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Field Performance of Hybrid Power Systems

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FIELD PERFORMANCE OF HYBRID POWER SYSTEMS

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Abstract

The increasing costs of line extensions and fossil fuel, combined with the desire to reduce foreign exchange charges, are encouraging various countries to consider using renewable energy technologies in rural electrification programs. There is much anecdotal information about the operation of small wind-hybrid systems, but a lack of high-quality, well-documented information allowing a clear understanding of true performance and costs of such systems. Through the detailed monitoring and evaluation of pilot systems, a large discrepancy has been found between the power produced by small wind turbines in a hybrid application and energy production estimates based on the site's climatic conditions and the turbine power curve. The reasons for this discrepancy vary but can result in a 75% reduction in turbine output. Partial solutions include the wider use of discretionary loads and improved system control. System design impact should be considered and computer models need to be evaluated to accurately assess this problem.

Introduction

The increasing costs of conventional approaches to rural electrification are leading to the deployment and evaluation of pilot-scale community-based hybrid power systems for cost-effective, sustainable solutions for such applications. There is a great amount of anecdotal information about wind-hybrid systems, but high-quality, well-documented information about the operation of these systems is lacking. This hinders a clear understanding of the true performance and cost of wind-hybrid systems, and in many cases prevents their further optimization and widespread use. The National Renewable Energy Laboratory (NREL) has participated in the design, installation, instrumentation, and evaluation of more than 18 small hybrid power systems in Mexico, Chile, Russia, Brazil, Ghana, and the United States. These systems are characterized by having the renewable energy connected to the DC bus, referred to herein as "DC-based" systems. An analysis of the performance of these systems, especially those for which detailed monitoring information is available, is resulting in a new understanding of how these systems operate.

One of the key findings to date is the apparent difference in expected vs. actual energy production by the wind turbines in these systems. In some cases the energy capture of the wind turbines is only one quarter of the amount expected based on the wind speeds and turbine power curves. This paper discusses some of the more important operational characteristics that lead to this phenomena based on data collected from five wind-hybrid pilot projects, including two located at the National Wind Technology Center (NWTC). Topics discussed include the impact of the renewable capacity/battery capacity ratio, dumped wind energy as a function of battery voltage, and the impact of climatic conditions on power capture. Control of dispatchable fossil-fueled generators, used as backup in many systems, is also evaluated. The majority of this analysis is based on steady-state average performance data, but transient loads and their impact on inverter performance are also addressed. Also included is the effect that inverter set points have on battery charging, system dispatch, and overall system performance.

Globally, rural electrification is a national policy that can improve the well-being of rural populations. Hybrid power systems are being offered as an alternative to the conventional forms of rural electrification. Before there can be widespread acceptance of the hybrid rural solution; however, there need to be documented examples of economically competitive, commercial systems, which have good operational histories. This paper aims to facilitate the adoption of rural hybrid systems by providing a first step in a rigorous analysis of the operation of these systems.

NREL DC-Based Hybrid and Engineering Applications Programs

NREL monitors and/or operates 18 hybrid power systems installed worldwide as part of existing development projects (Flowers et al., 2000). These include two operational demonstration and test hybrid systems located at the NWTC. The NWTC also maintains an advanced program in the application of small-scale wind technology, focusing on issues such as water pumping, water purification, battery charging, and advanced power electric control of hybrid systems (Corbus et al., 1999). As part of this program, and the ongoing DC-based wind turbine application program, engineers at the NWTC have gained considerable experience in the operation of hybrid power systems, all of which are drawn on in the analysis of these findings.

System Description

All of the systems being monitored use the same basic architecture. In the typical DC-based hybrid system monitored, the connection of all of the energy-producing components occurs on the DC bus bar. The only exception to this is the conventional generator that, if present, is capable of supplying energy through a rectifier to the battery bank or directly to the AC load. The typical system uses at least one wind turbine and may use a photovoltaic (PV) array, both of which provide power directly to the DC bus through dedicated controllers. The typical system also contains a power inverter, which inverts DC power to AC power to meet the AC load and rectifies AC power from the generator to charge the batteries. The inverter may also automatically start the generator, and the system may also provide power for DC loads directly from the battery. The battery bank on the typical system uses flooded lead acid batteries with bank voltages ranging from 24 to 240V DC, and there is no power conditioning between the battery bank and the DC bus bar. Figure 1 depicts the basic system design for a single wind turbine system with a PV array. Table 1, page 6, summarizes 6 of the 18 sites that NREL is currently monitoring. Each site listed in Table 1 represents a specific system design as well as resource conditions.

