Appendix F

Shadow Flicker Analysis Report

Badger Wind, LLC
February 2022

BADGER WIND FARM

Shadow Flicker Analysis Report

Badger Wind, LLC

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Task and objective:
This report presents the results of a shadow flicker analysis conducted by DNV on behalf of Badger Wind, LLC.

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EXECUTIVE SUMMARY

DNV Energy USA Inc. (“DNV”) has conducted an analysis to predict the duration of shadow flicker expected to be experienced at receptors near the Badger Wind Farm (the “Project”). The site is located in Logan County and McIntosh County, North Dakota. At the request of Badger Wind, LLC (“the “Customer”), this analysis includes a total of 79 wind turbine generators (WTGs), of which 74 will ultimately be constructed. There are no neighboring wind farms or solar farms near the Project.

There were 40 receptors, representing inhabited residences, identified within 5,512 feet (1,680 m) of a Project turbine, which is the equivalent of ten tip heights of the WTG.

Receptor 39 is predicted to experience the most shadow flicker per year (expected case), with a total of 38 hours. This is a participating receptor.

There are certain simplifications and conservative assumptions inherent within the model that may result in an overestimation of shadow flicker duration. These are further explained in the report.

1 INTRODUCTION

Badger Wind, LLC (the “Customer”) retained DNV Energy USA Inc. (“DNV”) to perform a shadow flicker assessment for the Badger Wind Farm (the “Project”) located in Logan County and McIntosh County, North Dakota.

The Project layout considered for the analysis includes 79 GE3.4-140 wind turbine generators with a hub height of 322 ft (98 m). The turbine layout was provided by the Customer [1]. Only 74 of the 79 turbines in this analysis are planned to be constructed.

The GE3.4-140 has a maximum blade tip height of 551 feet (168 m), a hub height of 322 feet (98 m), and a rotor diameter of 459 feet (140 m).

The purpose of this shadow flicker assessment is to calculate the predicted shadow flicker duration for the proposed Project at nearby receptor locations. This report includes a brief presentation of the Project site, a description of the shadow flicker assessment methodology, results of the analysis including a map illustrating areas prone to shadow flicker and concluding comments. This report presents the results of DNV’s analysis.

1.1 Shadow flicker definition

Shadow flicker is defined as the modulation of light levels resulting from the periodic passage of a rotating wind turbine blade between the sun and a viewer. The duration of shadow flicker experienced at a specific location can be determined using a purely geometric analysis which takes into account the relative positions of the sun throughout the year, the wind turbines at the site, and the viewer. This method has been used to determine the shadow flicker duration at sensitive locations in the vicinity of the Project.

It should be noted, as described in Section 3, that there are certain simplifications and conservative assumptions inherent within the model that may result in an overestimation of shadow flicker duration.

2 DESCRIPTION OF THE WIND FARM SITE

2.1 Site description

The Project is situated in relatively simple terrain, consisting of flat farmland, with wind turbine base elevations ranging from approximately 2,000 feet to 2,200 feet above sea level. The ground cover on and near the site is primarily composed of farmland and open fields. Dwellings are interspersed throughout the Project site.

The site is in Logan County and McIntosh County, west of the town of Lehr, North Dakota.

2.2 Wind farm layout and turbine model

The current Project layout consists of 79 GE3.4-140 WTGs. Ultimately, 74 of these turbines will be constructed. The turbine layout was provided by the Customer [1].

The GE3.4-140 has a maximum blade tip height of 551 feet (168 m), a hub height of 322 feet (98 m), and a rotor diameter of 459 feet (140 m).

The coordinates of the Project equipment included in the assessment are presented in Appendix A.

2.3 Neighboring wind farms

There are no neighboring wind farms in the vicinity of the Project.

2.4 Receptor locations

A list of 348 receptors was provided by the Customer [4], most of which were clustered in a nearby town of Wishek over 1 mile from the nearest turbine. Of the total number of identified receptors, results for 40 receptors, representing inhabited residence, located within the affected study area defined in Section 3.2 are reported. Coordinates of each receptor are presented in Appendix B.

2.5 Applicable regulations

No applicable shadow flicker regulations were identified at the state and county level when the report was issued.

3 SHADOW FLICKER ASSESSMENT

3.1 Overview

Shadow flicker may occur under certain combinations of circumstances with regard to the sun's position and wind direction; when the sun passes behind the rotating blades of a wind turbine, a moving shadow is cast in front of or behind the turbine. When viewed from a stationary position, the moving shadows cause periodic flickering of the sunlight, otherwise known as the "shadow flicker" phenomenon.

The effect is most noticeable inside buildings, where the flicker appears through a window opening. The likelihood and duration of the effect depends on a number of variables, namely:

- Orientation of the building relative to the turbine;
- Wind direction: The shape and intensity of the shadow are determined by the position of the sun relative to the blades (the turbine rotor continuously yaws to face the wind so the rotor plane will always be perpendicular to the wind direction);
- Distance from turbine: The farther the observer from the turbine, the less pronounced the effect;
- Turbine height and rotor diameter: A larger turbine rotor diameter will cast a larger shadow, meaning a larger area will be prone to incidences of shadow flicker;
- Time of year and day: Position of sun relative to the horizon;
- Weather conditions: Cloud cover reduces the occurrence of shadow flicker;
- Vegetation and other obstacles that help to mask shadows;
- Operational status of turbines.

3.2 Assessment methodology

The number of hours of shadow flicker experienced annually at a given location can be calculated using a geometrical model which takes into account the sun's position, topography of the wind farm site, and wind turbine specifications such as rotor diameter and hub height.

