NREL/CP-440-22108 ◆ UC Category: 1213 ◆ DE97000083

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Prepared for
1997 ASME Wind Energy Symposium
Reno, Nevada
January 6–9, 1997

National Renewable Energy Laboratory
1617 Cole Boulevard
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under contract No. DE-AC36-83CH10093

Work performed under task number WE712360

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AN ANALYSIS OF THE PERFORMANCE BENEFITS OF SHORT-TERM ENERGY STORAGE IN WIND-DIESEL HYBRID POWER SYSTEMS

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Abstract

A variety of prototype high penetration wind-diesel hybrid power systems have been implemented with different amounts of energy storage. They range from systems with no energy storage to those with many hours worth of energy storage. There has been little consensus among wind-diesel system developers as to the appropriate role and amount of energy storage in such systems. Some researchers advocate providing only enough storage capacity to supply power during the time it takes the diesel genset to start. Others install large battery banks to allow the diesel(s) to operate at full load and/or to time-shift the availability of wind-generated electricity to match the demand. Prior studies indicate that for high penetration wind-diesel systems, short-term energy storage provides the largest operational and economic benefit. This study uses data collected in Deering, Alaska, a small diesel-powered village, and the hybrid systems modeling software Hybrid2 to determine the optimum amount of short-term storage for a particular high penetration wind-diesel system. These findings were then generalized by determining how wind penetration, turbulence intensity, and load variability affect the value of short term energy storage as measured in terms of fuel savings, total diesel run time, and the number of diesel starts.

Introduction

The main performance objective of a wind-diesel hybrid power system is to maximize fuel savings relative to a diesel-only system. The role of energy storage in accomplishing this goal has been addressed in previous studies.[1-14] In a system without storage, the diesels must either be run continuously or switched on and off to meet the instantaneous net load, defined as the consumer load minus the available wind power. Fuel savings will be small for the continuous diesel case, and the diesel start/stop frequency will be high for the intermittent diesel case.[1,3,4,6,8,9] While the diesel start/stop frequency can be reduced by imposing a minimum run time on the diesels, this has the effect of decreasing the fuel savings.[1,6,8] In addition, since diesel generator sets cannot be started and brought on-line instantaneously, fuel savings is further limited in no-storage systems by the need to maintain a spinning reserve (additional on-line diesel capacity) to meet net load peaks, due to wind and load fluctuations. It has been shown that the introduction of even a small amount of energy storage increases the fuel savings while significantly reducing the number of diesel starts.[1,3,6-14]

Our purpose is to further investigate the value of energy storage as measured in terms of fuel savings, total diesel run-time, and the number of diesel starts relative to a no-storage system. We restricted our attention to short-term storage, i.e., storage that is used to cover peaks in the net load due to stochastic wind and load variations, not to time-shift the wind resource to match the diurnal load pattern. This study attempts to quantify the benefit of short-term storage in a particular high penetration wind-diesel system and then to generalize the findings by determining how wind penetration, turbulence intensity, and load variability affect this value of storage. It was our intent both to corroborate and to extend the prior studies cited above. Although our results are not specific to batteries as the storage medium, in this study we have assumed battery storage, since it is currently the only field-proven industrial storage technology with sufficient capacity and power delivery capability.

The study site is Deering, Alaska, a small diesel-powered village of approximately 160 inhabitants, where Kotzebue Electric Association, in partnership with the National Renewable Energy Laboratory and the Alaska Department of Community and Regional Affairs, is planning to install a high penetration wind-diesel demonstration project. The system was modeled using wind speed and load data collected from Deering and NREL's hybrid system simulation model, Hybrid2. Hybrid2 is a computer software tool which can predict the long-term performance, including fuel use, diesel run-time, and diesel starts, of hybrid power systems under user-specified renewable resource and load conditions.[15,16] In addition, we were able to use Hybrid2 to perform a sensitivity analysis using different levels of wind penetration, turbulence intensity, and load variability, allowing the results to be applied to power systems at different sites and of different size and wind penetration levels than the Deering system. This paper presents the methodology and results of the Hybrid2 analysis.

Methodology

We selected fuel use, diesel run-time, and diesel starts as the criteria by which to judge the value of energy storage, all of which are simulation results provided by Hybrid2. Hybrid2 was thus a good tool for evaluating the benefit of various amounts of energy storage for the Deering wind-diesel system. After determining the benefit of energy storage under the conditions applying in Deering, we used Hybrid2 to determine the sensitivity of these results to varying levels of wind penetration, turbulence intensity, and load variability.

The performance of a hybrid system depends on wind penetration, wind power variability, and load variability. Wind penetration, as used here, is the ratio of the generated wind power to the primary system load. Most often, we are referring to average wind penetration, for example, the annual wind energy generated divided by the annual electric demand. In our analysis, we have expressed wind power variability as turbulence intensity, which is a property of the local wind. Turbulence intensity is defined as the standard deviation of the wind speed divided by the mean over a given averaging interval. The term turbulence intensity is normally used in the context of short averaging intervals (up to several minutes). At the time scales we are interested in here (several minutes to half an hour), it may be more correct to speak of the coefficient of variation of the wind speed. The mathematical definition is the same, and in this paper we use the term turbulence intensity merely to be consistent with the terminology of Hybrid2, our principal modeling tool. The actual relation between turbulence intensity and wind power variability depends on the specific model of wind turbine and the number of wind turbines used. Load variability is defined as the standard deviation of the load divided by the mean over a given averaging interval.

