Distributed
Wind Generation Study
For Northeast Colorado

by

Wind Utility Consulting
December 2005

Table of Contents

Section 1 - Executive Summary

This study by Wind Utility Consulting ("Consultants") was commissioned by the Colorado Governor's Office of Energy Management and Conservation and the Department of Energy's *Wind Powering America* program. The purpose of the study was to determine the ability to interconnect large wind turbines to a typical distribution system in northeastern Colorado. The Highline Electric Association's (HEA) distribution grid was used for the study. HEA provided design and operating data on its electric system. This data included maps showing locations of all of its facilities, conductor sizes, transformer sizes, transmission system data, and electric load data by substation and feeder. The Consultants evaluated 17 of HEA's load-serving distribution substations in Colorado that are connected to 69 kV or 115 kV transmission lines. HEA's peak electrical load in this area is about 180 MW during the peak of the irrigation season. Outside of the irrigation season the typical monthly peak, average, and minimum loads are about 40, 30, and 20 MW respectfully.

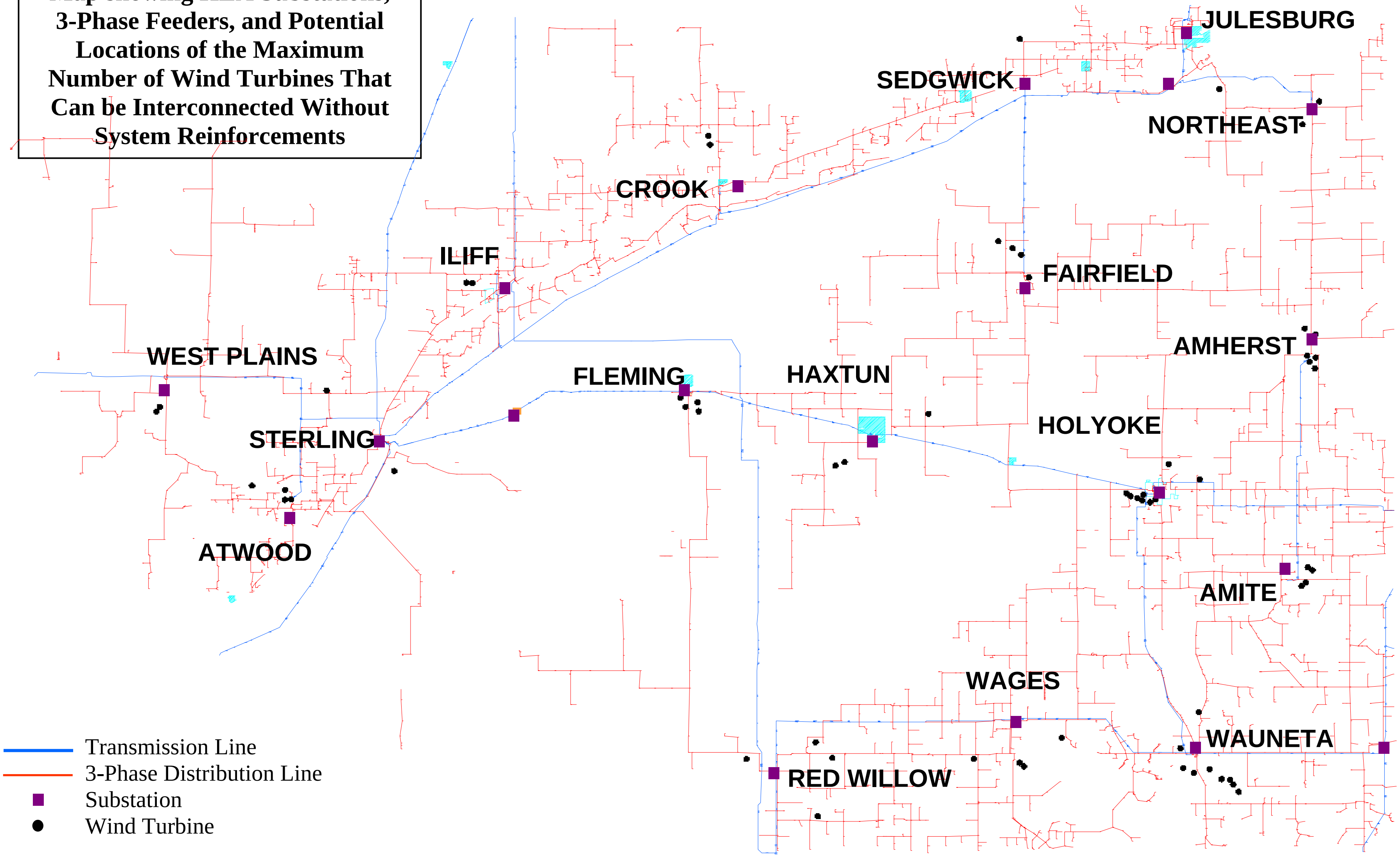
Three scenarios were evaluated in this study. The first scenario analysis determined how far away from each of the substations that a single GE 1.5 MW wind turbine could be connected to the main sections of the 3-phase feeders, without causing unacceptable levels of flicker or other power quality problems. That analysis indicated that the GE wind turbines could be typically connected up to 4-6 line miles from the substation.

A second scenario analysis determined that up to 63 GE 1.5 MW wind turbines, or 94.5 MW, could collectively be added to the 17 existing substation distribution grids, without causing power quality problems, or overloading conductors or substation transformers. The maximum number that would be reasonable to connect to each substation's grid, without system reinforcements or line extensions, varies from zero to nine turbines. Wind speed maps were developed for the area around each substation as an aid for the Consultants in selecting potential wind turbine sites for this scenario. Even though the locations were determined to be potentially feasible from an electrical interconnection perspective, little consideration was given from other perspectives, such as proximity to nearby homes, wildlife areas, or other restricted areas. Therefore, the locations selected were simply indicative of sites where turbines might be connected to the existing distribution systems.

A third analysis was done to project what types of distribution system reinforcements might be economically viable for increasing the number of connected wind turbines. Figure 1-1 shows a map of the HEA system and the 63 potential wind turbine locations. As the map indicates, there are large areas wherein no 1.5 MW wind turbines should be connected to the rural distribution system, because there are either no 3-phase lines in the area or the area is too far away (4-6 line miles) from the substation. At three substations, it may not even be economically attractive to connect the wind turbines to the existing grid without building line extensions to nearby areas that are windier. From a practical point of view and in general, using the existing distribution system may be economical if the amount of wind generation being added is in the range of perhaps one to five wind turbines at a particular location or area.