Advanced System Monitoring

Of the 18 systems described, 7 are outfitted with advanced data acquisition systems that measure parameters that can be used to assess system performance. The data acquisition systems are designed to assess long-term performance of system operation, but can be reprogrammed to look at short-term operation periods as required. All of the power systems monitor and record at least the following parameters:

1) Wind speed and direction
2) Current from the wind turbines
3) Current to the battery bank
4) Current to the inverter
5) DC bus voltage
6) AC bus voltage

7) AC active and reactive power

All measurements are taken using transducers from Ohio Semetronics and are recorded with Campbell Scientific Data loggers. All data parameters are processed internally and then undergo quality-control assessment after being collected.

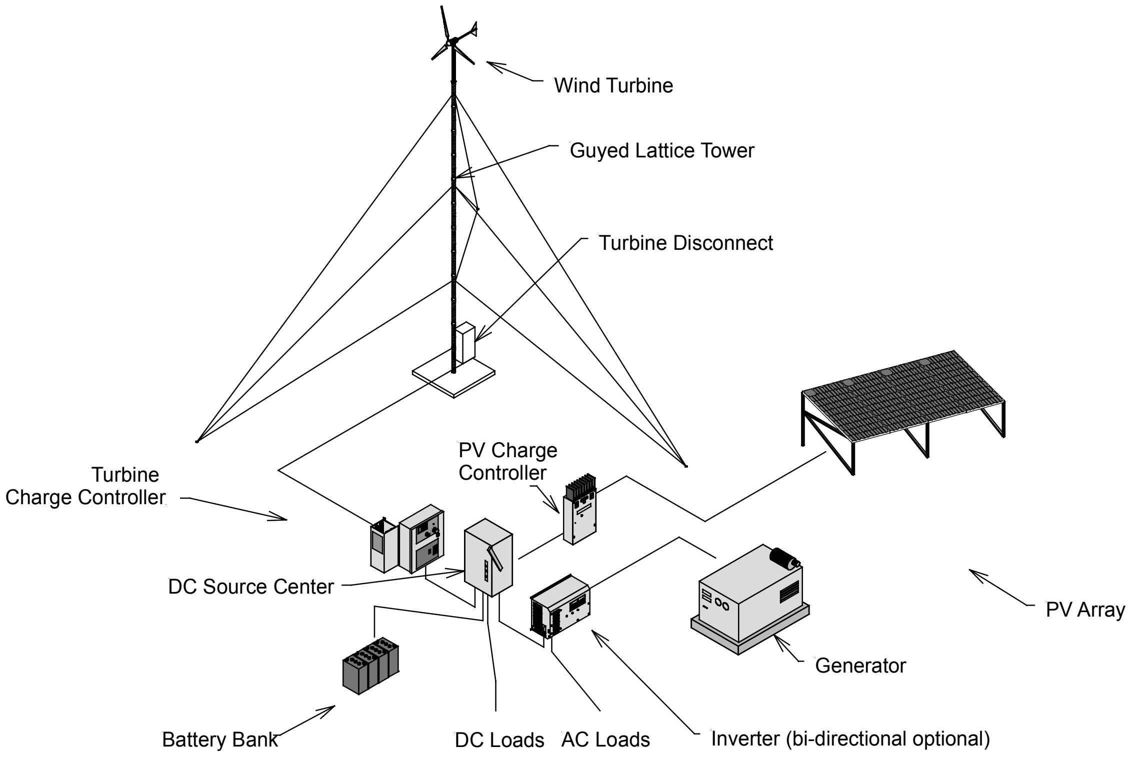

FIGURE 1: TYPICAL DC-BASED HYBRID POWER SYSTEM

Energy Concepts of DC-based Hybrid Systems

The maximum potential for energy capture from a renewable generator is dependent on the renewable resource. Furthermore, the ability to use energy from a renewable generator requires either a load to absorb energy or a means to store the energy for later use. *Spilled energy* is the term used to account for the difference in these two conditions, i.e., when the resource is available to produce power, but there is insufficient load or insufficient storage to make use of the energy.

