U.S. DEPARTMENT OF ENERGY

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under Contract DE-AC05-76RL01830

Demonstration of Security Benefits of Renewable Generation at FE Warren Air Force Base

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GD Seifert

December 2010

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Prepared for
U.S. Air Force
FE Warren Air Force Base and the
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Pacific Northwest National Laboratory
Richland, Washington 99352

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Executive Summary

The 2006 National Defense Appropriations Act directed the Department of Defense (DOD) to coordinate the testing of a wind turbine (new to the U.S. market) at an Air Force installation as a follow on to analyses conducted by the Pacific Northwest National Laborabory (PNNL) as part of the 2005 DOD Renewable Assessment. The earlier study simulated the performance of renewable power produced from wind turbines, solar photovoltaics and geothermal energy as part of a Base-wide energy security solution. The simulation concluded that integration of renewable generating resources with emergency generators, typically diesel-fired, could significantly enhance energy security and extend power supplies during prolonged commercial grid power outages. A simulation is insufficient to convince skeptics of the reliability of renewable resources, especially those that produce power only intermittently, like wind and solar. Therefore, Congress requested a field demonstration be performed using a wind turbine because wind power is the most erratic of all renewable resources.

Following this direction, the Air Force identified a site for the wind turbine demonstration and contracted with the Idaho National Laboratory (INL) and PNNL to conduct the demonstration and implement other provisions in the appropriation bill. INL identified a wind turbine that met the legislative requirements (the Gamesa G-80), and with the support of PNNL and the Air Force, selected FE Warren Air Force Base for the demonstration. FE Warren has an excellent wind resource and was already a host to two wind turbines and could accommodate a third. The G-80 is rated at 2 MWs versus the two existing 660 kW turbines, consequently wind production would more than double. Procurement, siting, and acceptance testing of the new turbine was completed in early 2010. The field test was conducted in late April 2010. (The use of specific brands and trade names in this document is for research documentation only and does not constitute an endorsement of these items)

Coincidently, in 2006 the Defense Science Board (DSB) empanelled advisors to address DOD's dependence on fossil fuel both in theater and on Base. This panel issued its report "More Fight, Less Fuel" in February 2008[1]. One of the primary conclusions reached by the panel was that military facilities are almost wholly dependent on electrical power from the commercial power grid, which is in turn vulnerable to potentially catastrophic outages from a variety of conventional and unconventional sources. Loss of commercial power for a prolonged period would seriously jeopardize DOD's mission and national defense. A risk the panel recommended DOD address was to take independent action to isolate critical missions and installations from this vulnerability. One means to do so is through increased use of indigenous energy sources; resources that do not face resupply risks such as those dependent on fossil fuels. These energy sources are predominately renewable resources, although stored fuels in the form of reservoirs behind

[1] Defense Science Board (DSB). 2008. DOD Energy Strategy: More Fight – Less Fuel. Washington, D.C. http://www.acq.osd.mil/dsb/reports2000s.htm. Accessed December 2, 2010.

dams, coal reserves at power plants, and nuclear fuel in reactors provide similar protection.

To address the energy security concerns raised by the DSB panel, generators dedicated to DOD loads need to provide a level of reliability and power quality similar to that of the commercial power grid. There is widespread skepticism that renewable resources can do so, although the PNNL security simulation indicated that if they are integrated with existing emergency generators, they can meet this challenge. If this can be demonstrated, it will reduce some of the barriers to implementing the recommendation of the DSB panel to increase reliance on renewables and other indigenous power resources to secure power supplies for critical military missions and installations. With this in mind, the FE Warren demonstration took on new significance, and the test plan was developed accordingly.

The field test was successfully completed in April 2010 and achieved all of its major objectives. The test demonstrated that a DOD Base can operate without grid power by relying on a mix of wind power and conventional diesel generators representative of the kind of back-up generators widely used by DOD for emergencies. The test demonstrated that wide variance in wind turbine output can be accommodated by diesel generators equipped with appropriate controls without noticeable impact on power reliability or quality and therefore, that intermittent renewable power resources can be a part of DOD facility energy security plans. Moreover, renewable resources can produce power year-round as well as during grid outages. As a result, they can reduce utility power purchases and thereby pay for some or all of their costs. In fact, after this test, the three wind turbines at FE Warren have continued to operate as expected. They provide 100% of Base power during limited periods when winds are favorable and about 20% of the overall energy used by the Base.

