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Land-Use Requirements of Modern Wind Power Plants in the United States

Paul Denholm, Maureen Hand, Maddalena Jackson, and Sean Ong

Technical Report
NREL/TP-6A2-45834
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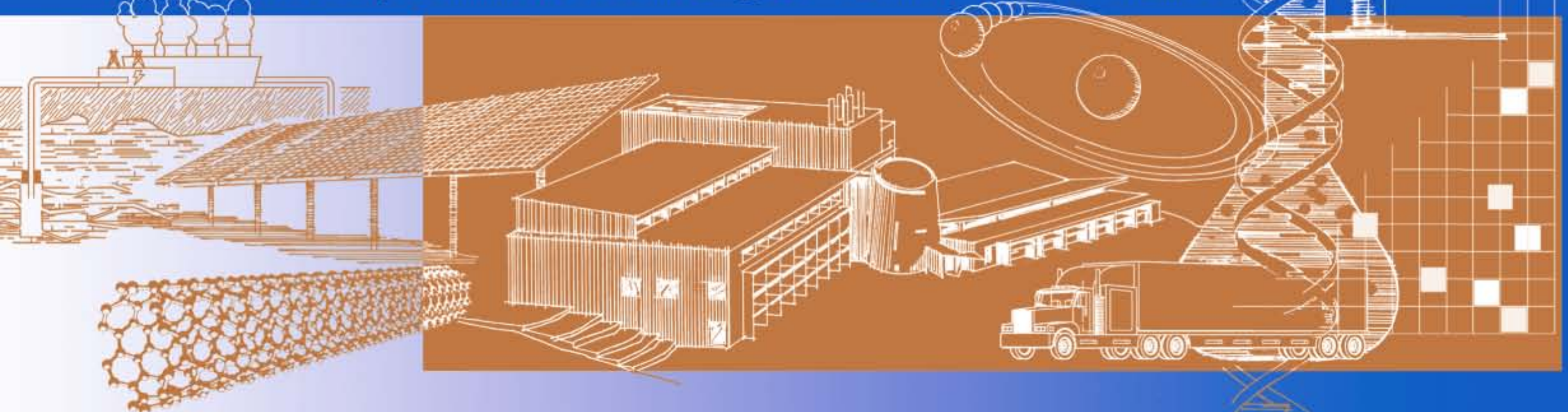

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Prepared under Task No. WER9.3550

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National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
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Acknowledgments

Substantial assistance in preparing this analysis, including the land-cover data, mapping, as well as general advice and guidance, was provided by Donna Heimiller, Anelia Milbrandt, and Billy Roberts at the National Renewable Energy Laboratory (NREL). Additional graphics and editorial support were provided by Jim Leyshon and Michelle Kubik.

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1 Introduction

By the end of 2008, a combination of environmental, economic, and policy factors resulted in the cumulative deployment of more than 25 gigawatts (GW) of wind generation capacity in the United States (AWEA 2009a). Continued growth is anticipated due to renewable portfolio standards and expected constraints on carbon emissions in the electric sector. One of the concerns regarding large-scale deployment of wind energy is its potentially significant land use. Estimates of land use in the existing literature are often based on simplified assumptions, including power plant configurations that do not reflect actual development practices to date. Land-use descriptions for many projects are available from various permitting agencies and other public sources, but we are not aware of any single source that compiles or summarizes this data. In addition, there is limited information comparing land use for wind power plants across different terrain and plant configurations. The existing data and analyses limit the effective quantification of land-use impacts for existing and future wind energy generation, particularly in comparison to other electricity generation technologies.

In this report, we provide data and analysis of the land use associated with modern, large wind power plants (defined as greater than 20 megawatts (MW) and constructed after 2000). We begin by discussing standard land-use metrics as established in the life-cycle assessment literature, and then discuss their applicability to wind power plants. We identify two major "classes" of wind plant land use: 1) direct impact (i.e., disturbed land due to physical infrastructure development), and 2) total area (i.e., land associated with the complete wind plant project). We also provide data for each of these classes, derived from project applications, environmental impact statements, and other sources. We also attempt to identify relationships among land use, wind plant configuration, and geography. We evaluated 172 existing or proposed projects, which represents more than 26 GW of capacity.

In addition to providing land-use data and summary statistics, we identify several limitations to the existing wind project area data sets, and suggest additional analysis that could aid in evaluating actual land use and impacts associated with deployment of wind energy.

2 Wind Power Plant Land-Use Metrics

There are a number of existing and proposed metrics for evaluating land-use impacts. While there is no generally accepted methodology (Canals et al. 2007), review of the life-cycle assessment (LCA) literature suggests at least three general categories for evaluating land-use impacts: 1) the area impacted, 2) the duration of the impact, and 3) the quality of the impact (Koellner and Scholz 2008).

In this report, we focus on quantifying and summarizing the first component of land-use impact identified above (area of impact), recognizing that the quality and duration of the impact must be evaluated on a case-by-case basis. The quality of impact, which may also be stated as a "damage function," evaluates both the initial state of the land impacted, and

the final states across a variety of factors including soil quality and overall ecosystem quality (Koellner and Scholz 2008).

Quantifying the area of a wind power plant is challenging given the discontinuous nature of its configuration. “Area” includes not only land directly disturbed by installation of the turbines, but also the surrounding area that potentially may be impacted. In reviewing various environmental impact assessments and other evaluations of wind plant land use, it appears that there are two general types of “areas” considered. The first is the direct surface area impact (i.e., disturbed land) due to plant construction and infrastructure. The second is more vaguely defined, but is associated with the total area of the wind power plant as a whole. Figure 1 provides a simplified illustration of the two types of areas, which are vastly different in both quantity and quality of impacts as discussed in subsequent sections.

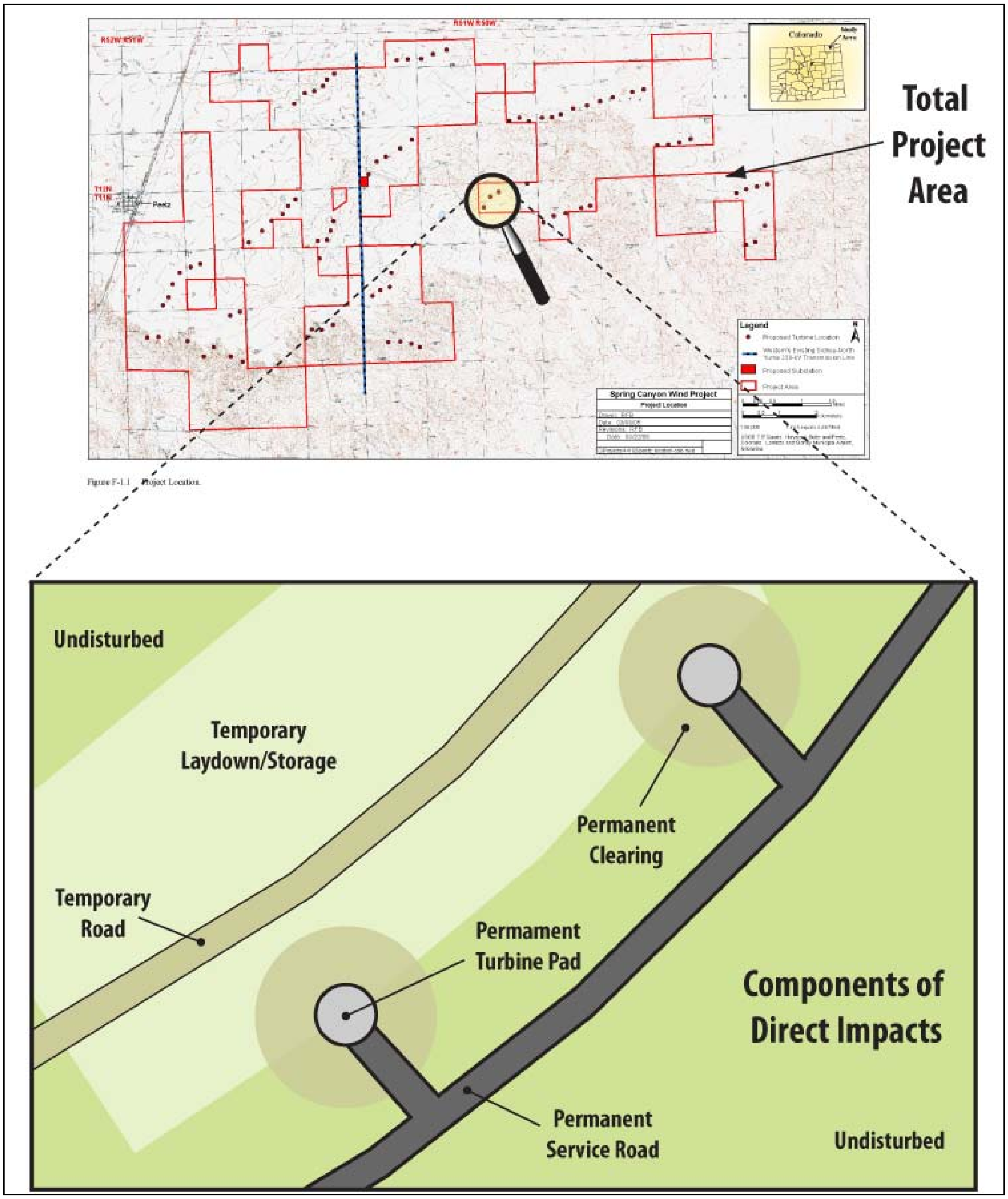

Figure 1. Illustration of the two types of wind plant land use: total area and direct impact area (including permanent and temporary)[1]

[1] The total project area map is adapted from an actual project application (U.S. DOE 2005). The direct impact area is a simplified illustration meant to represent typical components and does NOT represent this or any actual project.

2.1 Direct Impact Area

Development of a wind power plant results in a variety of temporary and permanent (lasting the life of the project) disturbances. These disturbances include land occupied by wind turbine pads, access roads, substations, service buildings, and other infrastructure which physically occupy land area, or create impermeable surfaces. Additional direct impacts are associated with development in forested areas, where additional land must be cleared around each turbine. While land cleared around a turbine pad does not result in impervious surfaces, this modification represents a potentially significant degradation in ecosystem quality (Arnett et al. 2007).

In addition to permanent impacts, which last the life of the facility, there are temporary impacts from plant construction. These impacts are associated with temporary construction-access roads, storage, and lay-down. After plant construction is completed, these areas will eventually return to their previous state. The amount of time required to return to its "pre-disturbance condition" is estimated at two-three years for grasslands and "decades" in desert environments (Arnett et al. 2007).

An illustration of the direct impact area is shown in the magnified section of Figure 1, and demonstrates the components of direct impact, including the impermeable turbine pad and road, the permanently altered clearing around the turbine, and the temporary lay-down area. This illustration is not meant to represent any specific project and the actual components and configuration of direct impact area will vary among projects.

2.2 Total Wind Plant Area

While the area and impacts associated with physical infrastructure described in Section 2.1 may be the easiest to quantify, the more commonly cited land-use metric associated with wind power plants is the footprint of the project as a whole. However, unlike the area occupied by roads and pads, the total area is more challenging to define and subjective in nature. Generally, the total area of a wind power plant consists of the area within a perimeter surrounding all of the turbines in the project. However, the perimeter is highly dependent on terrain, turbine size, current land use, and other considerations such as setback regulations. An example of the total area of a project is illustrated in Figure 1, showing the individual turbine strings, and the very irregular perimeter. There is no uniform definition of the perimeter or boundary surrounding a wind power plant – in fact, the total area of a wind power plant could have a number of definitions. The boundary could be defined based on the required turbine spacing as a function of rotor diameter, or use a standardized setback from turbines at the edge of a project. As discussed in Section 3, this paper relies on the area defined through project applications or other documentation associated with each project.

The character of impact of the total area of a wind power plant is very different from the direct impact area, or the area associated with other types of energy production facilities. Many previous comparisons of total land use associated with energy production only include the total area affected, and provide little discussion of the damage function as a comparative metric. A wind plant in an agricultural area with low population and minimum avian impacts would have a much lower damage function than an area mined for coal or flooded by a hydropower project, for example. As a result, using the total area

metric without qualification may significantly overstate the land impacts of wind power compared to other sources. Alternatively, wind power projects should consider the impacts associated with habitat disruption, avian impacts, and aesthetics. Ultimately, the actual quality of impacts, captured in a damage function, is needed to compare the land impacts of wind to other sources.

