Modeling Results of Wind/Diesel Retrofit Options for Santa Cruz, Galapagos

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Executive Summary

This report summarizes the findings of an analysis considering the inclusion of wind driven power generation technology into the existing diesel stations at Santa Cruz and Baltra Islands in the Galapagos Archipelago. The analysis was conducted by staff at the National Renewable Energy Laboratory, a U.S. Department of Energy funded, contractor operated National Laboratory of the United States. This report is one part of a wider United Nations Development Program study lead by ProViento S.A. Energias Renovables Ecuador and draws heavily from information provided in other documents created by the project team.

To conduct the analysis data on the current diesel plant conditions, wind resource, expected load, and cost data were obtained. Whenever possible, exact information was used and the results validated. The Hybrid Optimization Model for Electric Renewables (HOMER) was used to study the initial feasibility and cost effectiveness of using wind turbines for power generation, while the Hybrid2, hybrid power system simulation model was used to conduct more detailed analysis.

This is an initial feasibility analysis of the potential for wind turbines to be introduced into the power grid in Santa Cruz and Baltra Islands in the Galapagos. There are three potential wind turbine locations considered and two different load scenarios. The three wind turbines sites evaluated are Baltra Island, Santa Rosa, and El Camote. The two load scenarios include the city of Puerto Ayora combined with several smaller nearby loads and small village centers including Bellavista and Santa Rosa, and these locations combined with the load for Baltra Island, mainly comprised of the airport and the nearby military installation. This last load scenario would include the installation of a medium voltage line to extend the Puerto Ayora grid from Santa Rosa to Baltra, about 40 km apart. The wind site at El Camote was analyzed in an initial analysis but dismissed in the more detailed analysis due to low wind speeds.

This analysis uses approximate costs for various components and initial modeling of the interaction and control of the wind-diesel system. This level of analysis is adequate to provide initial investigation of power system design and sizing while specific control algorithm development would still need to be completed. This analysis also allowed for the comparison of the different electrification options based on several key design factors such as the amount of diesel fuel consumption and percent of energy generated from wind technologies.

Based on the analysis conducted it does not seem advantageous to electrically connect the existing grids on the islands of Santa Cruz and Baltra based solely on the operation of the power system. However, the authors of this report understand that there may be other extenuating factors that may make this interconnection preferable.

Without an interconnection, four Made AE59, 800 kW turbines could be considered for installation at the Santa Rosa site on the island of Santa Cruz, with the Made turbine resulting in the highest energy output. The lowest risk alternative would be to install seven Enercon E-33 turbines because these turbines have a demonstrated history of use in wind-diesel applications. Due to the land constraints limiting the potential installed capacity of wind when using these smaller turbines, the potential impacts on fuel consumption are greatly reduced.

To the authors knowledge, out of all the wind turbines evaluated, only the Enercon E-33 wind turbine has demonstrated operational experience in wind-diesel systems. These turbines, when combined with advanced system controls and other power smoothing equipment, such as flywheels or low load diesels, has shown to be successful in controlling voltage and frequency fluctuations on a high penetration grid. The Vergnet GVE-MP is also being incorporated into wind-diesel applications in Australia but has yet to develop a proven track record in these applications.

Measures to actively control power and power quality would have to be implemented as part of most of the wind diesel systems considered. Current analysis indicates that the variability in the wind speed can result in high wind turbine output variability that will impact diesel plant operation. To this point only the use of wind turbine curtailment and controlling dump loads have been considered as a method to improve power system stability, although the use of short-term storage, such as fly wheel technology, grid control equipment and low load diesels should be assessed once specific sites and wind turbine technology have been identified. Since there will be cases where more wind energy will be available than can be consumed by the current load, efforts should be undertaken to analyze the availability of dispatchable loads; such as water desalination, ice making, and water pumping that could be used at times of high wind power availability.

The Hybrid2 analysis indicates that the installation of the four Made AE59 wind turbines while using turbine curtailment to limit power variability would result in the highest fuel savings of the alternatives considered with around 20% fuel savings, resulting in an annual fuel consumption reduction of approximately 270,877 gallons (1,025,381 liters). This amounts to supplying almost 26% of Santa Rosa's electrical energy needs using wind power and would reduce carbon dioxide emissions by approximately 3000 MMTE/year. An additional 541,800 kWh a year would also be available for dispactchable loads, further reducing energy consumption at other times.

If the interconnection is implemented the installation of the wind turbines at Baltra, or possibly several turbines at both sites becomes, becomes a preferable. In this case the option to use a larger number of smaller turbines, most likely the Enercon E-33, provides similar levels of fuel savings as the use of the Made AE59 but provides additional benefit of more defined project experience and greater ease in installation and maintenance.

An important next step in this wind analysis would include obtaining better load and power system data from each of the communities and more advanced wind measurement at both Santa Rosa and Baltra, including higher frequency data collection and correlation to long term wind speed and direction data from other regional sites.

1.0 Introduction

This report summarizes the findings of an analysis considering the inclusion of wind driven power generation technology into the existing diesel stations at Santa Cruz and Baltra Islands in the Galapagos Archipelago. The analysis was conducted by staff at the National Renewable Energy Laboratory, a U.S. Department of Energy funded, contractor operated National Laboratory of the United States. This report is one part of a wider United Nations Development Program study lead by ProViento S.A. Energias Renovables Ecuador and draws heavily from information provided in other documents created by the project team.

To conduct the analysis data on the current plant conditions, wind resource, expected load, and cost data were obtained. Whenever possible, exact information of parameters were used and then validated. The Hybrid Optimization Model for Electric Renewables (HOMER)[1] was used to study the initial feasibility and cost effectiveness of using wind turbines for power generation while the Hybrid2 model[2,3] was used to conduct more detailed analysis. More information on these models are provided in Appendix A.

The use of wind technology to reduce the loading and fuel consumption in remote diesel plants is not a new concept, however, like any integrated power system, it is not a simple matter. Primer's on wind/diesel power systems and power system control are provided in Appendix B and C respectively. This initial feasibility study was focused on answering several key questions regarding the installation of wind turbines on Isla Santa Cruz and/or Isla Baltra. These questions include 1) which of the three potential sites should be used, 2) which of the four turbines considered seems to provide the most power for this application, 3) what is the impact of different amounts of wind power based on the turbines selected, and finally 4) what is the potential impact of installing turbines at more than one site simultaneously.

This analysis provides answers to these questions and then makes final recommendations based on all of the information and modeling used in the analysis. This report is a documentation of the analysis, so it includes descriptions of the analysis methodology and assumptions. Section two of this report reviews the existing power system and generating capacity on the two islands. Section 3 describes the three wind sites, while section 4 describes the inputs into the modeling tools. Section 5 describes the results of the analysis with section 6 providing final recommendations and conclusions. Additionally, this document is the second phase of an initial pre-feasibility study that was completed as part of this work. A summary of that initial study is provided in the body of the text while the complete report is provided in Appendix D.

2.0 Review of existing facilities

The following provides a review of the existing facilities on Isla Santa Cruz and Isla Baltra, including a description of the power facilities at Puerto Ayora and Baltra and the wind turbine sites at Santa Rosa, Baltra and El Camote.

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[1] HOMER, the optimization software for distributed power: http://www.nrel.gov/homer/

[2] Baring-Gould E.I., "Hybrid2: The Hybrid System Simulation Model." NREL/TP-440-21272, Golden, CO: National Renewable Energy Laboratory, (1996).

[3] Hybrid2, hybrid power system simulation software: http://www.ecs.umass.edu/mie/labs/rerl

2.1 Isla Santa Cruz

Santa Cruz Island is a primary island in the middle of the Galapagos Archipelago and sits just to the south of the Island of Baltra, which houses one of the major airports in the Archipelago. The town of Puerto Ayora lies at the south end of the Island and has an electrical grid that serves Puerto Ayora as well as several smaller nearby loads and small village centers including Bellavista and Santa Rosa. Population growth, and subsequently electricity consumption, has been increasing in the town and surrounding areas.

Existing generation facilities

A good description of the diesel plant and controls is necessary to evaluate the diesel system and to also design the interface between the diesel system and any potential wind system. In some cases, the bid solicitation for the wind turbine and related wind system components will be separate from the diesel plant upgrade, which will require more understanding of the diesel plant design, configuration and control.

The existing diesel plant in Puerto Ayora supplies power to Puerto Ayora and the surrounding areas that are connected to the local grid. The diesel plant is well kept and the diesels are well maintained. The facility is made up of the diesel plant, several maintenance facilities where heavy equipment is located and maintained, the office, and switchyard.

There are five 650 kW Caterpillar diesels and one 1100 kW Caterpillar diesel. One of the 650 kW diesels was out of service for maintenance and not available, which is a normal occurrence. The five available diesels during the site visit had 32,931, 37,505, 43,113, 45,832, and 65,578 run hours. Power flow and speed control between diesels is accomplished by using a Woodward 2301A controller. The controller can control the speed and power sharing between multiple diesels. Specifications for the Woodward controller are in the Appendix. Photos 1 to 7 show pictures of the diesels, the controller, some of the heavy equipment at the plant, and the substation connecting the plant to the utility grid.

Photo 2: Several of the diesels at the Puerto Ayora diesel plant

Photo 1: 1100 kW diesel at the Puerto Ayora diesel plant

Photo 3: Woodward diesel load sharing and speed control

Photo 4: Diesel controller display

Photo 5: Beginning of the distribution system in Puerto Ayora

Photo 6: Step up voltage transformers at the diesel plant

Photo 7: Heavy equipment at the diesel plant

Load

A daily, average hourly load-profile for each month was created for the electrical load on Santa Cruz based on expected load growth for the community as supplied by Carlos Jacome of the

United Nations Development Program (UNDP) and Impresa Electrica. This analysis resulted in 12 different, 24-hour load profiles that were combined by NREL to form a full yearly time series. Figure 1 shows a plot of the future load of the Puerto Ayora grid, including the water desalination load.

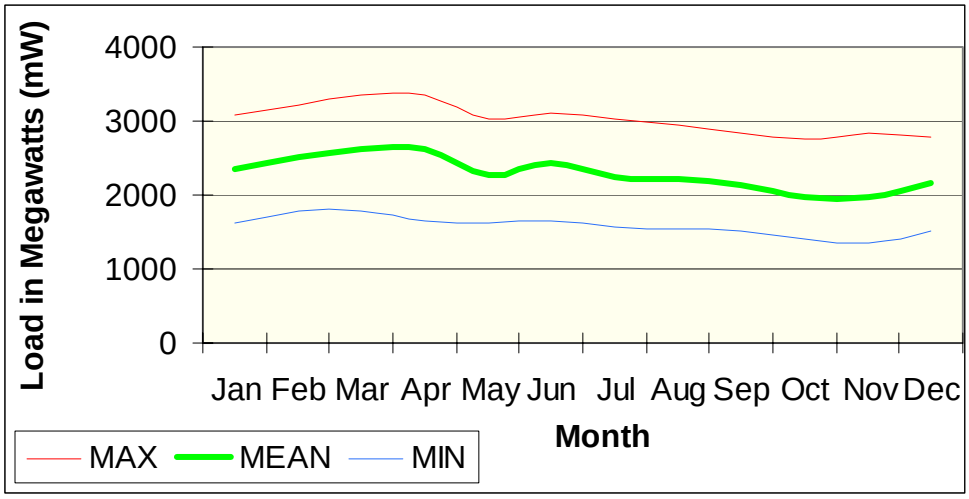

Figure 1: Future projected load for the communities on Isla Santa Cruz

There are a few large loads in the town, with one of the largest being the water desalination plant. Future plans to install a new water desalination plant are being considered but could not be evaluated for this report because specific information was not available. Combining the analysis and planning for a potential wind-diesel plant with the desalination load could lower the cost for both systems, so more information should be obtained about the new water desalination plant. Figure 1 and 2 shows the load of Santa Cruz Island and a combination of the Santa Cruz and Baltra loads respectively.

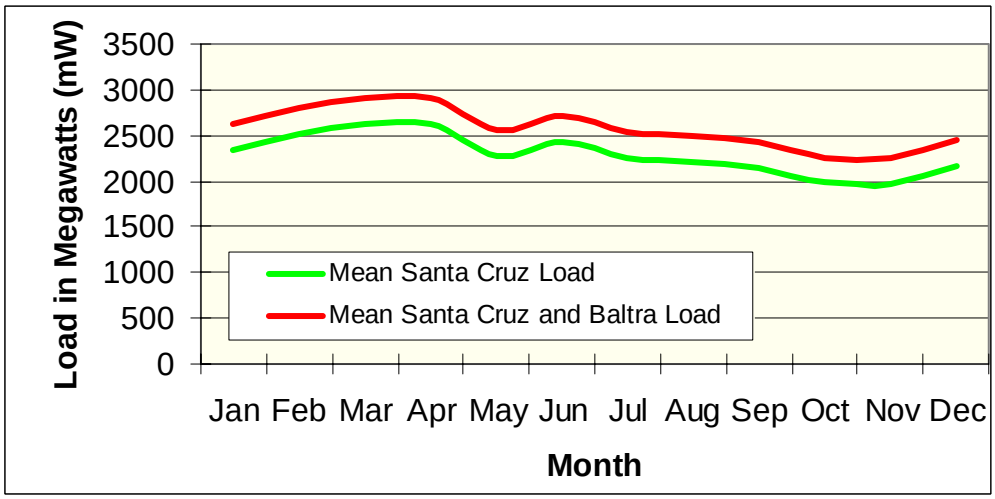

Figure 2: Future projected load for the communities on Isla Santa Cruz and Isla Baltra.

2.2 Baltra

Many people fly into the Galapagos Island's using Baltra's airport. The island also has a small military population next to the airport. There is a small diesel plant that meets the airport electrical requirements and some remote loads. There are plans to expand the electrical grid in Baltra, including one option all the way to Puerto Ayora, and there also plans to buy a new diesel generator.

Existing generation facilities

There is a small detached facility about 100 meters from the airport where the main diesels are located. Several older diesels were kept inside the airport but did not appear to be regularly used. The main diesels are a 150 kW John Deere diesel and a 200 kW Detroit diesel. Neither of the diesels are in very good condition. It was reported that Impresa Electrical, the local utility, was considering adding a new 1400 kW diesel that could run on bio-diesel fuel as part of future upgrades. This planned new diesel is included in the modeling in later sections of this report but has been modeled as part of the Puerto Ayora diesel plant. The Baltra diesel plant is shown in Photos 8 and 9.

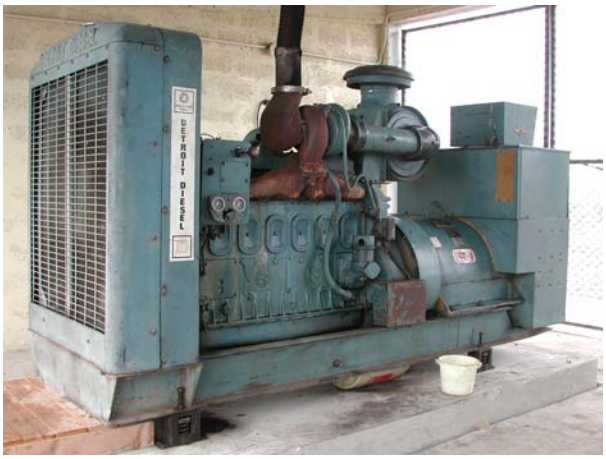

Photo 8: 200 kW Detroit Diesel at Baltra

Photo 9: Diesel plant at Baltra

Load

As with the load data for Santa Cruz, load data supplied by the UNDP was analyzed by NREL. Model inputs consisted of the average hourly load-profile for each month, resulting in 12 different averaged 24-hour load profiles. Figure 3 shows the future load profile of Baltra, which is much smaller than the Puerto Ayora load. Most of the load is from the airport, for which there is a planned expansion, but there are also other smaller loads not related to the airport, including the military facilities.

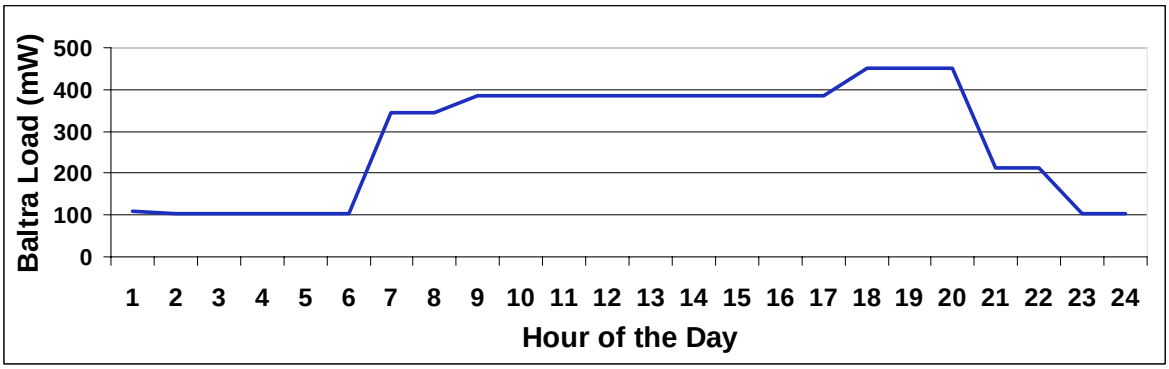

Figure 3: Expected future load for Baltra Island

3.0 Review of Potential Wind Sites

Three potential site locations were identified for the installation of wind turbines; Santa Rosa, Baltra, and El Camote. Hourly wind resource data from July 2005 was collected at all three sites and was used as input to this analysis. The average wind speed for Santa Rosa is 6.17 m/s, and Baltra is 6.02 m/s and Camote is 5.5 m/s.

3.1 Santa Rosa

Initial site description

The site of Santa Rosa sits atop the small mountain range in the center of Santa Cruz Island, just off the road connecting Puerto Ayora and Baltra, near the community of Santa Rosa. The site itself is approximately 580m above sea level and is quite open, with limited trees and ground cover. Due to the available land and proximity of buildings in the area in which the turbines could be installed, restrictions will be required on the number of wind turbines that can be installed.

The site is about 15km from the town of Puerto Ayora and a single phase power line follows the road as far as Santa Rosa. The exact location of the anemometer tower is (W789640.16, S9929421.41, WGS84 15M). More information on the site and wind resource can be obtained from a separate report conducted by ProViento S.A. Energias Renovables Ecuador in conjunction with this document.

Data description

10 minute time series data taken at a height of 40 m from August 15th 2005 to the end of July 2006 shows an annual average of 5.95 m/s and has a standard deviation of 0.4372 m/s. This data was converted to 50 m for use in modeling efforts and has a subsequent average wind speed of 6.17 m/s at 50m. Figure 4 shows a frequency distribution plot for Santa Rosa of the wind throughout the end of July, 2006.