System Configuration

The existing Deering diesel power system consists of four diesel gensets rated at 60 kW, 113 kW, 125 kW, and 135 kW. The planned Deering wind-diesel hybrid power system (see Figure 1) consists of the smaller three diesel gensets, three 65-kW wind turbines, a rotary power converter, a battery bank, an 180-kW optional resistive heating load ("dump" load) and associated power controllers, and a main system controller. The village load varies from around 30 to 130 kW. Over the data collection period (Jan 26 - July 14, 1996), the average village load was 53 kW while the expected average wind power (from Hybrid2 results) was 42 kW, giving an average wind penetration of 80%.

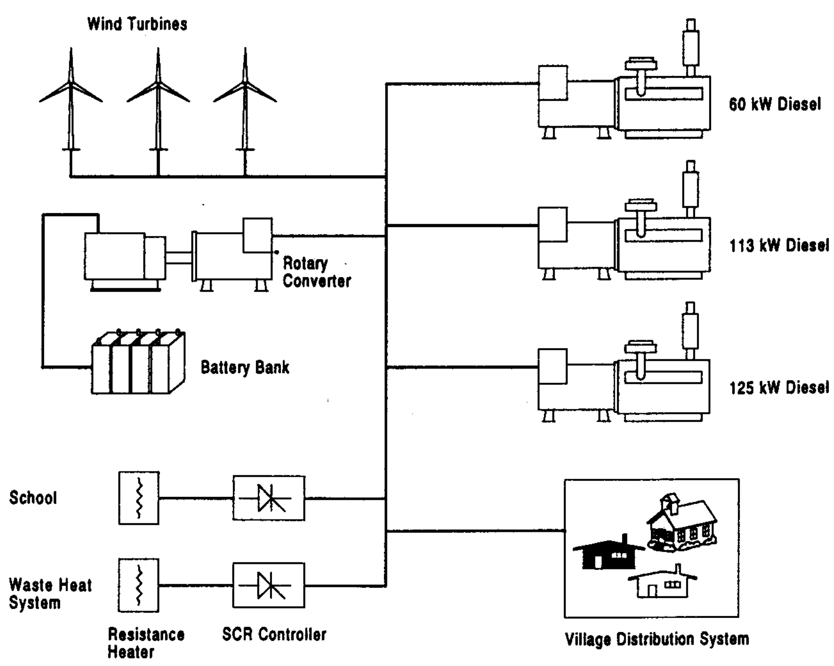

Figure 1. Layout of the Deering Wind-Diesel System

Choice of Simulation Time Step

Hybrid2 is a combined probabilistic/time-series simulation model which uses a time-series to predict long-term performance and applies statistical analysis to predict short-term behavior within each time step.[15,16] To run a simulation in Hybrid2, the user must input time-series of wind speed and load data, as well as specify the complete power system and control (dispatch) strategy. The system dispatch strategy determines the interaction between the storage and the diesel generators and how each will be used to supply the load. For this study, the selection of an appropriate dispatch strategy and the simulation time step turned out to be non-trivial.

In the Deering system, batteries will be used for "peak shaving." Diesels will be dispatched as necessary to meet the average net load (based on, for example, a 15-minute moving average of the net load). Power will only be drawn from the battery to eliminate the need to bring a(nother) diesel on-line to meet a short-term increase in net load that exceeds the diesel capacity already on-line. In Hybrid2, this operating strategy is effectively modeled if one specifies the "Multiple Diesel Load Following" dispatch strategy, which dispatches only enough diesel capacity to cover the average net load for each time step. Hybrid2 uses a statistical algorithm, based on the user-specified standard deviation of wind and load during each time step, to determine the maximum net load during each time step. If, according to Hybrid2's battery model, there is not enough available energy stored in the battery to meet the peaks within that time step, then additional diesel capacity is run for that time step.

In this Hybrid2 dispatch strategy, the battery is only discharged to cover any (probabilistically determined) transient peaks above the rated power of the on-line diesels within each time step. Consequently, this method will only model battery charge and discharge events which are shorter in duration than the time step. If the simulation time step is small, e.g., one minute, then the batteries will only be used to cover net load peaks smaller than one minute, and enough diesel capacity will be dispatched to cover the minute-average load. In this case, Hybrid2 will underestimate the battery usage, and overestimate the diesel cycling frequency. In order to use Hybrid2 to model longer storage discharge events, we were obliged to use a longer simulation time step.

Conversely, since Hybrid2 cannot model diesel state transitions within a time step, it requires that the minimum diesel run-time be greater than or equal to the simulation time step. However, the longer the diesel minimum run-time, the lower the fuel savings. Thus, we were forced to strike a balance between a time step long enough to allow the batteries to cover all net load peaks within our range of interest, and a time step short enough to allow for a useful minimum run time. As a compromise, we selected a time step of 30 minutes.

The specified time step and diesel dispatch strategy ensure that there is enough diesel spinning reserve to meet the 30-minute average load. Thus, on average, battery discharges (to cover net load peaks) would be limited to 15 minutes in duration. Consequently, our method (using the 30-minute time step) cannot accurately evaluate the performance of a system in which the battery storage is used to cover net load peaks of more than 15 minutes duration. This is not a major shortcoming, however, because, as will be seen, the performance gain due to the addition of energy storage decreases rapidly beyond around 10-minutes nominal storage capacity (10 minutes at average system load).

Model Inputs

The data inputs for Hybrid2 are time-series of wind speed and load data from Deering for Jan 26 - July 14. The wind speed was logged over this time interval as one-minute averages and standard deviations. One-minute load data was only available for June, so the June data was scaled for the rest of the months using monthly load averages from Deering. The one-minute data was converted to 30-minute data for use in Hybrid2. The nominal turbulence intensity of the 30-minute wind speed data was calculated as 0.12. Since standard deviation was not included in the load data, a constant load variability of 0.10 was specified. Both of these values, as well as the average wind penetration, were scaled up and down for each of the test cases in the sensitivity analysis to determine each parameter's effect on the value of energy storage.