3 Wind Power Plant Land-Use Data

Our goal was to collect and provide a summary of reported land-use data associated with modern, large wind power plants. As a result, we restricted the sample of sites to projects constructed after 2000 and with a nameplate capacity greater than 20 MW.[2] We included proposed projects, but only those with detailed, formal applications (or environmental assessments) to a regulatory agency.

A variety of sources for land-use data were used for this study and fell into three general categories. First, where available, we collected official project data from federal, state, and local regulatory agencies, including environmental impact statements (EIS), environmental assessments (EA), and project applications to utility regulatory bodies. The availability of this data is highly dependent on state and local regulations. Some states require very detailed environmental assessments, while others require little in the way of analysis of potential land use. Second, we collected project fact sheets, news releases, and other data provided by the project owner or developer. When no other source of data could be located, we used news articles, Web sites and other secondary sources. As a supplement to area data, we also collected location and land-cover data for individual turbines from publicly available data sets. The following sections provide details about the specific types and sources of data collected.

3.1 Direct Impact Area

The direct impact area was identified in project materials as land "permanently occupied," "permanently disturbed," or using similar wording. When provided, most projects report a single number for land directly occupied; however, some provide a breakdown of occupation categories. Figure 2 provides an example of a detailed table of occupied area from a project application.

[2] We excluded older projects largely because they use turbines less than 1 MW. This excludes several large projects such as those in the Altamont Pass and Tehachapi regions in California.

Table 2.6-1
Site Disturbance Summary

Site Component	Disturbance
Number of Turbines	49-58
Turbine Sites	3.3-3.9 acres
New Access Roads	5.9 acres
Substation	0.6 acres
New Interconnect lines	0.8 acres
Permanent Disturbed Area*	***10.6-11.2 acres***
Temporary Disturbed Area**	***13.3 -15.7 acres***
Estimated Raw Cut	2,000 cubic yards
Estimated Raw Fill	2,400 cubic yards

*It should be noted that of this total permanent disturbed area, between 5.8 to 6.1 acres would be in areas already disturbed by CVWD activities (described in *Section 2.6*), thus reducing actual disturbance of natural areas to between 4.8 and 5.1 acres.

**Temporary disturbed areas include a 3,500 square foot staging area adjacent to each turbine and a 4.75 acre construction staging area in the northeast corner of Section 28 as well as trenching for interconnection of turbines. The temporary staging and trenching areas will be renaturalized at the completion of construction.

Figure 2. Example of direct impact area (adapted from BLM 2008)

When provided, we recorded the permanent direct impact area data for five categories: turbine pad, roads, substations, transmission, and other.

A number of applications also included temporary direct impact data associated with plant construction. We recorded temporary direct impact area data in four categories: temporary roads, staging, substation/transmission construction, and other.

3.2 Total Wind Plant Area

The total area was identified in project materials as "project area," "lease area," "site boundary," or similar terms. This area is not uniformly defined, and is often established by the individual project developer; it also will vary between developers and between states. In addition, many applications define the project area without a map or any additional information about how this boundary is determined.

3.3 Wind Power Plant Land-Cover and Configuration Data

In addition to area data, two additional parameters associated with wind plants were collected to aid in evaluating possible dependence of land use on wind plant configuration and location.

For each wind power plant evaluated, we collected location data for each turbine in the project from the Federal Aviation Administration (FAA 2009). This data set includes latitude and longitude for each turbine. From this database, we then acquired the land-cover type for each turbine using a U.S. Geological Survey data set (USGS 2006). Land cover in this data set is described as "the nature of the land surface at a particular location" with 21 classes of land cover. This data provides additional insight into the potential impact – for example, turbines located in primarily agriculture area should have

significantly less impact than turbines located in forested area, which are more likely to require additional clearing and have a greater potential for habitat fragmentation and other adverse environmental impacts.

Once we collected the location data for each turbine, we also examined the overall wind plant configuration to identify relationships between land-use area and configuration. After examining the various configurations, we created four general categories: Single String, Multiple Strings, Parallel Strings, and Clusters. These are qualitatively defined as follows:

- Single String: A single long string of turbines, including projects with one or more discontinuities.
- Multiple String: A series of identifiable strings of turbines, but not uniformly oriented.
- Parallel String: A series of well-defined strings that are roughly parallel to each other (i.e., strings do not intersect). This configuration is closest to the grid spacing often used to represent an "ideal" plant layout.
- Cluster: Sites that have very few to no observable turbine strings.

Examples of these configurations are provided in Figure 3.

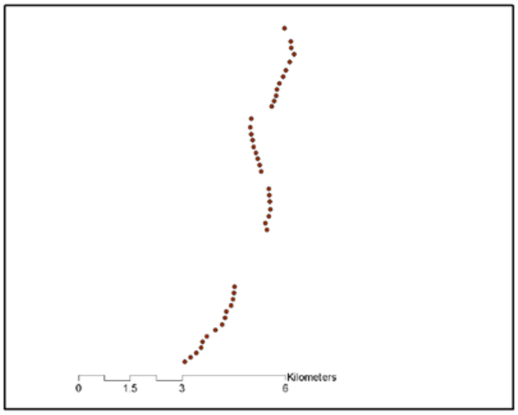

Figure 3.1. Single string configuration (Waymart, Pennsylvania)

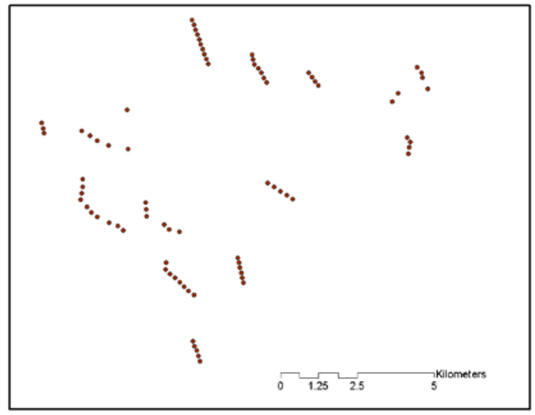

Figure 3.2. Multiple strings configuration (Wyoming Wind Energy Center, Wyoming)

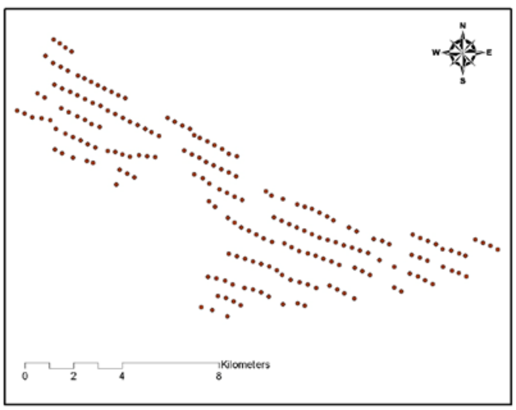

Figure 3.3. Parallel string configuration (Roscoe Wind Project, Texas)

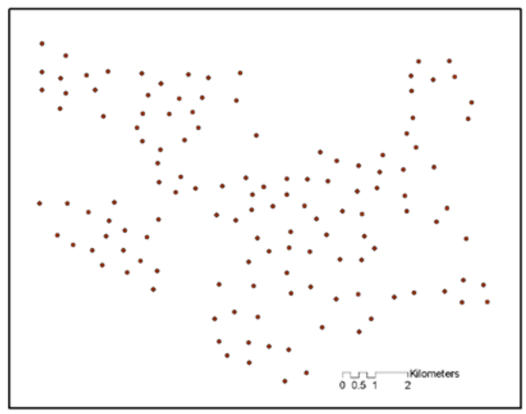

Figure 3.4. Cluster configuration (Spring Creek Wind Farm, Illinois)

Figure 3. Examples of wind power plant configurations

In these representative cases, the different configurations are easily visible. However, it is sometimes difficult to establish a single, uniform configuration for an entire plant, which introduces an element of subjectivity to this metric.

4 Results

We obtained one or more categories of land-use data for 172 individual projects, representing 26,462 MW of proposed or installed capacity. Of this capacity, 19,834 MW was completed as of March 2009, 2,892 MW was under construction, and the remainder consists of proposed projects. According to a the American Wind Energy Association (2009b), as of March 2009, 28,206 MW wind capacity had been completed in the United States, with 24,640 MW meeting our criteria as a large modern plant with a capacity of at least 20 MW and constructed after 2000. As a result, we collected at least some information on about 80% of the targeted installed wind capacity in the United States. Figure 4 provides a map of project locations. A complete listing of all projects, data sources, and individual project data is provided in the Appendix.

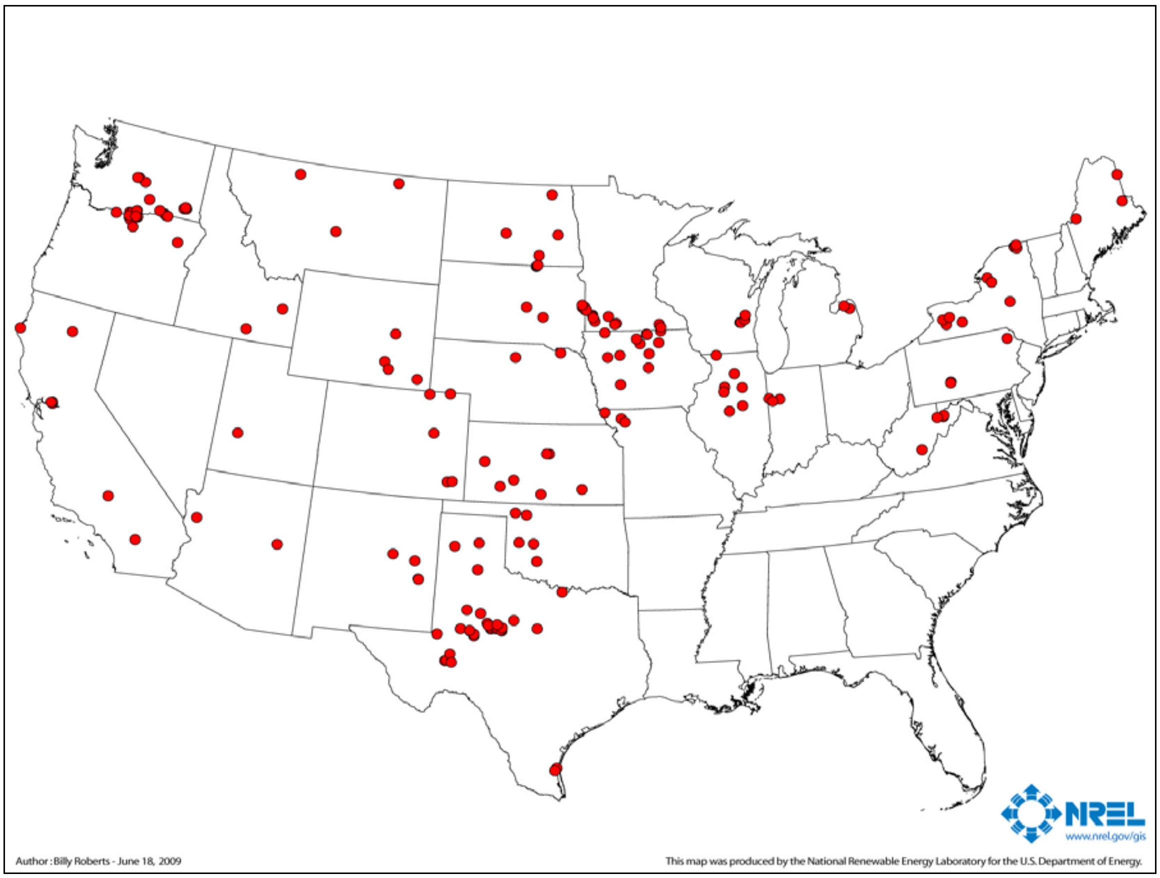

Figure 4. Locations of wind power plants evaluated in this study

4.1 Summary Results

Table 1 summarizes the direct impact area data and total area data for projects shown in Figure 4 and listed in the Appendix. As noted earlier, this represents a mix of data from the 172 projects. The number of projects where we obtained data for the corresponding area metric is listed in the first row of Table 1 – for example, we were able to obtain total impact area for 161 of the 172 projects, but only 52 of the projects had information on the temporary direct impact area. The average area requirements (hectare/MW) were calculated by summing the total area of all plants with corresponding land-use data and dividing by the total capacity of those plants.[3]

Table 1. Summary of Collected Wind Power Plant Area Data

Data Type	Direct Impact Area		Total Area
	Permanent	Temporary	
Number of Projects with Corresponding Data	93	52	161
Total Capacity (MW) with Corresponding Data	13,897	8,984	25,438
Total Number of Turbines with Corresponding Data	8,711	5,541	15,871
Total Reported Area (km^2)	37.6	61.4	8,778.9
Average Area Requirements (hectare/MW)[4]	0.3± 0.3	0.7 ± 0.6	34.5 ± 22.4

[3] This represents a weighted average and is not equal to the simple average. The simple average would sum each individual land use requirement (area per unit capacity) and the divide the sum by the total number of evaluated projects. This method would weight each wind plant equally, so that the land use "intensity" of a small plant would count as much as a much larger project.

