimize systems using a single metric termed "net present cost." Net present cost is calculated by summing the present value of all the costs of installing and operating each component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. These include capital costs, operating costs, replacement costs, fuel costs, and salvage value. HOMER attempts to minimize the net present cost of the system while also meeting the load, which in this analysis must be met 100% of the time.

This type of analysis requires detailed knowledge of the component costs to arrive at a system that is properly optimized for minimum cost. This would make sense for designing a specific project, especially one where cost is a primary driver, but does not work well for the objectives of this current analysis. Instead of optimizing for cost, this analysis aims to optimize for minimum transportation cost for a deployed system, building off the transportation cost analysis presented in the SoSAT results. Diesel generation at remote bases is a logistical burden because of the risks of transporting the fuel required to provide that power through hostile territory. By calculating and optimizing for a power system that results in the lowest overall number of transportation trips over the life of the base, components can be compared in a different and potentially more relevant way to mission objectives.

6.2.1. Component Transportation Assumptions

Before the component models can be properly represented in the HOMER simulation to analyze transportation costs, the underlying physical transportation assumptions must be made. Transportation assumptions were made for the diesel generator, diesel fuel, wind turbines, and batteries. The basic unit of transportation, a "truck trip," is based on the capacity of the appropriate HEMMT transport system. As described in section 4.1, the M1120 LHS with trailer can transport two 2,500-gallon modular fuel systems for a total of 5,000 gallons of diesel fuel per truck trip. Likewise, the PLS M1075A1 truck and PLS M1076 trailer can each hold a single 20-foot ISO shipping container. Using those two reference points, the transportation metrics are described in Table 16.

Table 16. Transportation Equivalents for Power System Components

Component	HEMMT with trailer "truck trips"
460 kW diesel genset (or ~8 60 kW gensets)	0.5
5000 gallons of diesel fuel	1
15-kW wind turbine (commercial or large-rotor)	0.5
1000 1-kWh battery (or single 1000-kWh battery)	0.5

These estimates are based on available information and professional judgment. The modular fuel system specification is 2,500 gallons for instance, and multiple companies provide 20-ft. containerized Li-ion battery systems with a 1,000-kWh capacity, but the shipping space for a single 460 kW generator or multiple 60 kW generators is based on equivalent volume, as with the turbine. A sensitivity study was performed on the turbine specifically since it is the focus of this research area and a target for potential design improvements. The sensitivity analysis considered transport of 2, 3, and 4 turbines per truck trip.

6.2.2. Representing Transportation Costs in HOMER

The transportation assumptions were then used to modify HOMER to optimize for lowest truck trips instead of lowest net present cost. To accomplish this, all costs were removed for each component, including capital cost, operations and maintenance costs, fuel costs, replacement costs, and salvage values. Then a specific value was entered for the fuel and the capital cost of each component based on the transportation requirements in Table 16. The capital cost values are straight-forward with the equivalent number of truck trips represented in dollars (i.e., 0.5 truck trips = $0.50 capital cost). The fuel cost is slightly more complicated because HOMER uses liters as the volume unit of fuel and the cost is entered on a per liter basis. The cost per liter was calculated as 1 truck trip divided by 5,000 gallons (18,927 liters) or 0.00005285 $/L.

Table 17. Capital Cost Values Used in HOMER to Represent Transportation Costs

Component	HOMER Capital Cost Representation
460 kW diesel genset (or ~8 60 kW gensets)	$0.50
Diesel fuel	0.00005285 $/L
15-kW wind turbine (commercial or large-rotor)	$0.50
1,000 1-kWh battery (or single 1,000-kWh battery)	$0.50

By incorporating only these values for capital cost and fuel cost and with all other costs set to zero including any finance rates, etc., the HOMER tool will optimize to minimize the number of truck trips using net present cost as a proxy.

6.3. HOMER Model Scenarios

After the system components are defined with technical and cost parameters, the final step before running the simulation is to define the optimization and sensitivity variables. The optimization variables summarized in Table 18 define the search space that HOMER explored in trying to optimize a system. The variables can be explicitly defined as the number of turbines, have a fixed value as the diesel generator and power converter, or define a range with an upper and lower bound as with the number of batteries. If explicit search space values are provided, HOMER will optimize every combination of those values. In this analysis, every system will have a fixed power converter and diesel generator, and then for each step of 5 additional turbines, the number of batteries will be optimized for lowest net present cost (i.e., "truck trips").

Table 18. HOMER Simulation Optimization Variables

Optimization Variables	Values
Number of turbines	0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60
Number of 1-kWh capacity batteries	Between 0 and 8900
Power converter capacity (kW)	9,999,999 ("unlimited")
Diesel generator capacity (kW)	460

The second set of variables that can be specified in HOMER are for sensitivity analysis. In Table 19, input variables for the project life, average wind speed, and wind turbine capital cost multiplier are listed. Project life and wind speed are straightforward input variables, but the wind turbine capital cost multiplier in this analysis reflects the transport burden. So, 1 is the baseline and a multiplier of 0.5 reflects that twice as many turbines can be shipped per container. HOMER will repeat the optimization process for each combination of input sensitivity variables. Selecting a wide optimization search space combined with many sensitivity variables can quickly lead to a large number of total simulations that HOMER will run and result in a very long simulation time. For that reason, some smaller preliminary sensitivity studies were completed to refine and select the final values listed here.

Table 19. HOMER Simulation Sensitivity Variables

Sensitivity Variable	Values
Project life (months)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Average wind speed (m/s)	4.32, 4.80, 5.27, 5.75, 6.22
Wind turbine capital cost multiplier (*number of turbines transported per truck*)	1, 0.75, 0.50 (*2, 3, 4*)

The optimization and sensitivity variables defined here were repeated in two separate scenarios, one with the commercial turbine and one with the large-rotor turbine technology. All other system details remained identical.

6.4. HOMER Simulation Results

The primary objectives of the HOMER analysis are to compliment and expand on some of the main results of the SoSAT analysis regarding the impact of the power system components and resource variables on the transportation burden. By incorporating a broader variable search space and incorporating the optimization capabilities of HOMER, additional conclusions can be made of the potential benefits and optimal use of deployable wind turbines at contingency bases.

6.4.1. Optimal System Configuration

The first set of results looks at the impact of the three sensitivity variables (wind speed, project life, and turbine transport cost) on the optimal system configuration. For a given set of sensitivity variables, HOMER identifies the system design that results in the lowest number of truck trips. The system includes a 460-kW diesel generator and power converter by default, but the number of turbines and batteries are optimized.