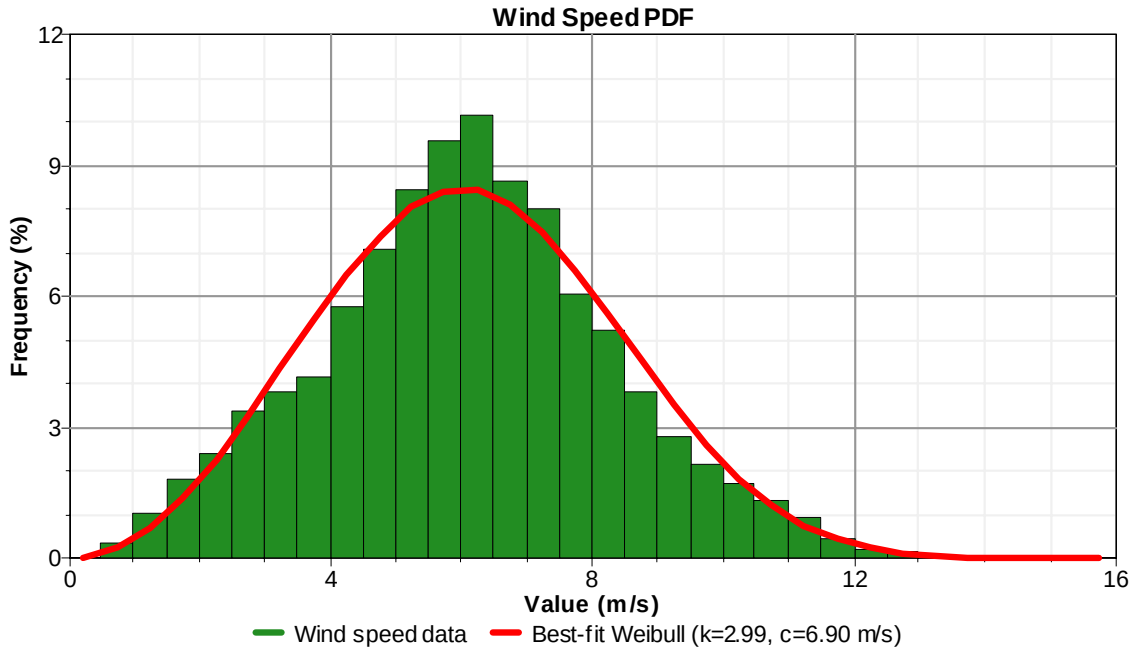

Figure 4: Frequency Distribution Plot of the Santa Rosa Wind Resource.

Time series data showing the 10 minute, hour average and standard deviation for the first two days of January, 2006 are shown in figure 5. Although purely illustrative in nature, the site does show that the winds are quite variable, even over 10 minute averaged data. No information was available on the variability of the wind speed within each 10 minute averaging period. The wind site also has a comparatively low wind shear and turbulence intensity.

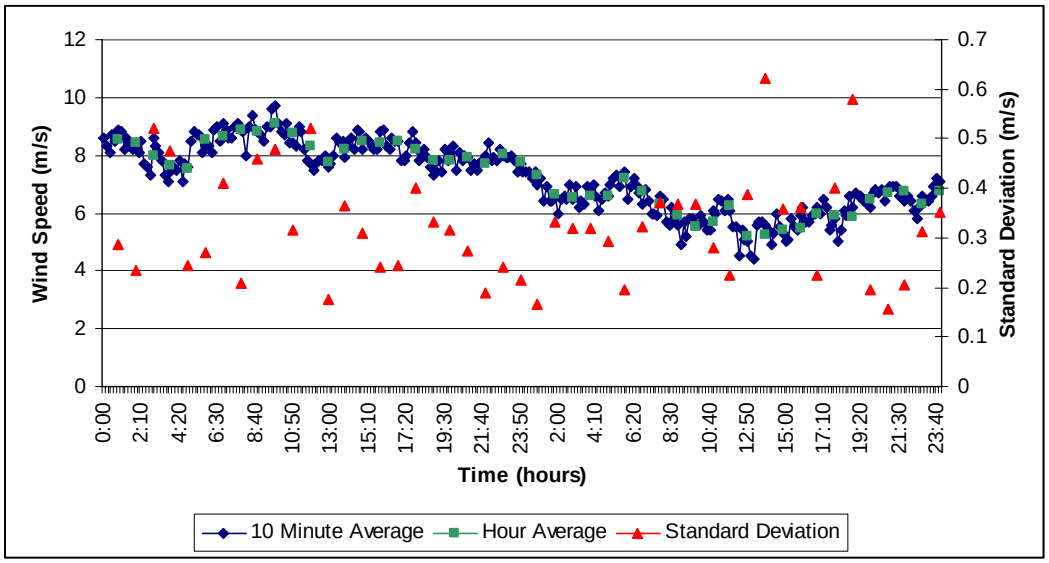

Figure 5: 40m wind speed time series data from January 1st and 2nd, 2006 showing variation of hourly and ten minute average data for the Santa Rosa wind site

3.2 Baltra

Initial site description

The site of Baltra sits near the end of the Baltra airport on the eastern side of this smaller island to the north of Isla Santa Cruz. The site is basically at sea level and is quite open with very little structure or ground cover. Although the site is in close proximity to the airport and associated height restrictions would apply, there is ample area for wind turbine installation.

The site is quite close to an unimproved dirt road and is close to the airport facilities. There is no electrical connection between the site and Puerto Ayora. One particular challenge at this site is there is virtually no grounding potential for electrical systems. The exact location of the anemometer tower is (W802140.89, S9928817.48, WGS84 15M). More information on the site and wind resource can be obtained from a separate report conducted by ProViento S.A. Energias Renovables Ecuador in conjunction with this document.

Data description

10 minute time series data taken at a height of 40 m from August 14th 2005 to the end of July 2006 show an annual average of 5.77 m/s and a standard deviation of 0.455 m/s, slightly higher than that for Santa Rosa. This data was converted to 50 m for use in modeling efforts and has a subsequent average wind speed of 6.02 m/s at 50m. Figure 6 shows a frequency distribution plot of the wind speeds for Baltra using data through July of 2006.

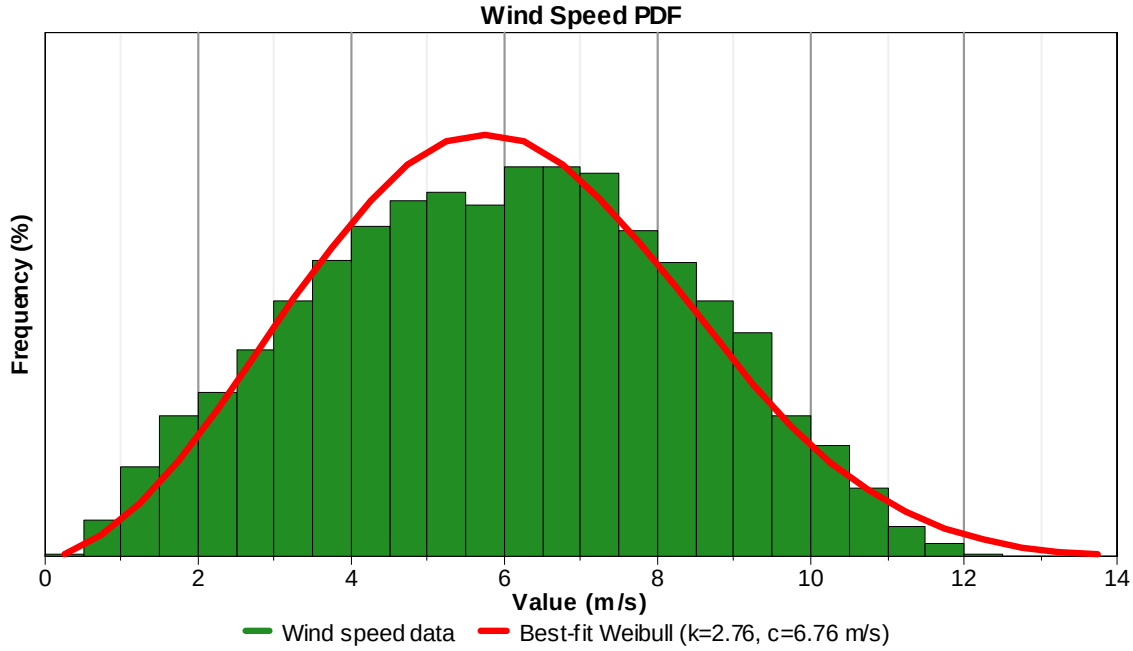

Figure 6: Frequency Distribution Plot of the Baltra Wind Resource.

Time series data showing the 10 minute, hour average and standard deviation for the first two days of January, 2006 are shown in Figure 7. Although purely illustrative in nature, the difference in the wind speed and variability is striking, especially when compared to the wind speeds at Santa Rosa for the same time period. No information was available on the variability

of the wind speed within each 10 minute averaging period. The Baltra site also has a slightly above normal wind shear but a slightly lower turbulence intensity.

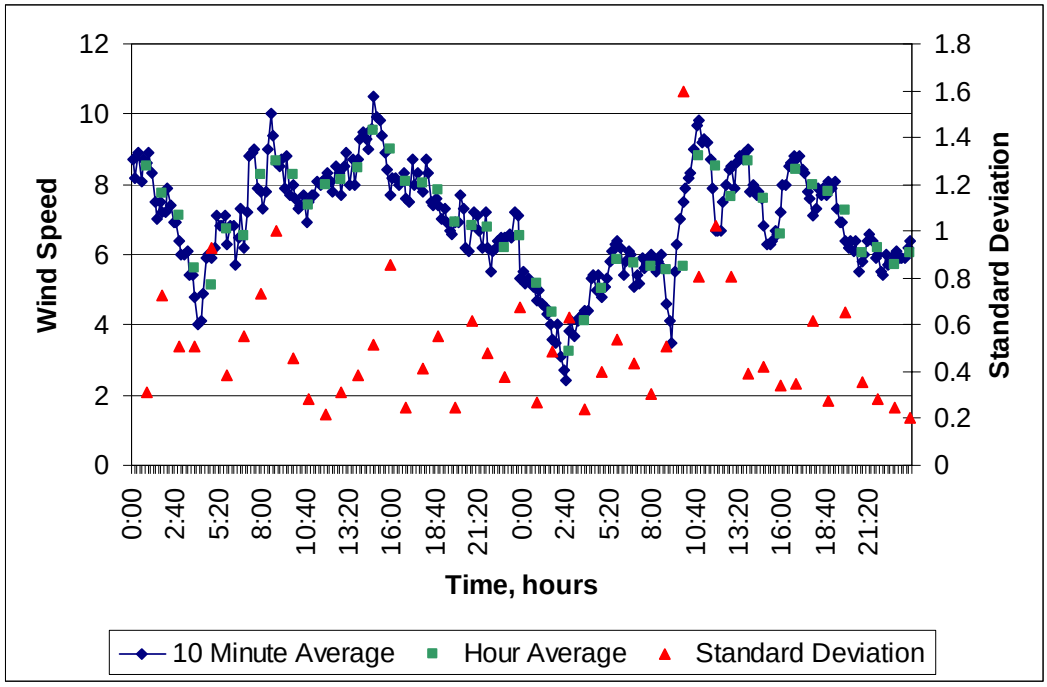

Figure 7: 40m wind speed time series data from January 1st and 2nd, 2006 showing variation of hourly and ten minute average data for the Baltra wind site

3.3 El Camote

Initial site description

El Camote is located in the high country on the eastern side of Isla Santa Cruz. The site is approximately 8 kW north east from the community of Bellavista, which sits on the main road between Puerto Ayora and Baltra. The site itself varies in elevation but is approximately 400m above sea level and is quite open, with limited trees and ground cover. There are several small geographic structures in the area and some terrain variations.

The site is about 12km from the town of Puerto Ayora and is in close proximity to the single phase power line follows the road through Bellavista. The exact location of the anemometer tower is (W800657.91, S9926169.29, WGS84 15M). More information on the site and wind resource can be obtained from a separate report conducted by ProViento S.A. Energias Renovables Ecuador in conjunction with this document.

Data description

The average annual wind speed for El Camote is 5.5 m/s at 50m based on 10 minute data collected at 40m from August 14th 2005 to the end of July 2006. Plots of the El Camote data are

not provided in this report since the wind resource is significantly lower than the two other available sites.

4.0 Analysis of Power System Options

What follows is a description of the analysis of the potential to retrofit the existing diesel facility at Puerto Ayora and Baltra. This section describes the data that was used in the analysis as well as the assumptions regarding the installation and operation of the current diesel power station. This initial analysis looks primarily at the amount of wind energy that could easily be absorbed into the diesel grid.

The following chapter describes the analysis considering the two primary sites in question, Santa Rosa and Baltra. Included in the analysis are power output calculations for different turbines, the impact of different amounts of wind energy, and the impact of installing turbines at more than one site simultaneously.

There are three types of data that are important for the analysis of re-powering options. The first relates to the technology that can be used to provide power at each of the sites, the second is the energy consumption at each site, and finally the wind resource availability. This data must then be analyzed based on an understanding of the current plant structure and other limitations that each site may present.

4.1 Turbines used in the analysis

Four different wind turbines were considered for this analysis and are listed in Table 1. Although there are differences between specific turbines, at this level issues of basic cost, generation capacity, weight, and size are the most critical. Specific information on each turbine can be found in Appendix D of this document.

Table 1: Wind turbines included in analysis

Company	Country	Turbine	Power (kW)	Hub Height (m)
MADE	Spain	AE59	800	50
Vergnet Wind Systems	France	GVP MP	275	55
ENERCON GmbH	Germany	E-33	330	50
ENERCON GmbH	Germany	E-48	800	50

Of these turbines being considered, several of them have been used in hybrid power systems. The MADE AE59 is being used in the wind/diesel power station on San Cristobal Island in the Galapagos Archipelago, but has not been used in hybrid power systems previously. The Vergnet GVP MP has been used in rural applications and is being installed in a high penetration wind diesel application in Australia. The Enercon E-33 has been used in several successful wind-diesel projects, most notably in the Mawson Australian Antarctic base and at Flores Island. The Enercon E-48 has not been used in hybrid applications to the authors knowledge, though the experience obtained with operation of the E-33 would assist in the implementation of these units.

4.2 Wind Data

Hourly wind speed data was used for the analysis of all three sites. This data was developed using the multi level, 10 minute average data collected at each site. In all cases 10 minute data had been collected from mid August of 2005 through the end of July 2006. Two methods were used in separate parts of the analysis. In the initial HOMER analysis and primary Hybrid2 analysis the hourly time series data was manually manipulate with the average increased to accurately depict the expected hourly average at a height of 50m based on the calculated directional wind shear. It is believed that this data most accurately reflects the wind speeds at the expected turbine hub heights between 50 and 55 meters. Although only applicable to the Hybrid2 software, during the analysis a generally standard 20 % variability in the inter hour wind resource was assumed. This simply states that the wind speeds within each hour average time step will vary by 20%.

In order to obtain a better understanding of the impact of the actual inter hour variability of the wind resource an analysis was completed using the original 40 m wind speed data. In this case the 10 minute averages were converted to hour averages with standard deviations. Based on the annual average wind shear and other parameters the Hybrid2 software was then used to determine the applicable wind speed and inter hour variation at the different turbine hub heights. This analysis allowed the authors to obtain a better estimate of the variability of the wind power that would be produced by the wind turbines at the different sites considered.

4.3 Load data

Two different load scenarios were considered, a combination of the communities on Isla Santa Cruz, including Puerto Ayora, Bellavista and Santa Rosa, and then a separate load that also includes these communities but adds the expected load of Baltra Island. The total combined primary load of both islands would require the installation of a grid extension from the communities of Santa Rosa to Baltra.

4.4 Diesel Plant

In place of the power system that was described in the previous section the following diesel engines were used in the analysis, including a 1400 kW diesel that is currently planned but not installed. The specification sheets for the Caterpillar diesels are provided in table 2. Additional information on each of the diesels modeled is supplied in Appendix D.

The modeled fuel curves for these diesels are provided in figure 8. The specification sheets do not provide a no load fuel consumption values so a standard no-load consumption of 0.08415 l / kW rated

Table 2: Diesel generators used in the analysis

Company	Generator Model	Diesel Model	Number of Units	Power (kWe)
Caterpillar	SR4B-594	3412C TA	5	650
Caterpillar	SR4B-693	3512 TA	1	1100
Caterpillar	SR4B-2730	3512B TA	1	1400

power was assumed[4]. A standard minimum loading level was also assumed to be 35% of rated power, slightly lower than is recommend by manufactures but higher than what would be common in most remote diesel applications. Because of the relatively high minimum loading, the assumed fuel no-load consumption will have minimal impact on the total reported fuel consumption.

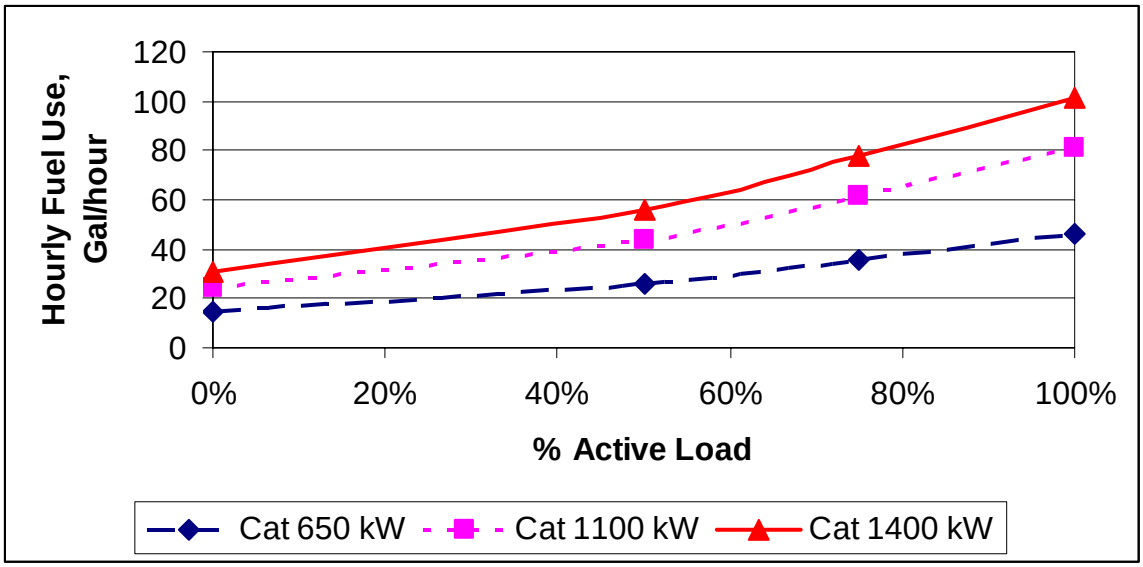

Figure 8: Fuel consumption as a function of load for diesel engines used in the Hybrid2 analyses.