[4] The standard deviation is also reported. It should be noted that the data sets do not represent normal distributions as can be observed in Figures 5-7.

4.2 Direct Impact Area Results

There is substantial variation among the reported area requirements as indicated by the large standard deviation values. For the permanent direct impact, the range is about 0.06 hectares/MW to about 2.4 hectares/MW; however, approximately 80% of the projects (both number of projects and total capacity) report direct land use at below 0.4 hectares/MW. Figure 5 indicates the range of direct impact area for the projects that provided this data. In this figure, the data were binned and reported as both the number of projects and the total capacity (MW) in each bin of direct impact area (hectares/MW).

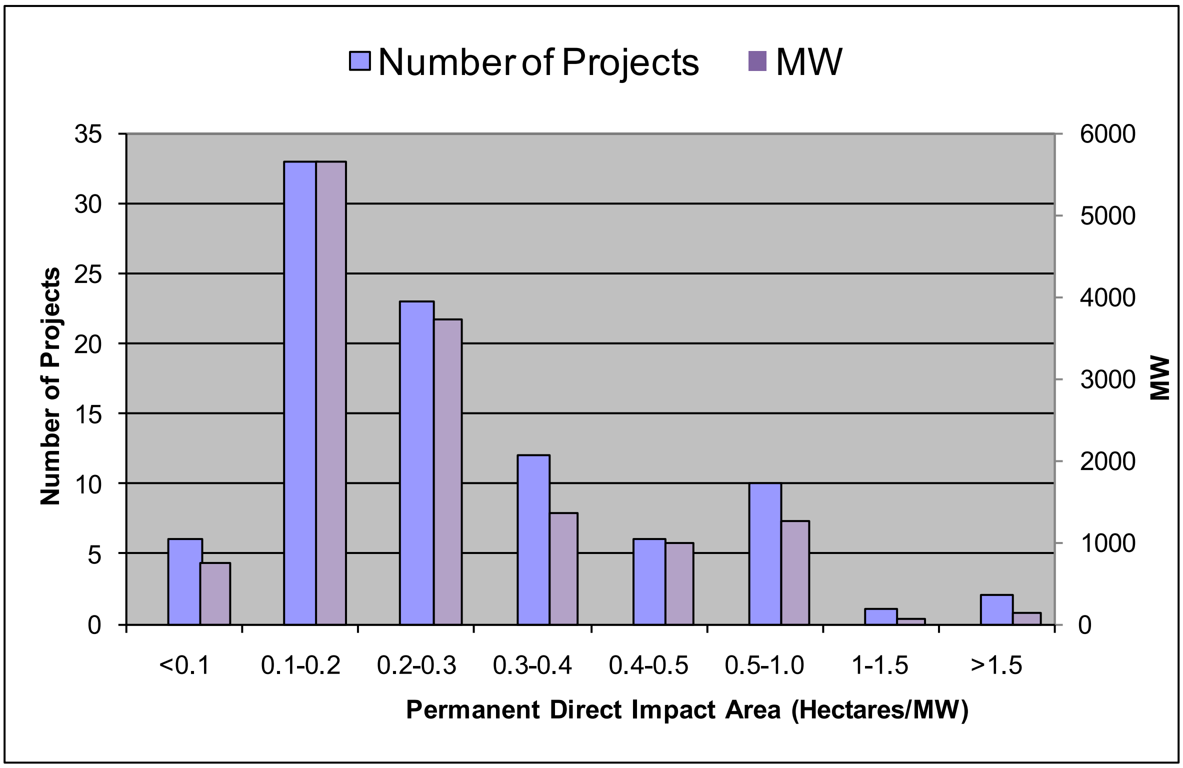

Figure 5. Distribution of permanent direct impact area

Figure 6 provides the distribution of temporary direct impact area. The temporary impact area is much higher than the permanent area, with about 50% of the projects (both number and capacity) reporting a temporary impact area of greater than 0.5 hectares/MW.

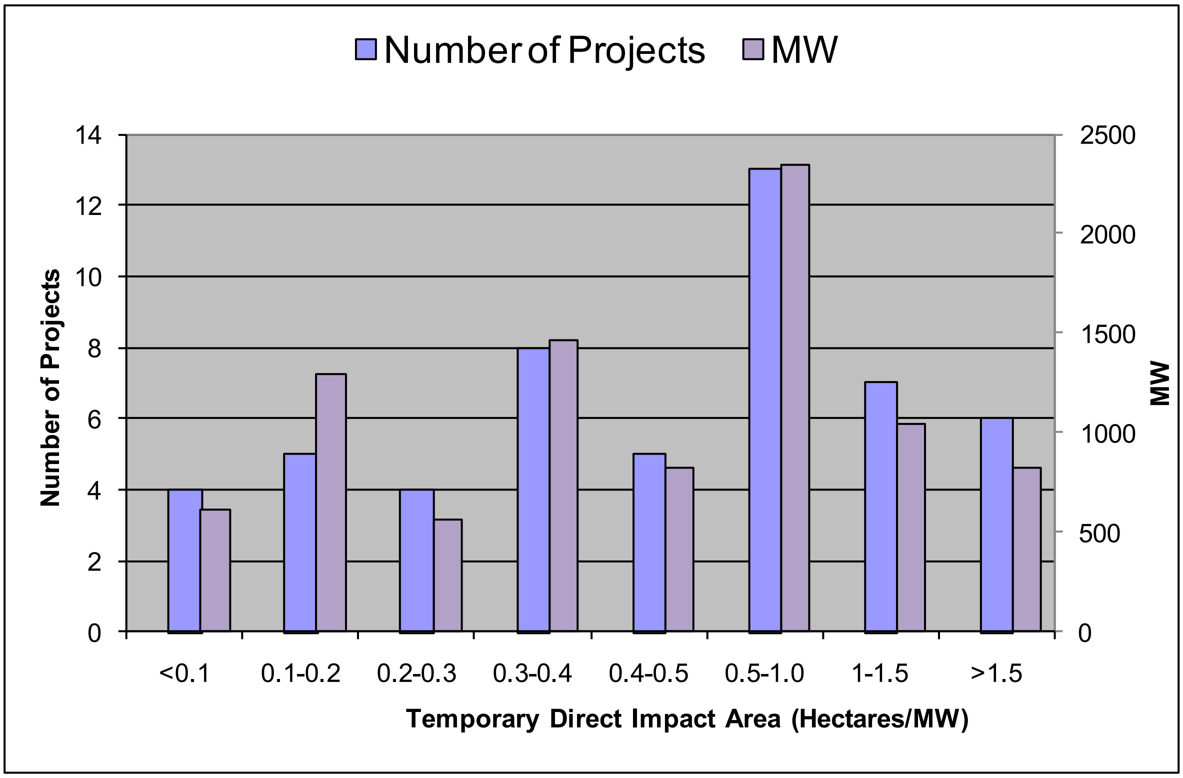

Figure 6. Distribution of temporary direct impact area

The overall average direct impact area is 0.3 ± 0.3 hectares/MW for permanent impact and 0.7 ± 0.6 hectares/MW for temporary impact, or a total direct surface area disruption of about 1.0 ± 0.7 hectares/MW.

The reported values can be compared to previous estimates of direct impacts. The Bureau of Land Management (BLM 2005) estimated a direct impact area (both permanent and temporary) of 0.4 to 1.2 hectares per turbine in the western United States. Assuming a 1.5 MW turbine, this corresponds to total direct impact area of 0.3 to 0.8 hectares/MW. Strickland and Johnson (2006) estimate permanent infrastructure impacts of 0.3 to 0.4 hectares per turbine, and temporary impacts of 0.2 to 1.0 hectares per turbine. Assuming a 1.5 MW turbine, this corresponds to a permanent impact area of 0.2 to 0.5 hectares/MW and temporary impact area of 0.1 to 0.7 hectares/MW.

Where provided, we collected data that breaks out the occupation categories as described previously. Less than a third of the projects that reported direct impact area provided detailed data. Tables 2 and 3 provide summary statistics of this data.

Table 2. Projects with Detailed Direct Impact Data

	Permanent	Temporary
Number of Projects with Detailed Data	23	17
Total MW	4,257	3,642

Table 3. Distribution of Direct Impact Area

Permanent Impact Category	% of Area	Temporary Impact Category	% of Area
Turbine Area	10%	Staging Area	30%
Roads	79%	Temp Roads	62%
Substation	6%	Sub/Trans construction	6%
Transmission	2%	Other	3%
Other	2%		

Table 3 indicates that the majority of direct impacts are associated with roads. In most cases, the road area provided in the documents only counts new road development or road improvement. For further studies, it would be useful to more closely review project documents to determine the amount of new roads that were constructed versus the extent to which the project used the preexisting road network.

4.3 Total Area Results

For total area requirements, the range of values is from about 9 hectares/MW to 100 hectares/MW, with five "outliers" – three projects with requirements below 6 hectares/MW and two projects with reported areas of greater than 135 hectares/MW.

Figure 7 provides a distribution of the total area requirements (hectares/MW).

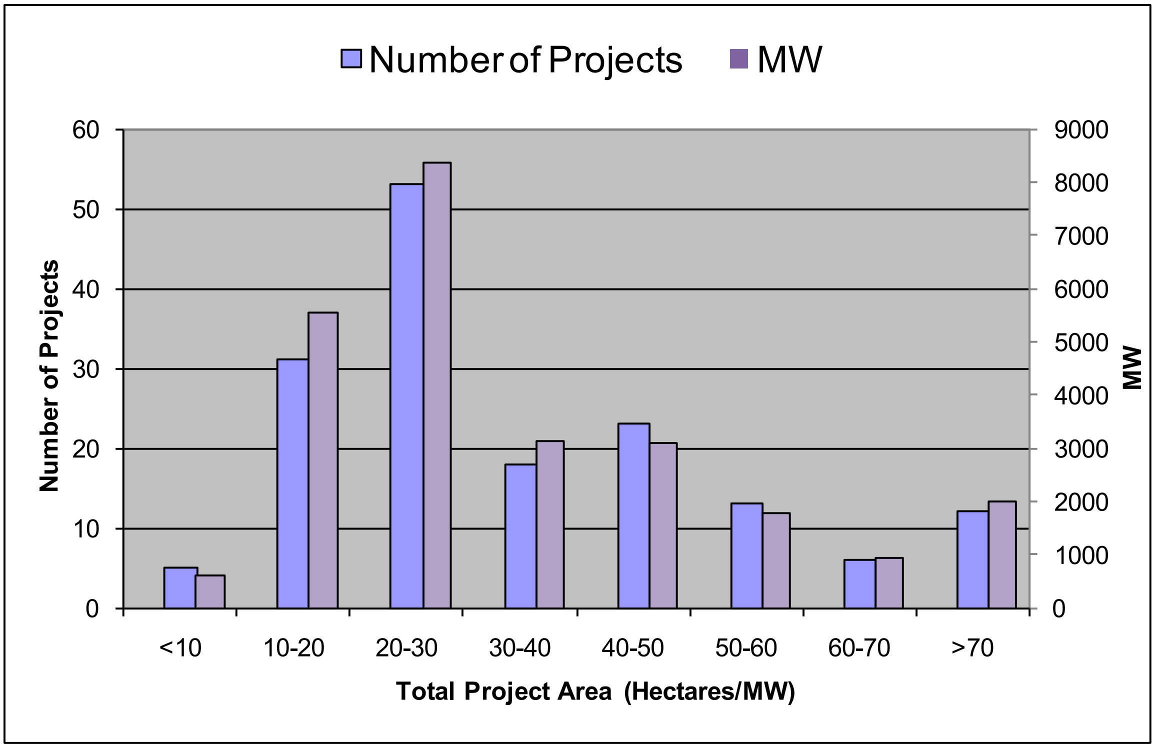

Figure 7. Distribution of total area requirements

Many estimates of total area often express wind plant land use in terms of capacity density (capacity per unit area, typically MW/km^2). Excluding the outliers, the reported data represents a capacity density range of 1.0 to 11.2 MW/km^2 and an overall average capacity density of 3.0 ± 1.7 MW/km^2. Figure 8 provides a distribution of the capacity density data. Of the 161 projects with total land-use area data, 125 (representing 80% of the evaluated capacity) have reported area of between 10 and 50 hectares/MW (or a capacity density range of 2-10 MW/km^2).