The following set of figures all have the same structure. The axes represent two of the sensitivity variables, average wind speed on the y-axis and project lifetime on the x-axis. The third sensitivity variable, turbine capital cost multiplier, is fixed for any given plot, so three figures are required to fully explore the sensitivity variables. The area of each plot shows a series of diamonds that represent explicitly optimized system designs, with the number next to the diamond indicating the total number of required truck trips for the life of that specific system. The black colored area represents configurations that only have a diesel generator and no wind turbines or batteries, while the blue colored area represents optimal system configurations that include some number of turbines and batteries in addition to the diesel generator.

The three plots in Figure 10 show the results for the scenario that incorporates the commercial wind turbine design. As evidenced by the blue area indicating systems that include the commercial wind turbine, the higher the average wind speed and the longer a project is deployed, the more likely wind turbines are included in the transportation optimized system. Also as expected, if more turbines can be packed into a single shipping container, the more likely wind turbines are part of an optimal system at shorter project lifetimes and lower wind speeds. The numbers under each diamond show the total number of truck-trips required to deploy that particular system. It is helpful to reference the 4.32 m/s wind speed cases in the top plot of Figure 10 as the diesel generator baseline where no wind is deployed. The truck trips increase from 3.7 at 1 month to 41.2 at 12 months strictly as a result of having to transport more fuel to sustain the longer deployment. This number will remain consistent going vertically up the plot with higher wind speeds if there is no wind deployed. However, if wind turbines are incorporated, as in the 12-month lifetime, the number of required truck-trips will decline with increasing wind speed as wind turbines are deployed and reduce the required amount of diesel by producing electricity.

The series of plots in Figure 11 show the same results but now replacing the commercial wind turbine with the large-rotor turbine. Trends are similar to the commercial wind turbine results with the primary difference being that the large-rotor turbine produces more energy per turbine as compared to the commercial turbine and is therefore more frequently incorporated into shorter lifetime and lower wind speed scenarios. A simple way to understand these results is to consider that a wind turbine requires the same transportation as 2,500 gallons of diesel in the baseline case of 1 turbine per 20-foot ISO container. Therefore, the turbine has to produce at least as much energy as 2,500 gallons of diesel in a generator to offset the transportation costs. Turbines produce more energy the longer they are deployed, the higher the average wind speed, and the larger the rotor is.

In both figures below, the black areas represent systems with only diesel generation, while blue areas incorporate wind and batteries in addition to the diesel generator. From top to bottom the turbine capital cost multiplier is 1, 0.75, and 0.5.

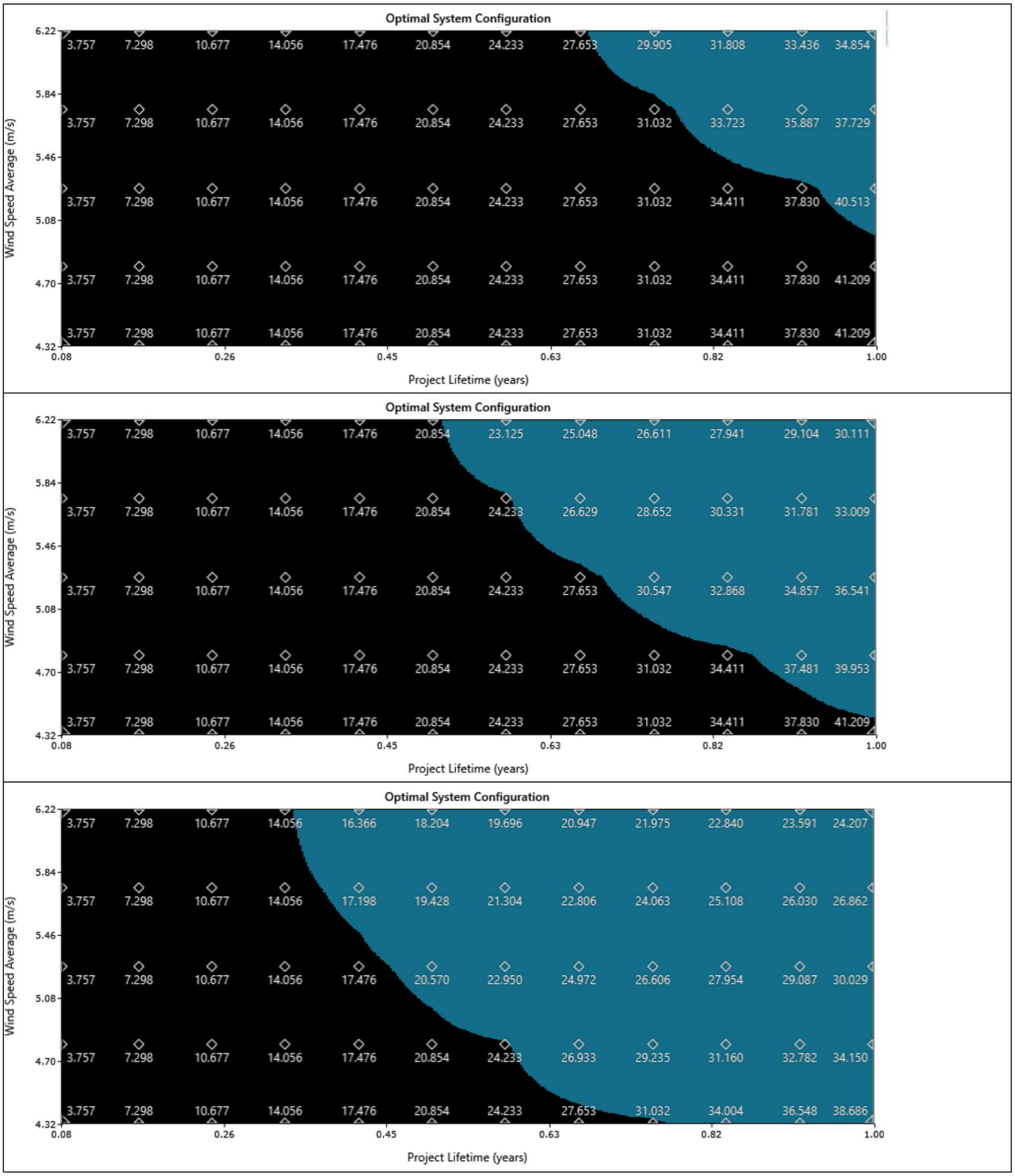

Figure 10. Optimal Power System Configuration for the Commercial Wind Turbine Design for the Cases for 2 (top), 3 (middle) or 4 (bottom) Turbines Shipped per Truck-trip. Black Areas Represent Diesel Generator Systems While Blue Represent Diesel Generator, Wind and Battery Systems. Diamonds Represent the Required Number of Truck-Trips to Deploy that System.