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Background

This field test report is the result of two related Congressional directives, as well as issues raised by the Defense Science Board (DSB) in its February 2008 report (the DSB report), "More Fight-Less Fuel."[2] Within the military construction budget for the Department of Defense (DOD) energy conservation investment program (ECIP) for fiscal year 2002, Congress requested a systematic and objective assessment of renewable resource potential on Department of Defense (DOD) lands. This request was partly in response to the California energy crisis in 2000-2001, the threat it posed to military missions in the state, and the potential contribution DOD could make by developing renewable resources on its lands and diversifying its resource base away from fossil fuels. The resulting report was provided in March, 2005[3]. The Renewables Assessment (RA) Program that resulted included an analysis of the security benefits of renewable generation. This analysis simulated the performance of selected renewable resources in conjunction with on-Base emergency generation to evaluate how long mission critical functions could be sustained by supplementing existing emergency generation and associated fuel supplies in case of a prolonged grid outage. A summary of project results was included in the RA report and a PNNL report. The latter report has restricted distribution due to data the installation used as an example for the simulation wanted to protect from public disclosure.

Findings from the energy security simulation resulted in further direction from Congress in the 2006 Defense Appropriation Act for a demonstration using wind turbines.

> "*Department of Defense STARBASE program: Provided further, that of the funds made available under this heading, $4,250,000 is available for contractor support to coordinate a wind test demonstration project on an Air Force installation using wind turbines manufactured in the United States that are new to the United States market and to execute the renewable energy purchasing plan.*"

Wind turbines were recommended because to address the widespread skepticism regarding the reliability of wind power and other renewable resources that are highly variable. FE Warren AFB, located on the eastern plains of Wyoming was selected as the demonstration site because of its superior wind resource.

On May 2, 2006, the Under Secretary of Defense asked the DSB to create a task force to examine DOD Energy Strategy. Citing the significant risks from increasing energy demands to both our nation and our military forces, he challenged the task force to find opportunities to reduce DOD's increasing energy demand, assess the potential commercial and security benefits to the nation from demand reduction, and identify institutional obstacles to implementation of demand reductions. The resulting report[2]

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[2] Defense Science Board (DSB). 2008. DOD Energy Strategy: More Fight – Less Fuel. Washington, D.C. http://www.acq.osd.mil/dsb/reports2000s.htm. Accessed December 2, 2010.

[3] Office of Secretary of Defense. 2006. Report to Congress, Department of Defense,DOD Renewable Energy Assessment Final report. www.acq.osd.mil/ie/energy/library/final_renew_asesmtreport.pdf. Accessed December 2, 2010.

highlighted the vulnerability of the commercial power grid as a threat to military missions as well as civil society. The report also recommended military installations develop the capability to provide their own power supplies in case of prolonged outages. These concerns were reflected in the final test plan for the FE Warren demonstration.

Summary of Initial Report

The DOD Renewables Assessment Program included a simulation of the performance of three renewable resources in conjunction with back-up diesel generators typically found at military installations. That simulation set out to establish the existing capability of a representative military base to provide continuous power for a prolonged period with the addition of supplemental power from three renewable resources: solar, wind, and geothermal. The resulting limited distribution report, "Security Benefits of Renewable Generation: A Case Study," provided the following key findings:

- *The definition of mission critical loads is both unclear and variable depending on circumstances.* This point was also noted in the DSB report, leading to a recommendation for the ability to "island" entire installations and potentially surrounding communities in case of catastrophic grid failures from natural or intentional events.

- *Each renewable resource had the potential to significantly extend the operation of emergency generators by increasing the hours of operation at the rated capacity of the generators.* By conserving fuel that would otherwise be used, the renewable resource allows the existing conventional generators to reduce operation to supply the same amount of power. One way to look at this is that the supplemental renewable generation acts as additional fuel storage. However, this observation assumes existing back up generators are grid connected. Most emergency generators do not run in parallel with the utility grid, although all can be modified to do so.

- *Each renewable resource can also be used to increase the* <u>*total*</u> *generating capacity at an installation because the generation is additive to the available emergency generation.* However, intermittent renewable resources require operating loads to match the additional capacity. This mode of operation does not extend the operating hours of existing conventional generation. In other words, the additional renewable generation can be used to meet non-critical power needs as available, although if it is used in this manner, existing emergency generators are still constrained by the available fuel supplies.

