Stochastic Dynamic Programming Control Scheme for Airborne Wind, Battery Storage, and Diesel Generator System

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Abstract

We formulate a hybrid energy system comprising an airborne wind turbine, battery storage, and a diesel generator. Using Stochastic Dynamic Programming (SDP), we design an optimization framework to minimize diesel fuel consumption by maximizing wind power output. A battery storage system is included to provide a buffer between periods of high demand and intermittent wind generation. Using the Altaeros BAT (Buoyant Air Turbine), the Tesla Powerwall, historical wind speed and power demand data for our model inputs, we test two scenarios over average wind profiles for each month: (1) a wind turbine with adjustable tether height and (2) a wind turbine at a fixed height. When allowing the wind turbine to adjust to the optimal height, we see significant reductions in diesel generator use; roughly 32 - 70% more diesel energy is consumed when the turbine operates at a fixed height of 80m.

1 Introduction

1.1 Motivation & Background

Throughout the past half-century, there has been an increasing consensus that the world must switch to renewably-generated energy sources. The need for clean energy is especially pertinent in developing nations, as access to energy is necessary for economic development. Many of these developing nations do not have the massive network of electrical infrastructure built connecting major generation systems to centers of demand as do developed nations. Increasingly, these developing nations are leapfrogging this infrastructure investment and turning instead to microgrid systems. In light of recent international accords, such as the Paris Conference of the Parties, developing nations are strongly encouraged to supply these microgrid systems with renewable electricity sources instead of relying on fossil fuels. We propose an intermediary solution where present diesel generation is still utilized to act as a reliable source of electricity, but the system is coupled with airborne wind turbines and battery storage to minimize diesel fuel use.

Airborne wind energy systems (AWESs) are mechanical systems that extract kinetic energy from the wind via turbine and tethered cable. Although they are mechanically similar to conventional wind turbines, they have many advantages over the typical windmill. They are easily movable, do not require massive foundations or steel structures, and can adjust their tether height to locate optimal wind speeds along a vertical profile. As wind speed typically increases with altitude, AWESs can extend their tether length during periods of low wind speeds, and retract their tether length during periods of high wind speeds. This vertical adjustment capability reduces wind power output intermittancy, providing a more reliable source of power. Coupling an AWES with battery storage and a backup diesel generator can provide a consistent supply of power while minimizing the total amount of diesel fuel consumed.

1.2 Relevant Literature

Current literature provides a review of presently proven AWE technologies and their potential capabilities [Cherubini 2015, Vermilion 2013]. Lujano-Rojas et al. discuss strategies for matching load and energy supply with a conventional wind/diesel/battery hybrid energy system [Lujano-Rojas 2012], and Ameen et al. discuss simplified performance models of PV/diesel/battery hybrid systems [Ameen 2015]. We contribute to present literature by creating a framework for the novel altitude-adjusting AWES technology in a microgrid setting with a battery storage system and diesel generator.

1.3 Focus of this Study

Through a stochastic dynamic program (SDP), we design a program minimizing the amount of diesel fuel consumed to produce electricity by implementing a joint airborne wind turbine, battery, and diesel generator system to meet system demand. We test the system for different load levels at different months during the year, and compare the reduction in diesel fuel consumption when an adjustable tether is used to that of a stationary tether.

2 Technical Description

2.1 Approach

The performance of this hybrid energy system is evaluated using stochastic dynamic programming methods. The control system takes two inputs: load demand and wind speed. Upon receiving this information, the control system, as shown in Figure 1, determines the optimal wind, battery, and generator output to supply power to the demand source. Power demand is treated as a deterministic variable, since power consumption behavior for a variety of demand types (residential, commercial, etc.) is fairly well known and predictable. The wind speed is treated as a stochastic variable, since there is a greater element of randomness associated with meteorological elements. Load demand data is taken from an Open Energy Information dataset for Arcata, CA [OEI 2016]. The dataset includes hourly demand for one full year. Hourly wind speed data is acquired from the National Climatic Data Center for Medford, OR, the closest town to Arcata with recorded hourly wind speeds [NOAA 2016]. For each month, an average wind speed and load demand was calculated for each hour of the day.