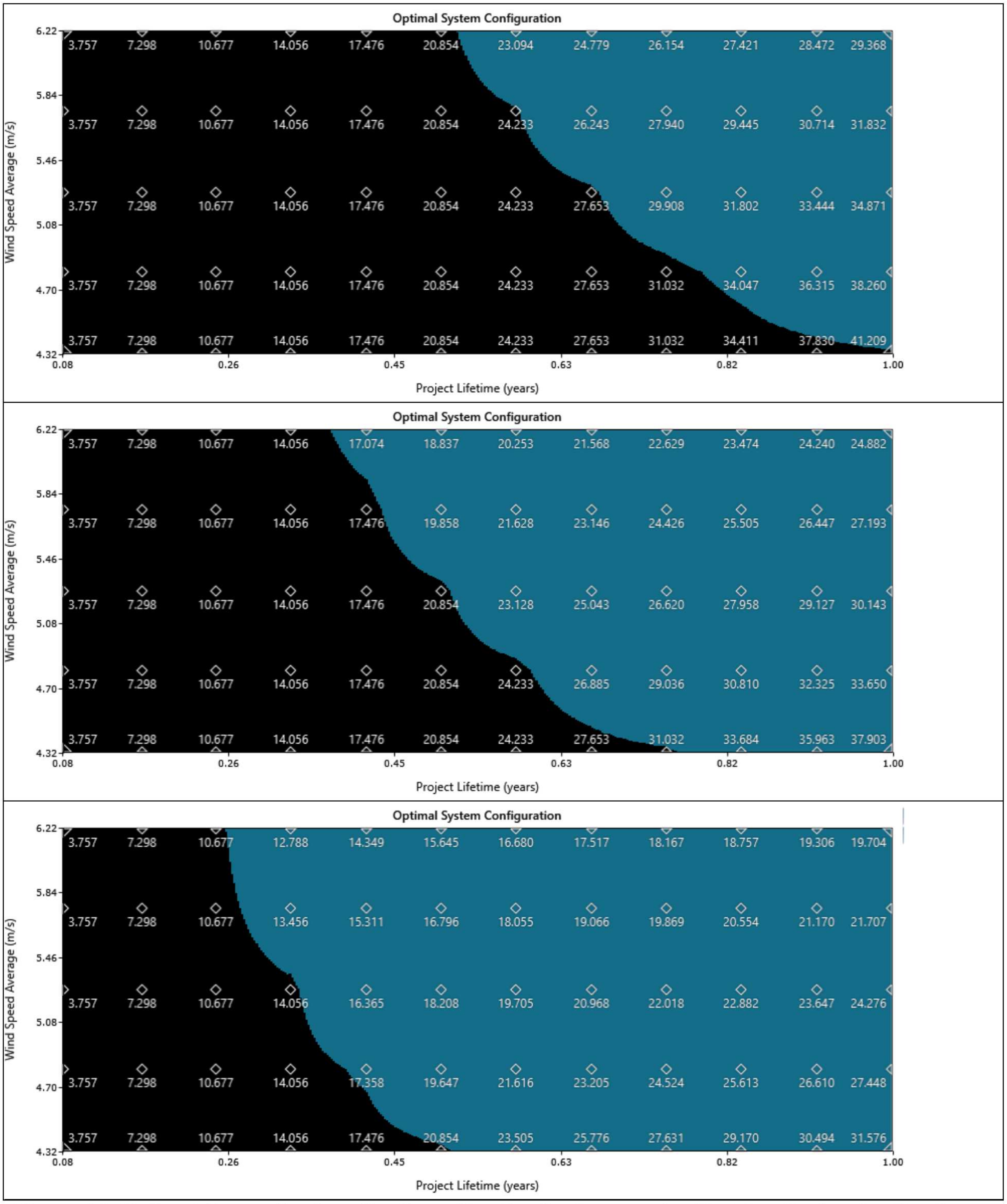

Figure 11. Optimal Power System Configuration for the Large-rotor Turbine Design for the Cases for 2 (top), 3 (middle) or 4 (bottom) Turbines Shipped per Truck-trip. Black Areas Represent Diesel Generator Systems While Blue Represent Diesel Generator, Wind and Battery Systems. Diamonds Represent the Required Number of Truck-Trips to Deploy that System.

6.4.2. Design Details for Large-rotor Turbine Optimal Systems

This section looks at more details of the optimal system configurations for the large-rotor turbine design under the baseline transportation cost case (1 turbine per 20-ft. ISO container) as previously shown at the top of Figure 11. The plots all have the same axes of average wind speed vs. project lifetime that were used in the prior plots but display different details on the particular optimal systems as described next.

Figure 12 shows the fuel consumption rate (liters per year) using a color gradient and the quantity of deployed turbines is overlaid on top next to the diamonds. The red color represents the diesel-only baseline case which consumes 770,272 liters/year (203,484 gallons/year). In the highest wind (6.22 m/s) and longest deployment (12 months) scenario, the addition of 35 wind turbines reduces the fuel consumption to 169,493 liters/year (44,775 gallons/year), a reduction of 78%. But even for lower, more likely wind speeds of 4.7 m/s, the deployment of 30 turbines still reduces fuel by nearly 50% demonstrating the potential for wind turbines to reduce the fuel dependence even in sites with lower wind resources.