In DC-based power systems, there is also a relation between the battery bank state of charge and the charging current that the batteries can accept. The internal resistance of the batteries primarily determines this relation. As the state of charge or the charge current to the batteries increases, the voltage across the battery bank also increases and the battery is able to accept less power. To protect the battery from overcharging, all wind turbine systems include controller circuits that limit the electrical power from the wind turbine at high battery voltages. Thus, the turbine controller accepts only a portion of the available energy above that which the load can use. Any energy not accepted by the controller is spilled energy.

Another parameter that we have determined to be important is a term we have coined *the renewable / battery capacity ratio*, which describes the amount of renewable energy production capacity as a ratio of the storage capacity that there is to store it when not used by the load. This value is given as a percentage, with values between 25 and zero. This value is also important as it indicates the amount of time that it will take to charge the battery bank using renewable resources. For example, the battery bank at NWTC site 1.8 has a capacity of 50.4 kWh (40 6V, 210 Ah batteries) and a wind turbine rated at 7 kW. The renewable/battery capacity ratio for this system is 7kW/50.4 kWh or 13.89%. Knowing that the system control logic limits the batteries useful capacity to roughly 50% of total capacity, the time it will require to fully charge the battery would be 3.6 hours, assuming that the turbine controller started limiting energy, which is likely to happen.

Initial Assessment of Monitored Data

While a number of insights have been gained from the detailed hybrid system monitoring, a key issue is how much of the energy available from the wind turbine is actually captured and used.

The impetus for analyzing the issue of poor energy capture was the realization that many of the hybrid system battery banks were beginning to display premature capacity loss, while their round-trip efficiencies were remaining high. In addition, the wind turbine production levels were consistently falling short of predictions and expectations based on the measured wind resource and power curves.

The variation in the amount of spilled energy observed in the monitoring data from the different systems indicates a strong dependence on wind resource variation, loads, system component sizes, and control strategies. Three concepts were identified (referenced in Table 1) that contribute to this phenomenon:

A. Short-term, but significant increases in battery voltage during wind turbine charging
B. Gale wind patterns in which the battery is fully charged in the first hours of the storm
C. Control-system shortfalls resulting in poorly timed diesel battery charging

These issues must be carefully considered when designing and modeling wind-based power systems, as the monitoring data indicate that only a percentage of the energy the wind turbines are capable of producing is captured for the given sporadic wind resource.

Dumped Wind Energy Due to Battery Voltage

When the battery bank is not already fully charged, a DC-based power system uses excess renewable energy to charge it. As the battery bank charges, the internal resistance of the bank increases, leading to a reduction in charge acceptance. The effects of increased internal resistance are most noticeable during periods of high charging current or during charging at high states of charge. In both situations, the battery bank voltage is driven up, in some cases up to the regulation voltage. The regulation voltage is the voltage on the DC bus at which point the wind turbine controller limits electrical power from the wind turbine so as not to overcharge the battery.

This effect is exaggerated in systems with weak or small battery banks. For weak battery banks, the internal resistance is higher. For smaller battery banks, the effective charge currents are higher, which also leads to higher internal resistance. In addition, the effective renewable generation capacity to storage capacity is large. The result of these cases can be reduced system efficiency because of premature regulation by the charge controller, and spilled energy when the battery bank appears full to the charge controller while a surplus of renewable energy remains. Furthermore, due to premature voltage regulation, the batteries do not become fully charged, leading to premature battery degradation. This degradation is typically in the form of sulfation, which further increases internal resistance. This positive feedback cycle eventually leads to premature battery failure.

Figure 2 illustrates this phenomenon for the system at the Mexican fishing village of San Juanico. As can be seen in the figure, the voltage of the battery increases rapidly when energy is available from the wind, going from 2.075 volts/cell up to 2.408 volts/cell in two hours, an apparent 25% increase in state of charge. While this clearly illustrates the effect of a weak battery bank where the battery bank voltage rises quickly, it also illustrates the similar effect of a small battery bank, which fills quickly, resulting in wind turbine regulation whenever the wind blows.