The Deering system and all of the modified systems were run with various amounts of storage. The storage size is indicated by its nominal energy capacity in kWh, which is its rated amp-hour capacity times the nominal battery bank voltage. Storage size is also expressed as the amount of time that the nominal energy capacity, if fully available, could cover the average system load. These values are nominal battery sizes presented for purposes of comparison only and do not necessarily represent the amount of energy storage actually available to the system at any given time, which is dependent on charge history and discharge rate.

In a no-storage system, the diesels would need to be dispatched to cover the instantaneous net load (load minus wind power). The Hybrid2 code "knows" what the future maximum net load will be (calculated from time-series data and statistics within each time step) and therefore can dispatch the minimum amount of diesel capacity necessary to ensure that the load can always be met. Real wind-diesel systems cannot predict the future, and so a system without storage must maintain enough spinning reserve to cover all possible sudden net load peaks due to village load peaks and/or wind power drops. Therefore, the fuel savings in a real system will be less than as predicted by Hybrid2 for the no-storage case. To approximate a real system in Hybrid2, we have added a fixed 20 kW offset to the maximum net load. The zero offset cases were included to show the theoretical fuel savings possible with a hypothetical no-storage system capable of accurate short-term load and wind prediction.

Finally, along with the "Multiple Diesel Load Following" dispatch strategy and 30-minute minimum diesel run time, we specified the minimum battery % State of Charge (below which the batteries will not be allowed to discharge) at 20%. In addition, the minimum allowed power of all diesels was specified at 20% of rated power.

Results

The Reference Case: The Deering Wind-Diesel System

The results for the Deering case are shown in Figures 2 through 4. We ran simulations varying the storage capacity from no storage to 65.8 kWh nominal, equivalent to a nominal 74 minutes of energy storage at average load. Fuel consumption, diesel run-time, and diesel starts all decrease sharply, relative to the no-storage case, with increasing storage, up to a storage equivalent of approximately 10 minutes at average load. A nominal 10-minutes equivalent worth of storage reduces the fuel use by 18%, the diesel run-time by 19%, and the number of diesel starts by 44% (from an average of 7.6 starts/day to 4.2 starts/day) compared to the no-storage case. In this case, there does not appear to be any benefit to increasing the amount of storage beyond a nominal 18 minutes at average load.

In order to determine the extent to which the amount of battery capacity that Hybrid2 shows to be sufficient is artificially limited by step-size, we ran a second set of simulations using 60-minute time steps. The 60-minute time step results did show slight improvement in performance from the nominal 18- to 37-minute storage sizes, however the difference is small. In addition, the shape of the 60-minute curve is almost identical to the shape of the 30-minute curve: the "knee" of the curve, where the majority of the benefits of storage have been realized, occurs at approximately 10-minutes nominal storage capacity for both time step results. While the use of longer and longer time steps will continue to show slight performance improvement for the larger storage cases, the rate of improvement becomes much smaller. Thus we conclude that there will in fact be little economic benefit to further increasing the storage size, considering the high cost of batteries. The optimum amount of storage for the Deering system appears to be 9-14 kWh nominal or 10-15 minutes nominal at average load.

Figure 4 shows that a small amount of energy storage greatly reduces the amount of "dumped" energy, i.e., the amount of wind (or diesel) energy generated (here expressed as a percentage of the village demand) in excess of the village demand. While it is intended in Deering to use all excess wind and diesel energy in space and water heating applications, thereby saving heating fuel, the value of this energy is not as high as that of the energy that goes to meet the village electric load. For a given level of wind penetration, the lower the excess energy the better the economics of the wind-diesel system.

Sensitivity Analysis

The value of short-term storage is apparent for the Deering specific case, but the question is, how does this value change as the wind penetration, turbulence intensity, and load variability of the system change? A sensitivity analysis on these variables enables us to generalize the results of the Deering analysis to other sites and other wind-diesel systems with more or less wind penetration.

Wind Penetration Figures 5 through 7 show the effect of wind penetration on fuel use, diesel run-time, and diesel starts. The fuel use trends are similar to those shown by Beyer et al., namely that even a small amount of storage has a strong effect on fuel savings relative to the no-storage cases, and that increasing the amount makes relatively little difference[1]. However, we are still faced with the question: to what extent is the lack of difference in performance between the storage sizes larger than 18-nominal minutes equivalent a reflection of our time step and operating strategy? Again, we ran a second set of simulations with 60-minute data. The results showed only marginal improvement in performance from an 18-nominal minute storage to a 37-minute storage. We conclude that for all these systems, the majority of the benefits of storage are realized by our strategy of using it only to cover peaks up to 15 minutes duration. Therefore the results in Figures 5 through 7 will still approximate actual trends concerning the value (or lack thereof) of increasing storage.

The value of short-term storage, in terms of fuel savings and diesel run time, increases as the wind penetration increases, because there will be an increasing amount of time that the available wind power exceeds the load. At 50% wind penetration the systems with storage have approximately 20% greater fuel savings and 20% fewer diesel run-time hours than the no-storage, 20-kW offset case. Beyond 50% wind penetration, these benefits increase only slightly.

The diesel cycling trends are similar to those shown by Beyer, et al..[3] Because the wind-hybrid diesels are approaching continuous operation at the lowest wind penetrations, the number of diesel starts approaches the diesels-only number of starts (2.4 starts/day). The number of diesel starts for all the hybrid cases increases sharply as wind penetration increases and then levels off at about 80% wind penetration. The inclusion of storage significantly mitigates this increase in diesel starts, so that above 80% wind penetration, diesel starts per day are reduced by 50% relative to the no-storage, 20-kW offset case.