Wind Utility Consulting
Thomas A. Wind and Andrew T. Coil

FIGURE 1-1
Map showing HEA Substations, 3-Phase Feeders, and Potential Locations of the Maximum Number of Wind Turbines That Can be Interconnected Without System Reinforcements



Section 2 – Introduction and Overview

As the delivered cost of wind power from large wind turbines continues to fall, the cost of wind power becomes ever more competitive with utility-supplied power. The improving economics of wind generation has prompted schools, businesses, and ranchers to consider the possibility of installing a single large wind turbine to sell power to the utility or to offset their own electrical needs. The cost of interconnecting to the high voltage transmission system is usually cost prohibitive for one or a few large wind turbines. Connecting them to the existing distribution system can be more cost effective in many cases.

Economic development officials in rural areas are looking for ways to help diversify their agriculturally based economies. If rationing of ground water for irrigation occurs in northeast Colorado, the economic loss to the area could be significant. Furthermore, the need for electricity to pump the water could fall significantly. If this happens, the existing electrical transmission and distribution grid in the area will be underutilized.

With the recent passage of a Renewable Portfolio Standard (RPS) in Colorado, there will be a growing need for wind generation. Part of this need could be met by smaller wind generation projects in northeast Colorado as well as other parts of Colorado's eastern plains. If these wind turbines were owned by local rural residents and connected to the existing distribution grid, then the local economies would benefit and the electrical grid would be more fully utilized.

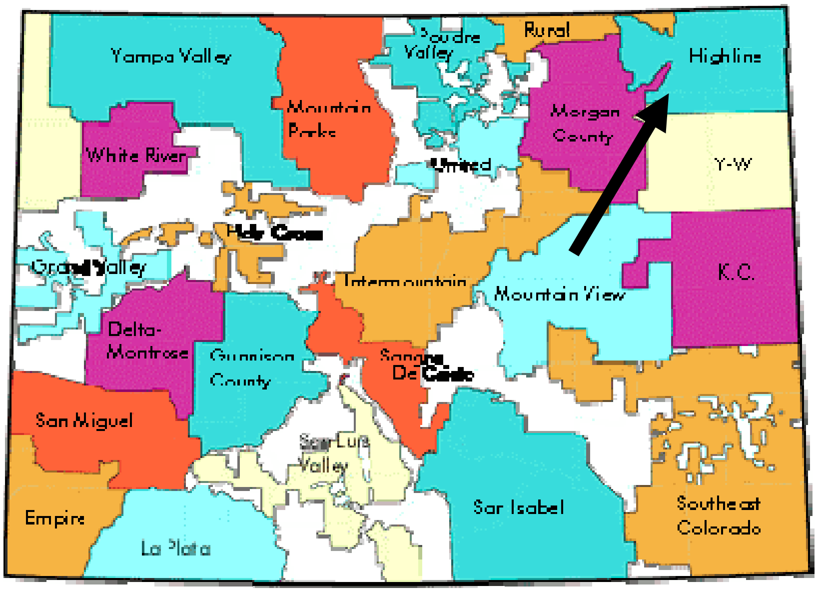


FIGURE 1 – Colorado Rural Electric Cooperatives

This study by Wind Utility Consulting (Consultants) was commissioned by the Colorado Governor's Office of Energy Management and Conservation (OEMC) and the Department of Energy's *Wind Powering America* program to determine the ability to interconnect large wind turbines to the Highline Electric Association's (HEA) existing 12.47 kV distribution grid. Figure 1 shows the location of all of Colorado's rural electric cooperatives. The black arrow indicates the location of HEA's electric service territory in Colorado.

The existing distribution system serving electric customers can be used to interconnect large wind turbines. However, there are limitations as to the number and location of the wind turbines. These limitations are related to how much the wind turbines change the power quality (sudden changes in distribution line voltage), and the power carrying capability of the distribution line conductors and the substation transformers. In general, an electric distribution system that serves large electric loads also has the ability to connect and absorb power from large wind turbines. Likewise, a distribution system designed for serving only widely scattered small residential and ranch loads has little ability to absorb power from large wind turbines.

This study determined how many large GE 1.5 Megawatt (MW) wind turbines could be connected to the existing distribution system, given the limitations of where they could be connected, based on the above power quality and power handling capabilities. In general, a 1.5 MW wind turbine can't be connected more than a few miles from an existing substation. The maximum distance primarily depends upon the substation transformer size, the distribution line conductor size, and the particular model of wind turbine.

Terrain Near the South Platte River
in Northeastern Colorado

Although not specifically required for this analysis, high-resolution wind speed maps were developed for the area around each substation as an aid to the Consultants in determining potential locations for siting the wind turbines. These maps were developed utilizing the RESoft Wind Farm program and other software, using wind speed data from the recent National Renewable Energy Laboratory (NREL) wind speed map for the state. Although the maps show the wind speeds in high resolution and detail, their overall accuracy is likely less than NREL's original map. Therefore, the wind speed maps should be used only as an indication of what areas are windier than other areas. The wind speeds shown should not be relied on as an accurate measurement of the wind speed for a particular site.

Rolling Dry Land and
Irrigated Crop Ground in the Area

The wind turbine siting analysis included three interconnection scenarios. The first scenario determined the farthest point from the substation that a single 1.5 MW wind turbine could be connected to the existing distribution lines. If a wind turbine were connected at that farthest point, then no other wind turbine could be connected to that same feeder without exceeding the power quality standards. The second scenario determined the maximum number and approximate locations of wind turbines that could be connected to the distribution system around each substation. Since the wind turbines couldn't be very far from the substation, they were often not in the windiest areas. The third scenario determined what type of system reinforcement would be necessary for more wind turbines to be connected. The system reinforcements could include the following: 1) adding a line extension into the desired area, 2) adding a dedicated collection circuit from the substation to the desired area, 3) installing larger conductors on specific existing distribution lines, or 4) adding a second or a larger substation transformer. The most cost-effective system reinforcement would depend upon the desired number of additional wind turbines that would be connected and the distance from the substation. Determining a range of cost-effective solutions is very site specific and time consuming, and is far beyond the scope of this study. Therefore, the Consultants simply used their judgment to project which type of system reinforcement option would most likely be the most cost effective for connecting a few additional wind turbines to the existing distribution grid.

The findings for both Scenario 1 and Scenario 2 are shown on the wind speed maps developed for each substation. All 17 wind speed maps are shown in the Appendix. The farthest distance from the substation to interconnect, that was determined in Scenario 1, is simply shown by the lengths of the 3-phase feeders drawn on the maps. The maximum number of turbines, and some potential locations that were determined in Scenario 2, are also plotted on the wind speed maps. The locations shown were determined to be potentially feasible from an electrical interconnection perspective. No consideration was given to other siting considerations, such as proximity to nearby homes, wildlife areas, or other restricted areas. Therefore, the locations shown simply provide a first-cut assessment at the number and general location of potential wind turbine sites. Summary tables and maps also provide an overview of the findings and results.