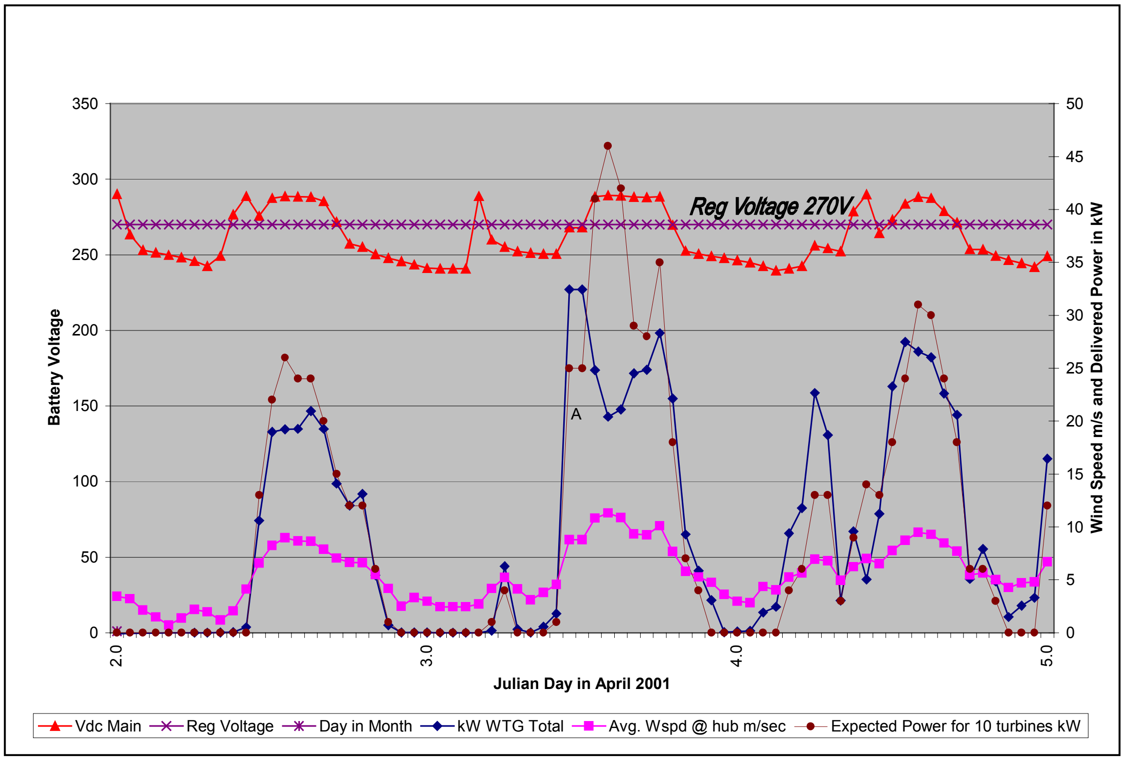

FIGURE 2: THREE DAY SAMPLE OF DATA FROM SAN JUNICO, MEXICO SHOWING THE RAPID CHAGE IN DC BUS VOLTAGE DUE TO CHARGING BY THE WIND TURBINE

Losses Due to Gale-Force Winds

Gale events, defined as a periods of prolonged strong winds, might be seen as desirable because they result in high annual or monthly average wind speeds. Depending on the length of the storm and the size of the battery bank; however, the battery bank may become fully charged early in the gale event. Any energy that cannot be used directly by the load is then spilled as it cannot be stored by the system. Depending of the frequency of the gales and their duration, this can lead to huge discrepancies between actual and expected energy capture figures using conventional estimations. Figure 3 shows an example of this event taken from the site at NWTC. Here the battery bank starts at a high state of charge and by the time of the storm on day 11, the batteries cannot accept any more power and a substantial portion of the energy available in the wind is not captured.