- *Baseload renewables, such as geothermal, offer more advantages and more modes of operation than intermittent renewables like solar and wind.*

- *The variability of renewables is not a significant factor as long as emergency generation and fuel storage (or replacement) is sufficient to cover periods when* *renewables are not available,* such as seasons when the wind may not blow and winter periods when solar panels are less productive.

- *Combinations of intermittent renewables, such as wind and solar, compensate for the variability of each by diversity of the energy production profiles.*

- *The primary limitation on operating level and duration is the amount and kind of renewable resources available.* If renewable resources are limited to on-site sources, the type and availability of renewable resource may limit both operating level and duration. If the resources available include those near-, but off-site, access to an increased range of renewable resources and power production increases the potential to supply more loads for longer periods.

- *Utilization of renewable resources near installations potentially provides multiple security and economic benefits*, including: access to higher quality, lower price resources; capacity to supply power to increased loads potentially including nearby civilian facilities; and integrating security planning with local utilities that would face the same energy disruption as the installation.

In addition, the report noted that the routine operation of on-site renewable resources would not only assure their availability during emergencies, it would also repay some or all of their initial cost by displacing purchases from the local utility. This contrasts with the installation of conventional generators just in case there is an emergency. These generators typically cannot be operated routinely due to restrictions on air emissions and thus are unable to repay their initial costs. Moreover, producing power from small fossil-fueled generators is rarely less expensive than purchased power from a utility; consequently routine operation would actually increase power costs.

The report concluded that renewable resources, even intermittent wind and solar, can be used to enhance energy security for military installations under specific conditions. Those conditions are that there is adequate back-up generation using conventional generators to supply critical loads and that these generators and additional renewable generation are all connected to the on-Base grid so they can provide power to critical loads. The enhanced security value is based on a reduced need for refueling conventional generators and, potentially, the ability to supplement power supplied by conventional generation to serve non-critical loads on an as available basis. Because this conclusion was based on a simulation rather than field data, the report recommended field demonstrations, particularly of wind and solar power, because they are the most intermittent of the renewable resources. Of these two, wind presents the biggest challenge because solar is generally more predictable, resulting is less uncertainty daily, weekly and from season to season.

Renewables Role in Installation Energy Security

The 2006 National Defense Authorization Act (NDAA) noted previously included direction from Congress to demonstrate the concepts described in the RA security report using a new design, domestically manufactured wind turbine. The purpose of the demonstration was "to test the security and reliability of wind generation on base." To implement this recommendation, PNNL reviewed wind resource information from the DOD Renewable Assessment Program in conjunction with the Air Force to identify sites where a demonstration would be the most productive in terms of making the best use of a new wind turbine and the least disruptive to installation operations during and after the demonstration. FE Warren Air Force Base in Cheyenne, Wyoming was selected. At the same time, INL surveyed new, domestic wind turbine models and identified the Gamesa G-80 as the closest match to Congressional direction. This turbine was newly introduced to the U.S. market and is being manufactured in Pennsylvania.

Once an appropriate site and turbine model was selected, the site was visited to identify a location for the new turbine and site-specific specifications developed to procure the test turbine for the demonstration. The procurement, site preparation, installation, and acceptance testing process was completed in early 2010. In the interim, the Under Secretary of Defense requested the DSB create a task force to examine DOD energy strategy and the risks that energy reliance presents to the nation and military.

DSB Energy Security Concerns

The DSB report[4] included two findings relevant to the FE Warren test. First, DOD faces an unnecessarily high and growing battlespace fuel demand and second, military installations at home and abroad are almost completely dependent on commercial energy infrastructures that are vulnerable to the disruption of a fragile power grid. The report's conclusions were informed by the findings from the earlier DOD Renewable Assessment, including the evaluation of the role renewables could play to enhance installation energy security. These results were briefed to the DSB energy panel in light of its concerns regarding the vulnerability of military missions and national security to disruptions of the power grid.