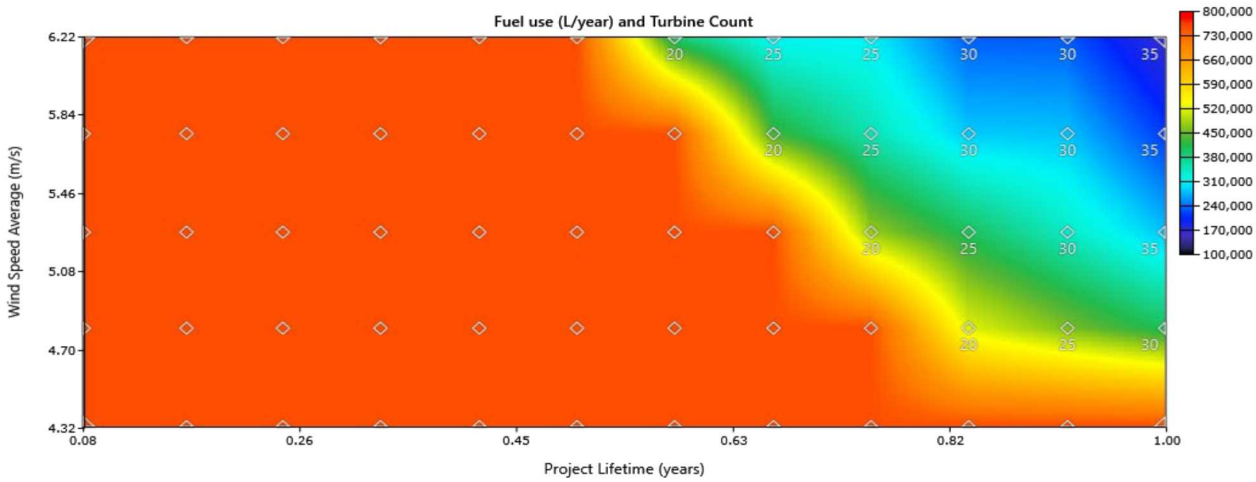

Figure 12. Fuel Consumption (gradient) and Turbine Quantity (Diamonds) Details for the Large-rotor Turbine Optimal Systems.

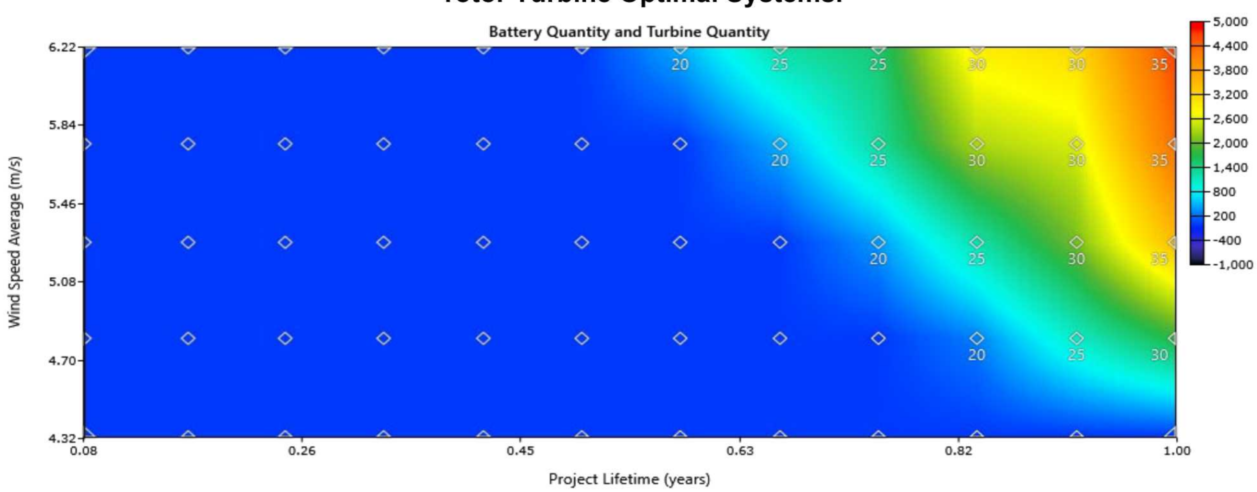

Figure 13. Battery Quantity (gradient) and Turbine Quantity (diamonds) Details for the Large-rotor Turbine Optimal Systems.

Figure 13 again shows the same turbine quantities next to the diamonds but the gradient variable is now changed to represent the quantity of 1-kWh batteries. The wind resource is variable and therefore the turbine electricity production is variable and doesn't always match the load at any given time. It is, therefore, very beneficial to include batteries to store excess wind energy for use later when the load is high, and the wind is low. In the SoSAT scenarios where batteries were included, they were sized to capture all the wind energy for maximum benefit, but there was no attempt to optimize the batteries. In HOMER simulations, the batteries have a transportation cost just like the fuel and turbine, so they are sized for optimal transportation benefit. In general, the more turbines and the higher the average wind speed, the more batteries that are deployed, which is expected.

Figure 14 shows another perspective on the system details with the gradient representing the percent of load being served by the wind turbines and the diamonds displaying the percentage of excess electricity generated. In the systems with wind deployed, the turbines provide between about 40% - 80% of the electricity load, and with the inclusion of optimized batteries, the maximum amount of excess electricity is just above 5%.

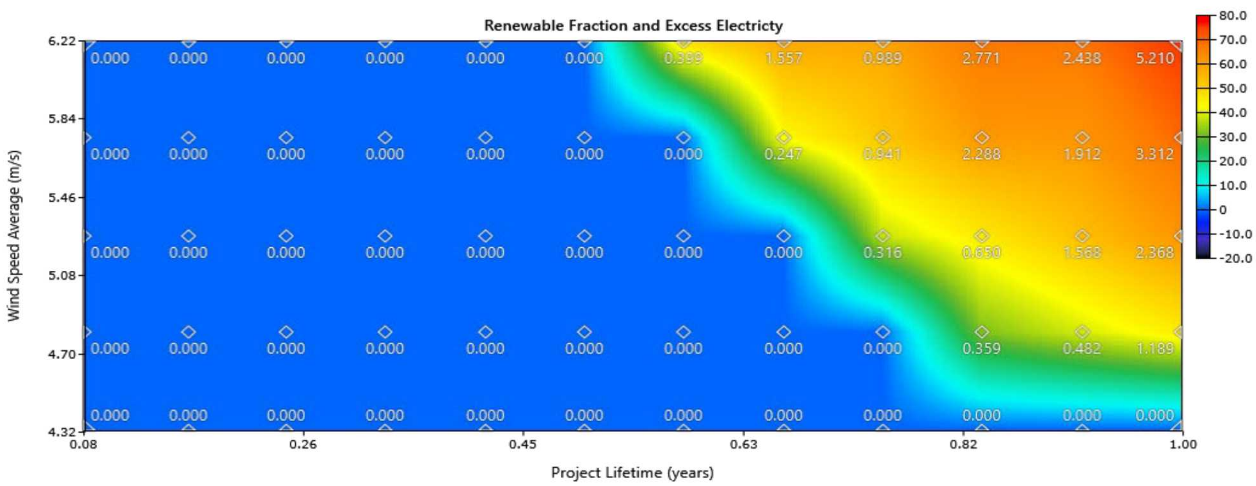

Figure 14. Renewable Energy Fraction (gradient) and Percentage of Excess Electricity (diamonds) Details for the Large-rotor Turbine Optimal Systems.