A separate controls system operates the tether length of the turbine, to seek highest wind speed and power output. At wind speeds less than the optimal wind speed, the tether increases in length until it either reaches the height of the optimal wind velocity or reaches its maximum tether length. At wind speeds greater than the optimal wind speed, the tether retracts until it reaches the height of the optimal wind velocity or it reaches the ground, where it docks and either continues to provide power or shuts off to prevent damage. The optimal wind speed was assumed to be 25 m/s, the speed at which the wind turbine produces its maximum power capacity. We estimate wind speeds at different altitudes using the equation:

$$v_x = v_{ref} \left(\frac{h_x}{h_{ref}} \right)^{\alpha} \tag{1}$$

Where v_x is the velocity at the new altitude, h_x, v_{ref} is the velocity at the reference altitude, h_{ref}, and α is the Reynolds number, representing the roughness of the surrounding terrain.

2.2 Component Sizing

To implement our SDP, we take sizing metrics from real-world components. We model the airborne wind turbine off the Altaeros BAT, an inflatable airborne wind turbine that can adjust its height to find optimal wind speeds, and can produce power at ground level or at its maximum height. The Altaeros BAT has a power rating of 30 kW and a tether length of 600m. The battery storage system is modeled off the Tesla Powerwall system, with a set power output of 30 kW and an energy storage capacity of 85 kWh. Finally, we chose a diesel generator at a power output of 30 kW to match the BAT. However, different values can easily be implemented in the model to solve for an optimal control scheme of different demand profiles and generation capabilities.

2.3 Markov Probability Matrix

To implement the stochastic dynamic programming problem formulation, the Markov chain analysis was used to evaluate the probability of the wind speed transitioning to the next possible wind speed. A Markov probability matrix was generated using the annual wind data from Arcata, CA. To create this probability matrix, each hour of the day was assessed separately, because wind patterns correlate strongly with time of day. For each hour of the day, the array of unique wind speeds was identified, j. For each unique wind speed (at each hour of the day), the array of wind speeds at the next time step was

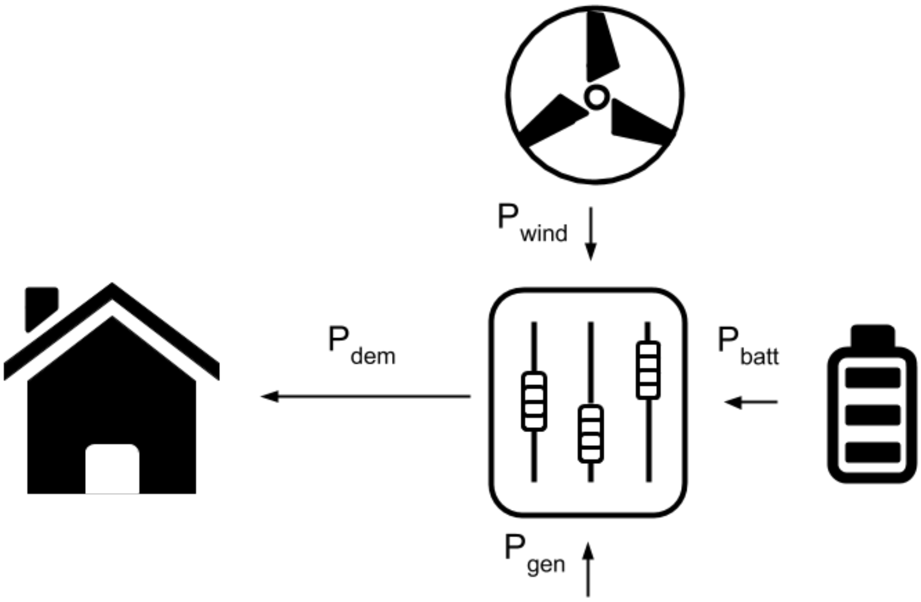

Figure 1: System components

identified, i. The probability of transitioning from one wind speed, j, to the next, i, is the ratio of the total number of j to i transitions divided by the total number of times that the wind speed is at value j.

3 Problem Formulation

The objective function of this framework is to minimize the amount of diesel fuel power consumed, $\sum\limits_{k=0}^{N-1} P_{gen,k}\Delta t$. The uncontrollable inputs to the system are wind speed at time step k, v_k, and electrical power load at time step k, $P_{dem,k}$. The decision variables for the system are the quantities of power from wind, battery, and diesel power generation: $P_{wind,k}$, $P_{batt,k}$, and $P_{gen,k}$.