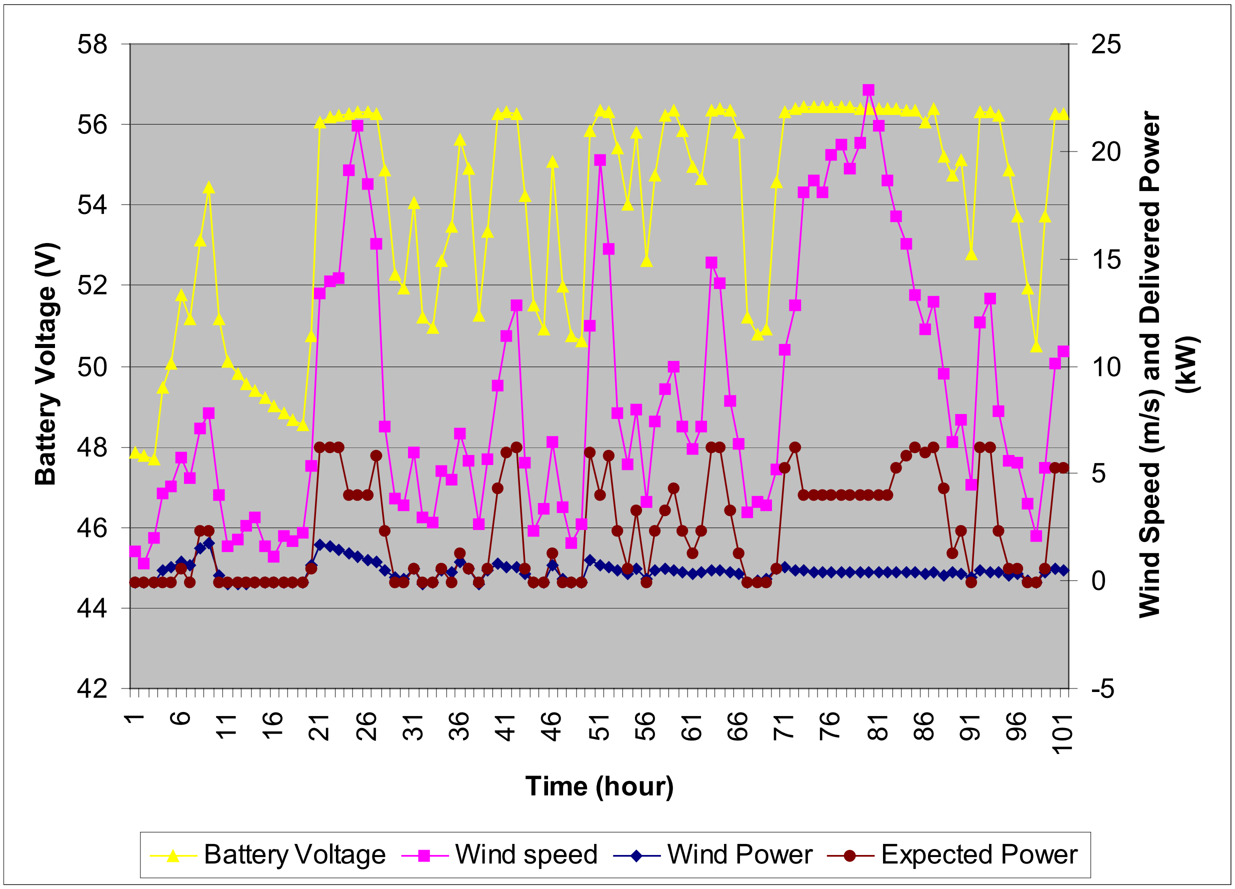

FIGURE 3: IMPACT OF GALE-FORCE WINDS ON THE ENERGY CAPTURE FOR POWER SYSTEM AT SITE 1.8 AT THE NWTC.

System Control Losses

There has been a great deal of research into the operation and control of hybrid power systems. These studies and dissertations (Barley, 1996) have looked at the issue of when the battery should be used to cover the load and when a backup generator should be started to cover the load and charge the battery bank. The principles involved are that renewable energy should be used when available, engine use should be kept to a minimum, and that the diesel, not the batteries, should be used to cover large, short-lived loads. In practice; however, most of the power systems in operation do not monitor the output of DC sources and thus have no way of determining if energy is available from renewable sources.