<u>Turbulence Intensity</u> Figures 8 through 10 show the effect of turbulence intensity on the value of storage. It has been shown that whereas the fuel use relative to the diesels-only case climbs as the wind turbulence intensity (and hence the wind power variability) increases, the greater the energy storage the less the impact of wind variability[9]. At high turbulence intensities (high wind power variability), there is apparent benefit to increasing the nominal storage size well beyond 15 minutes, even though the simulation is subject to the same 15-minute discharge limitation discussed earlier. This is to be expected, because under conditions of high wind power variability, there will be high magnitude net load peaks. The effective battery capacity drops with increasing discharge current. For the same delivered energy, the higher the battery power required to meet the net load peaks, the larger the battery must be.

The trend for diesel run-time is similar. Since most sites will have a turbulence intensity in the range from 0.1 to 0.2, it is evident in Figure 9 that some amount of energy storage is necessary to preserve the diesel-run-time-reducing benefit that addition of wind power offers.

The trend for diesel starts is similar but more pronounced. Anytime the storage is unable to cover a transient peak in the net load, another diesel must be started. The diesel may not need to be run for a long time, but it must be started. In addition, the performance of the smaller storage sizes not only decreases with increasing turbulence intensity, but also begins to approach or even fall below the performance of the no-storage cases. This is because the no-storage case diesels are dispatched according to the maximum net load (plus offset), but the storage-case diesels are dispatched according to the average net load with the storage covering any transient peaks (above the rated capacity of the on-line diesels) if possible. Thus there will be situations in a high turbulence intensity, small storage case, where depending on the size of the transient peak, a diesel may be required one time step but not the next, potentially leading to a higher number of diesel starts than with the no-storage case, in which the diesel in question would have been running continuously. In any case, Figure 11 shows that as wind turbulence increases, energy storage is increasingly important in limiting the frequency of diesel starts.

Finally, we must point out a potentially misleading aspect of our turbulence intensity analysis. Note that at high turbulence intensity, it appears that no-storage cases can have greater diesel run times and consume more fuel than if there were no wind power at all. This is due to the algorithm Hybrid2 uses to estimate the maximum net load in a particular time step. Diesels are dispatched to meet the maximum expected net load, which is the average net load plus the expected net load variation. The latter is determined by statistically combining the expected wind power variation (based on turbulence intensity) with the expected village load variation. In cases of very high turbulence intensity, and thus high wind power variation, this calculation leads to high values of net load variation, which can result in maximum net loads that actually exceed the maximum expected village load. This causes Hybrid2 to dispatch more diesel capacity than it would for a diesel-only system.

If the peak net load is higher than the village load, then there are moments when the wind turbines are drawing power from rather than delivering power to the bus. This can in fact occur with certain wind turbines in gusty wind conditions. The results presented in Figures 8 through 10 would therefore be accurate if the turbines were allowed to motor at significant power levels for short periods of time, because in that case, the maximum diesel load would indeed be greater than in the diesel-only case. Most wind turbines, however, are designed to preclude large motoring currents. With such turbines, we would expect the fuel use and diesel run-time curves to level off below the diesel-only values as turbulence intensity increased.

<u>Load Variability</u> Figures 11 through 13 show the

effect of load variability on the value of storage. Load variability is different than the other parameters we investigated in that the diesels-only performance itself changes as the load variability changes which means that as the load variability increases, the fuel consumption in all cases (storage and no-storage hybrid as well as diesel-only cases) increases, so that the performance of the hybrid cases relative to the diesels-only case may be the same or even increase. This is the case for fuel use, where the no-storage cases show only a slight decrease in performance from 0.1 to 0.3 load variability, while the storage cases actually show a slight increase in performance.

The trend for both fuel use and diesel run-time is for the value of storage to increase as the load variability increases; however, the actual amount of storage only makes a small difference. At low load variability (less than 0.1) the benefit of all storage cases above no-storage cases is essentially constant (17% reduction in fuel use and diesel run-time), because at low load variability, the variability of the net load is dominated by wind variability. Beyond 0.1 load variability, the storage cases begin to differentiate slightly, with the larger storage sizes showing slightly increasing benefit over the smaller storage sizes and all storage cases showing greater benefit relative to the no-storage cases.

Load variability most significantly impacts the number of diesel starts. The basic trend is similar to that for turbulence intensity in that as the load variability increases, the storage cases begin to separate, with the performance of the smaller storage cases approaching that of the no-storage cases. For load variability, however, the number of starts for the diesels-only case also begins to approach that of the no-storage cases, and exceeds the number of starts for all storage cases at any load variability above 0.15. This is another manifestation of the energy storage's beneficial effect of eliminating diesel starts that occur only to handle short-term peaks in the net load.

Conclusions

We evaluated the effect of various amounts of energy storage on the operating performance of the wind-diesel system planned for Deering, Alaska, and found that a modicum of energy storage, 10-15 minutes nominal capacity at average load, greatly reduced diesel fuel consumption, diesel run-time, and diesel starts, relative to the no-storage case. When modeled with three 65-kW wind turbines, using actual measured wind and load data, the fuel savings by the no-storage hybrid system, relative to the diesel-only case, were about 21%. The savings increased to about 37% with the addition of a nominal 15-kWh battery.