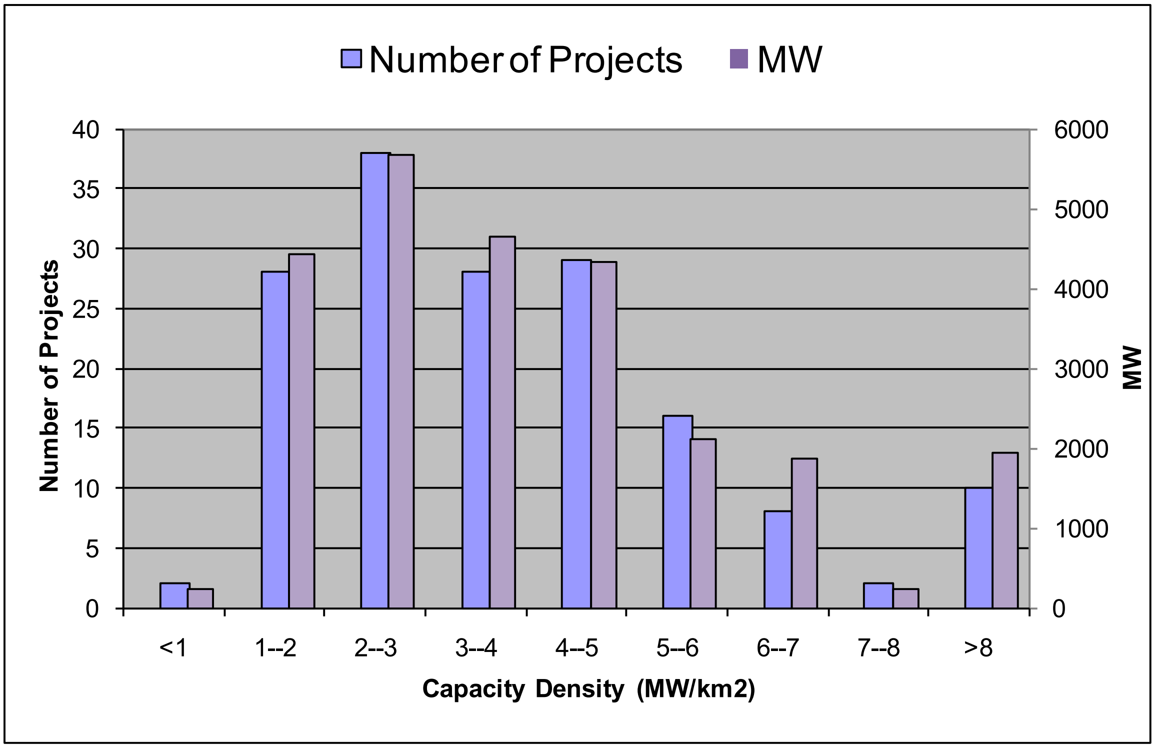

Figure 8. Distribution of total area expressed as capacity density

Previous estimates of total area are often based on theoretical potential to extract energy over a particular area, such as the U.S. DOE (2008) estimate of 20 hectares/MW (equal to a capacity density of 5 MW/km2). Other estimates assume turbines are configured in a grid with a fixed array spacing, such as 5 rotor diameters by 10 rotor diameters (a 5D by 10D array), or some alternative fixed spacing (Manwell et al. 2002, Fthenakis and Kim 2009). For modern wind turbines, a 5D by 10D array yields an area of 13-20 hectares/MW, equal to a capacity density of 5-8 MW/km^2 (Denholm 2006). These estimates represent minimum spacing to optimize energy extraction.

The overall average land use reported in this study is higher than estimates that use optimal grid spacing due, in part, to irregular spacing seen in actual projects. However, in reviewing the project applications and environmental assessments, we found several potentially significant sources of overestimates of the land use associated with some projects.

In some cases, developers lease (or propose to lease) all the land deemed necessary for a multiphase project at once, and all of that land then gets associated with an initial phase of the project rather than the final (larger) project.

We have also found that in several states, project areas are mapped based on discrete sections (where a section is defined as a 1 square mile parcel[5]), and that an entire section is included if there is a turbine located anywhere on that section. This can actually lead to double counting of sections, when two separate projects overlap on the same section, and

[5] http://www.nationalatlas.gov/articles/boundaries/a_plss.html

that section is assigned to both projects. Additional complete or partial sections may be assigned to the project area surrounding the outermost edge of turbines. These factors will tend to increase the reported land use, decreasing the reported capacity density of wind projects.

One example of potential land-use overestimation is the Moraine II Project in Minnesota (PPM Energy 2007). This project has the greatest total area of all evaluated projects equal to 226 hectares/MW, or a capacity density of 0.44 MW/km^2. This value was based on the application, which states that "The site boundary in Minnesota encompasses an area of approximately 26,992 acres." Examining the project map, the site boundary includes 40 complete sections of land, while turbines are located on only six of these sections. While this is the most extreme example, many other projects include large areas unoccupied by "initial phase" wind turbines or associated infrastructure.

4.4 Dependence of Area on Configuration, Geography, and Plant Size

Despite the inconsistent methods used to report area, it may be useful to examine the dependence of area requirements on configuration and geography. To further evaluate the potential sources of variation in land area, we first assigned each project a configuration and land-cover classification as discussed previously. Table 4 provides the distribution of configurations of all wind plants evaluated.

Table 4. Wind Power Plant Configuration

Configuration	Projects	% of Projects	MW	% of Capacity
Parallel Strings	67	39.0%	11704.5	44.2%
Single String	11	6.4%	1071.0	4.0%
Multiple Strings	40	23.3%	5979.8	22.6%
Cluster	54	31.4%	7706.6	29.1%

As illustrated in Table 4, fewer than 50% of the evaluated projects resemble a grid configuration, (noting that the parallel string configuration often only loosely approximates an ideal grid.).

Table 5 provides the predominant land-cover classification data determined by the combination of the turbine locations from the FAA database and the land-cover data from the U.S. Geological Survey (USGS) discussed in Section 3. The three different forest types (deciduous, mixed, and evergreen) are combined into a single category.

Table 5. Land-Cover Data

Primary Land Type	Projects	% of Projects	MW	% of Capacity
Shrubland	38	22.1%	7,169	27.1%
Forest	15	8.7%	1,711	6.5%
Grasslands/Herbaceous	34	19.8%	5,324	20.1%
Pasture/Hay	16	9.3%	1,997	7.5%
Row Crops	54	31.4%	8,199	31.0%
Small Grains	15	8.7%	2,063	7.8%

Tables 6 and 7 provide the average land-use data by configuration and land-cover classification. It should be noted that by splitting the project data by category, we substantially reduced the number of plants in each category. For example, while we identified 67 projects having the parallel strings configuration, only 11 had temporary land-use data available. We also calculate the average area and standard deviation using all reported data, despite the fact that there are significant outliers (reflected in the large standard deviation).

Table 6. Relationship between Configuration and Land-Use Area

Configuration	Average Area (hectares/MW)		
	Direct Impact Area (Permanent)	Direct Impact Area (Temp)	Total Area
Parallel Strings	0.33 ± 0.32	0.80 ± 0.55	34.7 ± 17.0
Multiple Strings	0.21 ± 0.15	0.38 ± 0.33	27.7 ± 24.0
Single String	0.34 ± 0.28	1.00 ± 1.13	30.3 ± 18.3
Cluster	0.24 ± 0.24	0.78 ± 0.63	39.8 ± 22.0

Based on the data in Table 6, cluster configurations appear to have greater total area than other configurations, probably due to irregular turbine placement resulting in greater spacing between individual turbines.

Table 7. Relationship between Land-Cover and Average Land-Use Area

Primary Land Type	Average Area (hectares/MW)		
	Direct Impact Area (Permanent)	Direct Impact Area (Temporary)	Total Area
Shrubland	0.22 ± 0.12	0.63 ± 0.50	26.3 ± 12.8
Forest	0.36 ± 0.22	1.11 ± 1.14	18.3 ± 12.6
Grasslands/Herbaceous	0.41 ± 0.22	0.37 ± 0.11	35.7 ± 16.7
Pasture/Hay	0.24 ± 0.15	0.59 ± 0.66	27.4 ± 15.4
Row Crops	0.24 ± 0.28	0.87 ± 0.65	47.6 ± 25.1
Small Grains	0.31 ± 0.52	0.50 ± 0.17	24.5 ± 7.7

Evaluated wind plants in forested areas have the highest temporary impact area – and higher than average permanent impact area – likely due to forest clearing for access roads, turbine pads, and a setback area around each turbine. However, these projects also have the lowest total reported area. Wind plants sited on land where the predominant land cover is row crops have the greatest total area requirements. This relationship can be observed in Table 8, which correlates turbine configuration with land cover and illustrates that cluster projects are most commonly associated with row crops.

Table 8. Relationship between Land Cover and Configuration

Primary Land Type	Number of Projects			
	Parallel Strings	Multiple Strings	Single String	Cluster
Shrubland	21	13	2	2
Forest	1	5	6	3
Grasslands/Herbaceous	20	6	3	5
Pasture/Hay	0	3	0	13
Row Crops	17	7	0	30
Small Grains	8	6	0	1

We also examined the relationship between overall wind power plant capacity (MW) and reported land-use requirements (hectare/MW). Figures 9 and 10 relate direct impact area and total area as a function of project size. In Figure 9, one temporary impact point equal to 4.5 hectare/MW has been omitted for chart clarity.

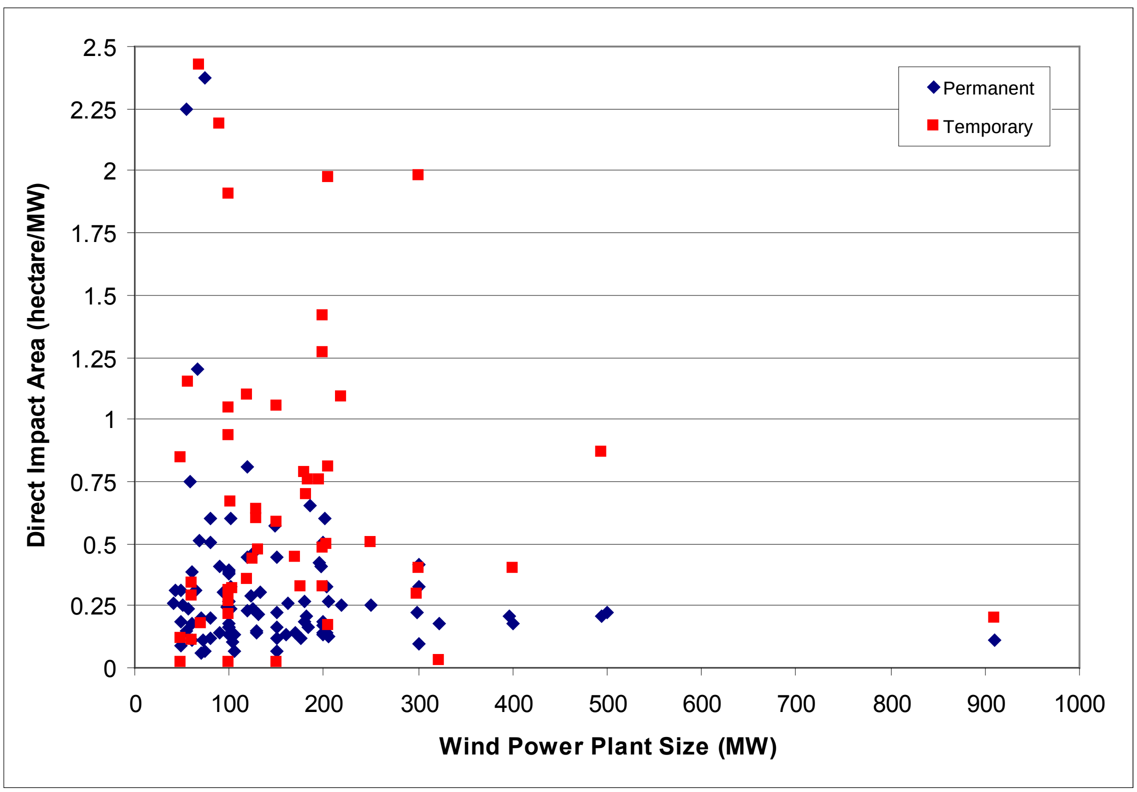

Figure 9. Direct impact area requirements (hectare/MW) as a function of wind power plant size