The framework the DSB report[4] adopted was of a prolonged (several month) outage that could be triggered by either physical or cyber attacks or a combination of both. The panel's concern about grid reliability was caused by "not only the complete dependence of critical national security missions on the grid, but also its centrality to all facets of the nation's economic life." [op. cit. page 19] These concerns were based on recent outages that illuminated the dependency of other infrastructures on reliable power supplies. Recent outages considered included power interruptions to water and sewage services that resulted in sewage spills; outages of booster pumps on mainline fuel pipelines resulting in fuel shortages; loss of broadcast and common carrier communication systems; and outages of district heating and cooling systems that could risk lives as well as lead to catastrophic damage to water systems during subfreezing weather. Also highlighted was the loss of critical safety systems at chemical plants and hazardous materials facilities, including laboratories at universities and other research institutes.

[4] Defense Science Board (DSB). 2008. DOD Energy Strategy: More Fight – Less Fuel. Washington, D.C. http://www.acq.osd.mil/dsb/reports2000s.htm. Accessed December 2, 2010.

These hazards are in addition to the expected economic damage from reduced commercial activity, disruptions of supply chains, and disruption of transportation systems from outages of traffic control devices, bridge lifts, locks, and central control systems. [op. cit. page 21]

The DSB report[4] highlighted four potential risks that would lead to grid outages of various durations.

- The first is *overloading of grid components*. Power system planners include cushions and options to prevent overloading. Although the direct cause of most recent grid outages were things like fires and trees contacting transmission lines, the primary outage *mechanism* was overloading of other lines from the loss of the lines in the path of the trees or fires. Planners and equipment manufacturers also plan for "protection in depth" starting with automatic relaying of devices so that they are not damaged and thereby protecting other facilities and equipment downstream from damage. More accurately, grid outages are the result of automatic protection than actual physical damage, although without that protection physical damage would result.

- The second risk is *natural disasters*. Utilities that are exposed to frequent natural disasters are relatively well prepared for them, and the resulting outages *of the bulk power system* are generally short-lived. However, outages *to retail customers* may be prolonged because the lower voltage distribution systems that serve retail customers are less robust and have fewer protections making them more susceptible to physical damage from wind, fire, trees, waves, flying debris, etc. Many critical military and civilian facilities are served at the distribution level rather than directly from the high voltage transmission system, although many installations are changing to high voltage service to obtain an extra margin of protection.

- The third risk is from *deliberate physical attacks*. These attacks may originate from agents hostile to the government or just disgruntled employees. Hostile acts against the power system have been linked to both domestic and foreign agents and to insiders or former insiders. Fortunately, few have been successful in the U.S.

- The final risk is from *deliberate cyber attacks*. Electricity flows at the speed of light, and generation must equal demand in real time. Maintaining this balance is critical to providing power quality as well as reliability. This process has been greatly aided by equipping the power grid with sensors, controls, and switches that can be monitored and operated remotely via the internet and over private networks that may be linked to the internet. Communication with these sensors and controls is an essential element of power system operations. Although most of this communication occurs over secure networks, there are often common connections to computers that are also connected to the internet. Anything linked to a communication system is vulnerable to a cyber attack. An attack on a private network would require physical access to that network; however a public communication system is vulnerable to a remote cyber attack. The vulnerability of the electric grid is also compromised because both power and transmission capacity are traded in real time through electronic exchanges, like the stock market. Manipulation of either control systems or markets can lead to scenarios that damage or disable critical facilities by overloading grid components and other control or management mechanisms.

Grid outages for any of these reasons could compromise critical military missions as well as the economy of the nation. The significance of an outage depends on both its duration and cause. An attack on the system from a foreign source (physical or cyber) that results in a prolonged outage could fundamentally change the military mission of a facility, for example from training to tracking down terrorists and sabatours. Accordingly, the DSB report placed a premium on resilience in the face of potential outages. That is reflected in the recommendation that installations reduce dependency on the commercial power grid by adopting an "islanding" capability. The "island" would be a self-reliant power grid within the larger commercial power grid but sustained by resources dedicated to and potentially controlled by the installation.

Islands could range in size from "microgrids" that just support specific, critical military facilities up to "regional islands" that have one or more military installations and on-site generation at their core, but take advantage of commercial power infrastructure to sustain the island using indigenous energy supplies, including stored fuels, that allow specific generators to be relatively self-sufficient. If power from these resources can be directed to support critical military and potentially civilian missions and infrastructures, those functions could continue for months despite a massive grid outage. This would obviously facilitate restoration of the power grid and minimize disruptions caused by a prolonged regional power outage. Using these criteria, roughly 400 of the 450 major DOD installations exist within a 50-mile radius of adequate, self-sufficient generating resources to support a "regional island." To be clear, these resources and the power grid supporting them would need to be reconfigured to tap this potential.