We define the following variables:

$$
\begin{aligned}
P_{gen,k} &= \text{generated diesel power at time k} \\
P_{dem,k} &= \text{total load demand at time k} \\
P_{wind,k} &= \text{generated wind power at time k} \\
P_{batt,k} &= \text{generated battery power at time k} \\
P_{fuel,max} &= \text{Power rating of diesel generator at time k} \\
P_{batt,max} &= \text{Power rating of battery at time k} \\
E_k &= \text{Energy stored in battery at time k} \\
\rho &= \text{density of the air} \\
A &= \text{swept area of wind turbine blades} \\
v_{wind,k} &= \text{measured wind velocity at time k} \\
v_{wind,cut-in} &= \text{cut-in velocity for wind turbine} \\
v_{wind,cut-out} &= \text{cut-out velocity for wind turbine} \\
h &= \text{vertical altitude of the wind turbine} \\
\theta &= \text{angle between horizontal wind component and cable} \\
G &= \text{aerodynamic efficiency,} \frac{\text{lift}}{\text{drag}} \\
C_L &= \text{lift coefficient}
\end{aligned}
$$

3.1 Optimization Function and Constraints

The optimization function is:

$$\min_{P_{gen,k}} \qquad J = \mathbb{E}\sum_{k=0}^{N-1} P_{gen,k}\Delta t \tag{2}$$

The program can be reduced by substituting $P_{gen,k}$ with $P_{dem,k} - P_{batt,k} - P_{wind,k}$, where $P_{wind,k}$ is a function of velocity $f(v_k)$. The canonical optimization equation for a stochastic dynamic program becomes:

$$\min_{P_{batt,k}, P_{wind,k}} \qquad J = \mathbb{E}\sum_{k=0}^{N-1} (P_{dem,k} - P_{batt,k} - P_{wind}(v_k))\Delta t \tag{3}$$

The system is subject to the equality constraints:

$$P_{dem}(k) = P_{wind}(k) + P_{batt}(k) + P_{gen}(k) \tag{4}$$

$$E(k+1) = E(k) - P_{batt}(k)\Delta t \qquad k = 0, 1, \cdots, N \tag{5}$$

$$E(0) = E_0 \tag{6}$$

$$P_{wind}(k) = \frac{1}{2}\rho(v_{wind}(k)\cos(\theta))^3 \frac{4}{27} G^2 C_L A \tag{7}$$

$$p_{ijk} = Pr[v_{k+1} = v^j | v_k = v^i] \qquad \forall v^i, v^j \in \mathscr{V} \qquad k = 0, 1, \cdots, N-1 \tag{8}$$

The system is subject to the equality constraints shown in equations (4)-(8). Equation (4) ensures that the total load demand is met by some combination of wind, diesel, and battery power, which is paramount to the success of this model. Equation (5) keeps track of the battery energy level with time, and equation (6) gives the initial state of the battery. Equation (7) gives the power output from the wind turbine based on input wind speed, and (8) represents the Markov chain model for wind speed.

The system is subject to the following inequality constraints:

$$-P_{batt,max} \leq P_{batt}(k) \leq P_{batt,max} \tag{9}$$
$$0 \leq P_{gen}(k) \leq P_{gen,max} \tag{10}$$
$$v_{cut-out} \leq v(k) \leq v_{cut-in} \tag{11}$$
$$h_{min} \leq h(k) \leq h_{max} \tag{12}$$
$$P_{wind,min} \leq P_{wind}(k) \leq P_{wind,max} \tag{13}$$
$$E_{min} \leq E(k) \leq E_{max} \tag{14}$$

The inequality constraints, equations (9) and (10) provide the limits of operation for battery and diesel power, respectively. The battery can either be charging or discharging, at the maximum battery power rating, $P_{batt,max}$. We model a variable power output diesel generator that can generate any power up to its maximum power rating, $P_{gen,max}$. The wind turbine will have a cut-in and cut-out speed, $v_{wind,cut-in}$ and $v_{wind,cut-out}$, which defines the wind speeds that the system must operate within. The wind velocity is a function of height, and the wind turbine tether will limit the altitude to a range between h_{min} and h_{max}. We then re-arrange each inequality constraint so that it is an upper and lower limit on $P_{batt,k}$, since $P_{batt,k}$ is our decision variable.