Figure 10 illustrates the relationship between total area (measured in terms of capacity density) and project size. Three outliers above 12 MW/km^2 are not shown. As with Figure 9, there appears to be no significant trends, and very little correlation (with r-values less than 0.05 for all relationships in the figures.)[6]

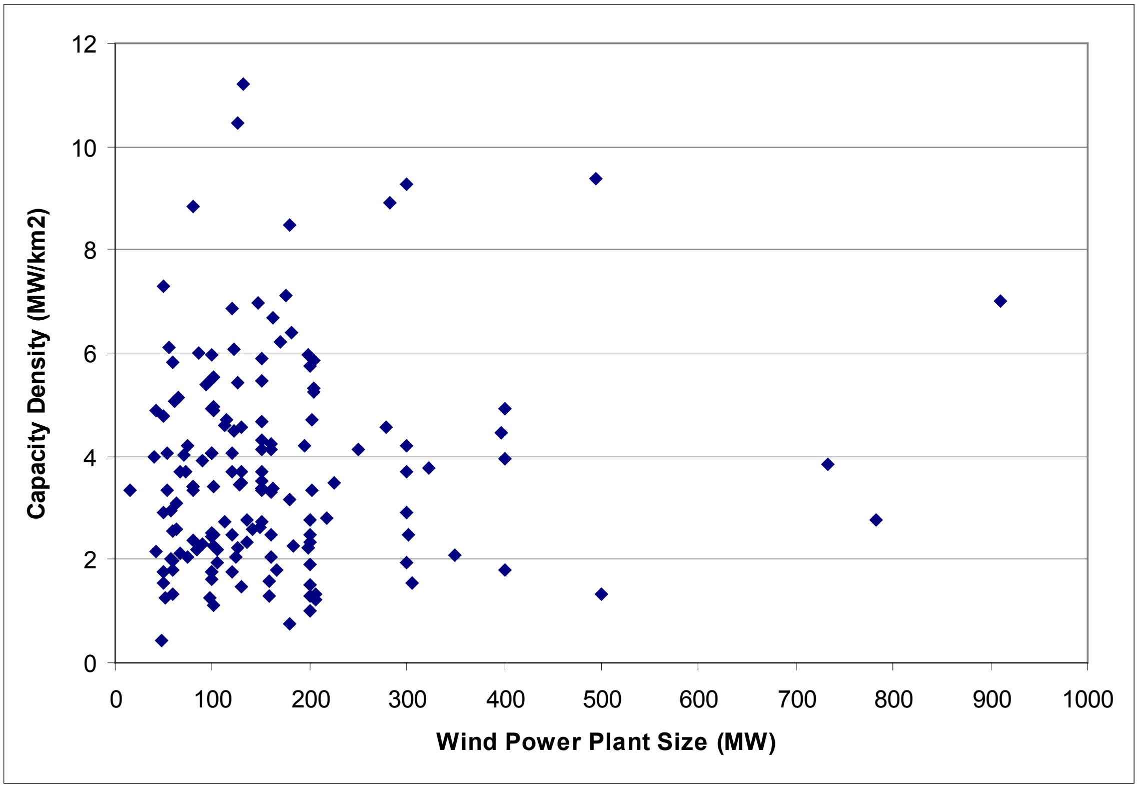

Figure 10. Capacity density as a function of wind power plant size

5 Alternative Area Metrics and Measurement Methods

There are a number of limitations to the evaluation of land use in existing data sets. Primarily, any metric that includes only area and does not include the quality of impact (damage function) will be unable to completely capture the land-use impacts of wind power plants or any electricity generation technology. However, there are additional "area only" metrics that could improve understanding of the land-use impacts of wind power plants. In this section, we suggest two additional area measurements that could be generally applied. The first is habitat impact area, which attempts to more directly measure the area of ecosystem impact. The second is a more general measure of total area, incorporating a standardized methodology.

[6] We also examined the relationship between turbine size and land use, hypothesizing that larger turbines would require less direct land impact area per unit of capacity. However, we found no significant relationship trends in the reported data.

5.1 Habitat Impact Area

One additional land-use metric that could be considered more generally would be a "habitat impact area," which measures the area of fragmentation or decrease in habitat quality. (Impact on habitat is often considered and reported in individual project applications and environmental assessments.) Summary estimates of regional ecosystem impacts are provided by the National Research Council (2007) and Arnet et al. (2007). As an example, Robel (2002) estimates turbines placed in certain grassland areas will reduce the available habitat for greater prairie-chicken nesting by about 800 hectares for each turbine (about 530 hectares/MW, assuming a 1.5 MW turbine). Turbines placed in forested areas can create an "edge effect" (Jordaan et al. 2009), which results in disruptions that can exceed 340 meters in all directions for certain species (Wood et al. 2006), or a habitat impact of more than 24 hectares/MW, assuming a 1.5 MW turbine. These examples show the limitations of the simple metrics provided in this report, as well as the limitation of quantifying wind power plant land use without qualifying their impacts on a regional basis.

5.2 Uniform Estimation of Total Area Requirements

As discussed previously, there is no uniform definition of the total area of a wind power plant. This paper describes the wind plant area in the United States that is reported to be leased or otherwise associated with a project application. As discussed previously, the measurement of total area varies by project developer and by state, and provides a limited basis to compare projects regionally or to estimate land use in future wind generation scenarios.

Addressing the limitations caused by using developer's estimates of project areas would require developing a more uniform metric for the total area of wind power plants based on setbacks or other relation to turbines. Figure 11 provides an example of three potential measures of total area that could be generally applied based on the availability of individual turbine locations from the FAA database or other sources. The method is based on the geometric concept of a "convex hull," which can be described by visualizing a rubber band stretched around the perimeter of a set of points. Applying this method to calculate wind plant area requires establishment of several parameters. First, the setback from the outermost edge of the wind turbines must be standardized. Second, the amount of "relaxation" into the interior of the project must be established. The effect of different relaxations is illustrated by buffer areas 2 and 3, where some of the open space inside the outermost perimeter is eliminated. A final element to consider is the effect of any large discontinuities in the project. A complicating issue in establishing these three parameters is that they would probably vary depending on land-cover type. For example, setbacks would be greater for turbines located in forested areas. If these parameters are established, it should be relatively easy to determine the total land use associated with all wind energy production in the United States.

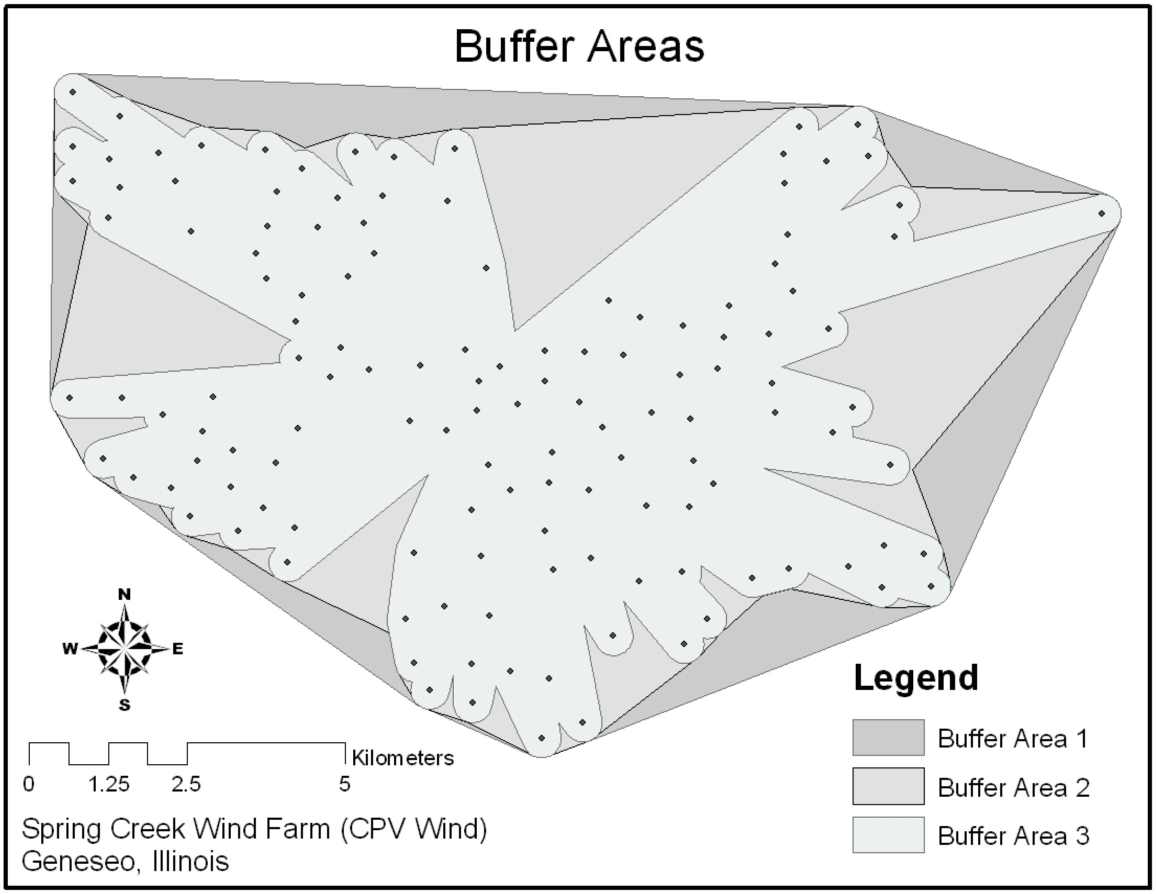

Figure 11. Possible methodologies for assigning uniform land metrics to total area of wind power plants

6 Conclusions

Although there is no uniformly accepted single metric of land use for wind power plants, two primary indices of land use do exist – the infrastructure/direct impact area (or land temporarily or permanently disturbed by wind power plant development) and the total area (or overall area of the power plant as a whole).

Based on the collected data, direct impact is mostly caused by road development, as opposed to the turbine pads and electrical support equipment. For 93 projects representing about 14 GW of proposed or installed capacity, the average permanent direct impact value reported was 0.3 ± 0.3 hectares/MW of capacity. Fewer projects (52 representing 9 GW of capacity) provide temporary direct impact data, with an overall average of 0.7 ± 0.6 hectares/MW of capacity. This implies a total direct impact area (both temporary and permanently disturbed land) of about 1 ± 0.7 hectare/MW, but with a wide variation in this area.

We also found reported total-area data for 161 projects representing about 25 GW of proposed or installed capacity. Excluding several outliers, the average value for the total project area was about 34 ± 22 hectares/MW, equal to a capacity density of 3.0 ± 1.7

MW/km^2. This capacity density is less than grid-based estimates used for optimizing energy extraction. We believe that some of this difference is due to inclusion of land that was set aside for future project expansion and double counting of land where projects overlap. The limited detailed data available for many projects, including a number of large projects, limits the ability to precisely identify the discrepancy between common estimates and reported data. However, it is clear that the ideal grid configuration used for some estimates is rarely used in practice, resulting in more widely spaced turbines.