Typically the conventional generator is dispatched using one of two parameters, if the battery bank voltage drops below a preset level for a specified period of time or if the load current exceeds a set value. For low-battery starts, the diesel is operated through a prescribed battery-charging regimen before it is turned off. For high-current starts, when the current drops below the set value for a specified period, the diesel is shut off. In both cases, when the diesel generator is operating, energy the generator produces that is not consumed by the load is used to charge the battery bank. Both of these conditions are based on the protection of the battery bank and neither account for power sources attached to the DC bus.

For example, if the diesel is started due to a low battery voltage, and then renewable production increases to where it can supply all of the current that the batteries are able to accept, the diesel will still remain in operation while the inverter executes its charge cycle. This process can last many hours, leading to spilled energy from the wind turbine. Similarly, if the diesel generator is started due to high load current, it is simultaneously possible for the renewable resource to be providing enough power to cover the load and charge the batteries. Since the inverter measures the load current on the inverter branch of the DC circuit, it cannot discern where the DC power is coming from and assumes the load is being supplied by the batteries resulting in an unnecessary diesel generator start. When this occurs, the generator meets the AC loads and the inverter then tries to charge the batteries from the generator until the load current falls below the set value, again leading to spilled energy from the wind turbine. Figure 4 shows this for the system in Aqua Fresca where the generator is started frequently to cover auxiliary loads and thus limits the energy that can be obtained from the ample wind resource.

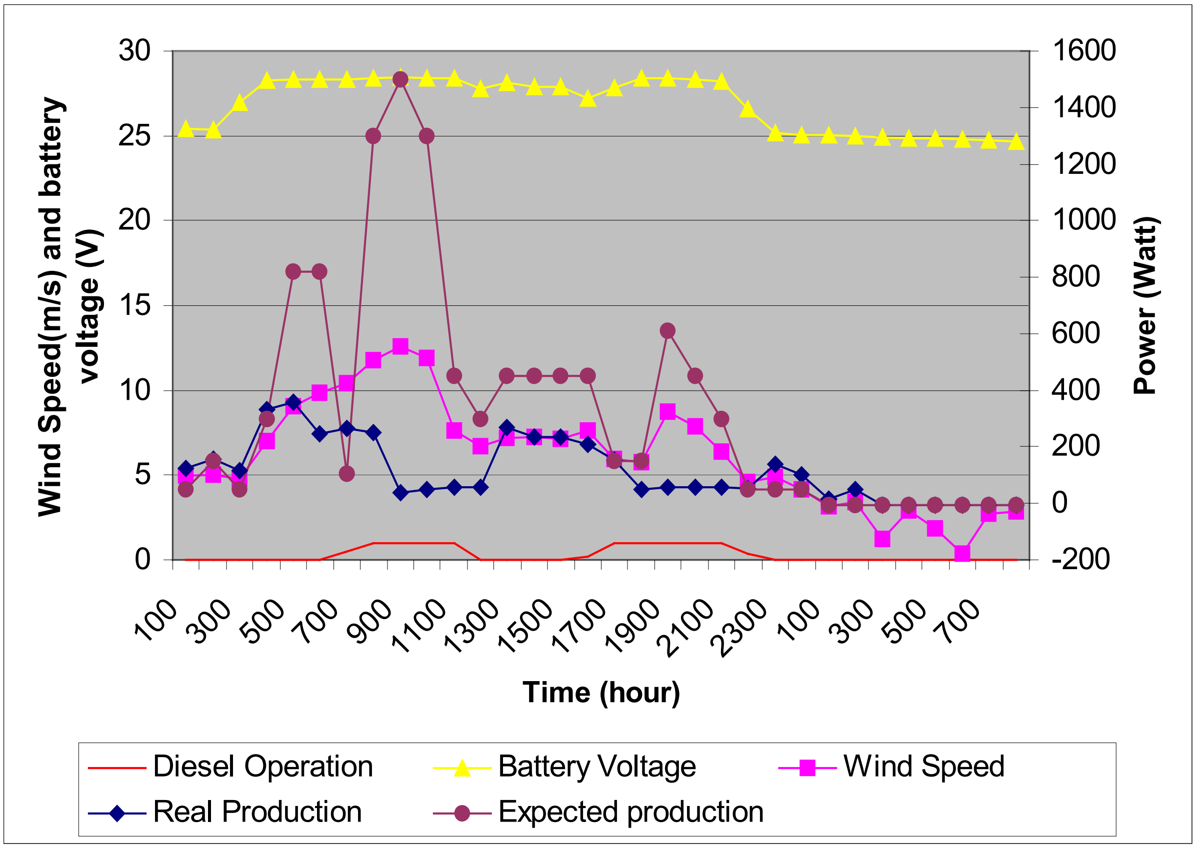

FIGURE 4: IMPACT OF CONTROL ISSUES AT THE AQUA FRESCA SYSTEM IN JUNE OF 2000

Impact of System Inefficiencies.