Once a diesel had been started it is assumed that it would remain operational for at least 6 hours. Shorter minimum operational times were investigated but due to the high variability of the wind resource, and the general assumption that wind energy will be maximized, diesel start cycles were excessive. Further investigation of the diesel control regime should be considered in further analysis.

In all cases it was assumed that a diesel would be operational all of the time to set system voltage, provide reactive power and assist in maintaining system frequency.

4.4 Analysis Constraints

Several constraints were considered in the analysis. Given the space constraints at many of the sites a separate analysis was conducted using micro-siting software to assess, based on land availability, acoustic constraints and wind resource, the number of turbines that could be installed at each site, table 3. ProViento S.A. Energias Renovables Ecuador conducted wind turbine power output estimates based on specific micrositing analysis for each turbine at each site. These power estimates are more accurate than either the HOMER and Hybrid2 simulations.

Table 3: Maximum Number of Turbines Allowed at Specific Sites

Turbine	Turbine Size	# Possible at Site
Santa Rosa		
MADE AE59	800	4
Vergnet GVP MP	275	7
ENERCON E33	330	7
ENERCON E48	800	4
Baltra		
MADE AE59	800	4
Vergnet GVP MP	275	12
ENERCON E33	330	10
ENERCON E48	800	4

[4] Skarstein and Uhlen, 1989

However, if attempts were made to exactly match the wind power output of the turbines at each site using these software tools it would add complexity to the results of the simulation outputs, which would make them more difficult to compare. With this in mind the results of the HOMER and Hybrid2 analysis should be considered comparative in nature. Final system simulations were conducted on the final recommended system configurations in an attempt to more accurately assess actual system performance.

The second primary constraint in the analysis was the acceptable level of power penetration for the system. As is described in more detail in Appendix B, the amount of wind power as compared to the load on an instantaneous basis is a key design criteria for power systems incorporating wind energy.

In diesel power systems the diesel engine controls maintain power system voltage, frequency, and power factor (the balance of real and reactive power requirements). Most wind turbines are passive devices and have limited ability to provide voltage or frequency stability. For this reason, when the percentage of energy coming from the wind turbine(s) becomes large as compared to the total system load, system stability can be jeopardized. For this reason, different devices, control strategies, and system architectures can be employed to address these issues. The Hybrid2 software allows assessment of these issues on a macro-scale, but it does not model the dynamic nature of the power system. Although the analysis described here does address these issues from a conceptual basis, further analysis of these issues will have to be addressed in a final system design once specific system components have been identified.

To assess simple installed capacity at the different turbine locations, the analysis considered different levels of wind penetration, using different approaches to address the issues of system stability.

Two general cases were considered, the first limiting power production through the use of wind turbine curtailment, and the second using short term energy storage to address stability issues, thus allowing additional wind turbine generation. The analysis also considered the benefits of adding additional wind turbine capacity, although this would require a higher amount of wind turbine curtailment.

Lastly, there was interest in considering wind turbines installed at both sites, Santa Rosa and Baltra simultaneously. Installing turbines at both locations would smooth out some power fluctuations since the wind resources at the two sites are spatially separated. Although a clear correlation of the hourly average wind speeds at the two sites exist, figure 9, it is not a strong correlation and thus it is likely that turbines installed at the two sites would provide a generally smoother total wind power production than if all of the wind turbines were installed at one location. Hourly average wind speed time series data for the month of January 2006 is also plotted in figure 10 to show the temporal difference between the two sites. As would be expected the wind speed at the two sites are similar, but clear differences are noted and the wind resource at Baltra is more variable than the winds at Santa Rosa.

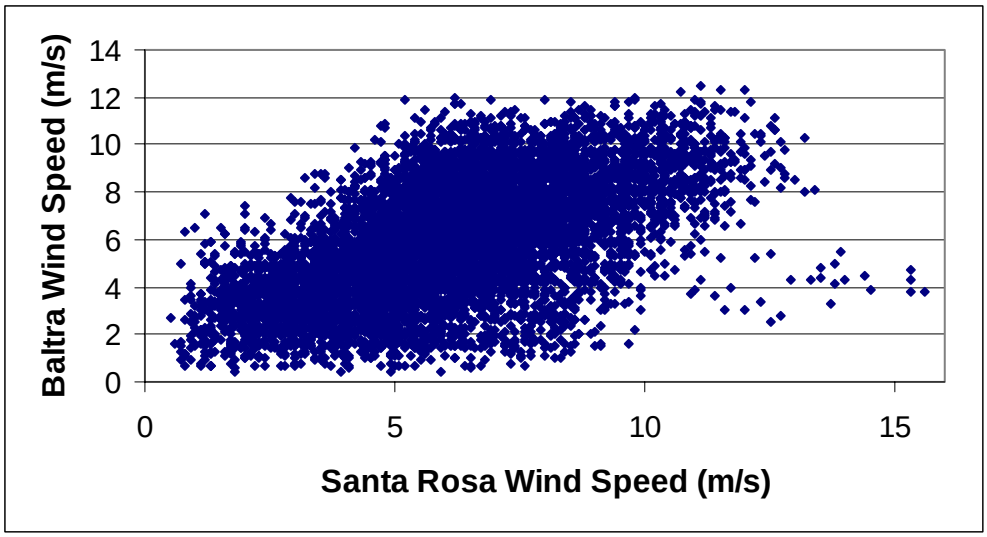

Figure 9: Hourly Average Wind Speeds for 2005 at Baltra and Santa Rosa, demonstrating a limited correlation between the two sites.

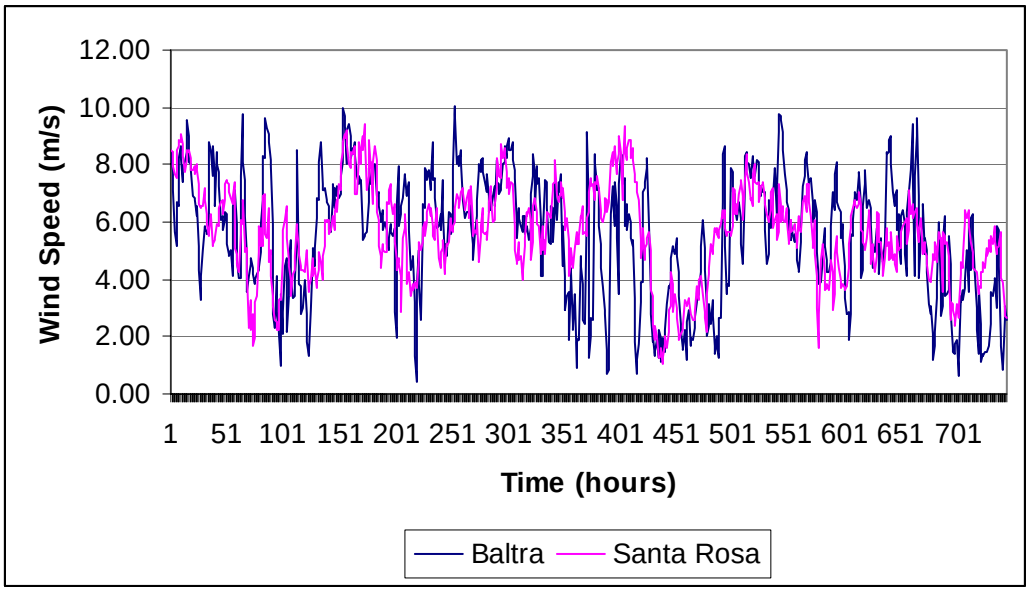

Figure 10: 40m wind speed data for the January 2006 at Baltra and Santa Rosa

Although the Hybrid2 software does address wind correlation between distinct turbines located at one location, it does not allow assessment of wind turbines at two independent sites. Additionally, the power smoothing resulting from the use of the two sites would have its most dramatic impact on a sub-hourly time frame, something that was not considered as part of this analysis. To address this issue independent simulations were run with the wind turbines installed at the two primary sites and then the power productions for each hour time step were averaged. To determine the potential impact on diesel operation with the combined wind turbines, the average turbine power was converted into a figurative wind speed time series. Using a new Hybrid2 simulation the combined power system was modeled. Although this method does

provide a reasonable approximation of hourly operation, it is not possible to determine the impact of using multiple turbine sites on short term turbine power variability.

5.0 Analysis

Two analysis were completed under this activity, the first was a preliminary analysis using the HOMER software and the a more detailed analysis using the Hybrid2 software.

5.1 Preliminary Analysis

An initial analysis was completed using the HOMER software to assess the different sites and potential wind turbine options. The full report is provided in the Appendix C of this document. Preliminary model results are shown for the comparison of wind power output at the different sites in Figure 11. The power output data is graphed against a range of one to eight Enercon E-33 turbines. The data show that a wind turbine at the Baltra site will produce a little bit more energy than at the Santa Rosa site. The El Camote site has a lower wind resources and thus has a much lower power production.

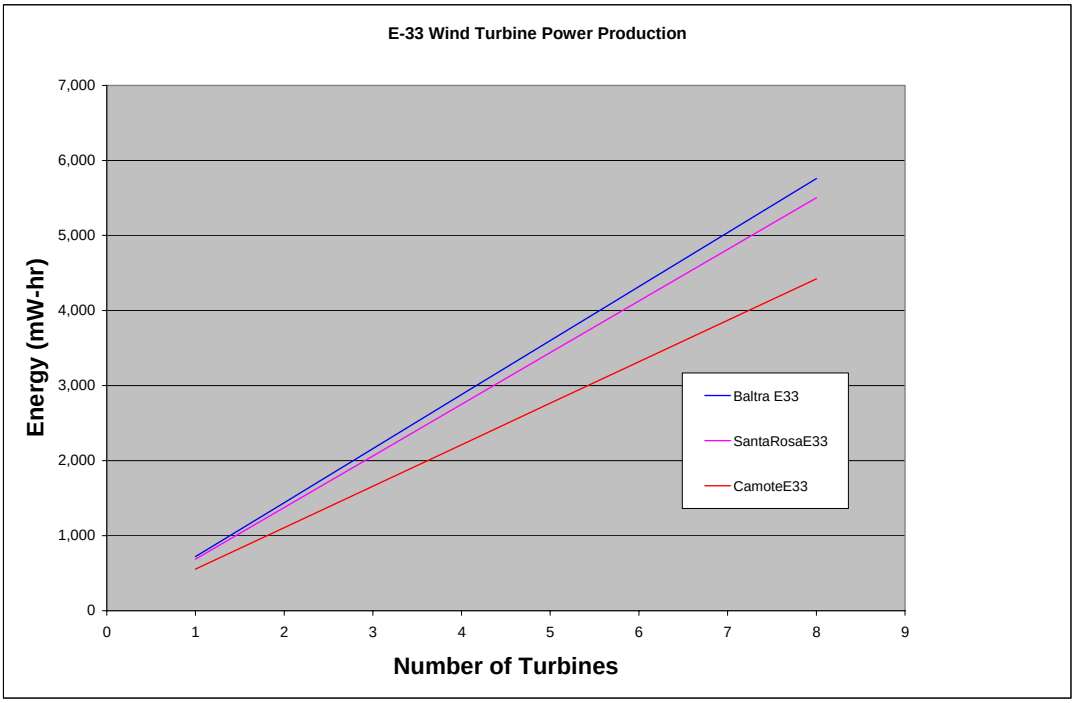

Figure 11: Power production from different numbers of Enercon E-33 wind turbines at Baltra

Other significant findings are that the wind turbines often did not operate at rated power due to the lower wind speeds. The annual energy penetration, as defined as the amount of energy out of the wind turbines divided by the total electrical grid demand for the full year, is shown in Figure 12. It is seen that for six to eight, 330 kW wind turbines the energy production is more than 20% of the total load, resulting in a fuel savings of up to 1,588,760 liters per year. The wind energy penetration is higher at Santa Rosa because the load is smaller, as it does not include the Baltra load. As a result, and partly due to the overlapping of the wind resource with the load, the Santa Rosa site results in more “excess” electricity.

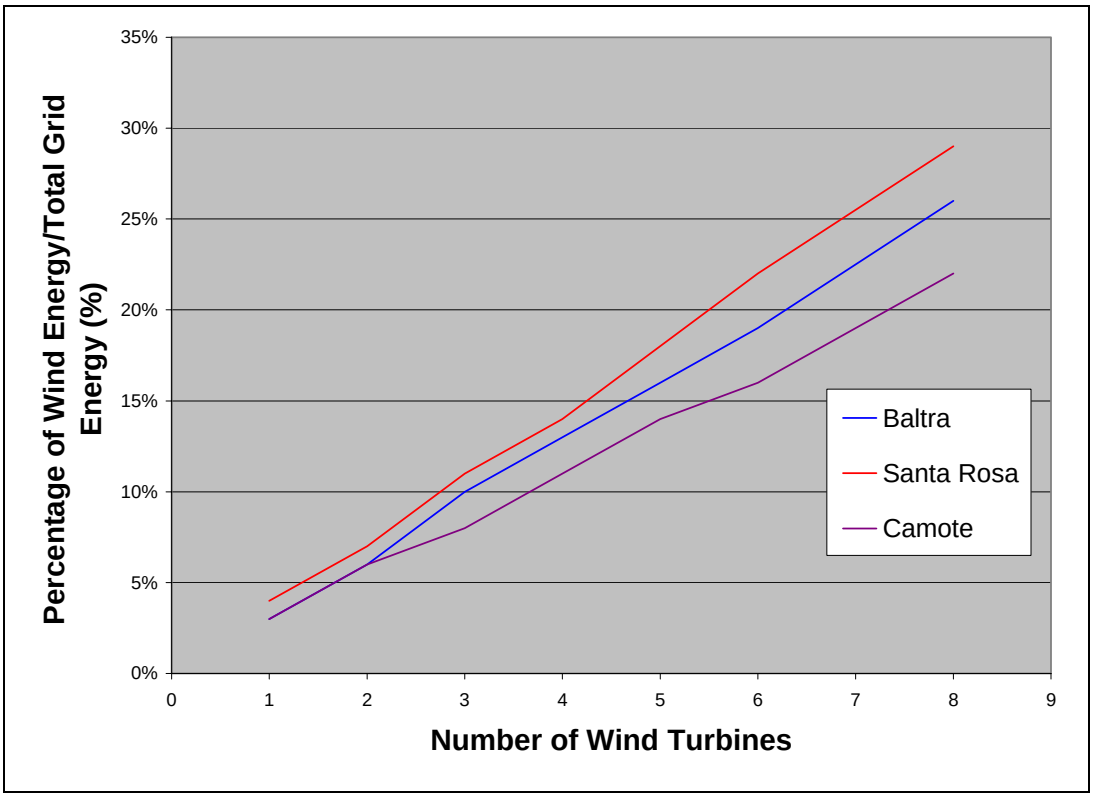

Figure 12: Power system wind penetration based on the installation of different numbers of Enercon E-33 wind turbines at all three sites

5.2 Detailed Analysis

A further analysis was conducted using the Hybrid2 software, which allowed a more detailed assessment of total system operation. The absence of accurate numbers for the capital, installation and balance of station costs led the analysis to focus on the technical aspects of power system design. Initial cost estimates are provided at the end of this section. The results of this analysis, which will be explained at length in this section, is provided in Table 4.

Based on the economic data currently available for the different turbines, the cost savings expected by the installation of wind turbines was also calculated. This cost analysis treats the inclusion of wind as an integrated part of the power plant and compares the cost of the system expansion to incorporate wind to the expected savings, generally in reduced fuel and operational expenses. This initial analysis indicates that given the current cost estimates, which do not include potential economic impacts of carbon reductions or other benefits so should be treated as demonstrative, the inclusion of wind technology does not reduce the overall cost of power production on Santa Cruz. Specific cost information and assumptions can be obtained from a separate report conducted by ProViento S.A. Energias Renovables Ecuador in conjunction with this project.

Site Comparison

As has been indicated in the site specific micro-siting analysis, the wind resource at Baltra produces a higher turbine energy output. Previous analysis also indicated that the power production at the El Camote site was quite low and thus has not been considered further. When comparing the two remaining sites the combined load of Baltra and Santa Rosa was used. Although the analysis finds that the wind turbines produce more energy at the Baltra site, the difference is an increased fuel savings of only about 0.3%, or about 5,000 gal / year, for a system comprising four MADE AE49 turbines. The reason for the small difference in fuel consumption is primarily that the extra energy produced when it cannot be used by the power system, resulting in a higher excess energy, but not increased fuel savings. The installation of the four Made AE59 turbines at the Baltra site would save approximately 276,784 gallons per / year of fuel. The use of the Baltra site does require the installation of a grid extension connecting the two locations and would result in a cost increase of energy production of 2.86 US cents/kWh over the analyzed diesel only system.

Table 4: Summary of the wind turbine and site option costs

Type of Turbines	# of Turbines	C02 Reduction MMT	% Fuel Savings	Wind Gen GWh	Hours Curtailed	Annual Penetration %	Excess Energy %	Diesel Run Hours	Retrofit Savings US$/kWh
Santa Cruz load with Santa Rosa Site									
E33	7	2,217	14.9%	4.68		23.3%	1.4%	32,498	-0.0147
E48	4	2,543	17.1%	5.74		28.5%	3.5%	31,883	-0.0137
E48	4 - Curt	2,427	16.3%	4.68	2176	23.3%	1.5%	-	
AE59	4	3,239	21.8%	7.34		36.5%	6.5%	32,433	-0.0145
AE59	4 - Curt	3,082	20.8%	5.36	3707	26.6%	2.8%	-	
GEV	7	1,603	10.8%	3.51		17.5%	0.6%	33,507	-0.0128
Santa Cruz and Baltra load with Baltra Site									
E33	10	3,022	18.8%	7.07		31.3%	3.1%	34,678	-0.0265
E48	4	2,307	14.4%	6.05		26.8%	1.5%	35,326	
AE59	4	3,038	18.9%	7.77		34.4%	5.2%	35,297	-0.0286
GEV	12	2,684	16.7%	6.37		28.2%	2.4%	35,228	
Santa Cruz and Baltra load with Santa Rosa Site									
AE59	4	2,981	18.6%	7.34		36.5%	4.9%	35,126	
AE59	2	1,410	8.8%	3.67		18.2%	0.8%	-	
E48	4	2,373	14.8%	5.74		28.5%	2.7%	35,798	
Santa Cruz load with Santa Rosa Site									
E48	4	2,543	17.1%	5.74		28.5%	3.5%	31,883	
E48	3	1,861	12.5%	4.31		21.4%	1.6%	33,515	
E48	2	1,092	7.4%	2.87		14.3%	0.6%	34,716	
E48	1	406	2.7%	1.44		7.2%	0.1%	35,965	
Turbines split between Baltra and Santa Rosa Sites, Santa Cruz and Baltra load									
AE59	4	2,825	17.6%	6.92		34.4%	3.0%	35,426	
AE59	4 - Curt	2,645	16.5%	5.94	2008	29.5%	1.3%	-	

If the wind turbine site at Santa Rosa is selected, two options are available; install the grid connection from Santa Rosa to Baltra and thus providing power to both communities or simply powering Santa Rosa. In the case of powering both communities using the Santa Rosa wind site the analysis shows a savings of approximately 271,600 gallons of fuel per year.