Common estimates of wind land-use requirements represent, in part, the theoretical potential to extract energy over a particular area. For example, estimates for wind resource potential assign wind project capacity to geographic areas as small as 200 m^2 based on average wind resource over that grid cell. Existing projects site turbines in locations that maximize energy capture accounting for normal terrain variations, avoiding depressions, and exploiting ridges. While the theoretical approaches are often useful (as indicated by the fact that many projects achieve capacity densities equal to or greater than 5 MW/km^2), practical considerations tend to increase the area actually used by projects. Without a systematic method to define project boundaries based solely on turbine spacing, the total land area required for wind projects to effectively extract energy from the flow cannot be determined. Although this paper presents the land area reported by wind project developers in the United States at this time, additional methods are needed to systematically determine land-use requirements for energy extraction, all while considering continuing advances in turbine design and plant configurations.

Total land-area metrics for wind projects are not consistently defined and provide information for different purposes. This paper explores the land area reportedly associated with U.S. wind projects based on official documents. Other approaches would explore turbine-specific dimensions (such as rotor diameter) to assess U.S. wind project area optimized for energy extraction – perhaps leading to new “rule of thumb” estimates. Finally, an automated methodology that defines a standard setback based on relative turbine locations within projects would result in a systematic approach that may reduce variation among projects.

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Appendix. Wind Power Plant Land-Use Data

Table A1. Land-Use Data

Name	State	# Turbines	Capacity MW	Total Area (hectares)	Total Area Per Unit Capacity (Hectares /MW)	Direct Impact Area (Perm.) (hectares)	Direct Impact Area (Temp.) (hectares)
Steel Park Wind Farm	AZ	15	15	448.7	29.92		
Dry Lake Wind Project I	AZ	42	63	2430.0	38.57		
Bear River Wind Power Project	CA	35	70			4.0	12.6
Hatchet Ridge Wind Project	CA	49	125	1193.9	9.55	29.6	55.1
High Winds I & II	CA	90	162	2430.0	15.00	42.5	
Mountain View IV	CA	49	49	671.9	13.71	4.5	5.8
Pine Tree Wind Project aka Wind Turbine Prometheus	CA	80	120	3240.0	27.00	53.5	42.8
Shiloh I	CA	100	150	2754.0	18.36	33.8	
Shiloh II	CA	88	176	2470.5	14.04	20.4	57.9
Solano Wind Project, Phase IIB	CA	66	85	1417.5	16.68		
Cedar Creek Wind Farm	CO	274	300	15390.0	51.30		
Cedar Point Wind Project	CO	150	300	8100.0	27.00		
Colorado Green Wind Project	CO	108	162	4795.2	29.60		
Spring Canyon	CO	87	130	8931.9	68.71	27.9	62.0
Twin Buttes Wind Power Project	CO	50	75	3645.0	48.60		
Buffalo Creek Wind Farm	IA	75	150	4455.0	29.70		
Crystal Lake	IA	180	350	16848.0	48.14		
Endeavor	IA	40	100	1822.5	18.23		
Floyd County Wind Farm Phase I	IA	50	75			5.1	
Hancock County Wind Farm	IA	148	98	7776.0	79.35	24.3	
Intrepid	IA	107	161	4860.0	30.28	21.7	

Pioneer Prairie Wind Farm Phase I	IA	183	302	12150.0	40.24		
Pomeroy Wind Project Phase I	IA	132	198	3321.0	16.77		
Story County	IA	100	150	3477.7	23.18	9.7	
Top of Iowa Wind Farm	IA	89	80	2389.5	29.87	40.5	
Whispering Willow Wind Farm (formerly Franklin County Wind Farm)	IA	250	500	37260.0	74.52		
Cotteral Mountain	ID	130	195	4657.5	23.88	82.2	147.8
Wolverine Creek	ID	43	64	1247.4	19.49		
Camp Grove Wind Farm	IL	100	150	5467.5	36.45		
Crescent Ridge Phase I	IL	33	55	891.0	16.35	8.1	
Grand Ridge Wind Energy Center	IL	66	99	2430.0	24.55	16.2	
Mendota Hills	IL	63	50	1053.0	20.89	12.8	
Providence Heights	IL	36	72	1944.0	27.00	8.1	
Twin Groves/Arrowsmith	IL	240	396	8910.0	22.50	81.0	
Rail Splitter Wind Farm	IL	67	101	4455.0	44.33		
EcoGrove I	IL	67	101	2956.5	29.42		
Fowler Ridge Wind Farm Phase I	IN	222	400	22275.0	55.69		
Orion Energy wind farm / Benton Wind Farm	IN	87	130	3746.3	28.82		
Meadow Lake Wind Farm	IN		200	10530.0	52.65	101.3	
Central Plains Wind Farm	KS	33	99	2430.0	24.55		
Elk River	KS	100	150	3202.3	21.35		
Flat Ridge Wind Farm	KS	40	100	2025.0	20.25		
Gray County Wind Farm	KS	170	112	2430.0	21.70		
Meridian Way Wind Farm	KS	79	201	8100.0	40.30		
Smoky Hills Wind Farm Phase I	KS	56	101	4050.0	40.18	24.3	
Spearville	KS	67	101	2025.0	20.15	27.1	
Smoky Hills Wind Farm Phase II	KS	99	149	5670.0	38.18	85.1	

Allegheny Heights	MD	67	101			16.6	105.3
Mars Hill WInd	ME	28	42	1944.0	46.29	13.2	
Stetson Mountain	ME	38	57	1944.0	34.11	13.4	65.4
Kibby Mountain and Kibby Ridge	ME	44	132	1177.7	8.92	40.5	
Harvest Wind Farm	MI	32	53	1296.0	24.55		
Noble Thumb Wind Park	MI	106	159	10125.0	63.68		
Chanarambie	MN	53	80	2332.8	29.34	9.3	
Elm Creek Wind Farm	MN	66	99	5670.0	57.27	17.8	2.0
Fenton Wind Project	MN	137	206	15552.0	75.68	25.9	166.5
Grand Meadow Wind Farm / Wapsipinicon Wind Project I	MN	137	206	16848.0	81.99	55.5	405.0
Mower County Wind Energy Center	MN	43	99	3942.7	39.87	26.5	188.3
Jeffers Wind Energy Center	MN	32	60	3369.6	56.16	6.5	6.5
Minndakota Wind Farm I	MN	100	150	4466.9	29.78	17.8	3.2
Moraine II	MN	23	48	10931.8	226.33	8.9	1.2
Moraine Wind Power project	MN	34	51	4050.0	79.41		
Prairie Star Wind Farm	MN	61	101	4050.0	40.22	32.8	67.3
Stoneray	MN	70	100	6253.2	62.53	13.0	93.6
Trimont Wind	MN	67	101	9072.0	90.27	16.2	
Bluegrass Ridge Project	MO	27	57	2835.0	50.00		
Conception Wind Farm	MO	24	50	2835.0	56.25		
Cow Branch	MO	24	50	2835.0	56.25		
Judith Gap	MT	90	135	5791.5	42.90		
Valley County Wind Project	MT	114	170	2736.2	16.10	23.9	75.2
Glacier / McCormick Ranch Wind Farm Phase I	MT	60	120	4860.0	40.50		
Langdon Wind Project	ND	106	159	12312.0	77.43		
North Dakota Wind I&2	ND	41	62	1215.0	19.76	10.7	17.7
Tatanka Wind Farm (SD/ND)	ND	120	180	5702.4	31.68	48.6	
Wilton Wind Energy Center	ND	33	50	3240.0	65.45		
Ashtabula Wind Center Phase II	ND	133	200	19958.4	99.79		

Ainsworth Wind Energy Facility	NE	36	59	4455.0	75.00	44.6	
Elkhorn Ridge Wind Energy Project	NE	27	80	3383.8	42.35		
Aragonne Wind LLC	NM	90	90	3888.0	43.20	36.5	
New Mexico Wind Energy Center	NM	136	204	3888.0	19.06		
San Juan Mesa	NM	120	120	1749.6	14.58		
Cohocton Wind Farm	NY	36	90	2308.5	25.65	13.0	196.8
Dairy Hills Wind Farm	NY	60	120	2956.5	24.64	27.5	131.5
Dutch Hill Wind Farm	NY	50	125	2308.5	18.47		
High Sheldon Wind Farm	NY	86	129	2835.0	21.98	19.0	77.8
Jordanville	NY	75	150	2551.5	17.01	24.3	158.4
Maple Ridge Phase I (2005 portion)	NY	195	322	8545.5	26.56	56.7	8.9
Marble River Wind Farm	NY	109	218	7820.6	35.87	54.3	238.3
Noble Altona	NY	68	100	1678.3	16.78	39.3	21.3
Noble Bliss Wind Park	NY	67	101	2053.8	20.44	37.7	26.8
Noble Chateaugay / Noble Bellmont	NY	86	129	3491.1	27.06	18.6	82.2
Noble Clinton Wind Park	NY	67	101	1817.2	18.08	38.8	31.1
Noble Ellenburg	NY	54	81	917.3	11.33	48.6	
Noble Wethersfield	NY	85	128	3706.2	29.07	59.5	
Blue Canyon Wind Power	OK	129	225	6480.0	28.74		
Centennial Wind Farm	OK	80	120			97.2	
OK Wind Energy Center -- A	OK	68	102	486.0	4.76		
Weatherford Wind Energy Center	OK	98	147	2106.0	14.33		
Red Hills Wind Farm	OK	82	123	2025.0	16.46	35.4	
Arlington Wind Farm Phase I	OR	63	104			10.9	33.2

Biglow Canyon Phase I	OR	225	400	10125.0	25.31	71.7	159.3
Cascade Wind Project	OR	40	60	2349.0	39.15	22.9	20.6
Combine Hills 1	OR	105	105	5416.9	51.59	7.3	
Condon Wind Project	OR	83	50	1701.0	34.16	15.4	42.1
Elkhorn Wind Power Project	OR	61	101	4050.0	40.10	60.8	
Klondike II	OR	50	75	1782.0	23.76	178.2	
Klondike III	OR	124	300	7128.0	23.76	30.0	119.5
Leaning Juniper (Arlington)	OR	133	200	3468.8	17.34	26.0	282.9
Shepherd's Flat	OR	303	910	13000.5	14.29	103.1	178.9
Stateline 3	OR	279	184	8100.0	44.02	30.4	139.7
Hay Canyon	OR	48	105			13.8	
Allegheny Ridge Wind Farm I	PA	40	80			16.2	
Allegheny Ridge Wind Farm II	PA	35	70			14.2	
Waymart Wind Farm	PA	47	60	347.5	5.79		
MinnDakota Wind Farm II	SD	36	54	1608.1	29.78	121.5	
South Dakota Wind Energy Center	SD	27	41	1012.5	25.00		
Wessington Springs	SD	66	99	2430.0	24.55		
White Wind Farm	SD	103	200	7257.6	36.29	37.7	253.5
Buffalo Ridge Wind Farm (SD)	SD	204	306	20032.5	65.47		
Brazos Wind Ranch	TX	160	160	7776.0	48.60		
Callahan Divide	TX	76	114	2430.0	21.32		
Champion Wind Farm	TX	55	127	5670.0	44.82		
Desert Sky	TX	107	161	3888.0	24.22		
Elbow Creek Wind Project	TX	53	122	2713.5	22.26		
Forest Creek Wind Project	TX	54	124	6075.0	48.91		
Goat Mountain Wind Ranch	TX	109	150	4252.5	28.35		
Horse Hollow Wind Energy Center	TX	419	733	19035.0	25.99		
King Mountain (I&II)	TX	214	278	6075.0	21.84		

Llano Estacado Wind Ranch at White Deer	TX	80	80	2332.8	29.16		
Lone Star Phase I (was Cross Timbers or Mesquite)	TX	200	400	8100.0	20.25		
Lone Star Phase II (Post Oak)	TX	100	200	15460.9	77.30		
Peñascal Wind Farm	TX	87	202	6075.0	30.07	121.5	
Red Canyon Wind Energy	TX	56	84	3847.5	45.80		
Roscoe Wind Farm	TX	627	782	28350.0	36.28		
Sherbino I Wind Farm	TX	50	150	4050.0	27.00		
Silver Star I Wind Farm	TX	24	60	3057.8	50.96		
Stanton Wind Farm	TX	80	120	6885.0	57.38		
Sweetwater Phase IV (Mitsubishi portion)	TX	135	135	4860.0	36.00		
Sweetwater Phase IV (Siemens portion)	TX	46	106	4860.0	45.94		
Trent Mesa	TX	100	150	3628.8	24.19		
Wildorado Wind Ranch	TX	70	161	6480.0	40.25		
Woodward Mountain I & II	TX	242	160	3785.1	23.66		
Bull Creek Wind Farm	TX	180	180	24300.0	135.00		
Panther Creek Wind Farm	TX	111	167	9315.0	55.95		
Wolf Ridge Wind Farm	TX	75	113	4131.0	36.72		
Ocotillo	TX	28	59	1012.5	17.22		
Gulf Winds Project	TX	118	283	3179.7	11.23		
Milford Wind Corridor Project Phase I	UT	159	300	10368.0	34.56	124.7	594.5
Big Horn	WA	133	200	8541.5	42.81	34.0	95.6
Desert Claim	WA	120	180	2121.0	11.78	33.4	141.1
Goodnoe Hills	WA	47	94	1741.5	18.53	28.4	