HOMER can also produce optimization plots for different combinations of variables. In Figure 15, the optimal number of batteries versus turbines is plotted for the two bounding average wind speed cases of 6.22 m/s and 4.32 m/s. Both follow a similar trend where a relatively small number of batteries are deployed until 20 turbines and then there is a sharper linear increase in batteries as the number of turbines increases above 20. In the 6.22 m/s wind speed case, there is a third area between 40 and 60 turbines where batteries do not increase as rapidly. These results likely reflect that at wind turbine quantities below 20, there isn't much excess electricity being produced by the turbines compared to the load so there is less of a need for batteries. This is an interesting result because it indicates that even without storage, some level of wind energy generation is still beneficial to offset fuel consumption.

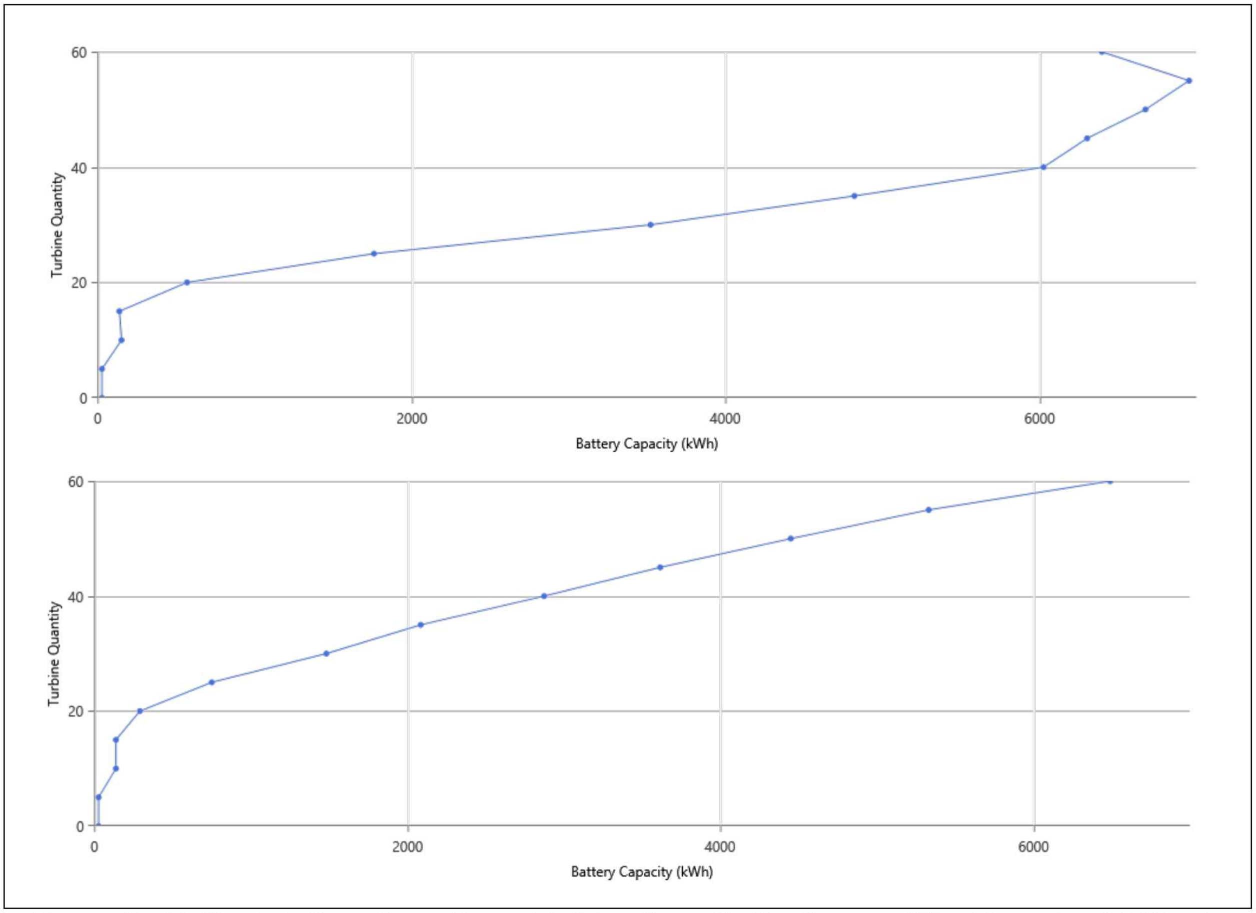

Figure 15. Optimal Battery Capacity vs. Turbine Quantity for Average Wind Speeds of 6.22 m/s (top) and 4.32 m/s (bottom)

6.4.3. Battery Storage Comparisons Between SoSAT and HOMER

Among the many thousands of simulations that HOMER ran are the same 16 scenarios run using SoSAT. None of those scenarios represent optimized systems as presented earlier in the HOMER results, but they do provide a useful comparison point to the SoSAT results, especially regarding the battery capacity. Table 20 shows the SoSAT and HOMER total battery capacity values for all 16 SoSAT scenarios for the XS2 base. In the SoSAT scenarios, the battery capacity was intentionally specified to cycle to zero charge, have a 100% efficient roundtrip efficiency, and be sized to store all excess wind generated. The HOMER model defined a more realistic 20% minimum state of charge and was sized to optimize the overall system transportation cost. As a result of these differences in modeling approach, the HOMER battery capacity is always optimized to a smaller capacity battery as compared to the corresponding SoSAT scenario as would be expected. The primary conclusion of this is that HOMER allows some excess wind generation to go uncaptured as represented by the excess electricity generation in Figure 14, but at the benefit of a lower shipping burden. While most of the scenarios are fairly close in battery capacity between SoSAT and HOMER, the scenario of 6.22 m/s average wind speed and 40 turbines shows a much larger discrepancy for both the commercial and low turbine with SoSAT incorporating at least double the battery capacity. This scenario was noted in the SoSAT results as being likely oversized and not feasible from a transportation perspective. HOMER scenarios confirm that the battery capacity can be much smaller and still provide a high value.