We also examined three factors that significantly effect the benefit of, and need for, energy storage. These are wind penetration level, wind power variability (expressed as turbulence intensity), and load variability. The benefits, relative to a no-storage case, of including energy storage increase to varying extents as each of these factors increase. At wind penetration levels below 25%, energy storage contributes very little, but even a small amount of storage contributes a great deal in most high penetration systems. However, there is not significant benefit to adding larger amounts of storage except in cases of high wind power variability. In a very steady wind, (e.g. trade wind) the benefit of energy storage will be much less than in a wind regime with higher turbulence intensity. A large enough storage can effectively eliminate a hybrid system's reduction in performance as turbulence intensity increases. The same trend is observed for load variability, but to a lesser degree. At low levels of load variability, however, the benefit of energy storage is somewhat insensitive to the actual value of load variability, since at those low levels, the variability of the net load is likely to be dominated by the wind power variability anyway.

In much larger wind-diesel systems than our reference case, say 1- to 2-MW average load, the potential performance gains from energy storage may be reduced, since both the short-term load variability and the wind power variability may be less than with a smaller system. The wind power variability would be less if a much larger number of similarly sized machines were used. On the other hand, it is just as likely that a small number of larger wind turbines would be used. A determination of the need for energy storage in large wind-diesel systems must be based on a similar analysis based on the actual system architecture and local wind and load conditions.

Note on Energy Storage System Design

The authors wish to stress that the results presented here are not sufficient in themselves to properly design a battery energy storage system, which consists not only of a battery but a power conversion system to interface it to the AC power bus. A variety of factors must be considered in such a design, including the real and reactive power demands, the conversion efficiencies of the power converter, and the actual pattern of charging and discharging that will be experienced by the battery. Knowing the actual charge and discharge profile is also essential to predicting the life of a given battery bank in a particular application. Hybrid2 is designed to be used with a relatively long simulation time step (typically in the range of 15 to 60 minutes) and is therefore unable to accurately model the actual high-rate short-duration charge and discharge events experienced by short-term energy storage. To overcome this limitation, we have developed a simple wind power surplus/deficit analysis program that determines the actual magnitude, duration, and frequency of occurrence of battery charge and discharge events in a hybrid power system with energy storage. This program uses one-minute average wind and load data as input. Examples of this analysis will be presented in a separate paper on battery life prediction.

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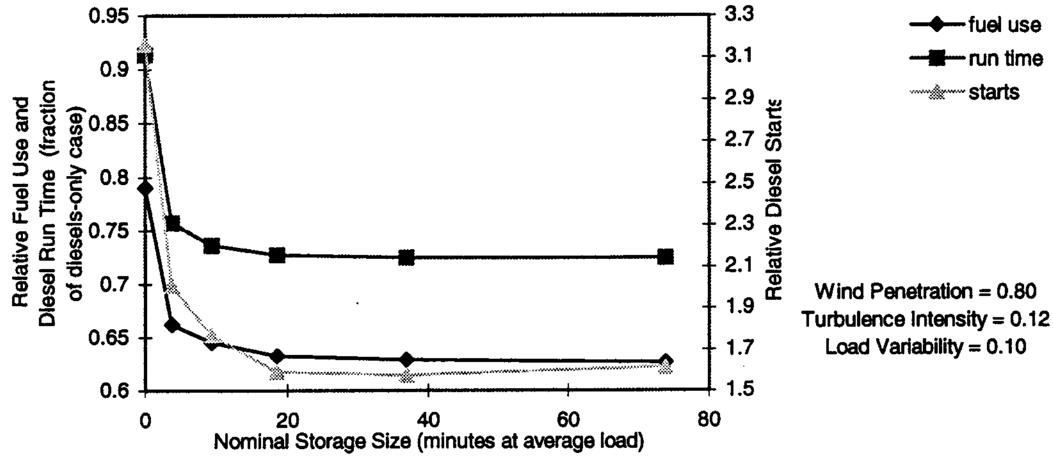