$$-P_{batt,max} \leq P_{batt}(k) \leq P_{batt,max} \tag{15}$$

$$-P_{wind}(k) + P_{dem}(k) - P_{gen,max} \leq P_{batt}(k) \leq P_{dem}(k) - P_{wind}(k) \tag{16}$$

$$P_{dem}(k) - P_{gen}(k) - P_{wind,max} \leq P_{batt}(k) \leq P_{dem}(k) - P_{gen}(k) - P_{wind,min} \tag{17}$$

$$\frac{E(k) - E_{max}}{\Delta t} \leq P_{batt}(k) \leq \frac{E(k) - E_{min}}{\Delta t} \tag{18}$$

It is clear that one of the lower and upper limits will dominate the others, so we can collapse them to the following set of inequality constraints. The lower bound is given by:

$$\max\left\{-P_{batt,max}, -P_{wind}(k) + P_{dem}(k) - P_{gen,max}, P_{dem}(k) - P_{gen}(k) - P_{wind,max}, \frac{E(k) - E_{max}}{\Delta t}\right\} \tag{19}$$

And the upper bound is given by:

$$\min\left\{P_{batt,max}, P_{dem}(k) - P_{wind}(k), P_{dem}(k) - P_{gen}(k) - P_{wind,min}, \frac{E(k) - E_{min}}{\Delta t}\right\} \tag{20}$$

3.2 Value Function

We define a value function, $V(E_k, P_{wind,k})$, as the expected cost-to-go from time-step k to the end of the time horizon N, given the current battery energy state is E_k and wind power is $P_{wind,k}$. Then the principle of optimality is given by:

$$V(E_k, P_{wind,k}) = \min_{P_{batt(k)} \in (D)} \left\{(P_{dem} - P_{wind}(v_k) - P_{batt_k})\Delta t + \sum_{v^j \in \mathscr{V}} p_{ijk} V_{k+1}(E_k - \Delta t P_{batt_k}, v_{k+1} = v^j)\right\} \tag{21}$$

We also have the boundary condition:

$$V_N E_N, P_{wind,N} = 0 \qquad \forall E_N, P_{wind,N} \tag{22}$$

Finally, the optimal control action is saved as:

$$P^*_{batt,k} = \gamma(E_k, P_{wind,k}) = \min_{P_{batt(k)} \in (D)} \left\{(P_{dem} - P_{wind}(v_k) - P_{batt_k})\Delta t + \sum_{v^j \in \mathscr{V}} p_{ijk} V_{k+1}(E_k - P_{batt_k}\Delta t, v_{k+1} = v^j)\right\} \tag{23}$$

4 Results

Figure 2 shows the dynamics of the hybrid energy system with the adjustable tether height over a 3-day cycle. This plot was generated with the average load and wind demand for the month of July, repeated over 3 days. The equality constraint is satisfied, and supply meets demand at all time steps in the simulation. It is interesting to note that although the load demand and wind power are identical for each day, the battery and generator behave differently. This is due to the different initial state of the battery at the beginning of each day. It is also important to note that the generator generates “negative” power periodically throughout the cycle. This is a representation of overflow of power in the system for times when the wind power generated exceeds the load demand. For simplicity, we assume this excess power to be transmitted to another load demand. Alternatively, surplus power could be stored in an additional battery, or the AWES control scheme could include an ”overflow” control setting, where it reduces its power output to prevent the over production of power.