Section 3 – Power Quality Impacts from Wind Turbines

The power output of a wind turbine varies all of the time due to changing wind speed. The distribution system voltage level will likewise change to a small extent as the wind turbine output changes. Furthermore, wind turbine start-ups and switching between the small generator and large generators (if the turbine has two generators) also cause transient power and current surges. All of these changes in power output affect the feeder voltage level to a small extent.

Center Pivot Irrigation
That Is Common in the Area

Electric utilities use company or national standards that specify appropriate voltage levels, and how much and how frequently small changes can occur without adversely affecting electric customers. These power quality standards are used to design and select substation equipment, distribution line equipment, and conductor sizes. The resulting design and equipment selection essentially determines how much electric load the distribution system can serve. If a large new electric load is added, or if a large wind turbine is connected, the equipment and facilities may need to be reinforced to maintain the power quality standards.

Special testing companies test each wind turbine model after they are operating to characterize the variability of the output for both switching and normal operation. These tests determine the worst-case inrush currents, flicker and voltage step factors, and harmonic currents. These measured characteristics can then be used with the substation and electric distribution line data to provide a relatively accurate estimate of the power quality impacts on the distribution system.

The three primary power quality standards that affect large wind turbine interconnections to the distribution system are voltage flicker, voltage levels, and harmonics. They are discussed below.

Voltage Flicker

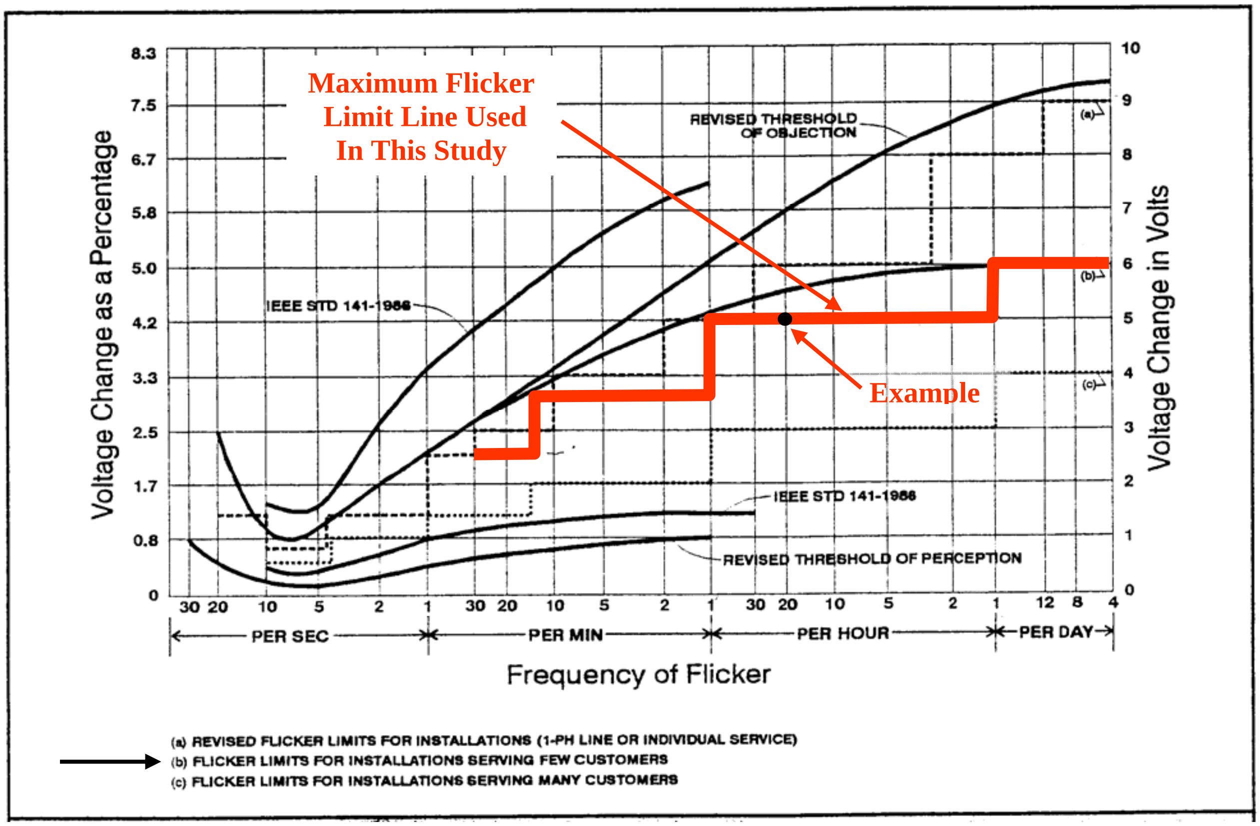
100 HP Irrigation Pump with Pad-
Mounted Transformer and Meter

Utilities try to provide a constant and controlled voltage level to their customers. Ideally, voltage levels should not vary more than about five volts above or below the nominal 120-volt base. One goal is to avoid making any rapid and frequent voltage changes (flicker), which would cause a noticeable change in light intensity, or lamp flicker, in homes and offices.

Any large customer load that does not use power uniformly can affect the voltage levels on a distribution system. For example, one of the most difficult loads for a utility to serve on a distribution system is an automatic spot arc welder used in manufacturing. The rhythmic pattern of large power surges causes the distribution line voltages to dip with the same pattern. Customers' lights then flicker in the same pattern. It should be noted that customer loads cause nearly all voltage flicker problems.

When a wind turbine starts up, or if the turbine switches from a low-speed generator to a higher speed generator, there is an initial surge of current into the turbine that energizes the generator's magnetic field and locks the generator into synchronism with the grid. Large wind turbines use soft-start power electronics to reduce the initial surge typically to only 110% to 150% of normal full load current. The surge in current causes a slight voltage dip on the distribution feeder lasting a few seconds.

FIGURE 3-1 – Maximum Recommended Flicker Levels



Electrical standards have been developed by the Institute of Electrical and Electronics Engineers ("IEEE") and the Rural Electrification Administration ("REA"), to provide guidelines on how much and how often the voltage can change, without causing complaints from customers. The graph in Figure 3-1 was taken from an REA bulletin on voltage flicker. The REA bulletin was based on the IEEE Standard 141-1986, and illustrates the percentage of voltage dip and how frequently it can occur without causing irritation to customers. The red line is the standard that HEA uses in the design of its electric distribution system, and the same standard was used in this study. For example, the red arrow points to a black marker on the red line showing that there can be up to 20 voltage changes per hour of 4.2% (or 5.0 volts) in magnitude without causing any customer complaints. If the 20 voltage changes are more than this, it doesn't meet the flicker standard used by HEA.