Hopkins Ridge Wind Project	WA	83	150	4455.0	29.70	66.8	87.9
Kittitas Valley Wind Power Project	WA	121	182	2835.0	15.62	37.7	126.0
Maiden Wind Farm	WA	330	494	5265.0	10.66	101.7	430.5
Marengo Phase I	WA	78	140	5390.6	38.39		
Nine Canyon I and II	WA	49	64	2073.6	32.55	19.8	
Stateline 1&2 Combined	WA	454	300			65.6	89.1
White Creek Wind I	WA	89	205	3847.5	18.77	25.9	34.8
Wild Horse Wind Power Project	WA	136	204	3483.0	17.07	66.7	
Windy Point Phase I	WA	97	250	6031.7	24.13	62.4	126.4
Marengo Phase II	WA	39	70	1741.5	24.81		
Blue Sky Green Field	WI	88	203	4293.0	21.20	28.4	100.0
Cedar Ridge Wind Farm	WI	41	68	3175.2	46.94	34.4	164.0
Forward Wind Energy Center	WI	133	200	13122.0	65.61	28.4	65.6
Beech Ridge Wind Farm	WV	124	186	810.0	4.35	121.5	
Mountaineer Wind II	WV	44	66	1782.0	27.00	79.4	298.1
Mt. Storm Phase I	WV	200	300	3240.0	10.80	97.2	
Foote Creek 1	WY	69	41	846.5	20.45	10.8	
Glenrock Wind Energy Project	WY	66	99	5670.0	57.27		
Seven Mile Hill/Campbell Hill Wind Project	WY	66	99	4050.0	40.91		

Table A2. Configuration, Land Cover, Status, and Data Source

Name	State	Configuration	Primary Land Type	%	Secondary Land Type	%	Development Status	Source Type
Steel Park Wind Farm	AZ	parallel strings	Shrubland	73%	Evergreen forest	20%	Proposed	Developer
Dry Lake Wind Project I	AZ	parallel strings	Shrubland	88%	Grasslands/ herbaceous	8%	Under Const	Third Party
Bear River Wind Power Project	CA	single string	Grasslands/ herbaceous	100%			Proposed	Application
Hatchet Ridge Wind Project	CA	single string	Evergreen forest	92%	Shrubland	8%	Proposed	Application
High Winds I & II	CA	multiple strings	Shrubland	55%	Grasslands/ herbaceous	45%	Completed	Developer
Mountain View IV	CA	parallel strings	Shrubland	100%			Proposed	Application
Pine Tree Wind Project aka Wind Turbine Prometheus	CA	multiple strings	Grasslands/ herbaceous	69%	Shrubland	28%	Under Const	Application
Shiloh I	CA	multiple strings	Grasslands/ herbaceous	64%	Pasture/hay	36%	Completed	Developer
Shiloh II	CA	multiple strings	Pasture/hay	51%	Grasslands/ herbaceous	49%	Completed	Application
Solano Wind Project, Phase IIB	CA	multiple strings	Pasture/hay	98%	Grasslands/ herbaceous	2%	Completed	Application
Cedar Creek Wind Farm	CO	parallel strings	Grasslands/ herbaceous	76%	Fallow	12%	Completed	Developer
Cedar Point Wind Project	CO	parallel strings	Grasslands/ herbaceous	44%	Small grains	29%	Under Const	Developer
Colorado Green Wind Project	CO	parallel strings	Grasslands/ herbaceous	92%	Small grains	8%	Completed	Developer
Spring Canyon	CO	single string	Grasslands/ herbaceous	78%	Fallow	20%	Completed	Application
Twin Buttes Wind Power Project	CO	parallel strings	Grasslands/ herbaceous	98%	Small grains	2%	Completed	Developer
Buffalo Creek Wind Farm	IA	parallel strings	Row crops	88%	Grasslands/ herbaceous	10%	Proposed	Third Party
Crystal Lake	IA	parallel strings	Row crops	93%	Pasture/hay	7%	Completed	Application
Endeavor	IA	multiple strings	Row crops	86%	Pasture/hay	9%	Completed	Developer
Floyd County Wind Farm Phase I	IA	parallel strings	Row crops	98%	Grasslands/ herbaceous	2%	Completed	Third Party
Hancock County Wind Farm	IA	cluster	Row crops	91%	Grasslands/ herbaceous	3%	Completed	Developer
Intrepid	IA	multiple strings	Row crops	92%	Pasture/hay	6%	Completed	Developer
Pioneer Prairie Wind Farm Phase I	IA	parallel strings	Row crops	94%	Grasslands/ herbaceous	2%	Completed	Third Party
Pomeroy Wind Project Phase I	IA	cluster	Row crops	94%	Grasslands/ herbaceous	2%	Completed	Developer

Story County	IA	parallel strings	Row crops	97%	Grasslands/ herbaceous	3%	Completed	Application
Top of Iowa Wind Farm	IA	parallel strings	Row crops	85%	Grasslands/ herbaceous	11%	Completed	Application
Whispering Willow Wind Farm (formerly Franklin County Wind Farm)	IA	cluster	Row crops	95%	Pasture/hay	2%	Under Const	Developer
Cotteral Mountain	ID	single string	Shrubland	100%			Proposed	Application
Wolverine Creek	ID	cluster	Pasture/hay	44%	Shrubland	33%	Completed	Developer
Camp Grove Wind Farm	IL	cluster	Row crops	99%	Pasture/hay	1%	Completed	Developer
Crescent Ridge Phase I	IL	cluster	Row crops	91%	Pasture/hay	9%	Completed	Third Party
Grand Ridge Wind Energy Center	IL	cluster	Row crops	91%	Pasture/hay	9%	Completed	Third Party
Mendota Hills	IL	cluster	Row crops	89%	Pasture/hay	10%	Completed	Third Party
Providence Heights	IL	cluster	Row crops	98%	Deciduous forest	2%	Completed	Developer
Twin Groves/Arrowsmith	IL	cluster	Row crops	100%			Completed	Developer
Rail Splitter Wind Farm	IL	cluster	Row crops	88%	Pasture/hay	8%	Under Const	Third Party
EcoGrove I	IL	parallel strings	Row crops	83%	Pasture/hay	15%	Under Const	Third Party
Fowler Ridge Wind Farm Phase I	IN	cluster	Row crops	95%	Pasture/hay	4%	Completed	Developer
Orion Energy wind farm / Benton Wind Farm	IN	cluster	Row crops	79%	Pasture/hay	15%	Completed	Developer
Meadow Lake Wind Farm	IN	parallel strings	Row crops	82%	Pasture/hay	17%	Under Const	Developer
Central Plains Wind Farm	KS	parallel strings	Small grains	48%	Grasslands/ herbaceous	33%	Completed	Developer
Elk River	KS	parallel strings	Grasslands/ herbaceous	79%	Pasture/hay	14%	Completed	Developer
Flat Ridge Wind Farm	KS	parallel strings	Small grains	52%	Grasslands/ herbaceous	32%	Completed	Developer
Gray County Wind Farm	KS	parallel strings	Small grains	64%	Grasslands/ herbaceous	30%	Completed	Developer
Meridian Way Wind Farm	KS	cluster	Grasslands/ herbaceous	71%	Small grains	15%	Completed	Third Party
Smoky Hills Wind Farm Phase I	KS	cluster	Grasslands/ herbaceous	88%	Pasture/hay	5%	Completed	Developer
Spearville	KS	parallel strings	Small grains	60%	Grasslands/ herbaceous	28%	Completed	Third Party
Smoky Hills Wind Farm Phase II	KS	multiple strings	grasslands/ herbaceous	81%	Pasture/hay	7%	Completed	Developer
Allegheny Heights	MD	single string	Deciduous forest	100%			Proposed	Application

Mars Hill WInd	ME	single string	Deciduous forest	83%	Mixed forest	17%	Completed	Application
Stetson Mountain	ME	single string	Deciduous forest	92%	Mixed forest	8%	Completed	Application
Kibby Mountain and Kibby Ridge	ME	multiple strings	Evergreen forest	57%	Mixed forest	32%	Under Const	Third Party
Harvest Wind Farm	MI	cluster	Row crops	97%	Pasture/hay	3%	Completed	Third Party
Noble Thumb Wind Park	MI	cluster	Row crops	90%	Deciduous forest	4%	Completed	Developer
Chanarambie	MN	cluster	Row crops	91%	Pasture/hay	9%	Completed	Application
Elm Creek Wind Farm	MN	parallel strings	Row crops	100%			Completed	Application
Fenton Wind Project	MN	cluster	Row crops	88%	Pasture/hay	10%	Completed	Application
Grand Meadow Wind Farm / Wapsipinicon Wind Project I	MN	cluster	Row crops	97%	Pasture/hay	2%	Completed	Application
Mower County Wind Energy Center	MN	multiple strings	Row crops	97%	Pasture/hay	3%	Completed	Application
Jeffers Wind Energy Center	MN	cluster	Row crops	90%	Pasture/hay	10%	Completed	Application
Minndakota Wind Farm I	MN	cluster	Row crops	79%	Pasture/hay	19%	Completed	Application
Moraine II	MN	multiple strings	Row crops	79%	Pasture/hay	21%	Proposed	Application
Moraine Wind Power project	MN	parallel strings	Row crops	56%	Pasture/hay	44%	Completed	Third Party
Prairie Star Wind Farm	MN	cluster	Row crops	97%	Pasture/hay	3%	Completed	Application
Stoneray	MN	cluster	Row crops	91%	Pasture/hay	9%	Proposed	Application
Trimont Wind	MN	cluster	Row crops	95%	Pasture/hay	3%	Completed	Application
Bluegrass Ridge Project	MO	cluster	Row crops	48%	Pasture/hay	40%	Completed	Third Party
Conception Wind Farm	MO	cluster	Pasture/hay	50%	Row crops	32%	Completed	Developer
Cow Branch	MO	cluster	Row crops	79%	Pasture/hay	21%	Completed	Developer
Judith Gap	MT	multiple strings	Grasslands/ herbaceous	43%	Grasslands/ herbaceous	33%	Completed	Third Party
Valley County Wind Project	MT	multiple strings	Shrubland	100%			Proposed	Application
Glacier / McCormick Ranch Wind Farm Phase I	MT	parallel strings	Small grains	47%	Fallow	41%	Completed	Third Party
Langdon Wind Project	ND	multiple strings	Row crops	69%	Small grains	21%	Completed	Unverified
North Dakota Wind I&2	ND	cluster	Row crops	100%			Completed	Application
Tatanka Wind Farm (SD/ND)	ND	parallel strings	Grasslands/ herbaceous	88%	Row crops	7%	Completed	Developer
Wilton Wind Energy Center	ND	parallel strings	Row crops	82%	Grasslands/ herbaceous	15%	Completed	Developer