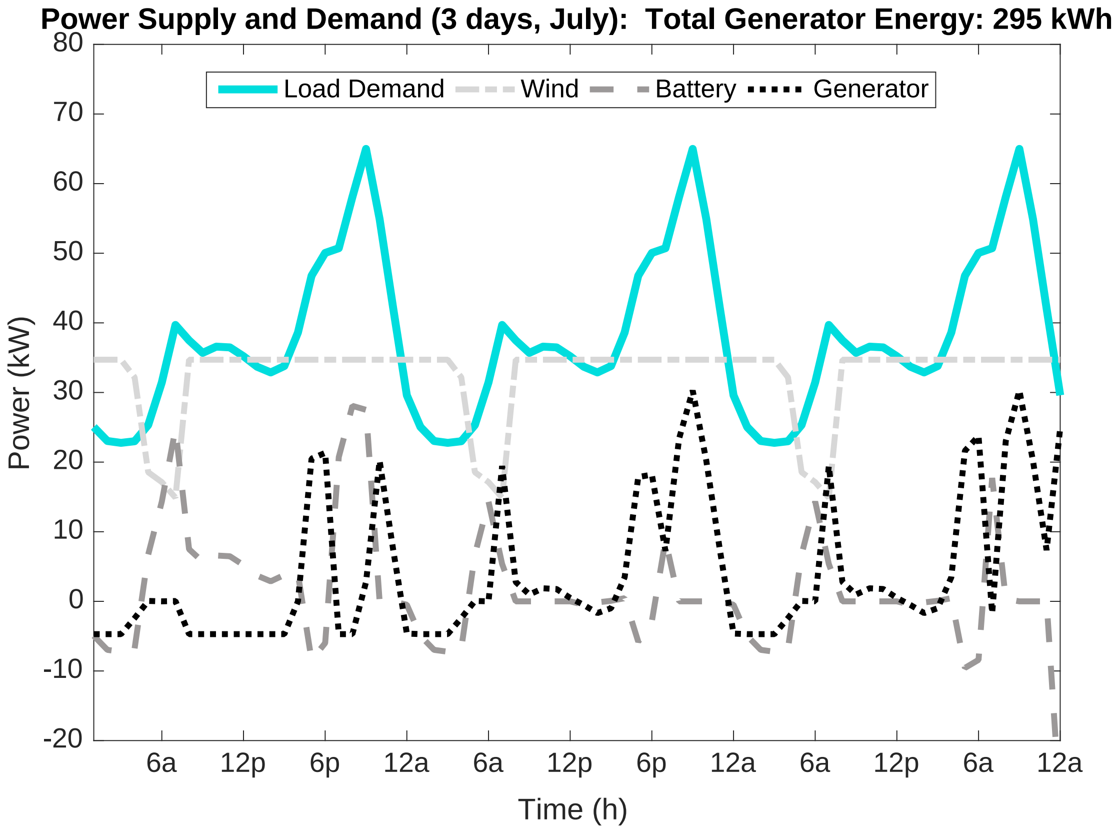

Figure 2: Hybrid Energy System Performance over 3 days

Figures 3 and 4 demonstrate the system performance in the months of January, April, July and October over a 24-hour period. These four months were chosen to represent typical conditions during each of the four seasons.