Typical HEA Distribution Substation

The International Electrotechnical Commission ("IEC") also has a flicker standard (IEC Standard 1000-3-7) that is more comprehensive than the IEEE standard. The IEEE Task Force on Light Flicker has recommended that IEEE adopt this more comprehensive methodology and standard. The IEC methodology quantifies the flicker into two numbers: 1) the short-term (10-minute) flicker severity index, P_{ST}, and 2) the long-term (2-hour) flicker severity index, P_{LT}. Wind turbines installed on distribution systems in Germany and Denmark must use the calculations outlined in the standard to estimate the amount of flicker a proposed wind turbine will cause on the electrical system. Since this is a more comprehensive standard, it was also used in this study, in addition to the HEA standard, to determine if flicker might become an issue. A maximum P_{ST} value of 0.9 was used. A flicker severity level that is higher than 1.0 will often cause customer complaints. Most customers on long rural distribution systems are less sensitive to changing voltages and voltage dips and would most likely tolerate flicker severity levels higher than 1.0.

Voltage Rise

When generation is added to a distribution system, the voltage will almost always rise, unless the generator's power factor is very poor. Because of the utility's requirement to keep the voltage within certain limits, the amount of generation that can be added is thus limited. In this study, the maximum voltage allowed on the distribution feeder primary was set to 127 volts. High voltage could only likely occur with full wind turbine output at either high electric load when the substation voltage regulator is at its highest, or at very low electric load when nearly all of the wind power is coming back to the substation. It was assumed that the voltage at the substation bus would average 125 volts during high-load periods and 122 volts during low-load periods. The voltage levels at the interconnection point with the wind turbine were then checked using peak loads and minimum loads to determine if voltage levels would be within the acceptable range.

Julesburg Distribution Substation

The power factor of the wind turbine also affects the voltage levels. Since the inductive generators used in many wind turbine models consume reactive power, low voltage capacitors in the base of the wind turbine are switched on line in steps, to maintain a power factor between 98% and 99% at various generation levels. The 1500 kW GE Wind turbine has an inverter connected to its wound rotor induction generator, which allows it to precisely control the generator voltage level and reactive power requirements. Since the GE 1.5 MW wind turbine has the ability to control power factors or voltage levels, the distribution feeder voltage levels can easily be managed, so that high voltage will not be a problem. Other wind turbines without this feature can be operated at lower power factors if high voltages are an issue. In this study, a power factor setting of as low as 97% was allowed if high voltage levels were anticipated. Even lower power factors could be used if necessary to mitigate potential high voltage situations.

Three-Phase Capacitor Bank

Harmonics

The presence of harmonics in the distribution system voltage can cause interference with communication circuits and other types of electrical equipment. Harmonics, which distort the voltage waveform, are caused by customer loads or by generators. Utility generators are designed to produce nearly pure sine wave voltages. However, the electrical current that customers' loads draw is not always sinusoidal. Most electronic equipment was not designed to use power uniformly throughout each cycle of voltage, which makes the currents distorted from a true sine wave. This non-sinusoidal current is said to have harmonic distortion. Incandescent lighting, electric motors, electric stoves, and electric heaters draw currents with essentially no harmonics. Televisions, microwave ovens, compact florescent lights, and most electronic equipment cause harmonics. Generators connected to the electric system can also cause harmonics. Most modern turbines with asynchronous generators have electronic soft-start equipment to minimize power surges when the units are initially connected to the grid. Some turbines use electronic power converters to convert part or all of the power output from a variable frequency to constant 60-cycle power. Wind turbines manufactured by Enercon and GE have electronic power converters. These power converters are designed to minimize the harmonic currents they produce.

Three Single-Phase Reclosers

The IEEE 519 Standard is referenced by utilities for harmonic problems. According to this standard, the Total Demand Distortion in a generator current must be less than 5% for transmission and distribution systems of 69 kV or less. Utilities can reference this standard when evaluating a particular turbine for interconnection to distribution networks.

A thyristor-based soft-start scheme is used to connect the generator to the grid during wind turbine start-up to limit the inrush currents. The thyristors are quickly bypassed after the generator is connected to the grid. Therefore, the wind turbines will have some momentary harmonic current flows during connection to the grid. Since all modern wind turbines meet the IEEE 519 Standard, harmonics from wind turbines are usually not an issue. Therefore, it was concluded that harmonics would not be a power quality issue in this study.

Section 4 - Study Procedure

115 kV Transmission Line and
3-Phase 12.47 kV Distribution Line

HEA provided design and operating data on its electric system. This data included maps showing locations of all of its facilities, conductor sizes, transformer sizes, transmission system data, and electric load data by substation and feeder. The Consultants analyzed 17 of HEA's load-serving distribution substations in Colorado that are fed by either 69 kV or 115 kV transmission lines.

Figure 4-1 is a map showing the transmission lines, substation names, distribution lines, and roads in HEA's service territory in Colorado. Although HEA's service territory extends to the north and to the east into parts of Nebraska, those areas were not studied and are not shown. The light gray lines are roads, so a light gray square represents one square mile. Only those substations with names shown were evaluated in this study, as the other substations were for dedicated industrial loads or were for transmission lines only.

The peak electrical load of the entire HEA service territory is about 180 MW during the peak of the irrigation season. Outside of the irrigation season the typical monthly peak, average, and minimum loads are about 40, 30, and 20 MW respectfully. HEA's peak load in the Colorado study area is 125 MW.