The original DOD Renewable Assessment report recommended a small-scale demonstration of the concept of coupling emergency generators with renewables to extend Base operations during an outage. Extended operation would be essential in light of the DSB report recommendation for Bases to develop islanding capability. Accordingly, the field test plan was modified to demonstrate Base islanding rather than a microgrid dedicated to a few critical loads or buildings.

Framework for the Energy Security Island Demonstration

The demonstration project was based on observations and conclusions from the initial DOD Renewable Assessment energy security report[5] [op. cit. pps iv-v]:

> "Military bases in the U. S. usually rely on the utility grid for electric power. The reliability of the grid is typically at least 99.9% or better. Under normal operating conditions, this means that the grid supply will be unavailable, on average, a total of slightly less than 9 hours per year. The military employs autonomous emergency back-up generation at each site to supply base power requirements during times when the grid supply is temporarily interrupted. Typically, this back-up generation is provided by multiple diesel-electric generating sets (or other fossil-fueled engine/generators) deployed as appropriate to serve the spatial load distribution and load priorities peculiar to each base. The ability to ride through any grid outage depends on fuel storage capacity. Bases usually store sufficient fuel to provide emergency power for the duration of the naturally occurring grid outages experienced historically at each site. In general, the fuel storage capability at any site is not expected to be adequate to provide continuous emergency power for the long-duration threat envisioned by the DSB.
>
> A military base could simply build more fuel storage capacity to run existing back-up generators through grid outages of longer duration, or add more generators to serve a greater share of an installation's needs. However, this solution has several drawbacks including the cost and logistics of maintaining strategic fuel supplies and environmental disadvantages associated with fossil fuel transportation, storage and combustion. Renewable energy, such as that provided by wind, solar and geothermal sources, offers environmentally benign power generation with zero fuel cost. On- or near-site renewables, even if they are intermittent generators (such as wind or solar systems) could supplant fossil-fueled emergency generation whenever they are available. Using renewable generation opportunistically would defer emergency fuel use and thereby extend the outage duration that can be accommodated. Thus, the use of renewables available in the vicinity of military bases can be considered the equivalent of installing bigger fuel tanks for emergency power needs. In addition to enhancing energy security and base mission readiness, renewables also offer the potential for economic power production and energy cost savings during periods of normal operation.
>
> The reliability value of renewables on military sites resides primarily in their ability to extend the autonomous operation of the base during times when grid power is unavailable, in conjunction with a modest number of conventional back-up generators. In this role, renewables primarily extend the operation of conventional generators without the need for additional fuel supply or re-supply.

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[5] Office of Secretary of Defense. 2006. Report to Congress, Department of Defense,DOD Renewable Energy Assessment Final report. www.acq.osd.mil/ie/energy/library/final_renew_asesmtreport.pdf. Accessed December 2, 2010

> Renewables' role in energy security rests in their indigenous nature, specifically, their lack of fuel requirements and ease of distribution on and near military installations. This provides military installations with access to local resources in times of power shortages, although this may require partnering with local utilities to reconfigure local power grids."

This vision is in contrast with the predominant emergency generation deployment mode on most installations, which is for back-up generators to be operated in isolation from the grid during outages and primarily located to protect loads where it is required by law, such as water and sewer pumps and hospitals rather than at each and every load that could be considered mission critical under some conditions. It also assumes the solution to military energy security can be found in concert with the local utility rather than independent of it.

Field Test Plan: Scope and Metrics

FE Warren AFB is well located for wind power production in terms of wind power potential. In 2005, two, Vestas 660-kW wind turbines were installed. The performance of these has exceeded expectations to date. The turbine selected for the energy security demonstration was a 2-MW turbine manufactured by the Spanish turbine firm, Gamesa, in its new U.S. plant in Pennsylvania. Its addition brought total on-site generating capability to just over 3.2 GW during peak production. The three turbines provide approximately 20% of the Base energy requirements on an annual basis and meet 100% of Base needs when winds are favorable. The presence of three turbines allowed for a test plan that could use various combinations of generation to both better match electrical demand and to vary the contribution to Base energy supply from wind power. Like most military installations, FE Warren's back-up generators are not grid connected. Unlike most installations, it has an energy management system that could be used to monitor power quality and other metrics during the demonstration.