The system inefficiencies discussed previously are often overlooked in system designs, yet they result in high system losses. Table 1 shows the different systems and the types of conditions that seem to impact the capture of wind energy most dramatically. Five of the systems are then discussed in more detail.

The system efficiency of the San Juanico hybrid system is affected by a small (and weakening) battery bank. The system has a high renewable/ battery capacity ratio of 18%. This ratio suggests that the wind turbine array alone, when operating at rated capacity, could completely charge an initially empty battery bank to full in only five hours, or from a 50% state of charge in two and a half hours. This high wind generation to battery capacity ratio indicates the tendency for rapid charging of the battery bank, leading to premature voltage regulation and thus spilled energy. In addition, the premature voltage regulation of the San Juanico system has lead to high levels of battery sulfation, which reduces battery efficiency and will ultimately lead to shortened battery life. The amount of energy spilled over the year 2000 due to battery bank size was 22% of the total energy produced by the wind turbine array over the same year.

TABLE 1: DESCRIPTIONS OF THE SUX POWER SYSTEMS ANALYZED FOR SPILLED ENERGY

Site Name	System Components ψ			Ren/bat capacity ratio	Basic weather	Logging start date	Basic loss effect ⁎
	PV	Wind	Diesel				
San Juanico, Mexico	16	70	85	18 %	Coastal	March '99	A
Isla Contoy, Mexico	0.256	1	4	6 %	Coastal	Jan '99	A, B
Isla Tac, Chile	0	14	12	14 %	Seasonal	Oct '00	B, C
Aqua Fresca, Chile	0	3	15	Unknown	Seasonal	April '01	A, B, C
Site 1.8: Chile Replication, NWTC	0	7	10	14 %	Storm driven	March '00	B
Site 1.9: Isla Contoy Replication, NWTC	0.256	1	None	6 %	Storm driven	May '00	B

ψ System components units in kW, except batteries, which are in kW-hours

⁎ See page 4 for descriptions different loss effects

The school power system in Aqua Fresca, Chile, suffered a 57.2% loss of energy during the month of December 2000. This was mostly due to two factors, poor diesel generator dispatch and gale-force wind events. The school is run on two circuits, one from the wind-battery systems and the second from the school's large diesel engine. The hybrid system is designed to provide power 24 hours per day, while the diesel provides power for peak load periods in the morning and evening. The power converter used in the system automatically initiates a charge of the battery bank when the diesel is operational, resulting in the battery remaining at a high state of charge and limiting the amount of energy that can be accepted from the renewables. The average battery bank voltage for the month given was 26.9V DC, 2.9V above the nominal value for the system. It is clear that the renewable portion of the system could provide more of the school load, though this would require modification to the control logic of the inverter and a change in the operational behavior of the diesel engine.

The test systems at NWTC suffer from losses primarily resulting from gale wind events. The typical wind profile for the test center is prolonged periods with little or no wind, followed by strong westerly winds accelerated as they sweep over the ridges and down through the canyons along the Colorado Front Range, primarily driven by large pressure fronts. These wind events last between 6 and 24 hours and are usually in excess of 6 m/s. Two power systems are installed at the NWTC and thus good comparisons can be made between them. The power system at site 1.8 has a renewable/battery capacity ratio of 14%, while the system at site 1.9 has a ratio of 6%. This means that site 1.8 will reach full battery capacity twice as fast as site 1.9 if the renewable energy is available to charge the batteries at the maximum rate. Given that most battery banks operate between 50 and 100% state of charge, using only half their capacity, an empty battery bank at site 1.8 will charge in roughly 4 hours at the maximum rate from the turbine, while the battery at site 1.9 will require over 8 hours. Given the length of most gale wind events, it seems clear that the system at site 1.8 will end up shedding more energy than site 1.9. And, in fact, site 1.8 experienced losses totaling 77.7% during December 2000, while site 1.9 had total losses between January and March 2001 of only 18%.