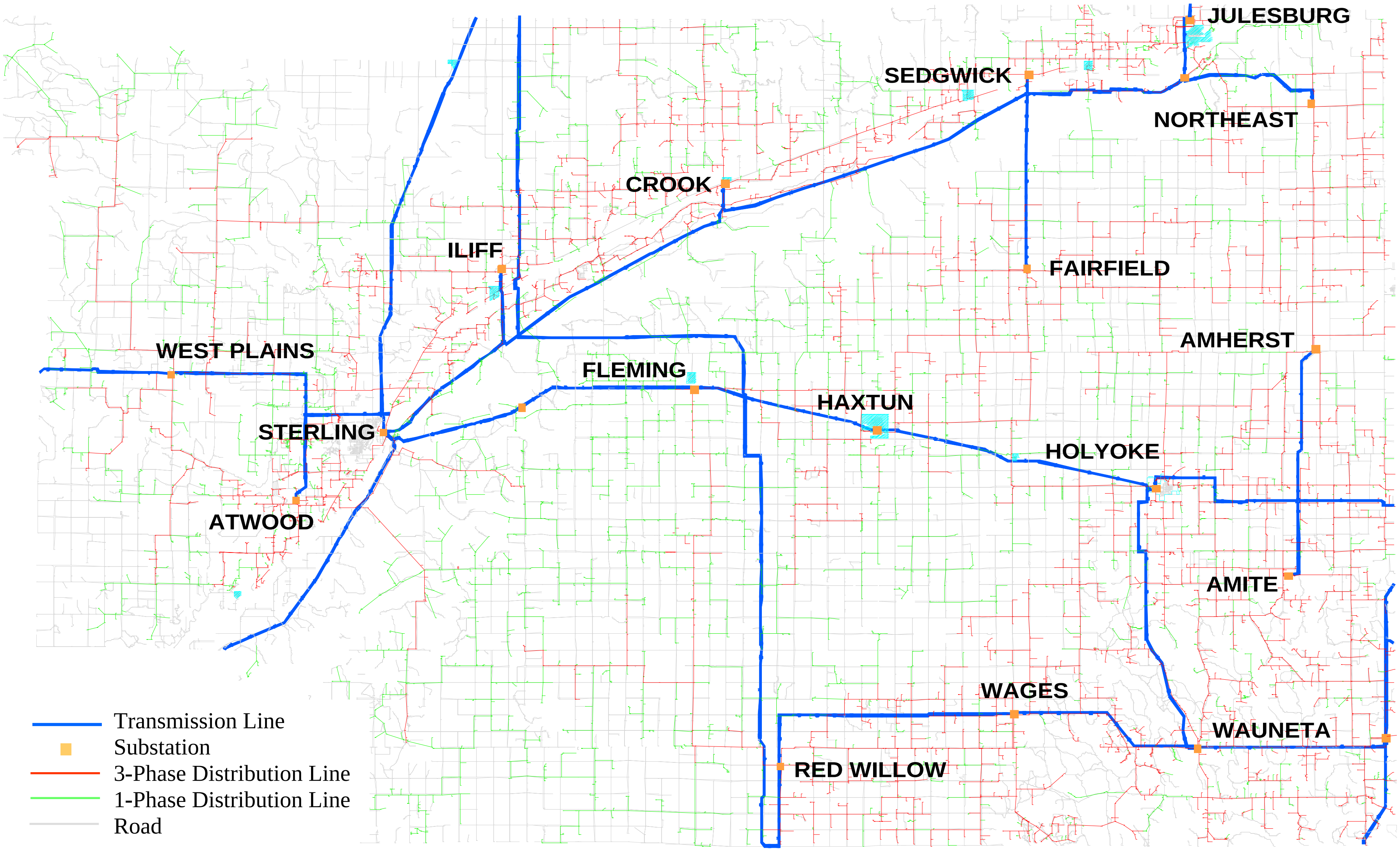
The Consultants used the data provided by HEA in a specialized spreadsheet program to analyze the power quality impacts of connecting the GE 1.5 MW wind turbine to all of the various 3-phase distribution feeders. Three scenarios were considered in this study.

Table 4-1
Wind Turbine Interconnection Study Scenarios for the GE 1.5 MW Wind Turbines

Scenario 1	*What is the farthest point from the substation on each main 3-phase feeder that a single wind turbine can be interconnected?* The limiting factor is always voltage flicker.
Scenario 2	*What is the largest number of wind turbines that can be installed on all of the feeders for each substation without needing distribution system reinforcements?* The limiting factor is usually voltage flicker, but can be the substation transformer capacity.
Scenario 3	*What types of system reinforcements could be economically made to increase the number of wind turbines that could be added to the distribution grid?* The limiting factor is always cost.

Notes: Up to about ½ mile of 3-phase underground line extension was allowed to reach each wind turbine site without calling it system reinforcement.

FIGURE 4-1 – Map of HEA Facilities in Colorado with Names of Substations Evaluated in This Study