It the grid extension is not implemented, the wind turbines would only support the power system for Puerto Ayora, a decrease of 2,468 MWh per year over the combined load with Baltra. Four MADE AE49 turbines would save 295,080 gallons per / year of fuel, or 22% of the total consumption, and would raise the total cost of power by approximately 1.45 US cents/kWh.

It is not possible to determine the specific fuel savings from connecting the two loads and supplying all of the power from a single wind-diesel application since the fuel consumption of the Baltra diesel plant is not known. A conservative estimate of fuel savings based on the difference when supplying both loads and only the Puerto Ayora load is 115,000 gallons/year. The real fuel savings is likely to be higher since the Baltra diesel plant is likely to have a lower efficiency than the Puerto Ayora plant.

This analysis indicates that the use of the Baltra site is not cost effective when compared to using the Santa Rosa site, largely due to the cost of the grid extension, table 4. If the grid extension was to be installed for other reasons, the use of the Baltra site has slight power advantages, however the savings is minimal and other considerations, such as turbine accessibility, power quality, and environmental issues would likely dominate. The Baltra site also has fewer restrictions on the number and location of wind turbines, which would be an advantage considering potential future load increases.

Wind Turbine Comparison

Discussions regarding the selection of a specific turbine are difficult to assess because of the many different issues associated with this decision, many not considered in this text. For example, the availability of wind turbines is a sever problem given the current tightness of the wind turbine market through 2009. Additionally, the cost of turbines is impossible to completely define without specific market bids, something most companies will not provide for feasibility level analysis. As stated previously, the number of wind turbines that could be sited at either the Baltra or Santa Rosa sites were identified in independent analysis using micro-siting software. The values for power production for the turbines is a combined total and does not include site specific topography information and thus should be construed as approximate and comparative in nature.

Concentrating on the Santa Rosa site with the Santa Cruz load as an example, the MADE AE59 clearly produces more wind energy, has a resulting higher potential fuel savings and a higher annual wind penetration. Since all of the energy produced by the turbine cannot be used and the diesel minimum operational load must be maintained, the excess energy is also higher than any of the other turbine combinations. For this site in specific, the next best turbine option would be the use of the Enercon E48 followed by the Enercon E33 and then the Vergnet GVP MP.

This demonstrates that all other things being equal, the installation of four Made AE wind turbines provides the lowest cost of the four wind turbine options considered. This analysis is based on energy analysis and does not take into account whether the wind-diesel system is a proven commercial hybrid system.

As indicated in table 4, it was determined that if the Baltra site was to be used, the selection of a turbine from a performance standpoint would also likely change. Although the four Made AE59 still produce more energy and provide increased annual penetration and fuel savings over the use of 10 Enercon E33's, the use of the Enercon turbines have a lower overall system cost. In this case other issues, such as turbine availability, dispatching, and ease in installation would be additional important factors in turbine choice.

As will be further discussed in the next section, there are important power control issues depending on the selected site. Since the diesel generators provide the primary control for system power quality, the farther the wind turbines are away from the diesel plant, the larger the issues associated with system power control. With this in mind, use of the Baltra site with the diesel plant located in Puerto Ayora will require more system control and likely the installation of power leveling equipment at this site. Use of the Santa Rosa site will likely not create such problems. This said, the impact of these issues will depend greatly on the selected site, the power station interconnection and the turbines selected for the project. Once these items have been defined, or at least reduced to one or two options, a more detailed power flow and system stability analysis will be required.

Impacts of Wind Penetration

One of the critical elements of the discussion regarding the applicability of using wind energy to provide power to the island of Santa Cruz is the continued ability to provide consistent, high quality power. As has been discussed previously and is provided in more detail in Appendix B, when incorporating wind-based technologies into large power systems, the amount of energy that will be obtained from the wind sources will play a key role in insuring system stability. The following classifications and definitions of system penetration characterize the levels of system complexity:

$$\text{Instantaneous Penetration} = \frac{\text{Wind Power Output (kW)}}{\text{Primary Electrical Load (kW)}}$$

and

$$\text{Average Penetration} = \frac{\text{Wind Turbine Energy Output (kWh)}}{\text{Primary Electrical Load (kWh)}}$$

The difference in these equations is in the units. Instantaneous penetration is in terms of power; thus, it is the ratio of how much power is being produced by the renewable resources at any specific instant. The average penetration is in terms of energy; it includes a time domain and is thus measured over days, months, or even years. In some sense, average penetration is in the domain of the economist and instantaneous penetration falls in the realm of the engineer. A three-level classification system based on system penetration that separates systems along power and system control needs has been developed, a summary of which is provided if table 5[5].

As discussed in more detail in Appendix B, there are a series of approaches that could be used depending on the variability in the turbines power output and thus the instantaneous penetration. Initially, since the variable nature of the wind drives the variable output of the turbine, the use of more wind turbines that are spaced out geographically helps smooth the fluctuations in the plant's total power since each variation in wind speed (a gust of wind) is unlikely to hit all of the

[5] Baring-Gould, E.I.; Flowers, L., Lundsager, P.; Mott, L.; Shirazi, M.; Zimmermann J.; (2003) "World Status of Wind Diesel Applications" Proceedings of the 2003 AWEA Conference, Austin TX. June, 2003.

turbines at the same time. Secondly, at times of high penetration, specific wind turbines can be shut off to reduce the total wind power generation, and thus the instantaneous penetration. A third option is the installation of fast acting controlled resistive heaters that would be used to remove excess energy from the grid, smoothing out the resulting power and providing better control of system frequency. The last option is the installation of power storage to the grid, generally in the form of a battery bank or flywheel that can be used to consume or provide small amounts of power. Advanced controls associated with these devices allow for better control of grid stability. This last option is often required for high penetration systems.

Depending on the level of average penetration desired, expected variability in the wind output and total system cost, a combination of these items would be utilized. A power system control logic would be developed to manipulate the different system components, wind turbines, diesel engines, possible dump loads and potential storage to insure proper power system stability and performance.

Table 5: Penetration class of wind-diesel system

PENETRATION CLASS	OPERATING CHARACTERISTICS	PENETRATION	
		PEAK INSTANTANEOUS	ANNUAL AVERAGE
LOW	▪ Diesel runs full-time ▪ Wind power reduces net load on diesel ▪ All wind energy goes to primary load ▪ No supervisory control system	< 50%	< 20%
MEDIUM	▪ Diesel runs full-time ▪ At high wind power levels, secondary loads dispatched to ensure sufficient diesel loading or wind generation is curtailed ▪ Requires relatively simple control system	50% – 100%	20% – 50%
HIGH	▪ Diesels may be shut down during high wind availability ▪ Auxiliary components required to regulate voltage and frequency ▪ Requires sophisticated control system	100% - 400%	50% – 150%

Although the Hybrid2 program is designed to assess the variable nature of plant operation with wind systems, the nature of a time step simulation model makes it difficult to accurately assess peak instantaneous penetration levels. Given the one hour time step currently being modeled, three individual cases were assessed. The first simply cataloged the expected penetration levels using the number of each type of turbine discussed above. The second case looked at reducing the number of turbines to determine the total impact on penetration level, and the third was to

conduct a curtailment analysis, looking at the expected impact of shutting turbines off for short periods of time to limit the system penetration level.

In each of these analyses several different penetration levels in addition to the ones discussed above were examined. The average and peak hourly penetration level provides an initial assessment of inter hour variability which would have to be managed by the power system controls. The theoretical maximum penetration level would mimic a worst possible instantaneous penetration level for each hour based on an extreme case of the statistical maximum wind power production coinciding with the statistical minimum consumer load.

In all of the cases provided in Table 6, the wind resource for Santa Rosa was used with the load of Isla Santa Cruz alone. Similar analysis was conducted considering the combined load of Santa Cruz and the Baltra for both sites with similar, through slightly lower results. The use of the Baltra site results in slightly lower penetration levels than is found using the Santa Rosa site.

Table 6: Penetration levels for different turbine scenarios for Santa Rosa site and load

Type of turbine	# of Turbines	% Fuel Savings	Wind GWh	Hours Curtailed	Penetration Level (%) Max pos Inst	Peak hour	Avg hour	Annual	Excess %
Standard operation - No assumed system limitations									
E33	7	14.9%	4.68		243.9%	148.0%	25.0%	23.3%	1.4%
E48	4	17.1%	5.74		365.7%	201.0%	30.7%	28.5%	3.5%
AE59	4	21.8%	7.34		398.3%	218.1%	39.3%	36.5%	6.5%
GEV	7	10.8%	3.51		195.4%	120.3%	18.8%	17.5%	0.6%
Standard operation - Reductions in number of turbines									
E48	4	17.1%	5.74		365.7%	201.0%	30.7%	28.5%	3.5%
E48	3	12.5%	4.31		282.8%	150.7%	23.0%	21.4%	1.6%
E48	2	7.4%	2.87		196.7%	100.5%	15.3%	14.3%	0.6%
E48	1	2.7%	1.44		105.4%	50.2%	7.7%	7.2%	0.1%
Curtailed operation - Maintaining a peak hourly penetration of 60%									
E48	4	16.3%	4.68	2176		60.0%	23.2%	23.3%	1.5%
AE59	4	20.8%	5.36	3707		60.0%	27.8%	26.6%	2.8%

Three general things can be clearly determined from this analysis. Initially, although the annual *energy* penetration is not very high, the *power* penetration levels on a shorter time scale are high and will require active designs to regulate power quality, unless there is only a small amount of annual wind energy penetration. Secondly, there is a benefit of using a larger number of smaller turbines, an activity that reduces the maximum peak hour penetration by as much as 100 percent. Lastly, although curtailment in the operation of the turbines does impact total wind power generation, it has rather limited impact on the savings of fuel which make it an attractive option as compared to the use of more expensive options such as flywheels. The power penetration levels are based on future load growth scenarios, so if near term loads are lower the corresponding power penetration levels would be higher.

The high short-term power penetration levels are partially a result of not having a high enough resolution of input data for the simulation process. An analysis was conducted using the original 10 minute wind resource data for both Baltra and Santa Rosa to obtain an indication of the inter hour variability. The results of this analysis showed only a 1% difference in the total fuel consumption of the different cases investigated, indicating that the original estimates were appropriate. Further analysis could be conducted if more information on the variation in expected load and wind resource can be obtained. This is discussed in the next section of this report.

Since the acceptable level of penetration is largely an issue of project economics, as more technology to control power plant stability can always be installed. However, a point of limiting returns can be reached where the additional costs, both monetary and in the form of system complexity, do not result in enough increased fuel savings to make further increases in penetration viable. The issue is that without detailed information on plant operation, expected layout, and the costs and technical specification of detailed project designs, it is hard to perform the analysis to provide specific recommendations.

Use of Multiple Sites

The last issue to be addressed was the use of multiple wind sites in considering the power system for the island of Santa Cruz. In this context wind turbines would be installed at multiple sites, relying on the spatial differences to smooth out power fluctuations in the wind turbine output.

As discussed in Section 4.4 regarding analysis constraints, although the Hybrid2 model is not designed to consider the installation of wind turbines at multiple sites, an initial analysis was conducted to determine the impacts of using multiple sites. The results of this analysis are shown in Table 7.

Table 7: System performance using four MADE AE57turbines at multiple wind sites

Site	Control Type		% Fuel Savings	Wind GWh	Hours Curtailed	Penetration Level (%) Max Inst	Peak Hour	Avg Hour	Annual	Excess %
Baltra	Standard		18.9%	7.77		359.5%	197.7%	34.7%	34.4%	5.2%
Santa Rosa	Standard		18.6%	7.34		368.2%	202.3%	35.3%	36.5%	4.9%
Combined	Standard		17.6%	6.92		297.7%	165.3%	32.1%	34.4%	3.0%
Combined	curtailment		16.5%	5.94	2008		60.0%	27.0%	29.5%	1.3%

The analysis indicates that using the two sites results in a slight reduction in fuel savings, highlighted in orange, but also reduces all of the short term penetration levels without impacting the total annual penetration levels. This would indicate, as expected, that there is an element of power smoothing resulting from installing turbines at multiple locations. The real impact however would be seen on a sub-hour time scale, something that can not be accurately assessed using the current modeling tools. This increase in power smoothing would come at the cost of additional complications and higher costs would also be likely by installing the turbines at two separate sites.

6.0 Design Recommendations

The following provides an initial recondition on the installations of wind turbines into the Santa Cruz diesel grid. It should be noted that many additional factors that were not explicitly assessed in this analysis will play a critical roles in any final design recommendation. For example, wind turbine availability is currently very limited due to increased installations in North America and Europe, resulting in many turbines not being available, especially for smaller projects.

Section 6.1 of this document also describes further information that could be gathered to improve this analysis. The incorporation of this and other data would likely change the analysis results and require updating of these key recommendations.

6.1 Recommendations Based on Current Analysis

Based on the analysis conducted thus far it does not seem appropriate to electrically connect the existing grids on the islands of Santa Cruz and Baltra based solely on the operation of the power system. However, the authors of this report understand that there may be other extenuating factors that may make this interconnection preferable. Without an interconnection, installing four Made AE59, 800 kW wind turbines at the Santa Rosa site on the island of Santa Cruz would provide the most energy. Given the high cost and limited impact of installing short term power storage it is further recommended that initial thought should be made to using resistive fast acting dump loads and turbine curtailment to maintain power system stability. Since there will be cases where more wind energy will be available than can be consumed by the current load, efforts should be undertaken to analyze the availability of dispatchable loads; such as water desalination, water pumping, or ice making; that could be used at times of high wind power availability.

Assuming the configuration provided above while taking to account the expected wind turbine generation using the micro-siting assessment provided by ProViento S.A. Energias Renovables Ecuador, the Hybrid2 analysis indicates that the installation of the wind turbines would result in a fuel savings of around 20%, resulting in an annual fuel consumption reduction of approximately 270,877 gallons (1,025,381 liters). This amounts to supplying 25.8% of Santa Rosa's electrical energy needs using wind power and would reduce carbon dioxide emissions by approximately 3000 MMTE/year. An additional 541,800 kWh a year would also be available for dispactchable loads, further reducing energy consumption at other times.

Key Design Issues based on Recommendation

Based on the configuration of four Made AE59 wind turbines installed at the Santa Rosa site as described above the following design issues should be considered.

Communications and turbine control: Due to the relatively close proximity of the proposed site of Santa Rosa and the main diesel plant at Puerto Ayora, approximately 15km, communications to the site, either through direct telecommunications (if available) or wireless links should not become an issue. Start, stop and other generic command functions for the turbines should be available at the diesel station. If the site at Baltra was eventually selected, communications between the diesel power station and wind turbines would have to be addressed in detail.

Power system stability: Due to the short distance between the Santa Rosa site and the diesel plant, power system stability will be less of an issue than if the turbines were installed at the Baltra site. It is expected that a new three phase power line will be installed to the site as part of the interconnection process. If this line is shared with other consumers, as compared to being a direct coupling of the wind turbines to the diesel station, voltage fluctuations will be expected on this line, especially at the end near the wind turbines where the controlling influences of the diesel station will be less pronounced[6]. The range of these voltage fluctuations will be greatly dependent on the transmission line, specific control functions of the wind turbines, relative wind penetrations, and a number of other factors. Although likely not a problem, an assessment of

[6] Lundsager, P. et al. (2001) *Isolated Systems with Wind Power – Main Report*. Risø-R-1256(EN), Riso National Laboratory, June 2001

voltage fluctuations should be undertaken as part of the final power system design. It is likely that either a fast acting dump load or power storage will need to be installed at the site. The exact size of this equipment will need to be determined based on further analysis once more specific system specifications have been determined.

Turbine Selection: As has been discussed previously, to the authors knowledge, out of all the wind turbines evaluated, only the Enercon E-33 wind turbine has demonstrated operational experience in wind-diesel applications. The Vergnet GVE-MP is also being incorporated into wind-diesel applications in Australia but has yet to develop a proven track record in these applications. The Made AE59 is being implemented in the wind-diesel project at San Cristobal and the operational experience with that turbine should be assessed prior to its incorporation into this project if possible.

6.2 Data needed to refine the analysis or system design.

There are several pieces of information that would assist in the further design and specification of the power system to be installed to support the power needs of Santa Cruz. This section provides a brief description of these needs.

More refined load data for Santa Cruz and Baltra

The current load information for Santa Cruz and Baltra is quite course and based on hourly average load profiles for typical days. More detailed load data, including current information on shorter term load fluctuations in addition to further definition of local resource, large loads, and system expansions such as the new desalination plant, would be beneficial. Such plant load information could include electronically collected data on the output power of the Puerto Ayora and Baltra diesel stations as well as hourly records of production output. This data would allow an assessment of the expected power variability for the community and would allow better assessment of power system control once an initial system design has been specified.

Historical wind resource data

Although not applicable to the analysis conducted using the Hybrid2 software, correlation of the existing year of data that was used in the analysis should be referenced to other longer term data sets to insure that the year of data analyzed, generally August 2005 through July 2006, are representative of historical wind speed averages.

Improved cost and turbine availability data

To allow a final assessment of different design options, specific cost data for each wind turbine should be formally obtained. In addition, more detailed information on turbine and transmission installation will also be needed.

7.0 Conclusions

A preliminary wind turbine screening analysis was conducted for three sites and two load scenarios, the islands of Santa Cruz and Santa Cruz combined with the load of Baltra. The analysis showed that the Baltra site with the addition of the Baltra load resulted in a slightly higher wind energy output but that the cost of the grid extension likely makes it more practical to install the wind turbines at Santa Rosa to power only the grid located around Puerto Ayora on the island of Santa Cruz. If the Baltra site is used, the distance between the wind site and the diesel

plant at Puerto Ayora will likely impact system communication and power quality of the grid in the Baltra area. This will require further analysis once initial system and loading specification had been completed.