Working within the assets available at FE Warren and the constraints of routine operation and mission, a test plan was developed by Idaho National Laboratory (INL) in conjunction with PNNL, installation staff, the local utility privatization contractor (High West Energy), the supplemental power provider (Rocky Mountain Generating Coop) and the Western Area Power Administration (WAPA). To replicate the operation of on-site diesel generation, it was necessary to have generators coupled to the Base grid. Modification of existing on-Base emergency generators was not practical simply for test purposes. Accordingly, two, 2-MW diesel generators were rented specifically for the test. Doing so provided modern generators with both state-of-the-art efficiency and emission profiles; it also provided additional sources for measurement of fuel consumption and related operating data. To assist with load balancing, a load bank with capacity up to 1.250 MW was also rented. Details for the test plan and of the test can be found in the INL report, "FE Warren AFB Energy Security Test Report[6]."

Purpose

The primary purpose of the test plan was to determine the impact wind turbines have on energy reliability, security, and power quality. Doing so under realistic operating conditions would validate the conclusions of the DOD Renewable Assessment Energy Security report. It would also reinforce the recommendations of the DSB task force that renewable resources are compatible with normal AFB mission loads and operations and can reduce diesel fuel requirements during "island" operation.

[6] Publication pending at time of this report.

Tests and Metrics

The tests planned would evaluate the impacts when wind turbine power is added in parallel with generator power versus generator power alone for a given average electrical load, over a given period of time, with various wind speeds. The test plan included documenting all power quality issues related to running the wind turbines and generators in parallel. A critical test objective was to determine if electricity users on-site noticed any difference in power quality or reliability during the test and if so, what they noticed. That was a qualitative measure but an important metric inasmuch as perceived power quality problems can lead to biases against renewable generation. Data from the test was also used to evaluate how wind energy impacts emissions, a metric of potential interest if wind power is used to supplement conventional power purchases during routine operations. Doing so would reduce emissions from power purchases that could be used to offset those associated with mission requirements. For example, displacing power from coal-fired power plants with wind will reduce the Base's emissions "footprint," which "makes room" for mission-related emissions from aircraft. In this test, however, the emission metric will be based on the power produced (and avoided) by the diesel generators used for the test.

The test was conducted using a portion of the FE Warren AFB electrical grid, wind turbines on the AFB, and rented, containerized, 2-MW sized diesel generators. The primary purpose of the test was to determine the impact wind turbines have on energy security by validating that wind turbines were compatible with normal AFB mission loads when in a back-up power scenario. The test also determined diesel fuel reductions and impacts when wind turbine power was added in parallel with diesel generator power. And, any power quality issues related to running the wind turbines and generators in parallel. Data from the test can be used to evaluate how wind energy can allow military installations to meet emissions requirements.

In planning the test, it was decided that a more basic scenario would be attempted to show that even a relatively simple wind-diesel hybrid power system could be utilized to maintain power supply for Base loads. This is a slight misnomer however, because even a simple wind-diesel hybrid system is complicated to plan and operate. The wind turbines have their own controls internal to each turbine, and have communication back to a centralized supervisory control and data acquisition (SCADA) computer, where basic observation and control could also be performed. The software packages on the SCADA computer are basic systems provided by the specific manufacturers, one called VRPWin for the two Vestas 660-kW turbines, and the other called SGIPE for the Gamesa 2.0-MW turbine. Communication from the SCADA computer to each Vestas turbine is done one at a time over a phone modem channel. Communication to the Gamesa turbine is over an Ethernet-phone modem-Ethernet channel. The computer can talk to the Gamesa and one Vestas at the same time, but not to both Vestas machines at once.

These communication and control systems could be integrated further in the future, but for the test used wind turbine SCADA/energy management system (EMS) and control systems separate from the diesel generator controls for the most basic system possible.