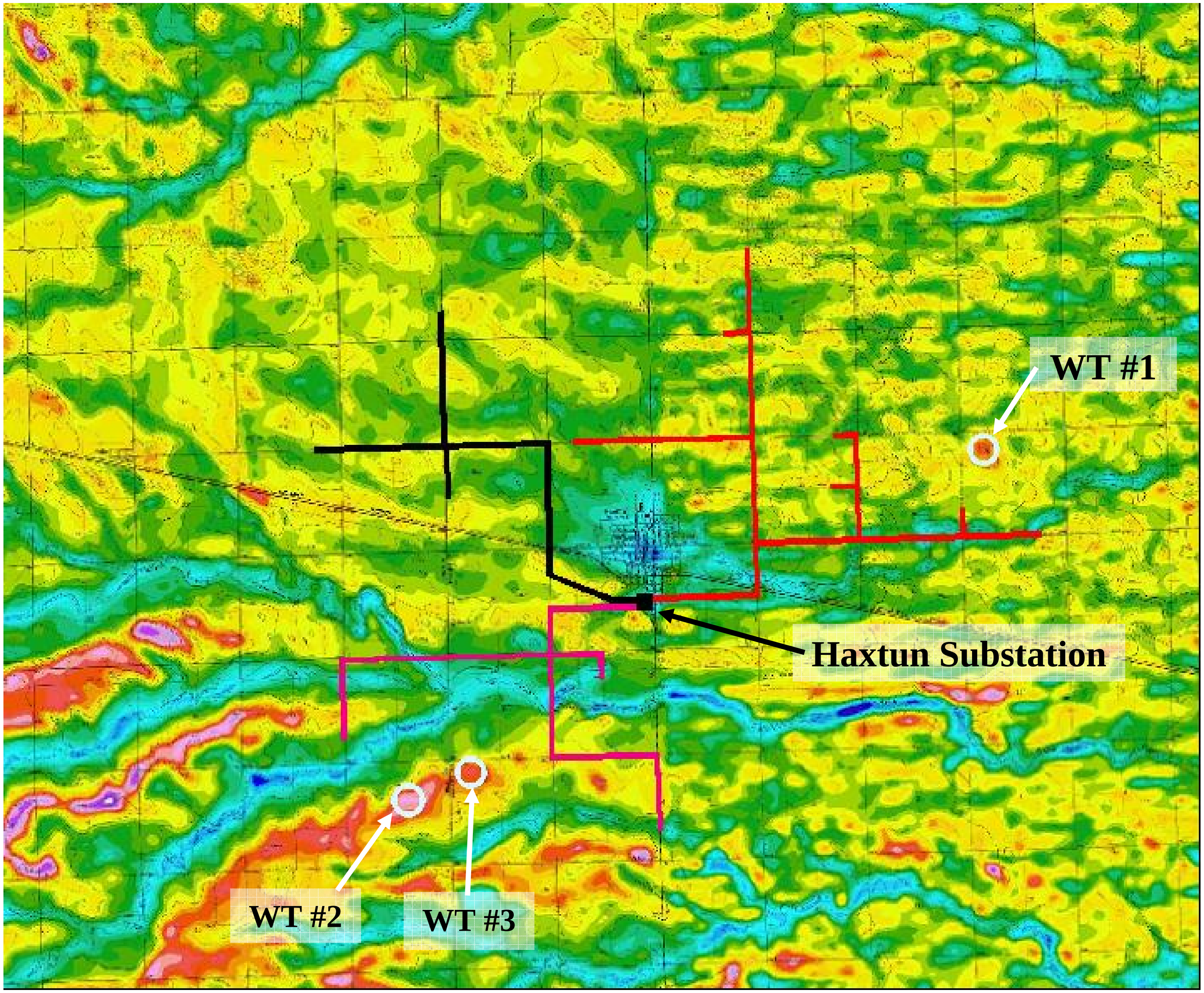


**FIGURE 4-2
Wind Speed Map
Showing Turbine
Locations that Can Be
Connected to the
Haxtun Substation
Grid**

12.47 kV 3-Phase Distribution Line
And 69 kV Transmission Line

The standard interconnection equipment for Scenario 1 included a generator step-up pad-mounted transformer, up to 1/2 mile of underground primary cable per turbine, a primary metering package, and a set of fused disconnects for connection to the distribution line. For example, if two wind turbines were to be installed at one location, there would be one interconnection to HEA's existing 12.47 kV line, and up to one mile (2 x ½ mile) of underground cable daisy chained between HEA's line and the two wind turbines. Some minor equipment changes and adjustments would likely be required by the utility. These would include adjustment and checking voltage-regulating relays at the substation, evaluation of protective relay and reclosing relay settings, and evaluation of operating and sectionalizing procedures. The cost of these changes and adjustments is relatively modest and was included as part of the standard interconnection cost.

<u>Example of Analysis for a Substation</u>

Figure 4-2 is a wind speed map showing the area around the Haxtun substation. The Haxtun substation has three main 3-phase feeders indicated by the black, red, and magenta lines. The full lengths of these main 3-phase feeders are not shown in the figure, nor are any of the many single-phase tap lines.

An analysis was first done to determine how far away from the substation that a single GE 1.5 MW wind turbine could be connected to the main sections of the 3-phase feeders without causing unacceptable levels of flicker. The length of the 3-phase feeders shown in Figure 4-2 represents the maximum distance that a single wind turbine can be placed on those feeders. In this example, that distance is typically about 4 miles away, and one wind turbine could be placed on each of the feeders without causing flicker problems on the Haxtun distribution system.

Looking North from the Substation
Towards Haxtun

The conductor size is typically 4/0 Aluminum Cable Steel Reinforced ("ACSR") near HEA's substation, and then it switches to 1/0 ACSR approximately two miles away from the substation. For a given wind turbine size and distribution voltage level, the maximum distance depends primarily on the following: (listed in order of importance) 1) substation transformer size, 2) conductor size, 3) the particular wind turbine model, and 4) the strength of the transmission system in the area. Smaller wind turbines could typically be connected at farther distances from the substation. Likewise, higher voltage distribution systems, such as 24 kV, allow longer distances.

A second analysis was then completed to determine the maximum number of wind turbines that could be added collectively to all of the feeders, without causing power quality problems or overloading conductors or substation transformers. This analysis concluded that a maximum of three GE 1.5 MW wind turbines could be added to the Haxtun substation grid. The locations of these turbines were based the electrical power quality impact and on judgment with little regard to normal siting criteria or any type of optimization. As a result, different locations may very well be more appropriate and acceptable than those selected. The locations are shown in Figure 4-2 as "WT #1", "WT #2", and "WT #3". They were sited in areas of higher wind speeds that were still close enough to the substation to not cause power quality problems. If a fourth turbine were added, then the cumulative effect of flicker from all of the wind turbines could be a problem. Each individual wind turbine by itself would not cause flicker problems. However, as more wind turbines are added, the potential number of wind turbine start-ups would be increased. It was assumed each turbine would be limited to four start-ups per hour. Under a worst-case condition with very light and variable winds, four turbines could result in 16 start-ups per hour. This worst-case condition might occur a couple of times per year. Given the calculated magnitude of the voltage dips for the 16 start-ups, the calculated flicker severity index (P_{ST}) would exceed the 0.9 level, which was selected as the allowed maximum in this study. Therefore, only three wind turbines could be added in the windier areas close to the Haxtun substation. If the lower wind speeds within a mile of the substation were acceptable, then four turbines could be added to the grid near the substation. However, this is likely not to be a reasonable situation, since using higher wind speed areas greatly improves the overall economics of wind turbine projects. In this study, it was usually more cost effective to build a dedicated line extension to a windier site, that is, a site that had three legend-color changes higher speeds, (0.15 mps higher).

115 kV Transmission Line at Haxtun

Looking South from the Haxtun Substation Towards a Windier Ridge

If the Vestas V82 1.65 MW wind turbines were used instead of the GE 1.5 MW units, then a fourth turbine could be added to the grid at Haxtun, because the flicker characteristics are different in several ways. However, a Vestas V82 turbine cannot be added nearly as far from the substation as the GE turbine because of the larger voltage dip it would cause during a start-up at higher wind speeds. Nevertheless, when the Vestas turbines are connected close to the substation, their cumulative flicker impact would be less than that from the GE turbines.

A third analysis was done to determine what types of system reinforcements could be economically made to increase the number of wind turbines that could be added to the distribution grid. Since flicker is the limiting factor, about the only thing that can be done would be to add a dedicated 12.47 kV collection circuit from the Haxtun substation for connecting additional wind turbines. In this case, two more turbines could be connected to the dedicated circuit without causing flicker or overload problems on the Haxtun distribution grid. If a new dedicated circuit were added, its length and destination would have to be determined by an economic evaluation of the trade-off between length and wind resources. A short 1-mile line that only reaches the yellow areas in the wind speed map close to the substation may be all that can be economically justified for adding two wind turbines.