Table 20. Battery Capacity Comparisons between SoSAT and HOMER Simulations for the Extra Small base 2 (XS2)

Wind Resource (m/s avg.)	Base Turbine Count	Commercial Turbine		Large-rotor Turbine	
		SoSAT Max Battery Capacity (kW*h)	HOMER Max Battery Capacity (kW*h)	SoSAT Max Battery Capacity (kW*h)	HOMER Max Battery Capacity (kW*h)
6.22	20	645	362	645	570
	40	10,259	5,006	17,934	6,026
4.32	20	212	139	398	292
	40	2,152	1,761	2,981	2,874

6.4.4. HOMER Summary

The HOMER results help to fill in some of the gaps of the SoSAT analysis by providing a wider parameter design space and optimization of systems to the key transportation metric. The HOMER results show which parameters most influence the transportation burden and provide a more resolved estimate of the breakeven time where it is beneficial to deploy wind turbines and batteries instead of just diesel generators due to the fuel offset potential. Both commercial and large-rotor turbines can provide an optimal choice with durations less than 1 year, but the large-rotor turbine generally provides earlier breakeven points, about three months earlier than the commercial turbine for the same scenario. The battery results show that there is an optimum battery capacity that is generally lower than what is dictated in SoSAT without losing too much excess wind energy.

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7. CONCLUSIONS

Wind turbines provide direct benefits to contingency bases in terms of reduced fuel consumption and the corresponding reduction in fuel transportation burden. The exact benefits provided by a wind system will always depend on the specific considerations of a particular contingency base, its mission and the available wind resource. However, some general observations can be made regarding the impact of some key parameters on the benefits of wind energy to contingency bases. The following observations are intended as preliminary guidance for those considering both developing and deploying wind technologies for contingency bases.

As with any energy harvesting approach, the location and the characteristics of the energy resource at that location are one of the biggest considerations for potential benefit. Wind energy resources vary considerably around the world, and seasonally and daily in many locations. Detailed information on wind resource globally continues to improve to support ever-improving energy production estimates to support mission planning. Statistically, the average wind speed at 50 m above ground on most of the global land area is around 4.32 m/s which is significantly lower than what would typically be considered for a commercial wind turbine deployment.

Even though most locations have relatively low wind resource at this height, wind turbines still produce energy from this lower resource and, more importantly, can produce even more energy with some design changes. The primary turbine design parameter explored in this analysis was to put a larger rotor (e.g. longer blades) on the baseline turbine (i.e., "commercial") design. This is primarily a cost of energy trade-off in commercial systems that is less applicable in the military application. The analysis showed that by increasing the blade length by about 27%, wind turbines were shown to be an optimal choice on shorter mission campaigns and in areas with lower wind resource. Such turbines do not exist commercially, but the development and manufacturing require low-risk research and development. Turbine power rating is another important consideration in terms of matching the technology to the base demand. This analysis only considered a 15-kW turbine because it was a good size to meet some basic transportation logistical constraints for the most forward bases, which in this analysis were the XS bases. However, other wind turbine designs that are larger, even up to 100 kW in size, can still be considered deployable and might be a better fit for the larger bases that have more specialized equipment and personnel to install and operate such systems.

The overall base power system design and composition is an important factor in wind turbine benefits. All the analysis began with the assumption that the base was networked into two or three grids with generators sharing loads among them. This is not always the case with bases today but is considered a necessary step before the benefits of wind can be fully harvested. The other key factor in power system design is the inclusion of battery storage systems. Batteries are crucial for addressing any mismatch in generation and load. Batteries not only store excess wind energy for later times of high load or low wind, but also benefit diesel generators to operate more efficiently and reliably. The addition of batteries increased the fuel savings benefit of wind turbines most in systems with many turbines and at higher wind speeds. Design tools like HOMER can optimize the number of batteries and turbines to fit the base mission.

The base location is another key factor in the potential benefits of wind energy. This analysis only considered the most forward, XS bases in the Infantry BCT base network for two reasons. First, as mentioned, the turbine size of 15 kW was a good match to the scale of the base load such that a reasonable number of turbines (20 – 40) could supply a high percentage of base power. Second, being the most forward bases, the fuel logistics burden and risk is also typically higher. Reducing a gallon of fuel at the more forward bases has compounding benefits all the way back to the port where fuel is delivered in bulk.

There are some final thoughts on additional considerations that were not included in this report that could be explored in some future work. This analysis only considered hybrid power systems that included wind, diesel generators, and batteries because very little information is available on these configurations for contingency bases versus systems that include solar photovoltaic systems. However, future work could consider systems with both wind and solar because often their resources are complimentary with additional benefits possible in terms of fuel reduction and logistics. Finally, this analysis only looked at two metrics, fuel consumption and convoy or truck trips. There are potentially more benefits that wind turbine systems could provide. Wind systems can provide some level of resiliency to a base under constrained logistics scenarios, stretching fuel to last longer or even to continue some critical loads when fuel runs out or is needed more critically for vehicles. Additional analyses could evaluate these scenarios to identify additional benefits of hybrid power systems to meet specific mission goals.