Given spacing constraints at the Santa Rosa site, of the four turbines investigated; the MADE AE59, Vergnet GVP MP, Enercon E33 and the Enercon E-48; performance figures indicate that the use of four Made AE59 wind turbines would result in a fuel savings of around 20%, resulting in an annual fuel consumption reduction of approximately 270,877 gallons (1,025,381 liters). Based on the initial analysis it was also determines that using advanced system control, wind turbine curtailment and the use of a large fast acting resistive controlling load at the wind turbine site would likely provide an appropriate level of power system stability without sacrificing significant fuel savings. The installation of power storage, such as through the use of a flywheel, may also be required to insure system stability.

Lastly, although there would be benefits of installing the turbines in more than one location, the Baltra and Santa Rosa sites, the cost of the grid extension to connect the two load centers would not be financially viable on a simple project economics standpoint.

Further analysis should be undertaken following more detailed assessments of the expected loads and once specific turbine and other components have been identified.

Appendix A: NREL modeling tools

The Hybrid2 Software

The Hybrid2 software was designed as an engineering analysis tool to consider the performance of remote power systems with special consideration to high-penetration systems with or without storage. The code can model many combinations of wind turbines, photovoltaic arrays, diesel generators, power converters, and battery storage in AC, DC, or two-bus systems. Hybrid2 also allows for more than 100 dispatch configurations with multiple diesel generators, renewable sources, and battery storage. Recent development in the software allows modeling of diesel generators that do not have a linear fuel vs. performance curves (a typical assumption for most performance models) and also allows the analysis of process or excess heat usage.

Baring-Gould E.I., "Hybrid2: The Hybrid System Simulation Model." NREL/TP-440-21272, Golden, CO: National Renewable Energy Laboratory, (1996).

Hybrid2, hybrid power system simulation software: http://www.ecs.umass.edu/mie/labs/rerl

HOMER, the optimization software for distributed power

The HOMER software is a broad-based optimization tool that is used to determine a basic system design given a specified resource, community load, and certain economic parameters. The model considers wind, PV, battery, micro-hydro, small modular bio-power, hydrogen, and diesel technology in its analysis. It is a very good screening model that allows a system designer to determine the basic system configuration before detailed design and analysis begin. It includes a sensitivity analysis capability that automatically reruns the model over a user-specified range of key input parameters. The most recent version of the software, version 2.0, allows the use of multiple diesel generators and can analyze systems with or without storage. The code only uses one-hour time steps and thus is more applicable to long-term performance modeling or component sizing. It would have to be followed by more detailed analysis of system performance issues for high-penetration wind/diesel systems.

HOMER, the optimization software for distributed power: http://www.nrel.gov/homer/

Appendix B: Primer on Diesel Retrofit Opportunities.

As background the following provides an overview of the different technology options available to retrofit a diesel power system. This is not meant to be all-inclusive and only covers internal changes to the power station. This does not address external efficiency measures that may also improve the performance of the power station.

There is a ranking of options for retooling a diesel power station, ranging from simply insuring that the diesels that are installed at the plant are appropriately sized for the expected loads through the implementation of very advanced renewable based power systems.

Resizing of diesel generators:

The first opportunity to reduce the fuel consumption of a diesel power plant is to consider the size of engines that make up the plant. In many cases diesel engines are oversized for the expected load since they are usually sized for the maximum possible load, not the normal or early morning load. Although this may seem like a safe procedure that lowers the risk of improper sizing, it may increase the fuel consumption of the plant. The impact of this will depend greatly on the size and age of the diesels under consideration as newer diesel engines have much better lower power efficiency.

Application of advanced diesel control

Larger diesel plants often contain multiple diesel engines of various sizes. In these systems, it is more likely that the diesels will be the appropriate size; however, the diesels operating at any given point may not be the most efficient combination to cover that load. In these systems, controls can be placed on the diesel generators to enable automated dispatch and more efficient operation. Each genset is provided with controls for auto starting, synchronization, and load matching while a master control is used to coordinate diesel dispatching and load sharing. Automated systems have the additional advantage of detailed operational data collection and monitoring. Fuel savings depend on the current system design and dispatch strategy, but tend to be cost effective in larger systems where the current dispatch strategy is either inefficient or labor intensive. The use of advanced controls may add a level of technical sophistication that will only be appropriate in larger communities.

Installation of batteries and a power converter to cover low load periods

This approach is applicable in a single-diesel system if the community has periods of the day with very light loading compared to the peak load. In these cases, the existing diesel is generally oversized for the low load period, thus it operates with poor efficiency. A retrofit battery bank and power converter, where stored energy from the battery is used to power the converter and cover the load, allows the generator to be turned off during periods of light loading. The batteries are then recharged when the generator is operating at higher efficiency. This approach may also be used to expand the hours of service of a particular plant without greatly increasing the system operation costs. In multiple-diesel systems, the addition of batteries can preclude the need to start an additional generator that must run at low loading to cover fluctuations in power over the rating of the primary generator. In either case, the generator recharges the batteries during other

periods of the day. The decision of whether to install a converter/battery bank or a smaller diesel to cover these low load periods is dependent on the ratio of low load to diesel size and should be considered carefully. The potential cost savings depend on the load profile and the sizes of the diesel generators. The size of the battery bank depends on the energy requirements of the low load period. The size of the inverter depends on the magnitude of the load during the low load period. Both the initial cost and the periodic replacement cost of the batteries must be weighed against the reduction in operation and maintenance expenses. In this system the batteries cover the load in the early morning and then are recharged by the diesel later. 27 liters of fuel is saved each day versus the original all-diesel system.

Install renewable technology to reduce diesel operation

Retrofitting diesel power plants to incorporate renewable based power generation allows for a potentially less expensive generation source to be used. In plants with many large diesels, where there is always a demand for power, the renewable based energy is used to offset power production by the generators, potentially to the point where all generators can be shut off. The addition of renewable based power may also reduce the number of generators operating at any given time, thus reducing the diesel maintenance requirements. Because system dynamics and power stability are of primary concern, the power system must be designed to insure that the inclusion of the renewable based generation does not degrade overall power quality.

This approach can be very cost effective but is capital intensive due to the cost of the new generation and system controls. The potential cost savings depend on the renewable resource, component maintenance costs, equipment capital costs and the fuel price. Based on current prices, PV is usually not cost effective in large systems when compared strictly to the marginal cost of diesel fuel. Plants with access to reasonable wind resources, generally greater than Class 1 (5.9 m/s annual average) could significantly reduce operating costs by the inclusion of some amount of wind generation.

The next sections describe different considerations and configurations of wind / diesel power stations.

Wind/diesel applications

Wind/diesel power systems can vary from simple designs in which wind turbines are connected directly to the diesel grid with a minimum of additional features, to more complex systems. Two overlapping concepts depict the system design and required components: the amount of energy that is expected from the renewable sources (system penetration) and the decision to use a storage device to cover system energy fluctuations. Given today’s technology, these issues are usually selected by the system designers as a starting point for system design. Both of these concepts are described in the following section.

Renewable Penetration

When incorporating renewable-based technologies into large power systems, the amount of energy that will be obtained from the renewable sources must be determined because this will dictate which components will be used. Steve Drouilhet developed the following classification and definitions of system penetration that characterize the levels of system complexity:

$$\text{Instantaneous Penetration} = \frac{\text{Wind Power Output (kW)}}{\text{Primary Electrical Load (kW)}}$$

And

$$\text{Average Penetration} = \frac{\text{Wind Turbine Energy Output (kWh)}}{\text{Primary Electrical Load (kWh)}}$$

The difference in these equations is in the units. Instantaneous penetration is in terms of power; thus, it is the ratio of how much power is being produced by the renewable resources at any specific instant. The average penetration is in terms of energy; it includes a time domain and is thus measured over days, months, or even years. In some sense, average penetration is in the domain of the economist and instantaneous penetration falls in the realm of the engineer. Drouilhet also proposed a three-level classification system based on system penetration that separates systems along power and system control needs (Table B.1).

TABLE B.1: PENETRATION CLASS OF WIND-DIESEL SYSTEMS

PENETRATION CLASS	OPERATING CHARACTERISTICS	PENETRATION	
		PEAK INSTANTANEOUS	ANNUAL AVERAGE
LOW	▪ Diesel runs full-time ▪ Wind power reduces net load on diesel ▪ All wind energy goes to primary load ▪ No supervisory control system	< 50%	< 20%
MEDIUM	▪ Diesel runs full-time ▪ At high wind power levels, secondary loads dispatched to ensure sufficient diesel loading or wind generation is curtailed ▪ Requires relatively simple control system	50% – 100%	20% – 50%
HIGH	▪ Diesels may be shut down during high wind availability ▪ Auxiliary components required to regulate voltage and frequency ▪ Requires sophisticated control system	100% - 400%	50% – 150%

Proposed by Steve Drouilhet

Wind / Diesel Power System Configurations.

Low-penetration systems: Many low-penetration systems have been installed worldwide. These vary from small to relatively large isolated grids, such as those found on several Greek islands. In fact, some large grids, such as those found in certain areas of the United States and Europe, reach a wind power penetration that would classify them in the same category as low-penetration systems. Basically, low-penetration systems are those in which the renewable generation source

is just another source, requiring no special arrangements. The control technology required at this level of generation is trivial, especially given the control, flexibility, and speed of modern diesel and wind systems. In many systems, no form of automated control is required—the wind turbines act under their commercial controllers and an operator monitors all system functions. Because the diesel engines are designed to allow for rapid fluctuations in power requirements from the load, the addition of wind has very limited impact, if any, on the ability of the diesel control to provide the remaining difference. Issues of spinning reserve, a term used to represent the availability of instantaneous system capacity to cover rapid changes in system load or energy production, are addressed by the allowable capacity of the diesel engines, which in many cases can run at 125% rated power for short periods of time with no adverse impact on the diesel or generator. A generic schematic of a low penetration system is shown in Figure B.1.

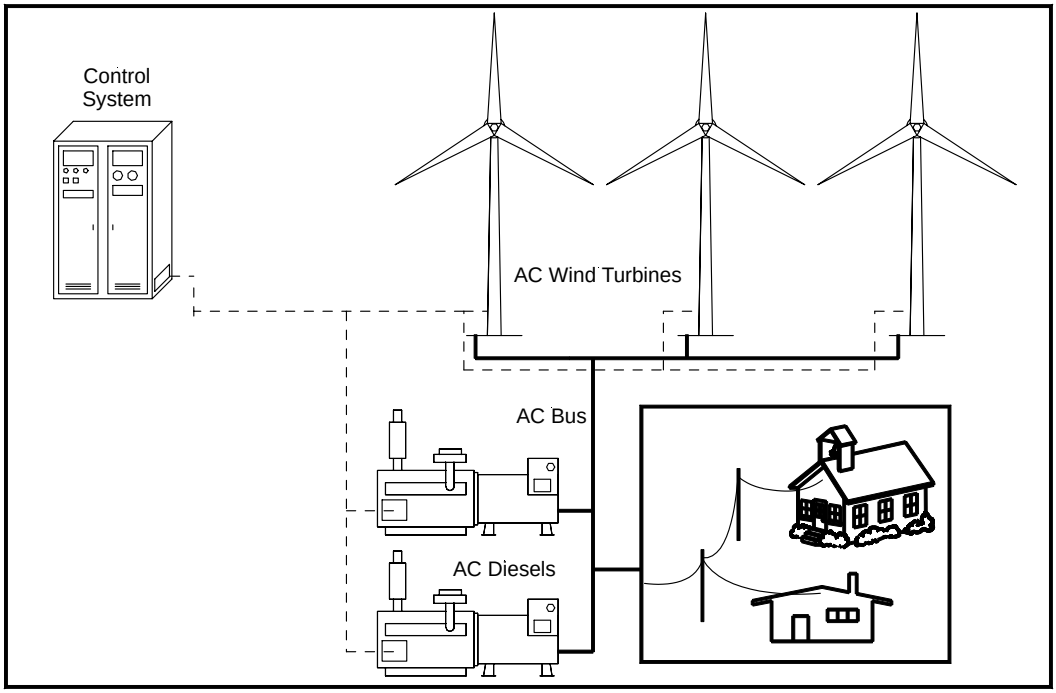

Figure B.1: Schematic of low penetration wind/diesel hybrid

Medium-Penetration Systems: Systems with larger ratios of renewable energy contribution fall into this category. Allowing power penetrations of up to 50% will allow any under-loaded diesel generators in multiple diesel plants to be shut off or for production to be switched to a smaller unit. This in turn will reduce plant diesel consumption and reduce diesel engine operation. However, this may also open the power system to potential shortfalls, assuming the loss of one or more of the wind generators or diesel engines. In addition, with a large penetration of energy being produced by the variable renewable source, it will become harder for the operating diesel units to tightly regulate system voltage and maintain an adequate power balance. There are options to ensure that the high-power-quality requirements of the power system are maintained, even with half of the energy provided by renewable sources. Some of the options include power reduction capabilities within the wind turbine controller, the inclusion of a secondary loads to ensure that no more than a specified amount of energy will be generated by the wind, installation

of capacitor banks to correct power factor, or even the use of advanced power electronics to allow real time power specification.

Spinning reserve on medium-penetration power systems requires experience in regard to proper power levels and system commitments but is not considered technically complex. Such spinning reserve questions should be handled on a case-by-case basis but can be partially solved by using options including the use of advanced diesel controls, the installation of a modern diesel engine with fast start and low loading capabilities, controlled load shedding or reduction, power forecasting, and proper system oversight. Combined with the use of variable-speed or advanced power conditional available on many modern wind turbines, the control requirements of medium-penetration systems are quite simple. The ability to provide high power quality in medium-penetration power systems has been demonstrated for years in a number of highly important locations. The most notable examples are the military diesel plants on San Clemente Island and Ascension Island and the power system in Kotzebue, Alaska. All of these systems have experienced power penetration at or above these guidelines set for medium penetration systems.

High-Penetration Systems: Although this technology has been demonstrated on a commercial basis, high-penetration wind-diesel power stations require a much higher level of system integration, technology complexity, and advanced control. The principle of operation of high-penetration systems is that the required equipment is installed in addition to the wind turbine so that the diesel can be shut off completely when there is an abundance of renewable-power production. Any instantaneous power production over the required electrical load, an instantaneous penetration over 100%, is supplied to a variety of controllable secondary loads. In these systems, synchronous condensers, load banks, dispatchable loads (and possibly storage in the form of batteries or flywheel systems), power converters, and advanced system controls are used to ensure power quality and system integrity. Spinning reserve is created through the use of short-term storage or the maintenance of a consistent oversupply of renewable energy. Although these systems are being demonstrated commercially, they are not yet considered a mature technology and have not been demonstrated on systems larger than approximately 200 kW average load. A generic schematic of a high penetration with storage is shown in Figure B.2.

Systems with storage and without: Until recently, it was assumed that wind-diesel systems without storage were theoretical, possibly born out of short-term testing in test-stand-based power systems. This is no longer the case. Commercially operating short-term and no storage systems have been installed in recent years, demonstrating that either technology choice is viable.

In systems incorporating storage, the storage is used to cover short-term fluctuations in renewable power. The premise of this system design is that a large penetration of renewables is used (up to 300% of the average power requirements), and when the renewable-based generators are supplying more power than is needed by the load, the engine generators can be shut down. During lulls in the renewable power generation, discharging the battery bank or other storage device supplies any needed power. If the lulls are prolonged or the storage becomes discharged, an engine generator is started and takes over supplying the load. Studies have indicated that most lulls in power from the wind are of limited duration, and using storage to cover these short time

periods can lead to significant reductions in the consumption of fuel, generator operational hours, and reduced generator starts.

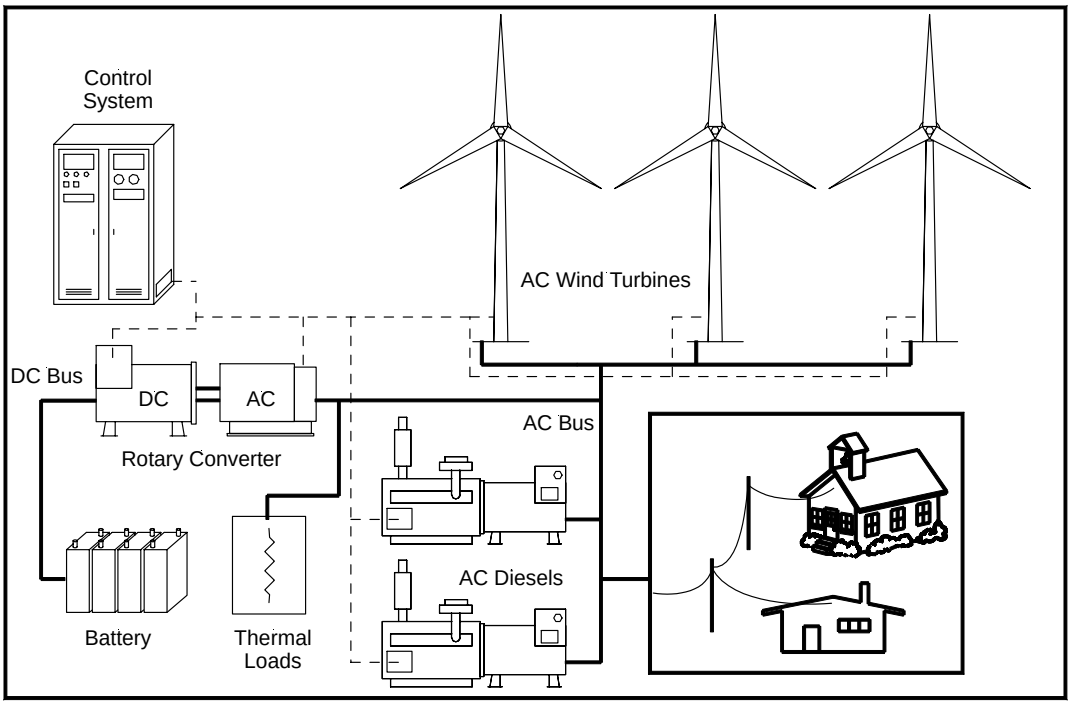

Figure B.2: Schematic of high penetration wind/diesel power system using a rotary power converter

In large power systems, the installation of a battery bank to cover shortfalls in renewable production may not be feasible, mainly due to cost. However, without the use of storage, it is very difficult to control the stability of a conventional power grid with large quantities of renewable power—thus the challenge of hybrid systems without storage. This configuration is based on the AC bus and does not use batteries to provide grid stabilization. The basic premise of these systems is that the installed capacity of the renewable technology is much larger than the load. When the renewable devices are operating and producing more energy than is needed by the load by some margin, usually between 125% and 150%, the dispatchable generators can be turned off. External control devices, such as dispatchable secondary loads, fast acting dump loads, synchronous condensers, and advanced diesel control are used to maintain system stability and control. If the renewable energy dips below a specified threshold, a generator is started to insure power security or some of the dispensable loads can be disconnected to increase the systems headroom. This type of system produces a large amount of extra energy that must be used if the project is to be economical. This is completed with a large thermal storage tank that acts as a buffer for the electrical load, allowing the smoothing of the variable wind energy and dispatching a diesel generator when there is not enough energy to cover the loads or if the thermal storage tank temperature drops below a specified limit. The control system and hardware requirements are less complex than a system using battery storage, however, the facility must have a large and expensive heating requirement to cover the cost of the additional infrastructure, which is the case for Antarctica.