If more than a total of 5 turbines were added to the Haxtun grid, then the Haxtun substation transformer would overload during light electric load conditions with full wind generation output. At those times, the total Haxtun substation electric load would be about 1.6 MW. If 6 turbines were added, the full output would be 9 MW. After subtracting the 1.6 MW load on the 12.47 kV Haxtun grid, the remaining 7.4 MW would have to be transformed back through the 7 MW transformer to the 115 kV grid. Since this amount of flow exceeds the substation transformer rating, 6 wind turbines would be too many. Therefore, to add more than 6 turbines would require either increasing the size or adding another substation transformer. If this much expense is contemplated, then an engineering analysis should be made to determine if there is a more cost-effective solution than simply reinforcing the existing grid. One alternative solution might include adding a dedicated substation transformer in the Haxtun substation that has a higher 24 kV secondary voltage. A higher 24 kV collection circuit voltage would allow longer circuits with lower losses to reach the windier areas west-southwest of the Haxtun substation. Another solution is simply to build a dedicated 115/12.47 kV or 115/24 kV substation west of Haxtun for the collection of power from the wind turbines located on the ridges with the purple-colored wind speeds. This option might be more economical if 10 MW or more of wind generation were being added, given the higher wind speeds west of Haxtun.

Lower Areas in River Valleys Have Significantly Less Wind Speeds

As the previous discussion suggests, connecting more and more wind turbines to the existing distribution grid may not always be economical with distribution system reinforcements. This would depend primarily upon the number of turbines being connected and the differences in wind speeds at alternative sites remote from the local substation. In the vast majority of the substations analyzed in this study, the cumulative flicker from multiple wind turbines was the limiting factor. There is usually no simple and economical reinforcement option, such as replacing a substation transformer. The most economical solution may be building new and dedicated facilities. In summary, there is usually no obvious and simple reinforcement that can be identified in this study for increasing the number of wind turbines that can be connected to the distribution system. A detailed analysis would be required for each substation and the results would depend upon the desired number of wind turbines that would be added.

Rolling Terrain Provides a Strong Incentive to Place Turbines on Hills Regardless of the Substation Location

A similar case study analysis was made for a rural area in Iowa in a National Wind Coordinating Committee report entitled "Distributed Wind Power Assessment" published in 2001. That analysis showed that the maximum number of interconnected 750 kW wind turbines could typically be doubled by simply doubling the size of the substation transformer. The terrain was flat in the Iowa study area, and additional wind turbines could be added close to the substations since the wind speeds were about the same everywhere. The rural substation transformers in the Iowa study were often the limiting factor, since they were typically 2.5 to 5.0 MW in size, which are much smaller than HEA's substation transformers. Since the distribution system designs and terrain are different and the wind turbines are much larger in this HEA study, it is more difficult to find cost-effective system reinforcements that would significantly increase the number of interconnected wind turbines.

Section 5 – Findings and Conclusions

It should be noted again that the purpose of this study was to determine how many large wind turbines could be connected to the existing distribution grid without causing power quality or operating problems. As a result, the turbines that were sited in this study were not optimally placed from a wind resource perspective. Furthermore, there was no detailed evaluation of the overall economics of using the existing distribution system rather than installing dedicated collection and substation facilities.

Table 5-1 below summarizes the results of the case study. It shows the approximate maximum distance that a GE 1.5 MW wind turbine can be connected from the substation and the maximum number of wind turbines that can be added to each of the substation distribution grids. The table shows a total of 63 1.5 MW wind turbines, or 94.5 MW, that could be connected to HEA's existing distribution grid. The cost of interconnecting these wind turbines is very nominal, with the primary expense being the short underground line extensions from HEA's overhead line to the wind turbine. No evaluation was made to determine the transmission impact if all of the 94.5 MW of wind generation were actually interconnected and operated. However, since the HEA grid in Colorado study area can serve at least 125 MW of electric load, it will likely be able to accommodate 94.5 MW of wind generation. There may be other transmission constraints beyond the HEA area that are affected by this amount of new generation, and an analysis of that was beyond the scope of this study.

In the Julesburg substation analysis, it was determined that no wind turbines would likely be connected to the substation, because the wind speeds near the substation were significantly less than the ridges both north and south of town. Since a 3-phase line extension longer than the ½-mile criteria used in this study would be required, it was considered as excessive added system reinforcement, which precluded those turbine sites from being counted in the study. However, building the line extension would be a cost-effective option for connecting one or two wind turbines on the ridges north of Julesburg.

The wind speeds around the Crook and Iliff substations were also substantially less than the ridges that were a couple of miles away. Although both substations and their existing feeders could handle more wind turbines, the turbines would have to be located in the lower wind speed areas closer to the substation, due to flicker problems. The Consultants determined that installing more turbines in these lower wind speed areas would not be economically prudent, therefore, these lower wind speed sites again were not counted. As in the Julesburg case, it would likely be cost effective to build some 3-phase line extensions or dedicated lines to the windier areas on the ridges.

Table 5-1 - Summary of Results

		Scenario 1	**Scenario 2**		**Scenario 3**
Substation Name	Substation Transformer MVA Rating	Farthest Distance in Miles from Substation	Most Number of Turbines	Limiting Factor	Potential Distribution System Reinforcement Options to Allow More Wind Turbines to be Connected to the Existing Distribution System
Amherst	14.0	5.4	6	Flicker	Dedicated collection line to a windy area
Amitie	14.0	5.5	4	Flicker	Dedicated collection line to a windy area
Atwood	7.0	4.2	4	Transformer	Larger transformer
Crook	7.0	5.1	2	Poor Wind	Two 1-mile Line extensions to windier sites would allow 2 more turbines
Fairfield	14.0	5.0	4	Flicker	Dedicated collection line to a windy area
Fleming	7.0	4.0	4	Transformer	Larger transformer
Haxtun	7.0	4.8	3	Flicker	Dedicated collection line to a windy area
Holyoke	14.0	6.6	9	Transformer	Larger transformer and dedicated collection line
Iliff	7.0	5.2	2	Poor Wind	Two 1-mile Line extensions to windier sites would allow 2 more turbines
Julesburg	10.5	4.3	0	Poor Wind [1]	A line extension would allow 2 turbines to be added.
Northeast	10.5	5.8	3	Flicker	Dedicated collection line to a windy area
Red Willow	14.0	5.5	4	Flicker	Dedicated collection line to a windy area
Sedgwick	5.3	2.8	1	Flicker	Dedicated collection line to a windy area
Sterling	7.0	6.5	2	Flicker	Dedicated collection line to a windy area
Wages	22.4	6.4	4	Flicker	Dedicated collection line to a windy area
Wauneta	22.4	7.0	9	Flicker	Dedicated collection line to a windy area
West Plains	3.8	3.3	2	Transformer	Larger transformer
Total Number of 1.5 Mw Turbines Added …..			63		

Notes: 1 - Since wind speeds are so much better on the higher ridges beyond the exsiting distribution lines, it was assumed no wind turbines would be connected to the existing distribution grid at Julesburg unless line extensions of at least one mile in length were constructed. This length exceeded the 1/2 mile limit set in the study.