Figure 2. Relative Fuel Use, Diesel Run-Time, and Diesel Starts vs. Storage Size

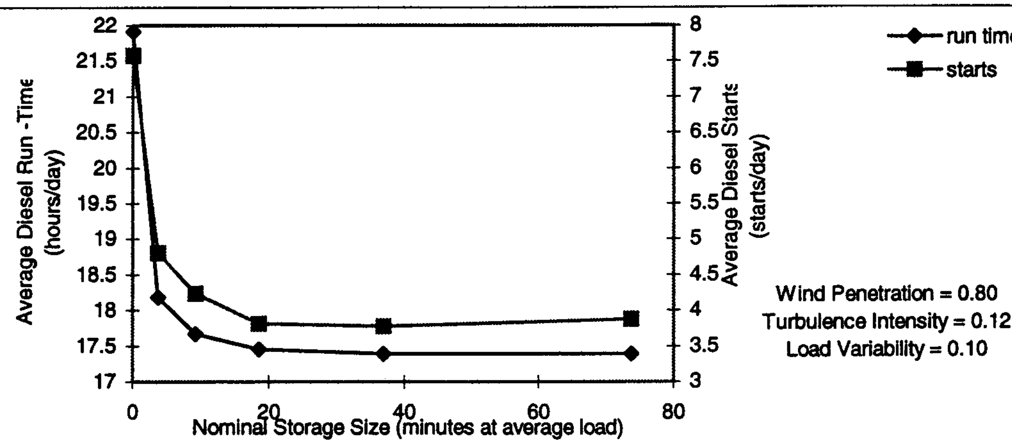

Figure 3. Absolute Diesel Run-Time and Diesel Starts vs. Storage Size

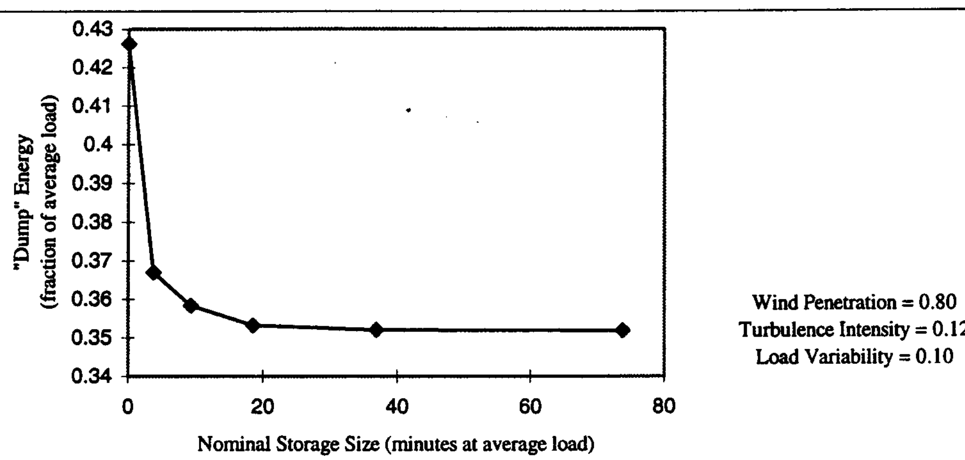

Figure 4. "Dump" Energy vs. Storage Size

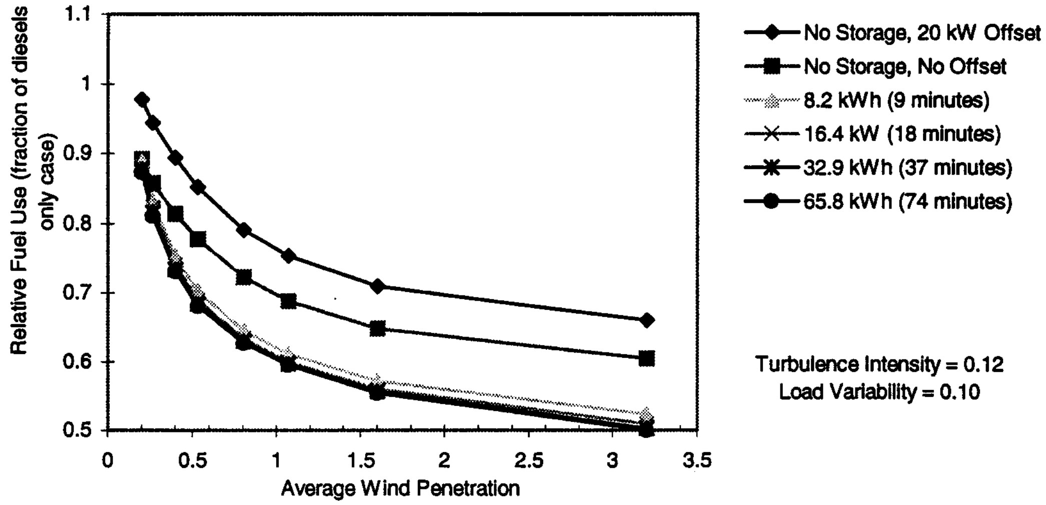

Figure 5. Fuel Use vs. Wind Penetration