The system on the island of Tac in southern Chile had losses of 42.1 percent during the month of June 2001, primarily due to gale events and poor diesel dispatch. This community suffers not only from high-wind events, but also the peak load in the evening usually forces the diesel to start and remain operational for several hours per day, even if there is sufficient wind to provide all of the power requirements. During this time; however, the diesel is used to provide energy to the battery bank and the renewable generators continue to provide power, which is also stored, resulting in high battery voltages, turbine regulation, and lower renewable energy capture. As described earlier, the large renewable/battery capacity ratio of 14%, combined with climatic conditions featuring gale wind events, result in the battery bank reaching a full state of charge early in the storm's cycle, as well as high spilled energy during the rest of the storm.

These examples suggest the need for improved design of wind-hybrid power systems and their control system components. While these effects have long been known to exist, they have not been clearly quantified. With better instrumentation at more sites, we have begun to get a clearer picture of the real impact of these effects, which have turned out to be quite large, and which warrant more study and evaluation.

Possible Solutions

Among the conclusions that can be drawn from this work is the need for a better understanding of the impact of the renewable capacity to battery capacity ratio. There may be a clear economic trade-off between the size of the battery bank and the installed renewable capacity although this is unknown. It is clear that in some systems there is an over capacity of renewables that cannot be used due to undersized storage or poor system control, so a trade-off between the battery capacity and renewable capacity is evident.

There are some options that can be used in the design of hybrid systems to reduce the losses of renewable energy potential, including:

- Improved use of discretionary loads so that any excess energy can be utilized instead of spilled. Examples would be water pumping, water purification, heating, and potentially, ice making or battery charging.
- Carefully considered renewable production/battery capacity ratios to ensure that system designs fit more closely with projected weather patterns for the site area.
- Improved battery selection to ensure that the batteries used and their capacities are capable of providing the required voltage regulation. For example, batteries with high internal resistances will have higher voltage variations when undergoing charge and thus will result in higher losses and more time spent at or above the wind turbine regulation voltage.
- Improved system control through better automation, supervisory control, and operator education to reduce the losses associated with poor control of the diesel generator.

An additional issue of importance is the modeling of small hybrid power systems. Most systems are initially investigated through the use of computer-based models that assess the components to be considered. Although some of these models consider battery voltage in determining the system losses, none that we are aware of consider voltage regulation on the part of the wind turbine or PV controller. The models are useful in predicting component operation, dispatching, and performance, which are useful in system design, but may be over predicting the available production of renewable energy. Since the power systems are very dependent on climatic conditions and the battery, both of which can lead to highly reduced power capture, any design tool for hybrids must accurately address this issue. Without this assurance, it will be hard to accept as accurate the predicted production rates of a wind turbine based solely on its power curve. Some manufacturers do include statements about the potential reduction in power delivery due to these types of issues, though none relate it to specific climatic conditions or system design.

Conclusion

The monitoring of several small wind-hybrid power systems in different areas worldwide has shown that the spilled energy from small wind turbines in hybrid applications is likely a more significant problem than previously considered. Reductions in energy capture as high as 78% were found in specific cases. In addition, all estimates of the losses due to uncaptured energy have largely been empirical in form, with little technical backing or scientific consideration. Given the installed unit cost of the equipment, losses are of critical importance in optimizing the performance of the equipment in hybrid applications. Through the analysis of data from different power system designs and climatic conditions, it is clear that there are specific phenomena that can lead to high rates of dissipated power. It is also clear that there exist engineering and design solutions that should be considered prior to the implementation of new projects. It is evident that although some computer simulation models do account for battery voltage when assessing losses and energy capture, they do not account for the voltage regulation provided by wind and PV controllers or the true impact of low renewable/battery capacity ratios. The difference and impact of these two controlling features is something that should be considered in future analysis. It is also shown that component and control manufacturers must become more aware of system power flow, specifically on the DC bus, so that equipment can be designed to maximize power capture from renewable sources. Finally, there are a number of easily implemented solutions that can reduce losses associated with these conditions.

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