All high-penetration systems, with and without storage, have been installed in northern climates where the extra energy can be used for heating buildings or water, displacing other fuels. In these systems, it may be wise to install uninterruptible power supplies (UPSs) on critical loads. Although few systems have been installed, the concept is economically attractive and can drastically reduce fuel consumption in remote communities.

Appendix C: Control of wind diesel power systems

Wind/diesel power systems can vary from simple designs in which wind turbines are connected directly to the diesel grid with a minimum of additional features, to more complex systems.[7][8] , Hunter et. al. (1994) and Lundsager et. al. (1994). The important complication of adding wind power to diesel plants is that the production of energy from the wind turbines is controlled by the wind, meaning most turbines can not control either line frequency or voltage and must rely on other equipment to do that. With only small amounts of wind energy the diesel engines can provide this control function while with larger amounts of wind energy other equipment is necessary.

Four issues are of primary importance when addressing power system stability; system voltage, system frequency, power factor balance and harmonic distortion. Power system voltage is generally controlled by voltage regulators on rotating machinery, although it can also be conducted by modern solid state devices. System frequency is controlled by maintaining a balance of power on the grid, if two much power is being generated, system frequency increases, if to much power is called for, frequency decreases. Reactive power again is generally managed by rotating machinery or advanced solid state devices. Lastly, harmonic distortion is the impact on the wave form of the power being supplied and can be a problem with systems incorporating a large number of electronic devices, both within generation and the load.

As an illustration of the balancing of generation and consumption of power, Figure C.1 shows the power balance of a basic wind diesel system, where the instantaneous consumer load is shown as 100% load. The system in the figure has an unusually high proportion of wind energy in order to highlight the issues.

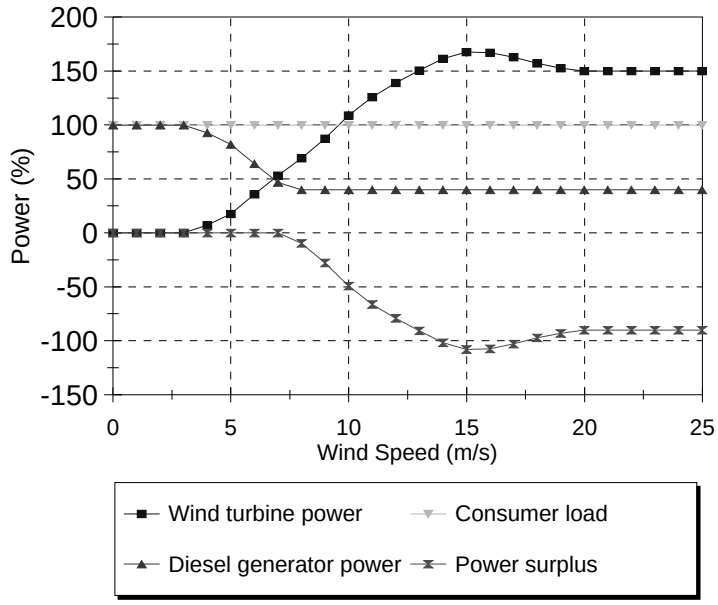

Figure C.1: **Simple power balance of a wind diesel power system**

At low wind speeds the diesel generator produces all the power required, but as the wind speed increases the increased power production from the wind turbine is reflected by a decreased production from the diesel generator.

At low wind speeds the diesel generator produces all the power required, but as the

[7] Hunter, R., Elliot, G. (Ed's) (1994) *Wind-Diesel Systems*. Cambridge, UK: Cambridge University Press, 1994.

[8] Lundsager, P.; Bindner, H. (1994) *A Simple, Robust, and Reliable Wind-Diesel Concept for Remote Power Supply.* World Renewable Energy Congress III, Reading, UK, 11-16 Sept. 1994.

wind speed increases the increased power production from the wind turbine is reflected by a decreased production from the diesel generator. Eventually the diesel generator reaches its minimum load defined by the manufacturer and the surplus power must be taken care of by either limiting the power production from the wind turbine or by diverting the surplus power in a controllable load. If the system configuration and control allow it, in this case the diesel could also be shut off, allowing the load to be supplied completely by wind energy.

Basic System Control and Operation

The simplest large wind diesel system configuration is shown in figure C.2 where a standard grid connected wind turbine with an induction generator is connected to the AC bus bar of the system. This represents a simple low penetration power system.

When the wind turbine power output is far less than the consumer load minus the diesel minimum load, the diesel governor controls the grid frequency while the voltage regulator of the synchronous generator of the diesel set controls voltage.

If the designed wind turbine output is about equal to the consumer load minus the diesel minimum load, controllable resistors, typically referred to as a dump load, may be included to absorb possible surplus power from the wind turbine, in which case the dump load controller helps to regulate the frequency. This would be termed a medium penetration power system.

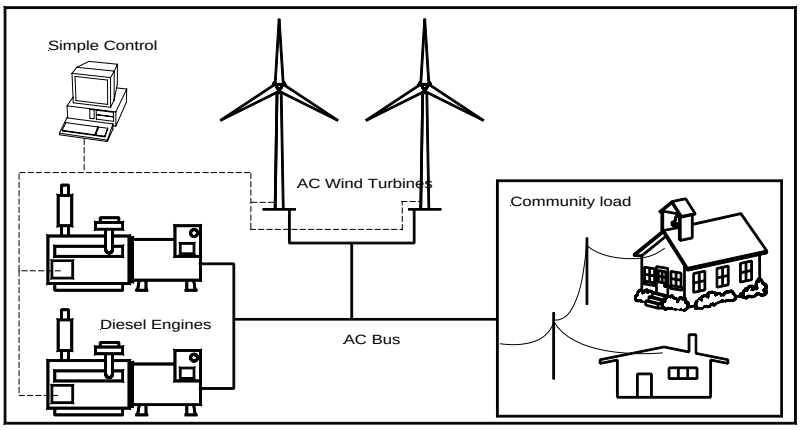

Figure C.2: Simple, low penetration wind / diesel power system

If the wind turbine can produce more power then is needed by the load a more complicated system is needed that may also incorporate energy storage to smooth out fluctuations in the wind energy. In this case some surplus energy is saved for later release when the need arises. If the wind production is more than the load, it then becomes possible to shut off all diesel generators altogether. Although this maximizes fuel savings it requires very tight control of all power system components to insure system stability. Additionally the fluctuating nature of the wind power may pose extra problems for the control and regulation of the system. This last configuration would be characteristic of a high penetration power system.
As can be intuitively understood, the higher the wind penetration, the more energy that can not be used by the electric loads is generated. Instead of just dissipating this surplus power in a dump load the power can be used to satisfy additional community loads such as

- Fresh water production by e.g. desalination, purification etc.

- Ice making
- Water heating
- House or district heating

and much more. Usually these loads are broken into two categories

- Optional loads, loads that will only be met if and when surplus power is available as other energy sources can be used when excess energy is not available, for example space heating.
- Deferrable loads, loads that must be met over a fixed period of time, for example on a daily basis, and if not supplied by surplus power will be served by primary bus bar power.

Additionally, some loads can be controlled by the power system to instantaneous reduce the required power demand, thus saving the system from having to start an additional generator to cover what is only a momentary defect of power.

Control of systems using energy storage

There are two general parameters that are used to control systems using energy storage, battery state of charge (SOC) and system load. Generally the inverter is used whenever the renewables and battery subsystem can satisfy the load, based on the battery state of charge, the generator is used for back-up power when renewables and energy from the battery bank can not satisfy the load.

Using battery SOC for system control has been used in industry for many years while the first published papers of come from Manwell et al., 1989[9], in a strategy that was coined Cycle Charging. Using this strategy the main goals is to reduce the run time of the diesel engines and insure that when they are operating, they are operated near peak efficiency. Cycle charging dictates that the batteries are used to cover any deficiency in renewable power to keep a diesel from being started. Once the batteries have been discharged the diesel is started and run covering the load and charging the batteries at the maximum rate possible. The diesel will continue to operate until the batteries have been charged to a state of charge specified by the operator at which point the batteries are again used to cover any deficits. The decision making process basically follows these two steps:

Battery SOC above ~ 30%: Inverter and/or renewables cover the load if possible. Excess renewable power is used to charge the batteries. The 30 % SOC limit on the battery is arbitrary and will depend on the type of batteries used.

Battery SOC reaches ~ 30%: Engine starts to cover the load and charges the battery bank. If any energy is generated by the renewables it is also used to charge the battery bank. When the battery reaches a set SOC, usually around 80 to 90% SOC, the diesel is shut off and the inverter takes over the load.

Figure C.3 demonstrates this method of control for a hypothetical power system. The method is advantageous for its simplicity in logic and control, requiring only the measure of battery state of charge, which is usually approximated by battery voltage. The simplicity of this method does have drawbacks in regards to use of the battery bank and the losses that result. This can be seen in Figure C.3 where the lower battery charge starts the diesel engine, resulting in a charged battery that is immediately discharged to cover the large evening load. The losses associated with this process would be quite large compared to operating the diesel to cover the evening peak load.

This introduces the second control factor, which is load. In many cases it is possible to select a load level, either in power or current, at which point the generator is started. This is done because of the inefficiencies of drawing large quantities of energy out of the battery bank. In this case, even if the

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[9] Manwell J.F.,McGowan J.G., Jeffries, W.Q., Stein W.M., (1989), “Developments in Experimental Simulation of Wind/Diesel Systems”, EWEC’89, Glasgow, Scotland, July, 1989.

batteries are full, the engine would be used to cover the high load periods. Care should be given to the selection of the location of power or current measurement so that energy generated by the renewables can be taken into account. In many cases, although the load to the community may be high, renewable sources may be generating a large portion of this power, only requiring limited energy from the battery bank. In this case, starting the generator to make up this small load threshold would be very inefficient.

In 1995 Dr. C.D. Barley introduced the concept that instead of using the engine generators to charge the batteries, they should be left discharged to maximize the capture of power from the renewables, (Barley, 1996)[10]. The engine generator is only used to provide equalization charges of the battery as required. Barley expanded on this topic to define the Frugal Dispatch Strategy where the battery through-put cost, the total cost for each kWh taken out of the battery, is used to determine a load over which it is less expensive to supply the load by starting a engine generator. The battery supplies all loads under this critical load while the generator supplies any loads above. The strategy recommended in this text is that a combination of these strategies. The battery should be used to cover loads below a specific amount, the critical load specified by Dr. Barley. When the battery is depleted or the load is large, the engine generator is started and used to cover the load and charge the battery. At any point during the charging, if the power from the renewables can cover the load or the load drops below the critical level than the generator is also shut off and the load is covered by the renewables and the battery bank. The generator remains off until the battery again reaches the low state of charge set point. This method allows

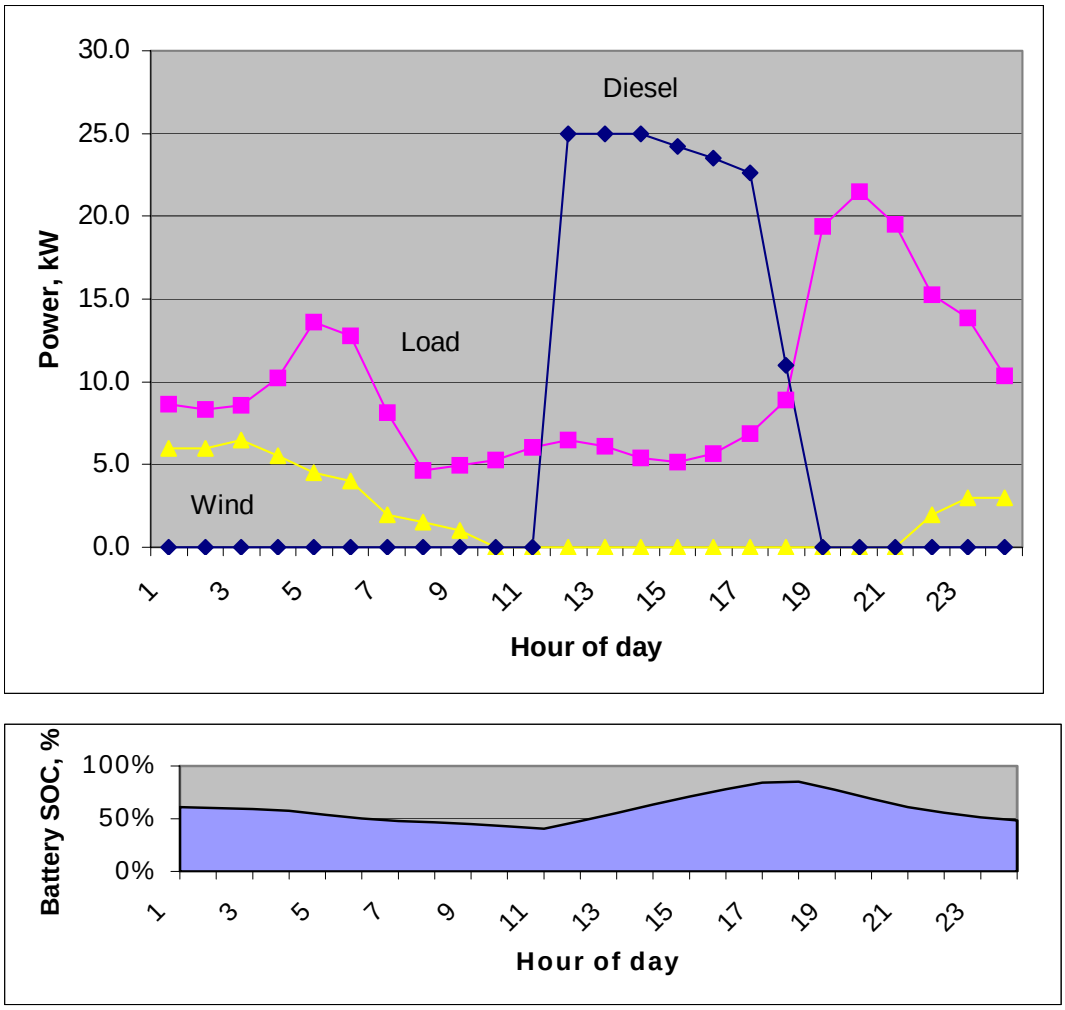

Figure C.3: Depiction of cycle the charging control strategy

[10] Barley, C.D. (1996). "Modeling and Optimization of Dispatch Strategies for Remote Hybrid Power Systems," Ph.D. dissertation, Dept. of Mechanical Engineering, Colorado State University, Ft. Collins, CO.

for the capture of power produced by renewables without the potential of leaving the battery bank at a low state of charge for extended periods of time. Again, it should be clear that there are many control methods available. The ability to accurately model different control options can assist in the determination of the best control logic for a specific system.

In most power systems of this type, system control is dispersed to a number of different components, usually using the voltage of the battery bank as the control variable. Each renewable generation device will come with or include a charge controller that moderates the energy that is passed to the battery bank, based on the voltage. The inverter/power converter usually uses battery voltage to regulate energy from the battery bank and to start any dispatchable generator if possible. Because of this, generally the system user has limited ability to specify system control other than through a few specific set points.

Short term energy storage (Power storage)

The second major use of battery storage is to cover short-term fluctuations in renewable power and allow a dispatch-able generator to start if the lapse in renewable power becomes prolonged. The premise of this system design is that a large penetration of renewables, primarily wind power, is used in the system design, up to 300% of the average power requirements. When the renewable based generators are supplying more power than is needed by the load, all of the engine generators are shut down. The power of the system is regulated through the use of dispatchable productive use loads, dump loads, and/or a synchronous condenser. During lulls in the renewable power generation, discharging the battery bank makes up any difference. If the lulls are prolonged, or the battery bank is becoming discharged, an engine generator is started and takes over supplying the load. The batteries are recharged and when the renewable power can again cover a portion of the load, the generator(s) are shut off and the process repeated. Studies have been completed which indicate that most lulls in power from the wind have only a limited duration and using battery storage to cover these short time periods can lead to significant reductions in the consumption of fuel, generator operational hours and reduced generator starts(Beyer, 1995 & Shirazi, 1997)[11,12].

Systems based on the power storage concept will be focused primarily on the AC bus, though DC based systems are also possible. In these systems the generators are designed to be an integral part of the system, not just a back-up power source if the batteries are depleted. The addition of the dump load, which may actually have productive uses like heating or the production of hot water, and a synchronous condenser will add to system cost but are required to maintain system stability. Figure C.4 provides a schematic of a possible hybrid system based on an AC bus architecture using the power storage concept. In this system the AC wind turbines and engine generator provide power directly to the AC loads. A rotary converter or large solid state power converter is used to either charge the battery when excess power is available, provide power from the battery when there is a deficit or simply to provide reactive power and voltage control when the engine generators are shut down. An advanced control system will be required to operate this system successfully. The battery bank will be quite small, providing power for only up to 30 minutes of the average load.

Since the generators are the primary devices that are used to control system frequency, voltage and reactive power requirements, when the generators are off, other devises must be used to perform these tasks. Two devises are commonly used, a synchronous condenser to provide voltage control and reactive power and a controllable load bank to maintain system frequency.

Figure C.5 shows how this type of system might respond given certain wind and loading conditions.

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[11] Beyer, H.G., Degner, T., Gabler, H., (1995). “Operational Behavior of Wind-Diesel Systems Incorporating Short-Term Storage: An Analysis via Simulation Calculations” Solar Energy, Vol. 54, No 6, pp.429-439, 1995.

[12] Shirazi, M. & Drouilhet, S. (1997). “An Analysis of the Performance Benefits of Short-Term Energy Storage in Wind-Diesel Hybrid Power Systems,” 1997 ASME Wind Energy Symposium, Reno, Nevada, January 6-9, 1997.

During the first 40 minutes of the data, the wind covers the load with the storage being used occasionally for short lulls. The wind then dies and the battery is required to cover the load. After five minutes, a diesel is started to supply the load, which happens two minutes later. The diesel is run for about 20 minutes charging the battery at which point the wind has strengthened and the diesel is again shut down. The strong wind is only temporary and the diesel is forced to restart in the 80th minute. Around the 100th minute, the wind again strengthens and the diesel is shut off. After another 40 minutes, the wind decrease, requiring the diesel to again be brought on line. The diesel remains active for the rest of the time with the diesel and wind turbine providing power for the load and re-charging the battery bank to a full state of charge.