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APPENDIX A. TURBINE DESIGN IMPACTS BASED ON ROTOR SIZE

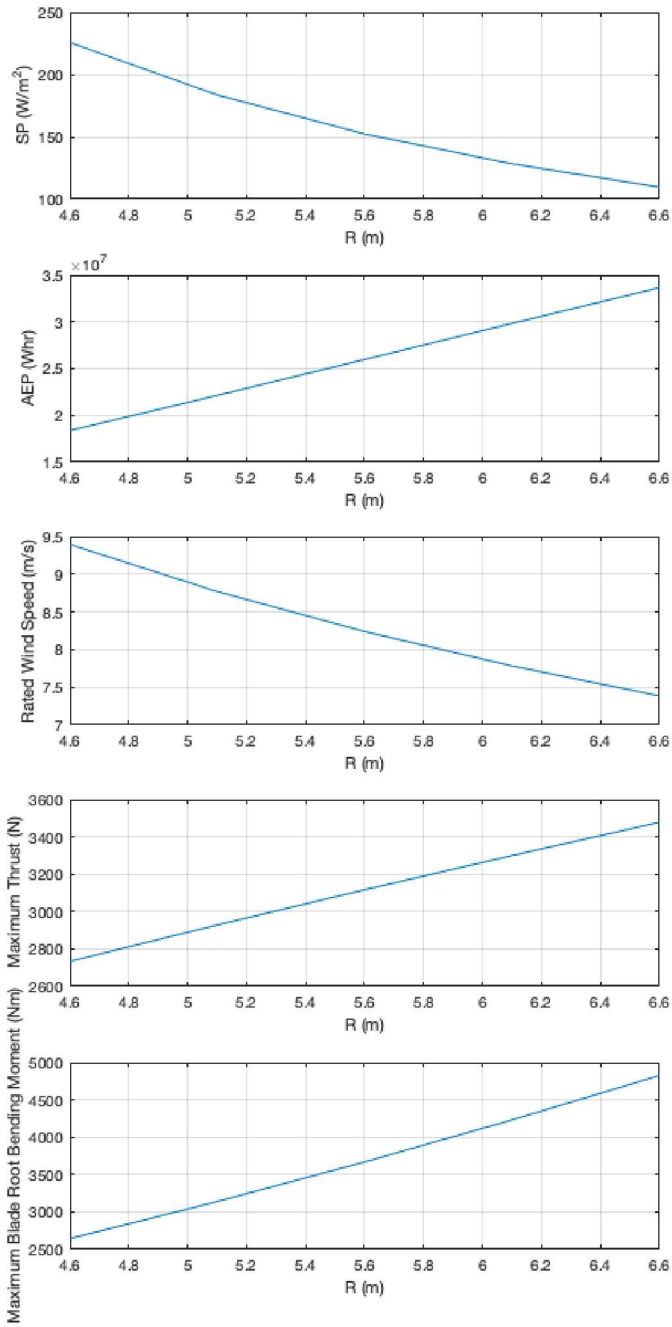
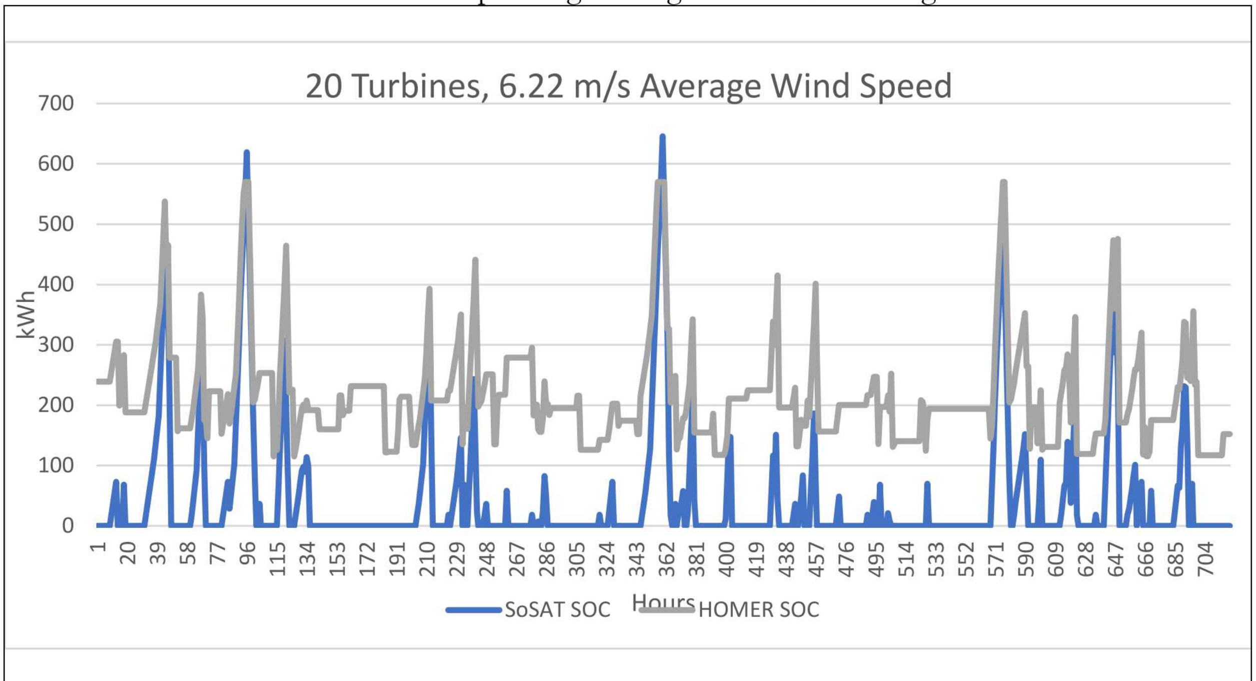
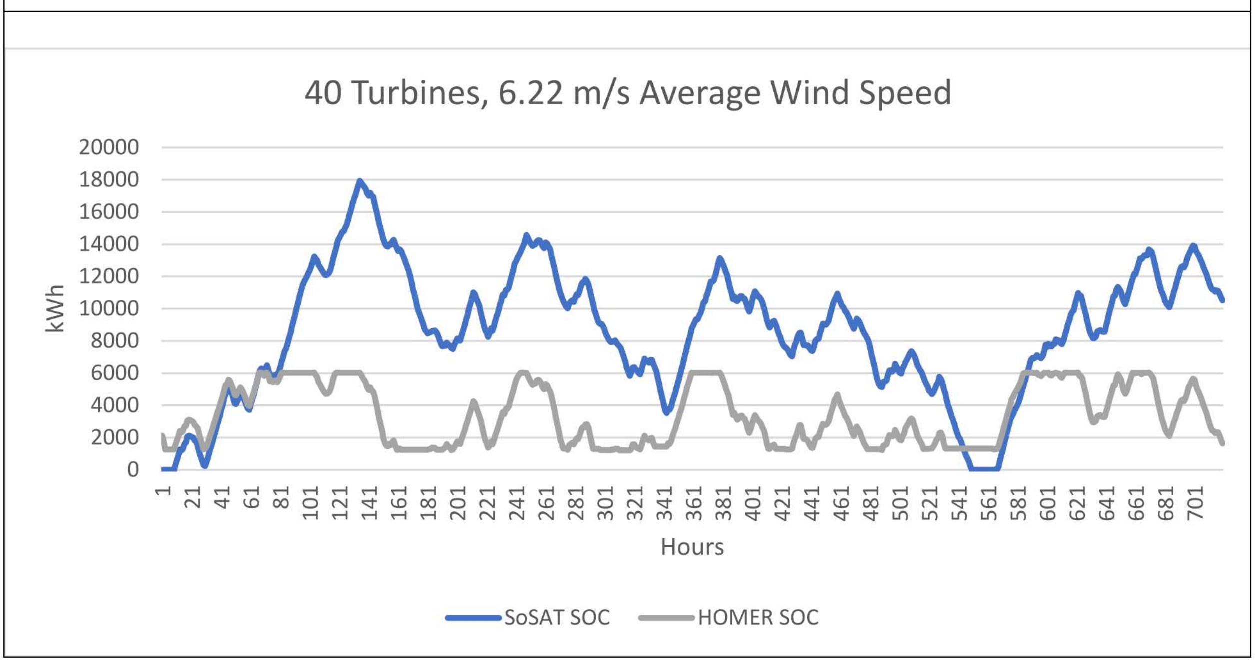