Figure 5-1 is a map of HEA's entire Colorado system showing transmission lines, substations, and the 3-phase feeders. The locations of all of the added wind turbines are depicted as black dots. As the map indicates, there are large areas wherein no 1.5 MW wind turbines can be connected to the rural distribution system, because there are either no 3-phase lines in the area or the area is too far away (4-6 miles) from the substation.

The appendix contains wind speed maps around each of 17 HEA's substations evaluated in this study. These maps show the portion of the main 3-phase feeders on which at least one 1.5 MW wind turbine can be connected without causing power quality problems. The wind speed maps also show the maximum number of turbines that can collectively be connected to the existing distribution grid. The specific turbine locations shown simply represent one possible layout scenario. There was no attempt to optimize or scrutinize particular locations, since the purpose of the study was to get an idea of the limitations of the existing distribution system to accommodate distributed wind generation.

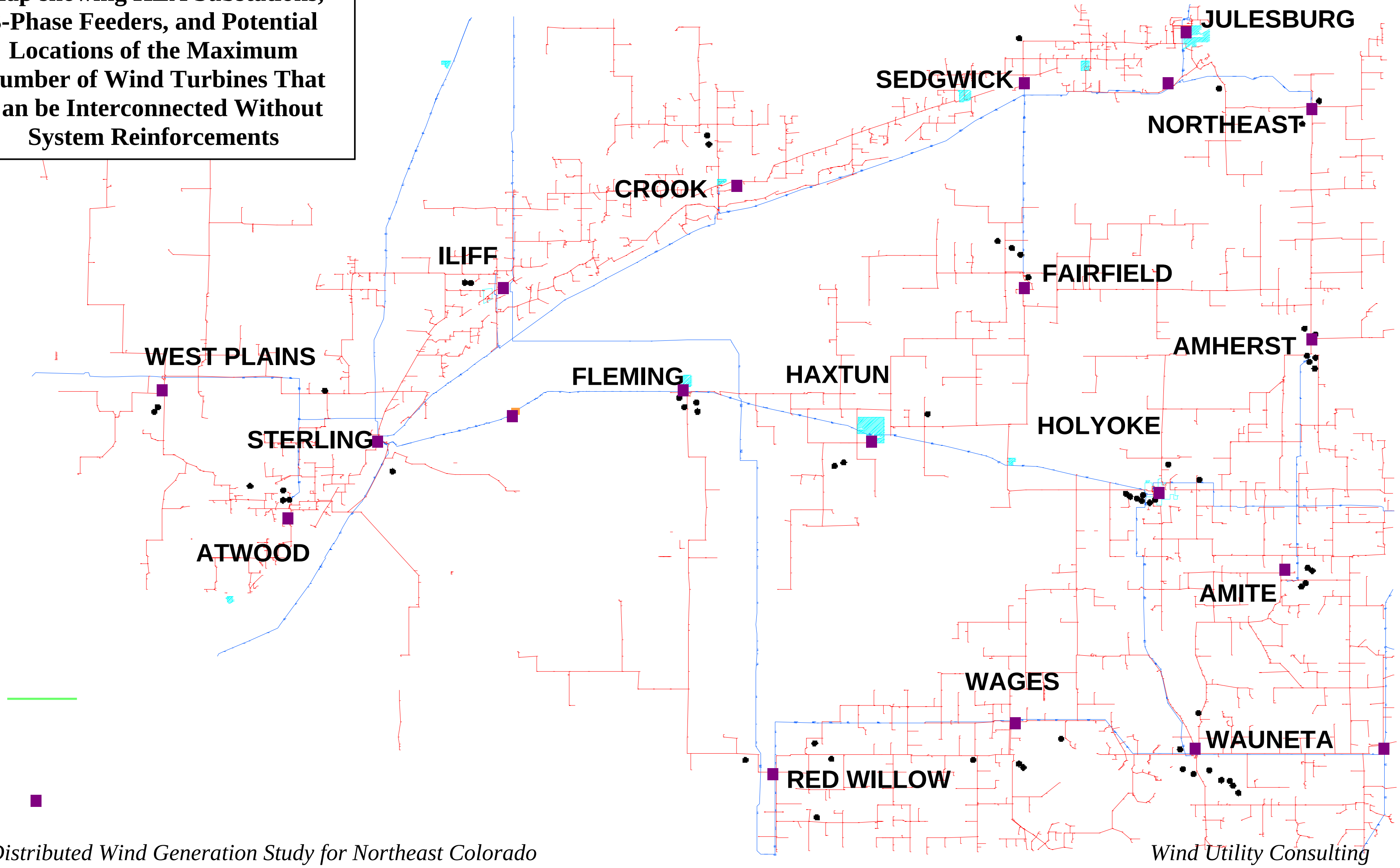
If the Vestas V47 0.66 MW wind turbine were used instead of the GE 1.5 MW turbine, then about twice as many turbines could be added to the distribution system. However, the total MW added would likely be comparable. The maximum distance from the substation that the smaller wind turbine could be connected would typically increase by about 1 mile. The smaller 0.66 MW wind turbine is simply not cost effective for bulk power generation when compared to the larger wind turbines. Therefore, no scenarios using the smaller wind turbine were evaluated in this study. The smaller wind turbine would only likely be used in very limited situations to provide power to schools or other large electric customers.

In conclusion, this case study has shown that large 1.5 MW wind turbines can be interconnected to the existing distribution system in the HEA study area. The potential interconnection locations are typically constrained to be within 4-6 miles of the substation. This constraint is due to power quality issues from voltage flicker. The maximum number that can be connected to each substation's grid varies from 2 to 9 turbines. However, at three substations, it may not be economically attractive to connect the wind turbines to the existing grid without building line extensions to nearby windy areas. This maximum number that can be connected without significant system reinforcements depends upon several factors, such as substation transformer size, line conductor size, and the distance from the substation.

From a practical point of view and in general, using the existing distribution system may be economical, if the amount of wind generation being added is in the range of perhaps one to five wind turbines at a particular location or area. Of course, there may be cases where fewer or more wind turbines than this could economically use the existing distribution system.

Wind Utility Consulting
Thomas A. Wind
Andrew T. Coil
June 1, 2005

FIGURE 5-1
Map showing HEA Substations, 3-Phase Feeders, and Potential Locations of the Maximum Number of Wind Turbines That Can be Interconnected Without System Reinforcements



APPENDIX

The 17 maps included in this appendix show the area around the 17 substations analyzed. Each map shows a very preliminary estimate of the wind speed at 50 meters height. At least one GE 1.5 MW wind turbine can be connected to any point on the main 3-phase lines shown. The individual wind turbine locations shown by the white circles depict one layout scenario that represents the total maximum number of wind turbines that can be connected to the existing distribution system, with less than a ½-mile line extension without significant upgrades or reinforcements to the distribution system.