In this architecture, it is helpful that the coincidence between the renewable resource and load is high because there is very little storage to allow energy generated at one time to be used at another. Unlike the long term energy storage case, it is important for the battery bank to be mostly recharged before the dispatch-able generator is shut down so that it can be used to smooth out fluctuations in the power produced by the renewables. In addition, the amount of energy going through the battery bank is small compared to the load and so the losses associated with charging the battery with energy generated from fossil fuel is minimal. A system of this nature will require more frequent generator starts and faster loading of the engine generators because of the variability in the renewable resource and limited storage capacity. This may require that the generator oil and/or cooling water be heated, allowing quicker engine loading but adding to maintenance cost and complexity.

One of the critical elements in regards to the design for systems incorporating power storage is that tight control needs to be kept over system power quality, voltage and reactive power requirements. In long term energy storage systems, the large battery bank provides a buffer that increases system stability while, due to their small size, the batteries in short term power storage systems are not able to perform this task. There are numerous ways to maintain stability in systems with small battery banks, some of the more popular are;

- Active control of the wind turbine(s) to reduce power production when an excess is being produced. This may be done by shutting turbines down or adjusting the power production through the use of alerons, mechanical pitching mechanisms or power control.
- Installations of dispatch-able loads to consume extra power, such as resistance heating or water purification.
- Load shedding, a process where non-critical loads are temporarily shut off to quickly reduce system load.
- Backdriving the diesel generator, a process where power is actually put into the generator to overcome the generator losses while keeping the generation running so that it can be loaded quickly. This is analogues to using a cars engine to control speed while going down hill.
- Installing systems, like block heaters, to allow quick starting of generators.
- Installation of a capacitor bank to smooth out rapid system fluctuations and partially correct the systems power factor
- Installation of a synchronous condenser or rotary converter, which is used to produce reactive power and help control system voltage.
- Use of fast acting dump loads to maintain a load balance and thus control system frequency.

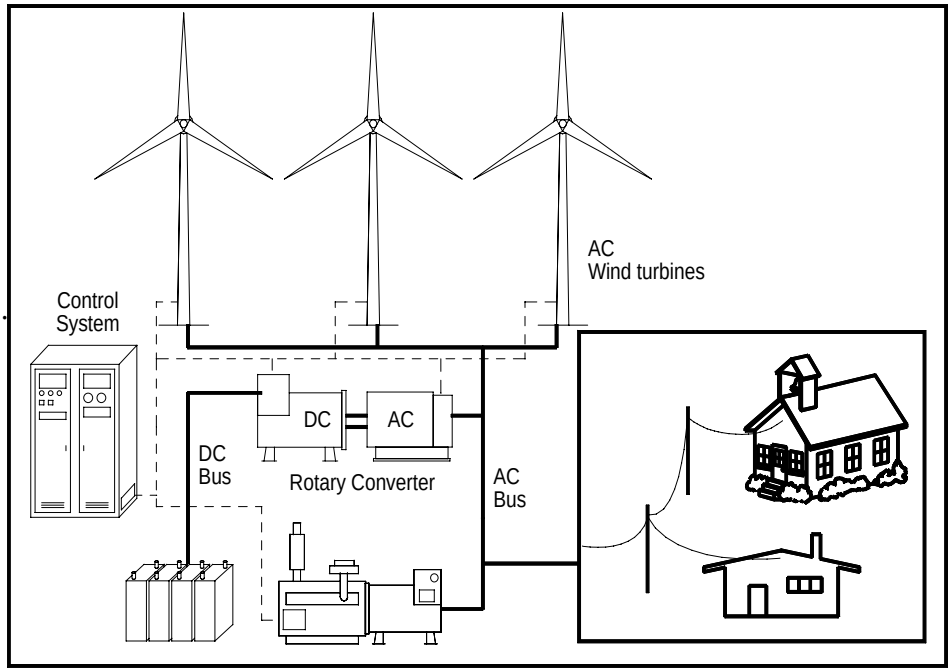
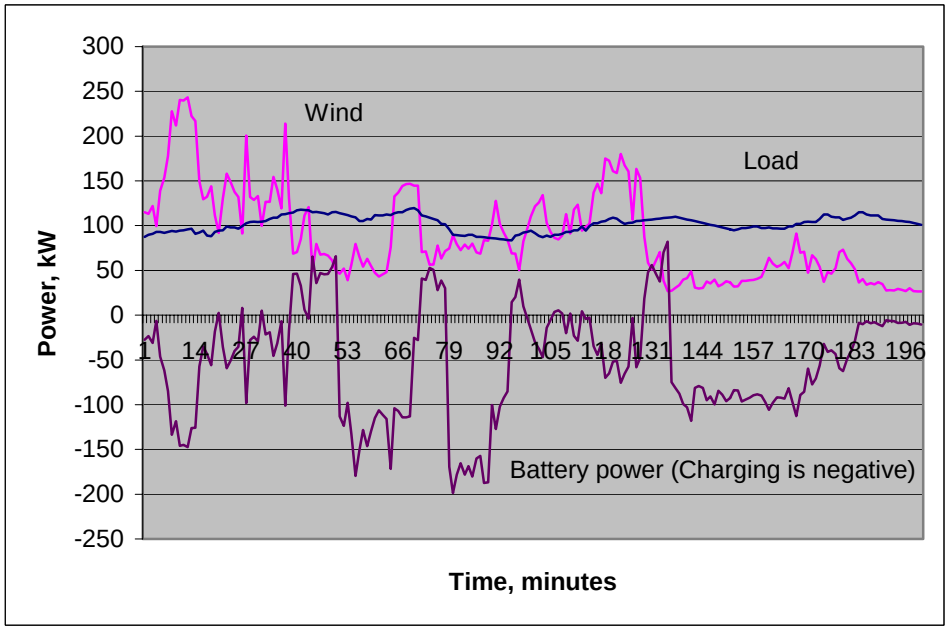


Figure C.4: Schematic of a power storage hybrid system with a rotary converter



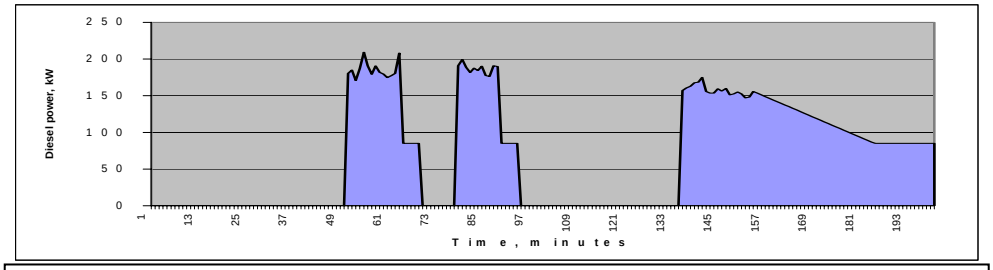


Figure C.5: Depiction of 24-hours of operation of power storage hybrid power system

Some of these devices are active mechanisms that are controlled by a central computer or operator while others are passive devices that need no manual interface. Generally, a number of these devices will be included in a power system to provide control during different modes of operation. In most cases one or more computer based controllers, programmable Logic Controllers (PLC's), are required in this type of system.

Control of systems using power storage

The type of control strategy used for these applications has been called Short Term Power Smoothing, (Baring-Gould, 1998[13]. & Barley, 1996). Battery storage is used to cover short fluctuations in the power output of the renewables, allowing diesels to be shut down during times of excess power and then started during a loss of renewable power. The strategy requires the diesel to meet the average net load, the system load minus the renewable power generation, with the batteries covering any power fluctuations above zero net load when the diesel is off. The diesel(s) are started if the battery bank is discharged to a moderate state of charge. When operating the diesel(s) will operate at a level to cover the load and charge the battery at the maximum rate possible. Diesel charging of the battery will stop and the diesel shut down if the renewables can again cover the portion of the load that a diesel was supplying. In multiple diesel systems, diesels may be switched off and on based on the same net-load condition, even if some diesel engines are already operational. The control question is, does the balance between the energy required by the user and the energy being generated by the system allow for a diesel engine to be shut down. The decision to start an engine generator must be made while the battery bank has the power to allow for proper warm-up of the generator before it is loaded. In this case, it is more important to have a full battery, even at the expense of diesel fuel.

Power system with renewable and conventional generation without storage.

In large power systems, the installation of a battery bank to cover shortfalls in renewable production may not be feasible, mainly due to cost. However, without the use of storage, it is very difficult to control the stability of a conventional power grid with large quantities of renewables power, thus the challenge of hybrid systems without storage. This configuration, as shown in figure C.6, is based on the AC bus and does not use batteries to provide grid stabilization. These systems range in size from 1 MWh/day upwards. Two general classifications of systems without storage are given, low and high penetration hybrid systems.

Low penetration systems are usually defined where the total power generated from the wind turbines is between 25 and 40% of the total power supplied to the load, usually called annual energy penetration. Because system dynamics and power stability are of primary concern, at least one diesel generator is operated continuously and the wind penetration is usually only a fraction, from 20% to 70%, of the average load at any given time, called instantaneous penetration. Advanced control components can be included with these systems to allow for the shutdown or control of individual wind turbines and/or diesels depending on the resource, load, and system control requirements. It is recommended that the wind turbines selected be considered based on their power impact on the system, the more benign the impact, the better the system will perform. Figure C.7 shows the hypothetical results of installing wind turbines and controls onto a diesel system for a large community.

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[13] Baring-Gould, E.I., "Hybrid2; The Hybrid System Simulation Model, Version 1.1, Users Manual". NREL/TP-440-21272, Golden, CO: National Renewable Energy Laboratory. 1998.

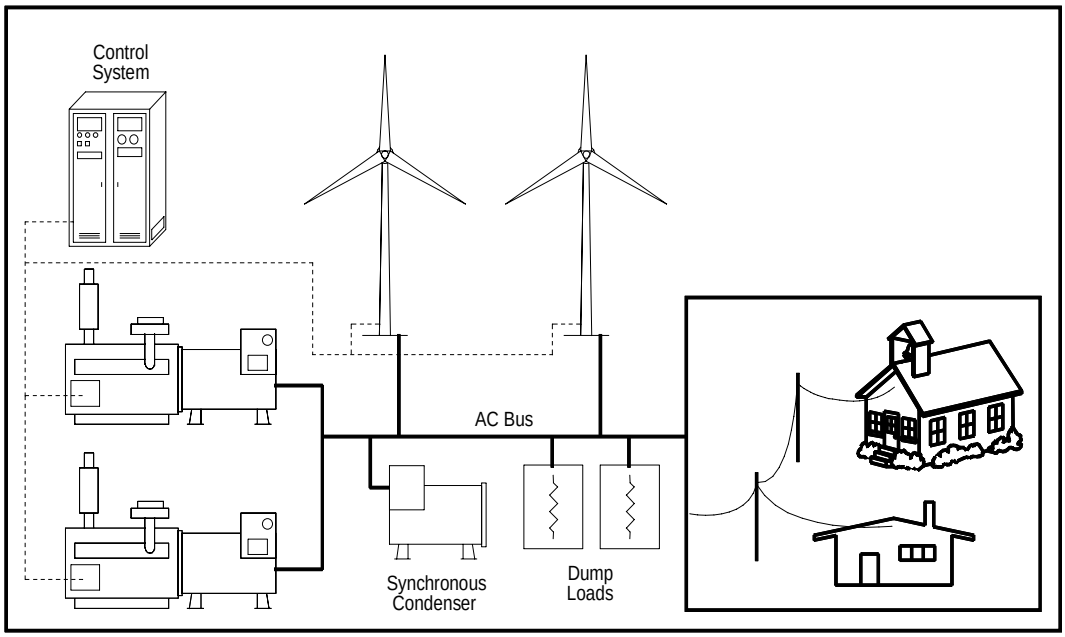

Figure C.6: Schematic of hybrid system with renewable and conventional generation without storage

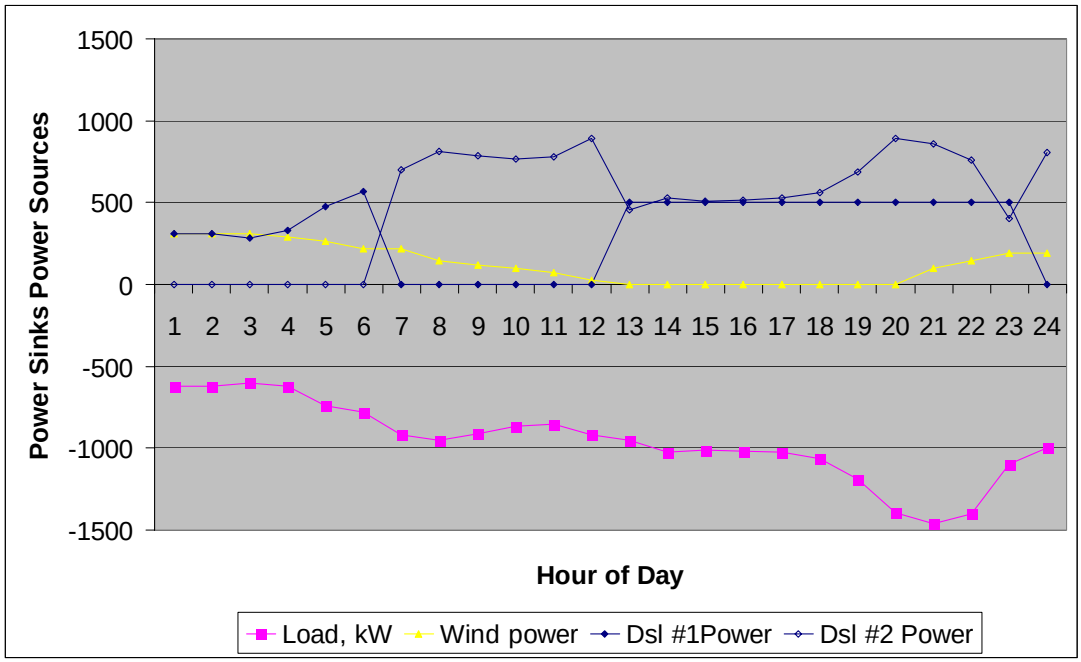

Figure C.7: Depiction of 24-hours of operation of a hybrid system without storage

In this case, wind power and the first diesel are initially being used to cover the load, each supplying about half of the needed power. As the wind decreases, the diesels are switched so that the larger of the units, diesel #2, provides for the load. Eventually the load increases and wind decreases to a point that both diesels are needed to cover the load. During the late part of the day the wind again increases and the system returns to only operating with one diesel unit. This configuration saves about 1200 liters of fuel per day, about 15% of the total consumption compared to a system with only diesel generators.

Other types of renewable technology could also be used in large, low penetration hybrid power systems. Such technology could include river run micro-hydro, solar electric, solar thermal and bio-gas/biomass. Each of these technologies have different, but more stable performance characteristics, which would greatly simplify the system stability questions. The problem however becomes one of economics, low penetration hybrid systems put renewables in direct competition with the avoided cost of fossil fuel, usually diesel, which, depending on the market, can be quite low. This forces the use of only the most mature and inexpensive renewable technologies.

High penetration renewable systems using wind power without storage are currently receiving much attention, although only one system has operated for any length of time. The basic premise is that the installed capacity of the renewable technology is much larger than the load. When the renewable devices are operating and producing more energy than is needed by the load by some margin, usually between 125% to 150% of the load, then the dispatchable generators can be turned off. External control devices, such as dispatchable loads, dump loads, synchronous condensers, and advanced diesel control are used to maintaining system stability and control. If the renewable energy dips below the threshold, a generator is started to insure power security. As can be imagined, this type of system produces a large amount of extra energy that must be used if the project is to be economical. At this point all high penetration systems, with and without storage, have been installed in northern climates where the extra energy can be used for heating buildings or water, displacing other fuels. In these systems, it may be wise to install un-interruptible power supplies (UPS's) on critical loads. Although few systems have been installed, the concept is economically attractive and can drastically reduce fuel consumption and power generation cost in remote communities.

Control of systems without storage.

Some of the considerations about the control of hybrid systems without storage have already been introduced and focus primarily on the interactions of the wind and dispatchable engines, usually diesel, components. As the above discussion hopes to make clear, the control of these systems is determined by the sizing of the different components and the expected system operation. In low to medium penetration systems, system control may be rather simple, relying on strong component control, but limited system wide control. In fact, some of the most successful large low penetration systems use no overall system control, just monitoring that allows system operators to dispatch different components as needed. In higher penetration systems, where the ratio of renewable energy to the load is larger, automated control, usually using PLC controllers, is required. These elements of system control can be rather complex, requiring a high degree of system understanding as well as prolonged testing prior to implementation.

One additional control concepts should be introduced due to its importance in remote plant operation, spinning reserve. The term spinning reserve is used to describe the headroom in production a plant has at any specific time to supply unexpected load increases. It is calculated by subtracting the operating power of a plant by the rated capacity of all of the components currently operating in that plant. However, spinning reserve costs money, in terms of fuel and increased maintenance for the diesels that our operating but not being used. Depending on the type of system configuration and control being used, retrofitting a diesel plant with renewable technologies can either increase or decrease the spinning reserve or the need for it.

Appendix D: Preliminary Modeling Results of a Wind System on Santa Rosa or Baltra Island -

Preliminary Modeling Results of a Wind System on Santa Rosa and Baltra Island

10/2/06

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National Renewable Energy Laboratory

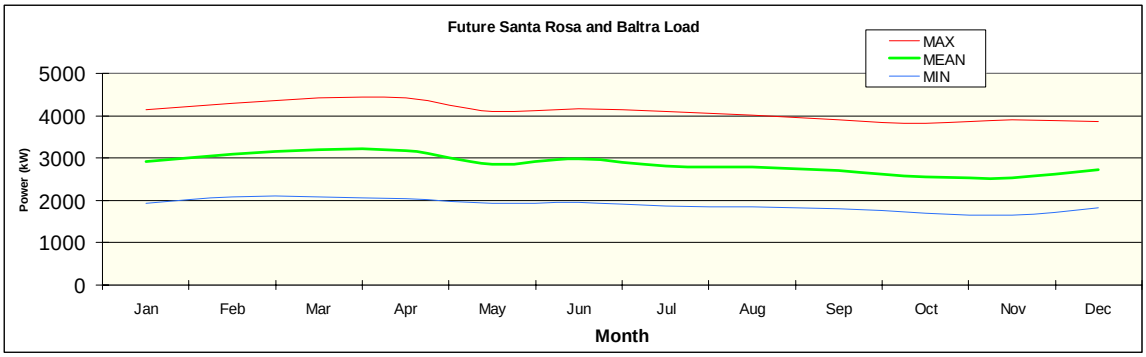
Background

This is a preliminary analysis of the potential for wind turbines to be introduced into the power grid in Santa Cruz and Baltra Islands in the Galapagos. There are three potential wind turbine locations considered and two different load scenarios. The three wind turbines sites evaluated are Baltra Island, Santa Rosa, and Camote. The two load scenarios are Santa Rosa and Santa Rosa combined with Baltra. This last load scenario would include the installation of a medium voltage line to extend the grid from Santa Rosa to Baltra.