Ashtabula Wind Center Phase II	ND	parallel strings	Row crops	82%	Pasture/hay	9%	Completed	Third Party
Ainsworth Wind Energy Facility	NE	parallel strings	Grasslands/ herbaceous	97%	Emergent herbaceous wetlands	3%	Completed	Developer
Elkhorn Ridge Wind Energy Project	NE	multiple strings	Row crops	78%	Pasture/hay	22%	Completed	Third Party
Aragonne Wind LLC	NM	parallel strings	Grasslands/ herbaceous	94%	Shrubland	5%	Completed	Developer
New Mexico Wind Energy Center	NM	multiple strings	Grasslands/ herbaceous	100%			Completed	Developer
San Juan Mesa	NM	parallel strings	Grasslands/ herbaceous	91%	Shrubland	9%	Completed	Developer
Cohocton Wind Farm	NY	cluster	Pasture/hay	37%	Row crops	27%	Completed	Application
Dairy Hills Wind Farm	NY	cluster	Row crops	100%			Proposed	Application
Dutch Hill Wind Farm	NY	cluster	Pasture/hay	35%	Row crops	33%	Completed	Third Party
High Sheldon Wind Farm	NY	multiple strings	Pasture/hay	51%	Mixed forest	25%	Proposed	Application
Jordanville	NY	cluster	Pasture/hay	53%	Deciduous forest	27%	Proposed	Application
Maple Ridge Phase I (2005 portion)	NY	cluster	Pasture/hay	47%	Deciduous forest	39%	Completed	Application
Marble River Wind Farm	NY	cluster	Deciduous forest	39%	Pasture/hay	28%	Proposed	Application
Noble Altona	NY	cluster	Deciduous forest	82%	Row crops	4%	Completed	Application
Noble Bliss Wind Park	NY	cluster	Pasture/hay	38%	Mixed forest	30%	Completed	Application
Noble Chateaugay / Noble Bellmont	NY	cluster	Pasture/hay	47%	Deciduous forest	38%	Completed	Application
Noble Clinton Wind Park	NY	cluster	Pasture/hay	38%	Pasture/hay	38%	Completed	Application
Noble Ellenburg	NY	cluster	Pasture/hay	46%	Deciduous forest	28%	Completed	Developer
Noble Wethersfield	NY	cluster	Pasture/hay	51%	Mixed forest	24%	Completed	Application
Blue Canyon Wind Power	OK	single string	Grasslands/ herbaceous	87%	Shrubland	11%	Completed	Developer
Centennial Wind Farm	OK	parallel strings	Grasslands/ herbaceous	86%	Shrubland	12%	Completed	Third Party
OK Wind Energy Center -- A	OK	parallel strings	Grasslands/ herbaceous	100%			Completed	Developer
Weatherford Wind Energy Center	OK	multiple strings	Small grains	80%	Pasture/hay	8%	Completed	Developer
Red Hills Wind Farm	OK	parallel strings	grasslands/ herbaceous	84%	Shrubland	14%	Completed	Third Party

Arlington Wind Farm Phase I	OR	multiple strings	Shrubland	51%	Grasslands/ herbaceous	28%	Completed	Application
Biglow Canyon Phase I	OR	multiple strings	Small grains	52%	Fallow	40%	Completed	Application
Cascade Wind Project	OR	multiple strings	Deciduous forest	100%			Proposed	Application
Combine Hills 1	OR	multiple strings	Shrubland	100%			Completed	Third Party
Condon Wind Project	OR	multiple strings	Small grains	55%	Shrubland	27%	Completed	Application
Elkhorn Wind Power Project	OR	parallel strings	Shrubland	95%	Grasslands/ herbaceous	5%	Completed	Developer
Klondike II	OR	parallel strings	Small grains	65%	Fallow	35%	Completed	Developer
Klondike III	OR	parallel strings	Small grains	49%	Small grains	39%	Completed	Application
Leaning Juniper (Arlington)	OR	parallel strings	Shrubland	44%	Fallow	27%	Completed	Application
Shepherd's Flat	OR	multiple strings	Shrubland	54%	Grasslands/ herbaceous	31%	Proposed	Application
Stateline 3	OR	parallel strings	Shrubland	66%	Fallow	16%	Completed	Application
Hay Canyon	OR	multiple strings	Small grains	33%	Fallow	33%	Completed	Application
Allegheny Ridge Wind Farm I	PA	cluster	Deciduous forest	83%	Mixed forest	18%	Completed	Developer
Allegheny Ridge Wind Farm II	PA	multiple strings	Deciduous forest	54%	Mixed forest	40%	Proposed	Developer
Waymart Wind Farm	PA	single string	Deciduous forest	88%	Mixed forest	12%	Completed	Third Party
MinnDakota Wind Farm II	SD	cluster	Row crops	81%	Pasture/hay	19%	Completed	Developer
South Dakota Wind Energy Center	SD	multiple strings	Grasslands/ herbaceous	70%	Small grains	11%	Completed	Developer
Wessington Springs	SD	parallel strings	Grasslands/ herbaceous	63%	Pasture/hay	31%	Under Const	Developer
White Wind Farm	SD	cluster	Row crops	52%	Pasture/hay	48%	Proposed	Application
Buffalo Ridge Wind Farm (SD)	SD	parallel strings	Row crops	67%	Pasture/hay	31%	Under Const	Application
Brazos Wind Ranch	TX	parallel strings	Row crops	42%	Grasslands/ herbaceous	38%	Completed	Developer
Callahan Divide	TX	multiple strings	Evergreen forest	38%	Shrubland	30%	Completed	Developer
Champion Wind Farm	TX	parallel strings	Row crops	78%	Shrubland	7%	Completed	Developer
Desert Sky	TX	multiple strings	Shrubland	89%	Grasslands/ herbaceous	11%	Completed	Third Party
Elbow Creek Wind Project	TX	cluster	Shrubland	81%	Grasslands/ herbaceous	17%	Completed	Developer
Forest Creek Wind Project	TX	parallel strings	Shrubland	89%	Grasslands/ herbaceous	11%	Completed	Third Party
Goat Mountain Wind Ranch	TX	parallel strings	Shrubland	100%			Completed	Third Party

Horse Hollow Wind Energy Center	TX	parallel strings	Shrubland	78%	Evergreen forest	10%	Completed	Developer
King Mountain (I&II)	TX	parallel strings	Grasslands/ herbaceous	51%	Shrubland	46%	Completed	Developer
Llano Estacado Wind Ranch at White Deer	TX	parallel strings	Row crops	48%	Small grains	25%	Completed	Developer
Lone Star Phase I (was Cross Timbers or Mesquite)	TX	cluster	Grasslands/ herbaceous	74%	Shrubland	18%	Completed	Developer
Lone Star Phase II (Post Oak)	TX	cluster	Grasslands/ herbaceous	74%	Shrubland	18%	Completed	Developer
Peñascal Wind Farm	TX	Parallel Strings	Grasslands/ herbaceous	88%	Shrubland	7%	Under Const	Third Party
Red Canyon Wind Energy	TX	cluster	Row crops	42%	Grasslands/ herbaceous	38%	Completed	Developer
Roscoe Wind Farm	TX	parallel strings	Row crops	85%	Shrubland	5%	Completed	Developer
Sherbino I Wind Farm	TX	parallel strings	Shrubland	82%	Grasslands/ herbaceous	18%	Completed	Developer
Silver Star I Wind Farm	TX	parallel strings	Grasslands/ herbaceous	45%	Shrubland	31%	Completed	Developer
Stanton Wind Farm	TX	multiple strings	Shrubland	59%	Grasslands/ herbaceous	21%	Completed	Developer
Sweetwater Phase IV (Mitsubishi portion)	TX	parallel strings	Shrubland	90%	Evergreen forest	7%	Completed	Developer
Sweetwater Phase IV (Siemens portion)	TX	parallel strings	Shrubland	80%	Grasslands/ herbaceous	20%	Completed	Developer
Trent Mesa	TX	parallel strings	Shrubland	52%	Grasslands/ herbaceous	33%	Completed	Developer
Wildorado Wind Ranch	TX	parallel strings	Grasslands/ herbaceous	79%	Shrubland	17%	Completed	Third Party
Woodward Mountain I & II	TX	multiple strings	Shrubland	100%			Completed	Developer
Bull Creek Wind Farm	TX	parallel strings	grasslands/ herbaceous	80%	Shrubland	17%	Completed	Third Party
Panther Creek Wind Farm	TX	multiple strings	Shrubland	88%	Grasslands/ herbaceous	12%	Completed	Third Party
Wolf Ridge Wind Farm	TX	cluster	grasslands/ herbaceous	41%	Pasture/hay	31%	Completed	Third Party
Ocotillo	TX	multiple strings	Shrubland	89%	Grasslands/ herbaceous	11%	Completed	Developer
Gulf Winds Project	TX	parallel strings	grasslands/ herbaceous	70%	Shrubland	13%	Under Const	Third Party
Milford Wind Corridor Project Phase I	UT	parallel strings	Shrubland	68%	Grasslands/ herbaceous	21%	Under Const	Application
Big Horn	WA	parallel strings	Shrubland	62%	Grasslands/ herbaceous	19%	Completed	Application

Desert Claim	WA	cluster	Small grains	100%			Proposed	Application
Goodnoe Hills	WA	cluster	Shrubland	55%	Grasslands/ herbaceous	19%	Completed	Application
Hopkins Ridge Wind Project	WA	parallel strings	Shrubland	100%			Completed	Application
Kittitas Valley Wind Power Project	WA	parallel strings	Shrubland	100%			Proposed	Application
Maiden Wind Farm	WA	parallel strings	Shrubland	100%			Proposed	Application
Marengo Phase I	WA	multiple strings	Small grains	51%	Grasslands/ herbaceous	27%	Completed	Third Party
Nine Canyon I and II	WA	parallel strings	Small grains	50%	Small grains	42%	Completed	Developer
Stateline 1&2 Combined	WA	parallel strings	Shrubland	66%	Fallow	16%	Completed	Application
White Creek Wind I	WA	multiple strings	Shrubland	76%	Small grains	13%	Completed	Developer
Wild Horse Wind Power Project	WA	parallel strings	Shrubland	100%			Completed	Application
Windy Point Phase I	WA	multiple strings	Shrubland	49%	Grasslands/ herbaceous	34%	Completed	Application
Marengo Phase II	WA	multiple strings	Small grains	95%	Fallow	5%	Completed	Third Party
Blue Sky Green Field	WI	cluster	Row crops	56%	Pasture/hay	33%	Completed	Application
Cedar Ridge Wind Farm	WI	cluster	Pasture/hay	51%	Row crops	40%	Completed	Application
Forward Wind Energy Center	WI	cluster	Pasture/hay	52%	Row crops	43%	Completed	Application
Beech Ridge Wind Farm	WV	multiple strings	Deciduous forest	95%	Quarries/str ip mines/grav el pits	4%	Under Const	Developer
Mountaineer Wind II	WV	single string	Mixed forest	36%	Deciduous forest	27%	Completed	Application
Mt. Storm Phase I	WV	parallel strings	Deciduous forest	80%	Mixed forest	11%	Completed	Developer
Foote Creek 1	WY	parallel strings	Grasslands/ herbaceous	92%	Shrubland	8%	Completed	Application
Glenrock Wind Energy Project	WY	multiple strings	Shrubland	77%	Grasslands/ herbaceous	23%	Completed	Third Party
Seven Mile Hill/Campbell Hill Wind Project	WY	Parallel Strings	Shrubland	87%	Grasslands/ herbaceous	13%	Completed	Third Party

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
August 2009

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Land-Use Requirements of Modern Wind Power Plants in the United States

5a. CONTRACT NUMBER
DE-AC36-08-GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
P. Denholm; M. Hand; M. Jackson; and S. Ong

5d. PROJECT NUMBER
NREL/TP-6A2-45834

5e. TASK NUMBER
WER9.3550

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-6A2-45834

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This report provides data and analysis of the land use associated with modern, large wind power plants (defined as greater than 20 megawatts (MW) and constructed after 2000). The analysis discusses standard land-use metrics as established in the life-cycle assessment literature, and then discusses their applicability to wind power plants. The report identifies two major “classes” of wind plant land use: 1) direct impact (i.e., disturbed land due to physical infrastructure development), and 2) total area (i.e., land associated with the complete wind plant project). The analysis also provides data for each of these classes, derived from project applications, environmental impact statements, and other sources. It attempts to identify relationships among land use, wind plant configuration, and geography. The analysts evaluated 172 existing or proposed projects, which represents more than 26 GW of capacity. In addition to providing land-use data and summary statistics, they identify several limitations to the existing wind project area data sets, and suggest additional analysis that could aid in evaluating actual land use and impacts associated with deployment of wind energy.

15. SUBJECT TERMS
NREL; life-cycle assessment; wind power; wind energy; wind power plants; land use; wind capacity; wind project; United States; land impact; Paul Denhom; Maureen Hand; Maddalena Jackson; Sean Ong

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		
					19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(10/2008)