With separate control systems, the primary means of frequency control on the islanded system was with the diesel generator governor controls. The wind turbine controls and power electronics were secondary to the diesel controls. The wind turbines were set to run in power factor mode as they normally do with a utility connection, and the power factor typically runs between 0.98 lagging voltage amps reactive (VARS) and unity.

Other equipment used for the test setup included the two 2.0-MW diesel generators, fuel monitors, cabling, step-up transformer, manually controlled load bank with steps up to 1,250 kW to provide extra load if Base loads did not meet expectations, three Elspec power quality meters to monitor power system parameters, anemometer tower and SODAR systems to monitor wind parameters during the test, temporary interconnect hardware and disconnects, and other various equipment to support the test. Even though this was an off-utility-grid system, it still met IEEE 1547 standards and recommendations for interconnection of distributed generation resources with electric power systems.

Other components were considered for the test, but were not included so that the most basic system could be proven first. Future tests could include these types of equipment to accommodate higher levels of wind power utilization. These other components include (but are not limited to): solar photovoltaic (PV) generation, an automatically controlled load bank with load steps and power electronics, load shedding or load management techniques for less critical loads and storage (electric, thermal, compressed air, etc.).

Despite the test plan, site and environmental conditions were expected to require on-the-fly modifications to the test plan. As expected, during the test setup, initial generator testing and operations manual reviews, INL found that switching the diesel generators from utility grid-tie (load management) mode into standby/islanded mode in a seamless transfer could potentially cause generator stability and power system issues, especially with both generators going into the load-share mode when switching to the islanded system. Therefore, it was determined that the three planned 8-hour test scenarios would require short system outages both at the beginning and end of each test. Having only planned for three intended outages, the test was modified to run for 2 days straight, with only one short outage at the beginning to switch over to island mode, and one outage at the end to switch back to utility power. The different generator and wind turbine combinations described in the draft test plan were all run during the 2-day test, although the exact time lengths were modified to achieve better fuel savings during the night and stretch the 2,400-gallon fuel supply. The diesel-only portion of the test was reduced in duration, but the wind turbine combination times were increased, so high quality data scenarios and collection were still archived during the test.

The main metrics to be collected during the test were power and energy production from the wind turbines and diesel generators, fuel rate and overall usage, voltage, frequency, current, power factor, various power quality factors, harmonics, wind speeds, wind direction, temperature, and a few other minor parameters. Large volumes of data and photos were collected during the test. Planning data leading up to the test is also extensive.

Summary of Field Test Results

Grid power is supplied to FE Warren AFB to separate sections of the Base. The wind turbines are located only one of these. To simplify the test, the plan focused on island operations on just this section of the Base. The concept was to operate without grid power using the wind turbines to provide up to one-third of system demand and for the 2-MW diesel generators to each provide roughly one-third of the power as well. Winds were highly variable during the test period. As a result, wind provided well over one-third of Base power during a particularly gusty period, when one of the generators was offline. Later in the test, winds died down and no turbine power was provided. Although The test was successful and generated large amounts of useful data, not all of which has been fully analyzed. Major results are described below. More detailed data and results are presented in the INL report noted previously.

1. The two diesels generated 53.779 MWh of electricity during the test period, between April 27, 2010 and 17:48 through April 29, 2010 at 01:04.
2. Generator #1 burned 2216.12 gallons of diesel fuel during this time period.
3. Generator #2 burned 2145.47 gallons of diesel fuel during this time period.
4. The generators averaged 12.33 kWh/gallon of fuel, and approximately 32.24% efficiency.
5. The Gamesa 2.0-MW wind turbine produced 5.27 MWh between April 27, 2010 at 19:58 through April 28, 2010 at 06:40 (10.7 hours), for an average capacity factor during that time period of 24.66%.
6. The two Vestas 660-kW wind turbines (total of 1.32 MW nameplate) produced 9.62 MWh between April 28, 2010 at 07:00 through April 28, 2010 at 14:37 (7.6167 hours), for an average capacity factor during that time period of 95.72%.
7. Vestas turbine #2 produced 1.93 MWh between April 28, 2010 at 14:37 through April 28, 2010 at 17:42 (3.0833 hours), for an average capacity factor during that time period of 94.74%.
8. The two Vestas 660-kW wind turbines produced 6.21 MWh between April 28, 2010 at 17:42 through April 29, 2010 at 01:04 (7.3667 hours), for an average capacity factor during that time period of 65.01%.
9. Total wind turbine energy production between April 27, 2010 at 19:58 through April 29, 2010 at 01:04 from the various combinations was 23.15 MWh. Total diesel generator energy production during the same time period was 50.02 MWh. This results in an average wind penetration level during the test of 31.64%.
10. Before the wind turbines were started, the diesel generator loading and electricity production rate was estimated to average 13.13 kWh/gallon of fuel, or 34.33% efficiency based on the varying load combinations, energy production, fuel use and other data.