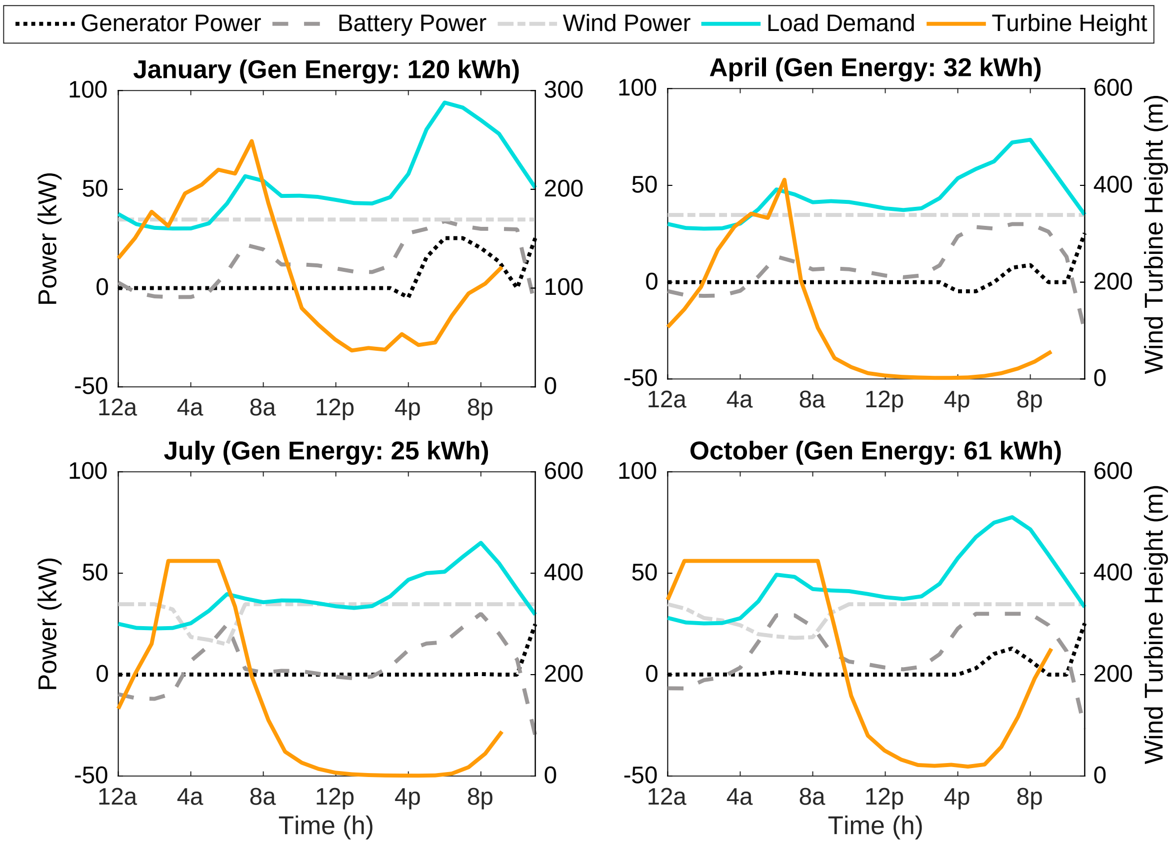

Figure 3: Seasonal Energy System Performance with Adjustable Tether Height

In Figure 3, the power sources and loads are plotted on the left y-axis, and the wind turbine height is plotted on the right y-axis. It is interesting to note that the wind turbine generates power at its maximum capacity throughout the entire day during the windier months of January and April when the tether height can be adjusted to seek the optimal wind speed. During especially windy afternoons, the turbine gets docked to ground level but continues to produce power, which we observe in the afternoon during the windier months of July and April. The role of the battery as a buffer to surplus power in the system can also be observed in the April and July. In both months, the battery charges in the morning hours (drawing negative power), when the demand is low and the wind turbine generates excess power. When the load demand increases in the afternoon, around 4pm, the battery provides the power for this increase in demand, avoiding use of the diesel generator. This feature is especially prominent in July, when the generator produces no power until roughly 11pm, when it is activated to charge the battery.