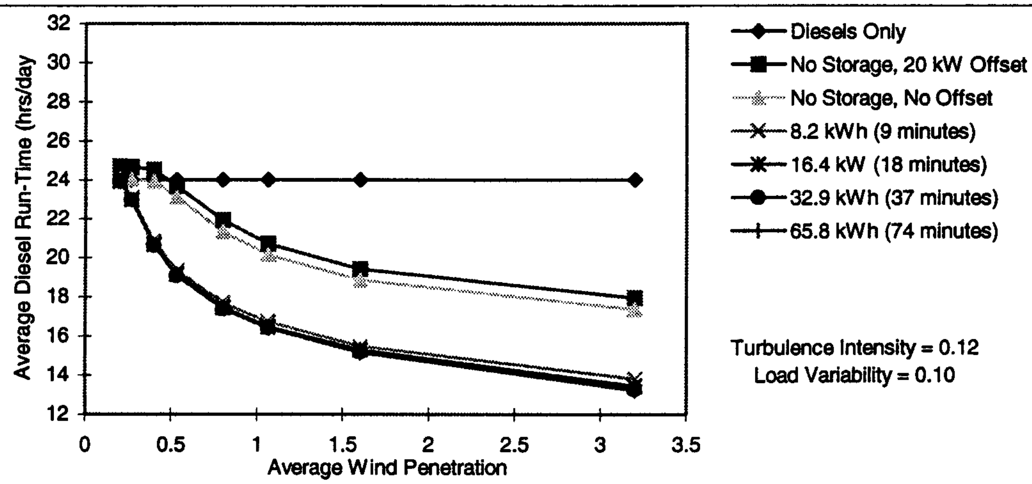

Figure 6. Diesel Run-Time vs. Wind Penetration

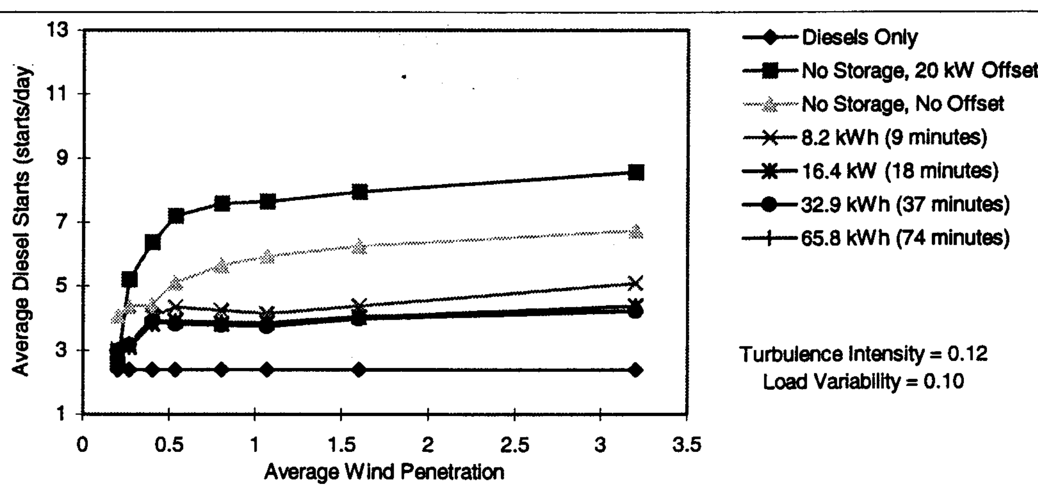

Figure 7. Diesel Starts vs. Wind Penetration

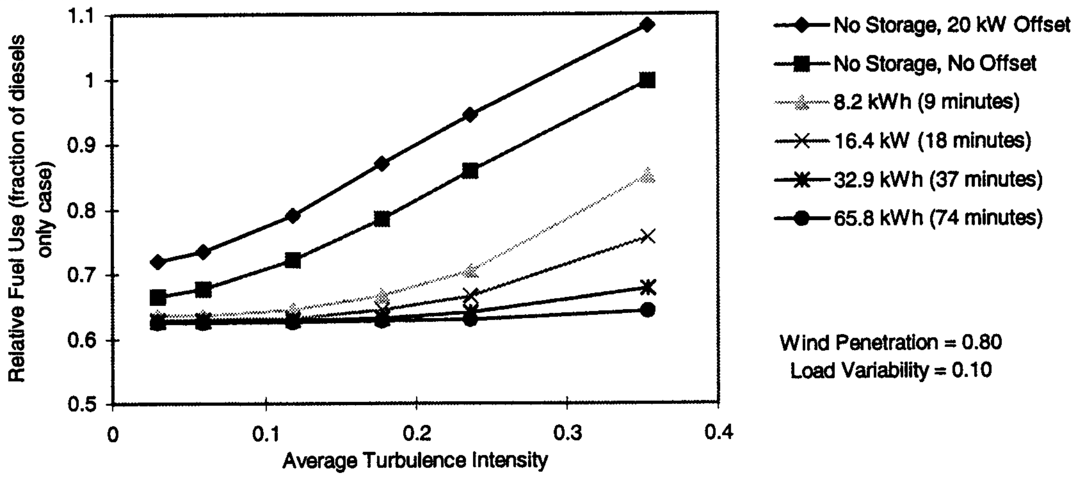

Figure 8. Fuel Use vs. Turbulence Intensity

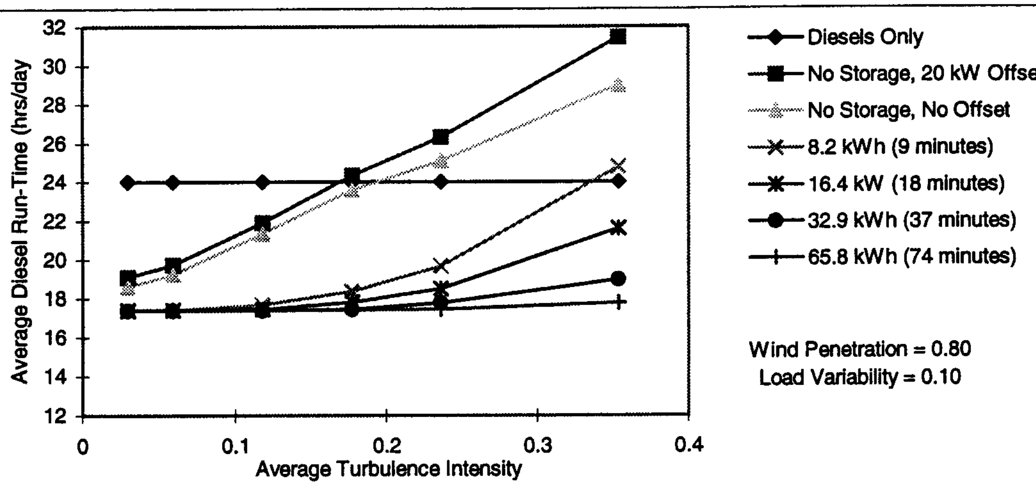

Figure 9. Diesel Run-Time vs. Turbulence Intensity