11. Total energy supplied to loads during the test was 76. 93 MWh. If that was supplied with diesels only the total amount of fuel used would have been 5,859.08 gallons. As tested, 4,361.59 gallons of diesel were used to generate 53.78 MWh. The other 23.15 MWh was generated by wind power.
12. The above numbers resulted in a savings of 1,497.49 gallons of diesel fuel during the test period. This equates to fuel reductions of just over 25.5%.
13. The frequency stayed between 59.6 and 60.4 Hz.
14. During the Gamesa run time, frequency band was better controlled and stayed between 59.85 and 60.15 Hz. The system frequency control was better when the diesels and Gamesa turbine were operating in parallel versus the diesels alone. The Gamesa double-fed induction wind generator with power electronics appears to do a good job in parallel with diesel generators in maintaining system frequency and voltage, even in medium to high wind penetration levels.
15. During the Vestas' run time, the frequency control was looser, but stayed between
16. System voltages were stable throughout the test. The only time low voltage was recorded was during initial load switching and transfer and other diesel generator events. No equipment issues were reported by customers during or after the test.
17. Harmonics were well below levels of concern.
18. Maximum wind penetration with the Gamesa turbine was 82.7%.
19. Maximum wind penetration with the Vestas turbines was 54.5%.
20. Total loads supplied varied between approximately 2.1 and 3.1 MW (this included 750 kW on the load bank for most of the test).
21. Wind energy production estimates based on turbine power curves and wind data collected during the test matched well with actual metered results.

The wind during the test was good for showing varying the effect of varying wind conditions on the system. The average wind during the Gamesa wind turbine run was a little below long-term averages, but there were times when the generator was at maximum output and other times when there was low or no power production. Just after 0600 on April 28, there was a significant ramp event and the Gamesa quickly went to full power output. This was a good test of penetration level with double-fed induction generator technology. After operating at very high penetration level for about 30 minutes, the Gamesa was turned off and the Vestas turbines were turned on to reduce the wind penetration levels closer to the planned level of one-third of total generation. As you can see from the Vestas capacity factors quoted above (items 6, 7, 8, and 19), the wind speeds stayed pretty high (but still below cut-out speed) for most of the day on April 28, and those turbines were close to maximum output for a significant amount of time. However, there were times when the wind levels reduced with the Vestas turbines, so we did get a good sampling of varying wind outputs on those turbines as well.

Conclusions and Recommendations

The application of diesel-renewable hybrid back-up power systems can have far-reaching impacts and benefits to the military, other federal agencies, or private companies with critical loads, renewable energy resources, and a critical need for back-up power. The premise of this field test was to demonstrate the role renewable resources can play to realize these benefits. The test was successful and demonstrated that renewable technologies can be combined with conventional generators or other dispatchable power systems to extend operations and fuel supplies without compromising electric system reliability, power quality, or mission performance and thereby enhance energy security.

Economic considerations must also recognize that renewables can be used at all times to help pay back their initial cost, while remaining available for use back-up power. This is in contrast to emergency generators that ideally will not be used at all, thereby representing a sunk cost with no associated benefit other than piece of mind. Although diesel or gas generator capital costs are much lower than renewables, the costs of fuel and hours of use (or non-use) should be major factors in system design and life cycle cost analyses of energy security solutions. Further, emissions reductions with renewable energies are significant in all operational configurations and should be accounted for when designing and justifying a system that includes them.

With these results, we can turn attention to other issues that should be addressed to increase use of any renewable resource for energy security. Future tests or permanent systems should include other types of equipment to achieve higher levels of renewable energy utilization. These other components could include solar PV generation, geothermal power plants, fuel cells, automatically controlled load banks, load shedding or load management techniques in lieu of load banks for demand management, flywheels for smooth transitions between renewables and conventional generators and any of a variety of storage technologies.