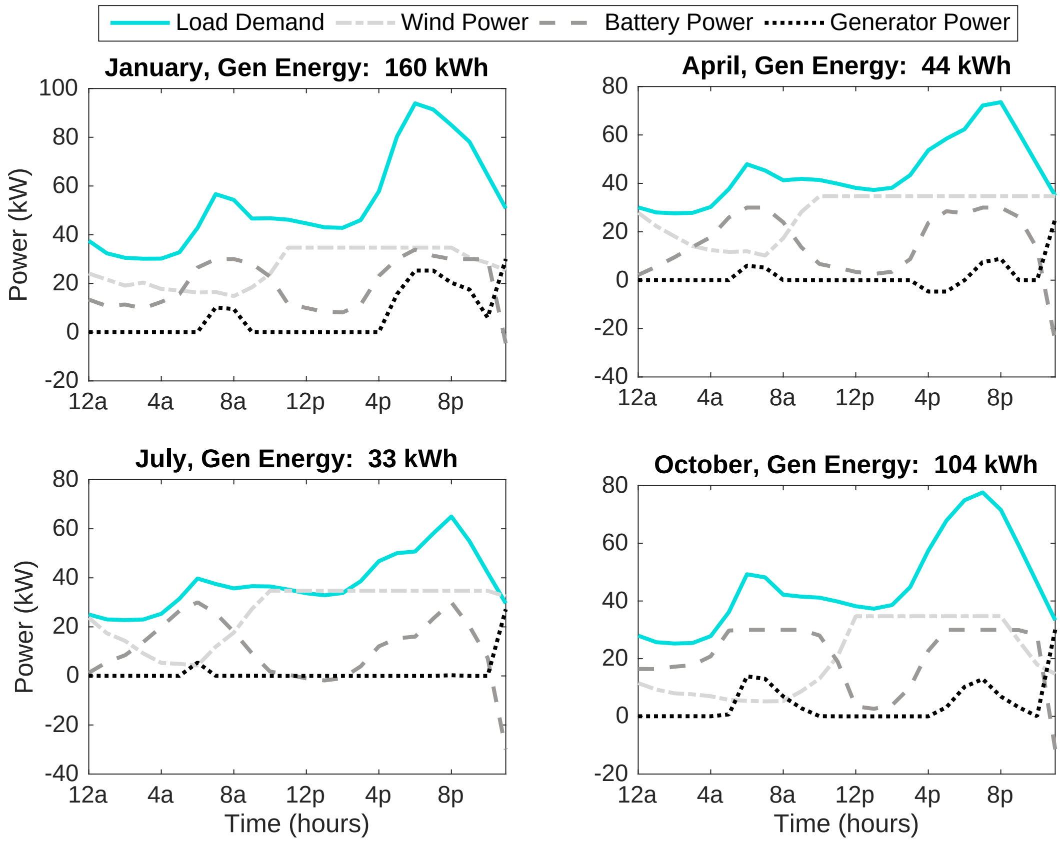

Figure 4: Seasonal Energy System Performance with Fixed Tether Height

Figure 4 shows the results of the hybrid energy system without the feature of adjustable wind height. For this scenario, it was assumed that the wind turbine was positioned at a fixed height of 80m above ground, a typical height for high altitude wind power. The battery and generator are much more active in producing power in this scenario, since the wind power turbine contributes less power to the overall load demand. In this scenario, the generator must contribute much more to the overall power provided by the system in order to meet load demand.

To provide an additional point of comparison, the hybrid energy system was evaluated without a battery. As anticipated, the energy system consumed substantially more diesel energy than the system with the battery. Table 1 summarizes the diesel generator energy consumption results from the different system evaluations. The ability to adjust the height of the wind turbine results in significant savings of diesel energy; roughly 32 - 70 % more diesel energy is consumed when the turbine is at a fixed height of 80 m. This value is highly dependent upon the height of the fixed turbine, as wind speed (and wind power) increase exponentially with height. The 161 - 609 % increase in generator energy consumption for the system without a battery demonstrates the essential role of a battery buffer system in hybrid energy systems. The battery provides an important store of energy that is used when the wind power is insufficient, or when there is a sudden increase in load demand, preventing the use of the diesel generator.

Generator Energy Production for Different Scenarios			
Scenario	With Adjustable Tether	Fixed Tether at 80 m	No Battery
Metric	Total Energy [kWh]	% Increase in Generator Energy	
January	120	33%	161%
April	32	38%	609%
July	25	32%	208%
October	61	70%	257%

Table 1: Diesel Generator Energy Production Results Summary

5 Next Steps

There are several issues raised in this project that could provide a more robust analysis of the wind-battery-generator hybrid energy system. First, is the question of how to treat excess wind energy. In this assessment, we assume that this energy is transmitted to another load demand. However, this may not be a feasible option in the case of hybrid energy systems in isolated developing areas. An investigation of storage options could provide useful information to facilitate the implementation of these energy systems. Additionally, the optimal sizing of energy systems is often an iterative process. The performance of a system depends upon its size, while the size of a system depends on its intended utilization and performance. In this assessment, the system was sized based on available technology, and a somewhat arbitrarily chosen load demand. Optimizing the system size to minimize cost or meet the demand of a specific isolated population would provide valuable information to this field of study.

6 Conclusion

This assessment demonstrates that a hybrid wind-battery-diesel energy system can successfully meet a typical load demand, subject to a stochastic input wind profile. One of the most important findings from this study is the ability of the adjustable tether height to significantly reduce the energy system dependence on the diesel generator. The system consumes 32% to 70% more diesel energy when the wind turbine tether height is fixed. Though high altitude wind energy is a much less mature technology than fixed height wind turbines, these results demonstrate one of the benefits of high altitude wind, especially in hybrid energy system applications.

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