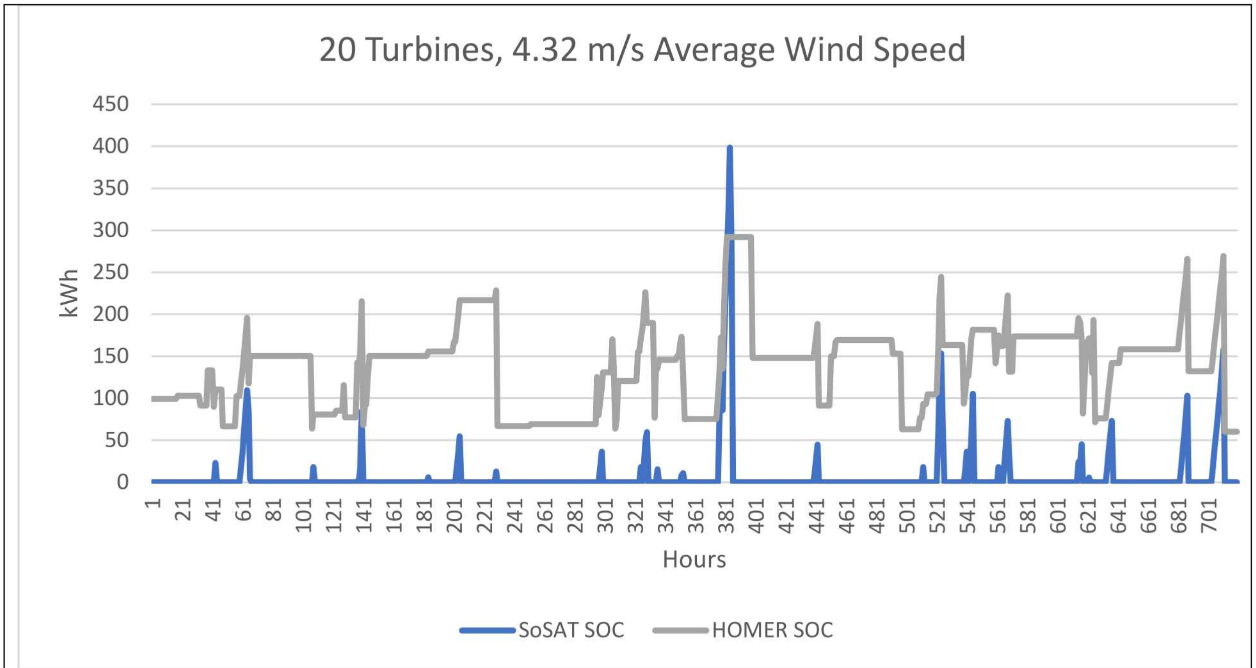
Figure A-1. The Relationship Between Rotor Radius and Various Turbine Parameters from Top to Bottom: Specific Power, Annual Energy Production, Rated Wind Speed, Maximum Rotor Thrust, and Maximum Blade Root Bending Moment.

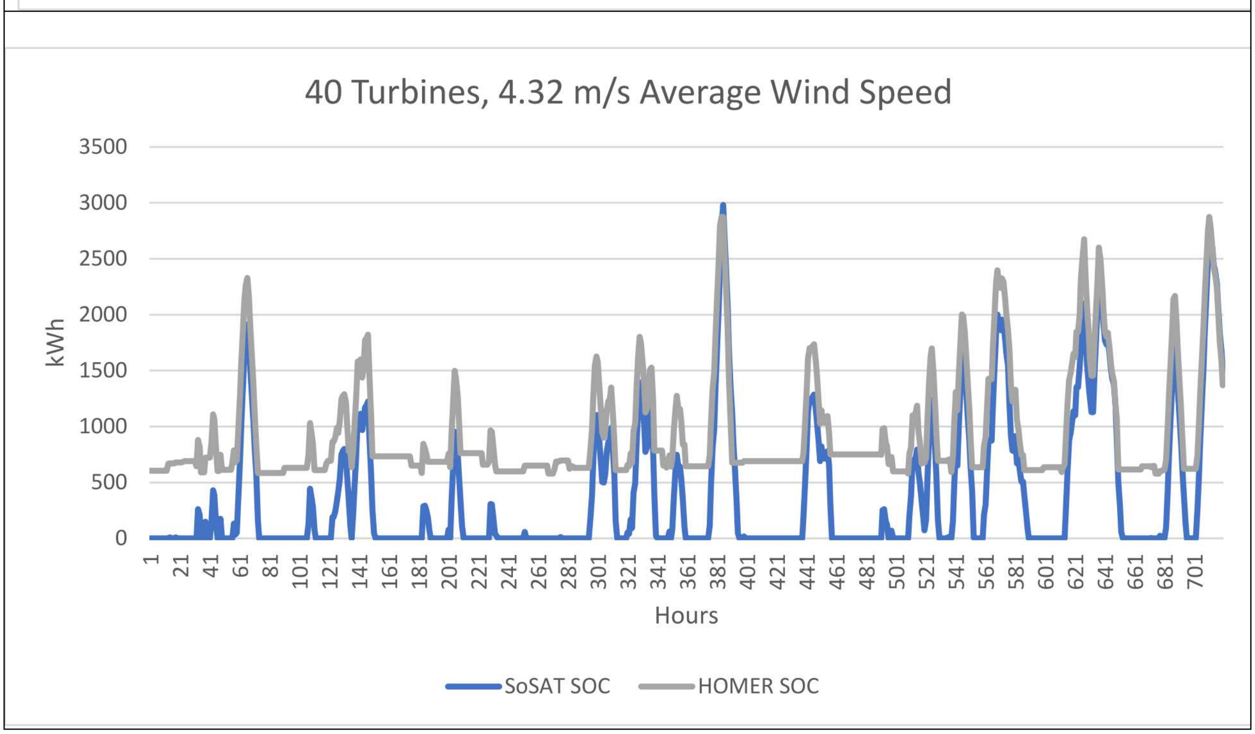
APPENDIX B. SOSAT-HOMER BATTERY COMPARISONS

The following figures show the hourly time series of the battery state of charge for SoSAT and HOMER for the same scenarios incorporating the large-rotor turbine design.






20 Turbines, 4.32 m/s Average Wind Speed
kWh
Hours
SoSAT SOC
HOMER SOC


40 Turbines, 4.32 m/s Average Wind Speed
kWh
Hours
SoSAT SOC
HOMER SOC

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