The Hybrid Optimization Model for Electric Renewables (HOMER) was used to study the feasibility and cost effectiveness of using wind turbines for power generation. This preliminary analysis uses approximate costs for various components and does not include detailed modeling of the dispatch of the diesels in this wind-diesel system. However, the level of analysis is good for a comparison of the three different sites and to evaluate the wind penetration for the two different load scenarios.

Model Inputs

Hourly wind resource data the year 2005 for all three sites was used as input to the analysis. Load data consisted of the average hourly load-profile for each month, so there were 12 different averaged 24-hour load profiles used. In this first analysis two wind turbines were analyzed, an Enercon 33 and a Furlhander 250. Turbines descriptions can be found in the Appendix along with a summary of the wind resource data. Figure 1 shows a plot of the future combined load of Santa Rosa and Baltra, including the water desalination load. Figure 2 shows the future load of Baltra, which is much smaller than Santa Rosa.



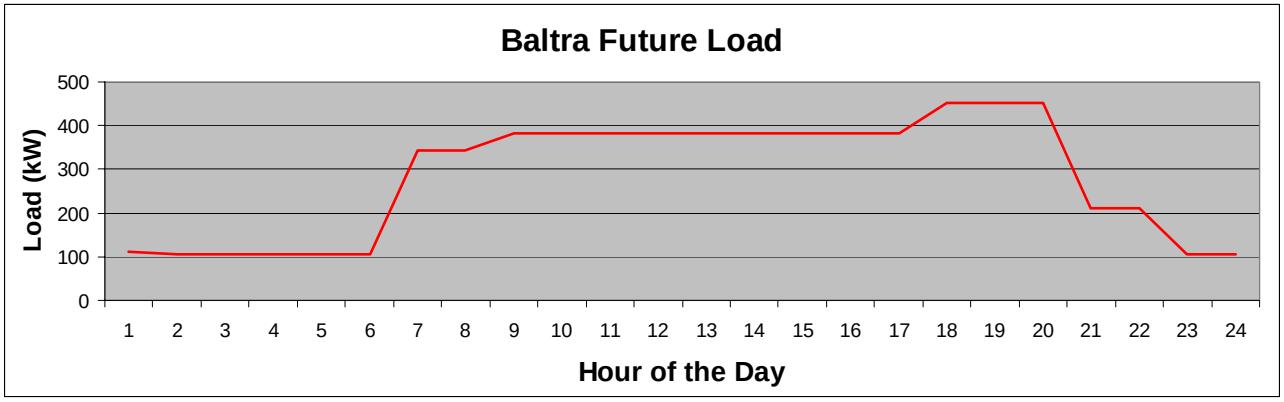


Figure 2. Future Baltra Load.

Model Inputs

Site location. The average wind speed for Santa Rosa is 6.17 m/s, and Baltra is 6.02 m/s and Camote is 5.5 m/s. Figure 3 shows a frequency distribution plot of the wind throughout the year for Santa Rosa, and Figure 4 shows one for Baltra. There is slightly more power in the wind at the Santa Rosa site mostly due to a higher frequency of winds around 12 m/s. The winds are very consistent and rarely reach the rated output of the wind turbine for both sites. The Camote plot is not shown here as the winds are lower.

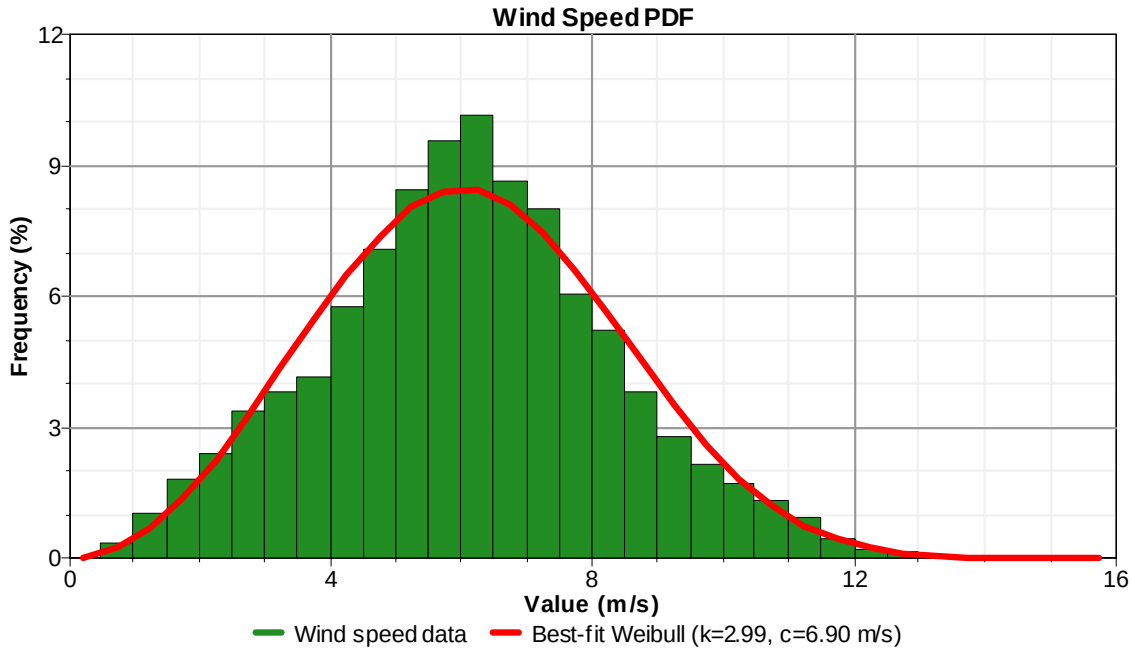


Figure 3. Frequency Distribution Plot of the Santa Rosa Wind Resource.

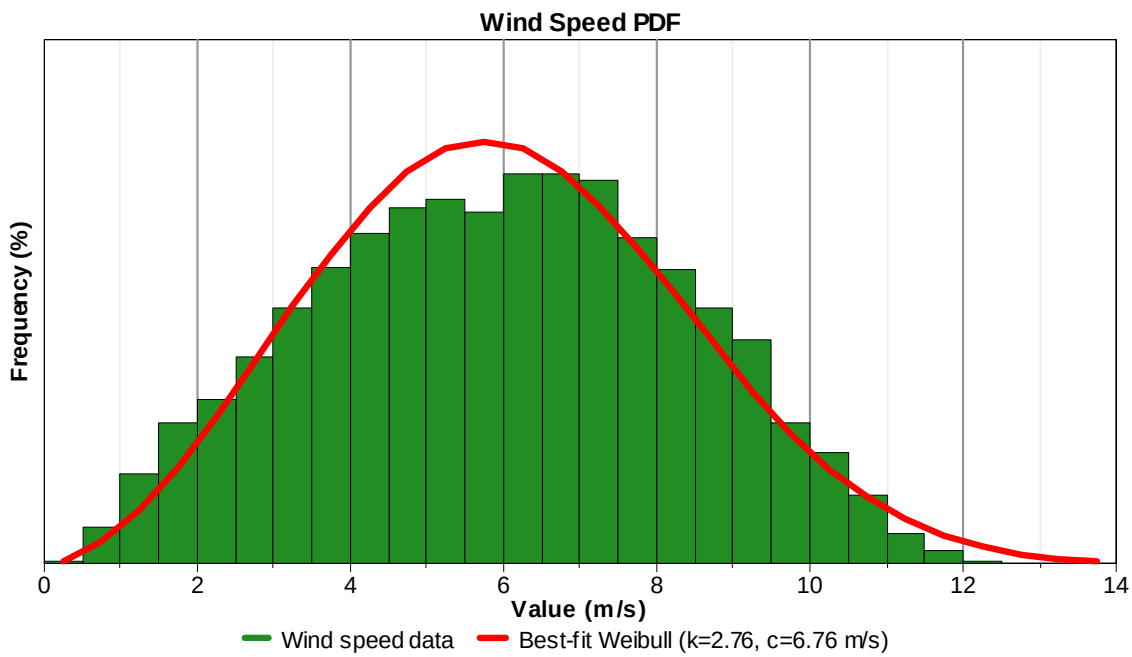


Figure 4. Frequency Distribution Plot of the Baltra Wind Resource.

Model Results

Preliminary model results are shown for the comparison of wind power output at the different sites in Figure 5. The power output data is graphed against a range of 1-8 Enercon E-33 turbines installed. The data show that the Baltra site produces a little bit more windpower than the Santa Rosa site, with the Camote site producing a lot less wind power than either of the other two sites.

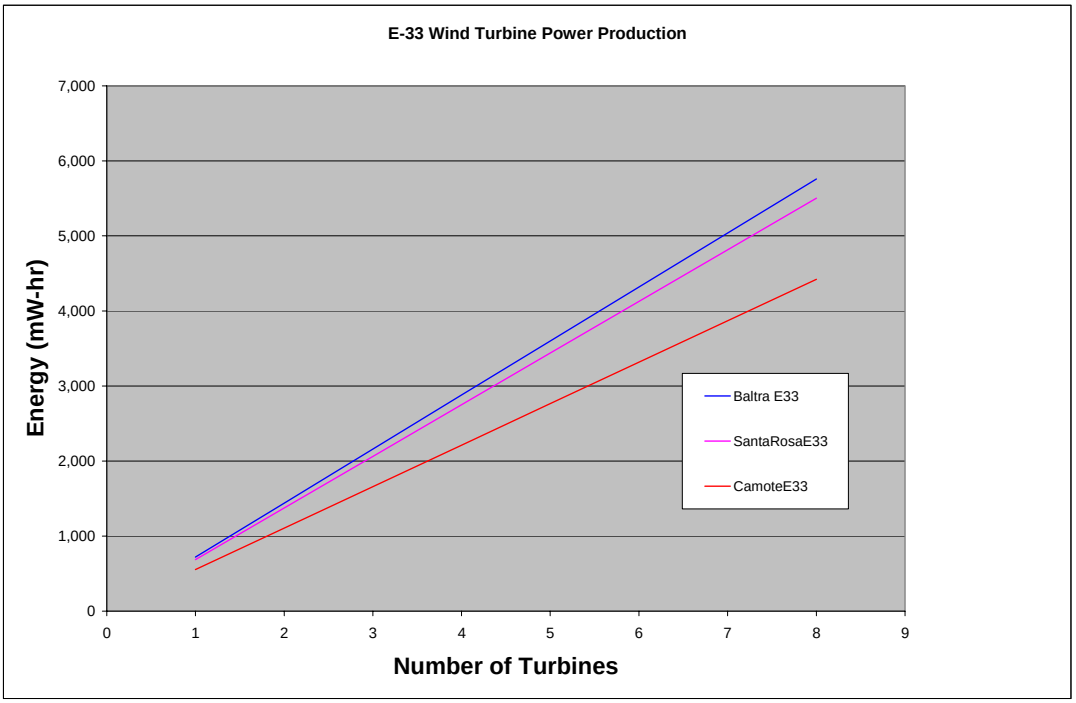


Figure 5. Wind Turbine Power Production for All Three Sites.

The wind turbines rarely operate at rated power output (i.e., 330 kW) due to the lower and very consistent wind speeds, hence the turbines do not typically result in a ratio of wind power to total grid power of over 100%. This level of wind power penetration on a grid can be accommodated. Depending on the number of wind turbines, special controls may or may not be needed, and this will require additional analysis with the Hybrid2 model to determine the exact penetration levels for different turbine scenarios.

The energy penetration, as defined as the amount of energy out of the wind turbines divided by the total electrical grid demand, is shown in Figure 6. It is seen that for 6-8 turbines the wind energy production is more than 20% of the total load, resulting in a fuel savings of up to 2,116,000 liters per year. The wind energy penetration is higher at Santa Rosa because the load is smaller, as it does include the Baltra load. As a result, and partly due to the overlapping of the wind resource with the load, the Santa Rosa site results in more “excess” electricity, although the amount of excess electricity is still below 1% of the total grid energy.

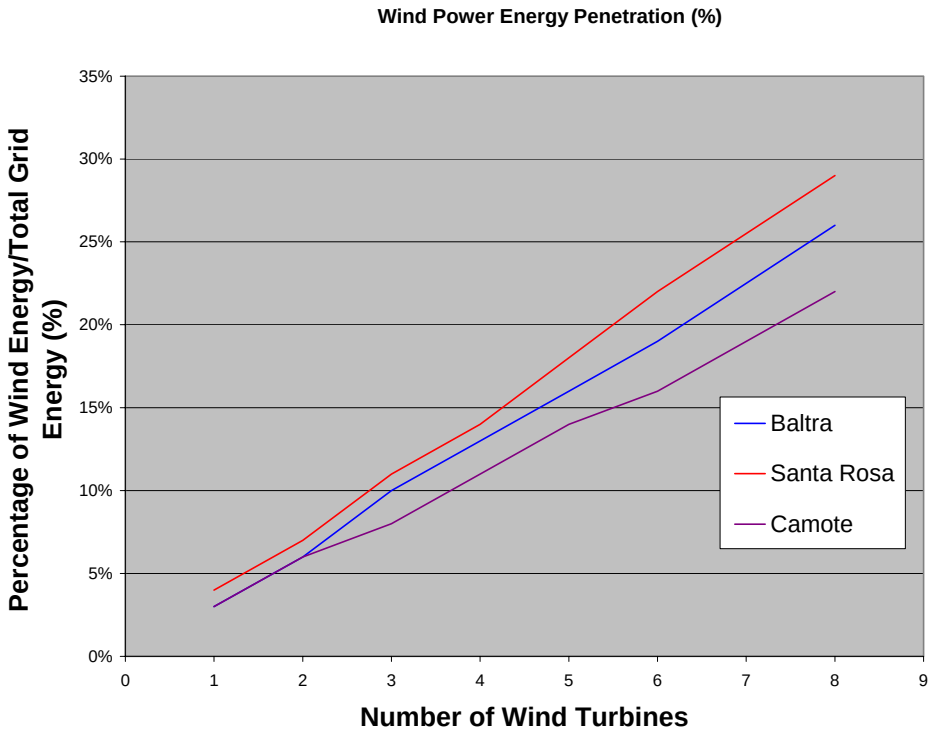


Figure 6. Wind Turbine Energy Output Divided by Total Electrical Demand.

Wind Turbine Comparison

Figure 7 shows a plot of the wind turbine energy output for two different turbines at the Santa Rosa site. The power output from the Enercon E-33 and the Furlander 250, rated at 330 kW and 250 kW respectively, is plotted versus the annual energy output. The Enercon E-33 produces more energy, but a more detailed analysis is needed to compare the cost of energy from the different wind turbine systems.

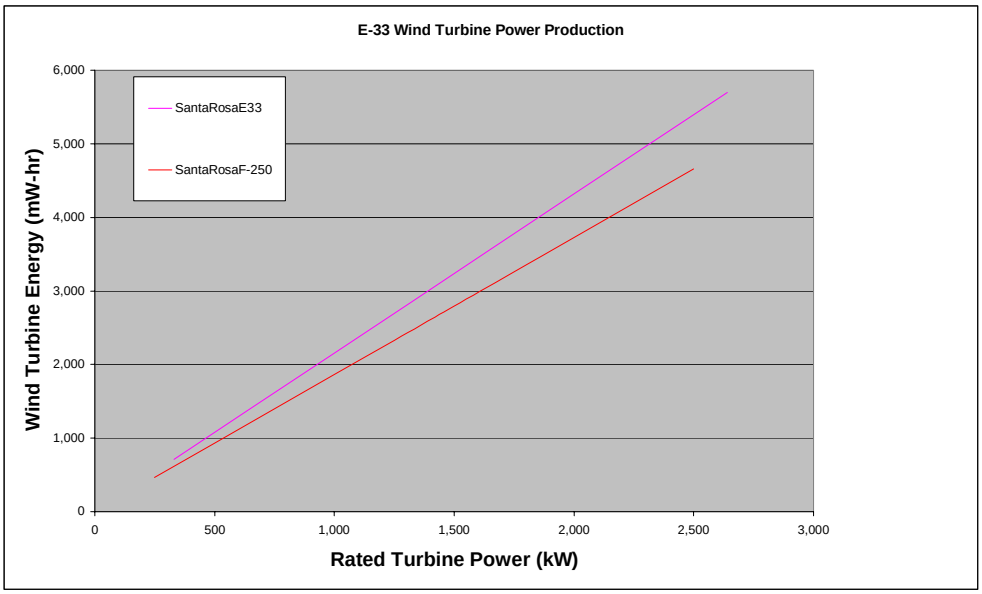


Figure 7. Wind Turbine Energy Output Divided by Wind Turbine Capacity.

Wind turbine power production could be significantly higher using a turbine in the size range of 250-350 kW that had wind turbine blades optimized for a lower wind speed regime and hence lower cut-in (i.e., start up) wind speed. Various turbine options should be modeled in the next phase of the project.

Summary

A preliminary wind turbine screening analysis was conducted for three sites and two load scenarios on the Islands of Santa Rosa and Santa Rosa and Baltra. The analysis showed that the Baltra site with the addition of the Baltra load resulted in a slightly higher wind energy output. The penetration of wind power could reach as high as 100% of the future Santa Rosa load.

Diesel run time and fuel could be reduced somewhere in the broad range of 15%-30% at either wind turbine site assuming that 5- 8 wind turbines were installed, although additional modeling with the Hybrid 2 model is required to accurately estimate this number. Diesel fuel savings in the range of 2,116,000 liters per year could be realized with 6-8 turbines installed. Because of the high cost of grid extension and limited funding, installing the turbines at Santa Rosa would result in more wind power penetration because there would be more money for wind turbines. However, additional factors such as environmental and space considerations should be evaluated for the two sites.

Appendix E: Equipment specification

Manufacture specification sheets for the following equipment used in the analysis are provided below:

1) MADE AE59 wind turbine
2) Vergnet Wind Systems
3) Enercon E-33
4) Enercon E-48
5) Caterpillar SR4B-594
6) Caterpillar SR4B-693
7) Caterpillar SR4B-2730