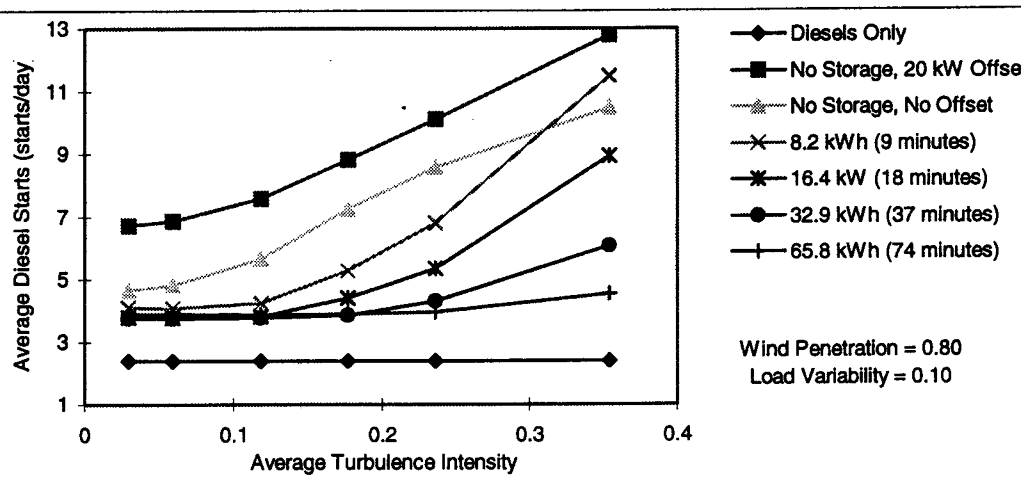

Figure 10. Diesel Starts vs. Turbulence Intensity

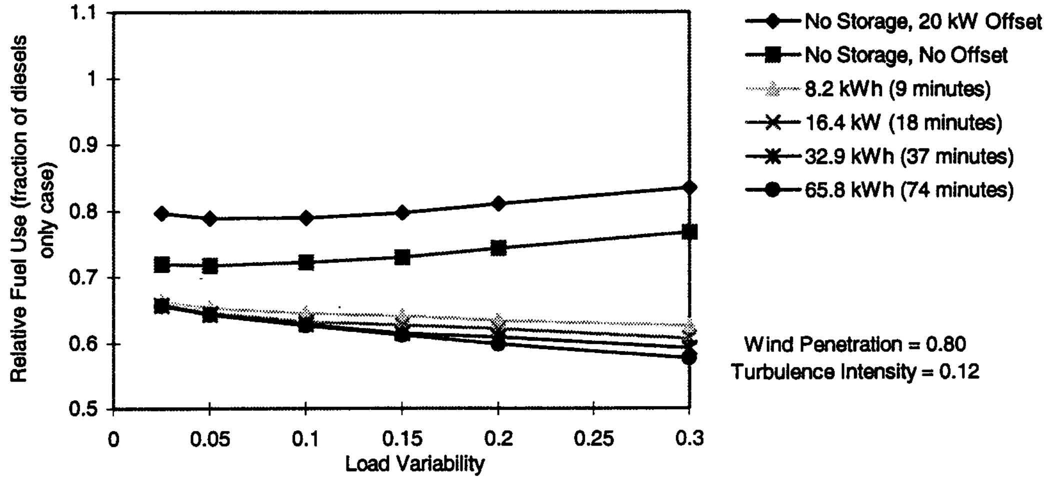

Figure 11. Fuel Use vs. Load Variability

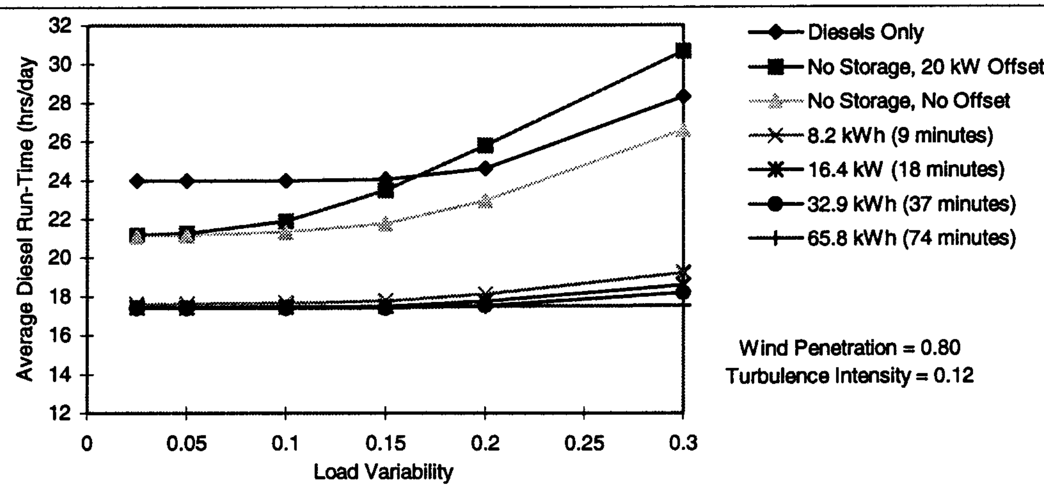

Figure 12. Diesel Run-Time vs. Load Variability

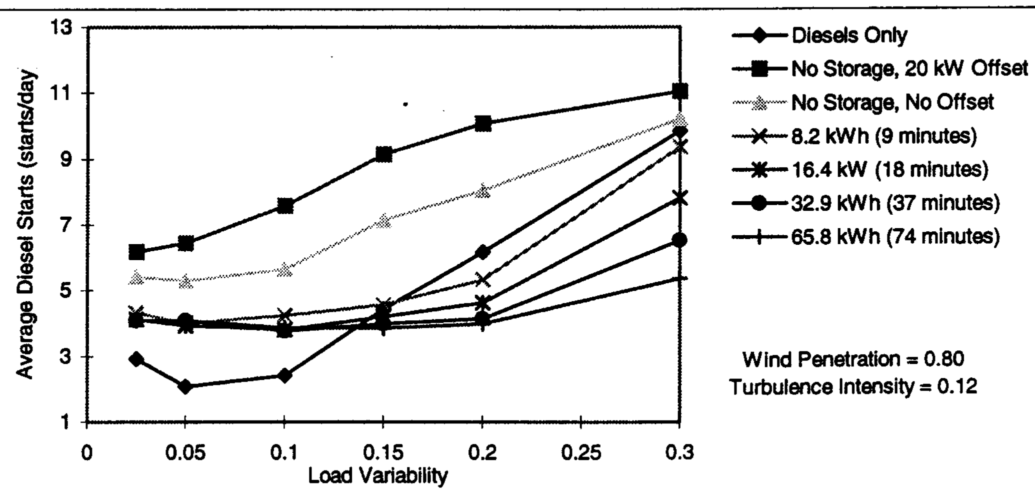

Figure 13. Diesel Starts vs. Load Variability