Shadow flicker has been calculated at the subject receptors (i.e. residences) at a height of 6.5 feet (2 m) to represent ground floor windows. Rather than facing a particular direction, shadow flicker receptors (windows) are simulated as horizontal planes, meaning they experience shadow flicker over 360°, often referenced as the "greenhouse" scenario; this assumption therefore represents a worst-case scenario. Simulations with WindFarmer Analyst software have been carried out with a resolution of 1 minute; if shadow flicker occurs in any 1-minute period, the model registers this as 1 minute of shadow flicker.

It is generally accepted that shadow flicker from wind turbines does not occur beyond a distance, D, from a given wind turbine. The UK wind industry considers this distance to be equivalent to 10 rotor diameters [2], while the Danish wind industry suggests a value of between 1,640 feet and 3,281 feet (500 m and 1,000 m) [3]. DNV has adopted a conservative approach and has assumed the length, D, that a shadow can be cast to be defined as follows:

D = 10 x (hub height + rotor radius)

Beyond this distance, a viewer does not perceive the turbine blade to be chopping the light, but rather as an object passing in front of the sun.

In the case of this Project, 10 x (hub height + rotor radius) is equal to 5,512 feet (1,680 m).

The annual hours of shadow flicker at receptors have been calculated using an “expected case” approach.

An “expected case” considers cloud cover and the site-specific wind rose in order to get a more realistic shadow flicker estimate, as described below. It is noted that additional attenuation factors are still not considered (see Section 3.4), and therefore, the “expected case” is still conservative.

3.3 Attenuations

Shadow flicker calculations can be adjusted using average monthly cloud coverage, which is based on historical meteorological data and statistics. According to data gathered from the Bismarck, ND, and Aberdeen, SD, National Oceanic and Atmospheric Administration (NOAA) stations, monthly cloud cover can be estimated and applied as a percentage decrease in flicker duration. Cloud cover percentages are shown in Table 3-1.

Table 3-1 Monthly cloud cover percentage (%) reduction

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percentage	64.1	64.9	68.0	65.0	61.3	55.9	43.5	43.5	50.8	56.5	69.2	66.1

The annual site-specific wind direction distribution was used in order to consider the probability of the turbines being oriented in a given direction. This produces a more accurate estimate of shadow flicker duration at receptors. The directional wind frequency that was measured on site [5] is shown in Table 3-2.

Table 3-2 Site specific directional frequencies (%) (Mast ID: M2000)

Sector (°)	0	30	60	90	120	150	180	210	240	270	300	330
Percentage	9.6	6.4	5.1	5.1	6.7	10.4	10.2	6.2	7.7	8.6	11.0	12.9

Note: The sectors are defined as 30° sectors centered at the given value.

No attempt has been made to account for vegetation or other shielding effects around each shadow receptor in the calculations of shadow flicker duration. Similarly, turbine operational shut-down has not been considered in this analysis. Consideration of these factors could lead to a reduction of the levels of shadow flicker predicted.

3.4 Simplifications and conservative assumptions

Shadow flicker duration calculated in the manner described above has several limitations and may over-estimate the annual number of hours of shadow flicker experienced at a specified location for several reasons, namely:

- The modeling of the wind turbine blades as discs rather than individual blades results in an overestimate of shadow flicker duration.
- Turbine blades are of non-uniform thickness with the thickest part of the blade (maximum chord) close to the hub and the thinnest part (minimum chord) at the tip. Diffusion of sunlight, as discussed above, results in a limit to the maximum distance that a shadow can be perceived. This maximum distance will also be dependent on the thickness of the turbine blade and the human threshold for perception of light intensity variation. As such, a shadow cast by the blade tip will be shorter than the shadow cast by the thickest part of the blade [6]. These distinctions are not modeled and shadow cast from any part of the blade is considered a shadow flicker event.
- Additionally, the orientation of windows on a given residence has not been taken into account, i.e. the model assumes that a window is always facing the turbine(s).
- Aerosols (moisture, dust, smoke, etc.) in the atmosphere have the ability to influence shadows cast by a wind turbine. The length of the shadow cast by a wind turbine is dependent on the degree that direct sunlight is diffused, which in turn is dependent on the amount of dispersants (humidity, smoke and other aerosols) in the path between the light source (sun) and the receiver [6]. The model does not consider any such factors.
- The presence of vegetation or other physical barriers around a receptor location may shield the view of the wind turbine, and therefore reduce the incidence of shadow flicker. No physical barriers have been modeled.
- Periods where Project wind turbines are not in operation due to low winds, high winds, or for operational and maintenance reasons will also reduce shadow flicker occurrence but are not considered herein.

In light of the reasons listed above, it is likely that the shadow flicker durations presented in Appendix B can be regarded as conservative.

4 RESULTS AND CONCLUSION

The results of the shadow flicker assessment (in terms of expected total hours per year) are presented in tabular format in Appendix B for all receptor locations in the study area.

Results for the “expected case” in hours per year take into account the average monthly cloud cover from two NOAA meteorological stations at Bismarck, ND, and Aberdeen, SD. The annual site specific wind directional frequencies were gathered from a meteorological mast deployed on site [5].

A detailed map illustrating predicted “expected case” shadow flicker duration at receptors lying within 5,512 feet (1,680 m) of the Badger Wind Farm are presented in Figure 4-1. The map takes into account average monthly cloud cover and annual wind direction distribution. Shadow flicker is shown in isopleths of 30 hours per year or more.

Receptor 39 is predicted to experience the most shadow flicker per year (expected case), with a total of 38. This is a participating receptor.

As described in Section 3, certain conservative assumptions have been made in this analysis, which likely results in an overestimation of the shadow flicker impacts that may be experienced at each receptor. Additionally, only 74 of the 79 turbines included in this analysis will be built. Results may be overestimated in areas where turbines may not end up being constructed.

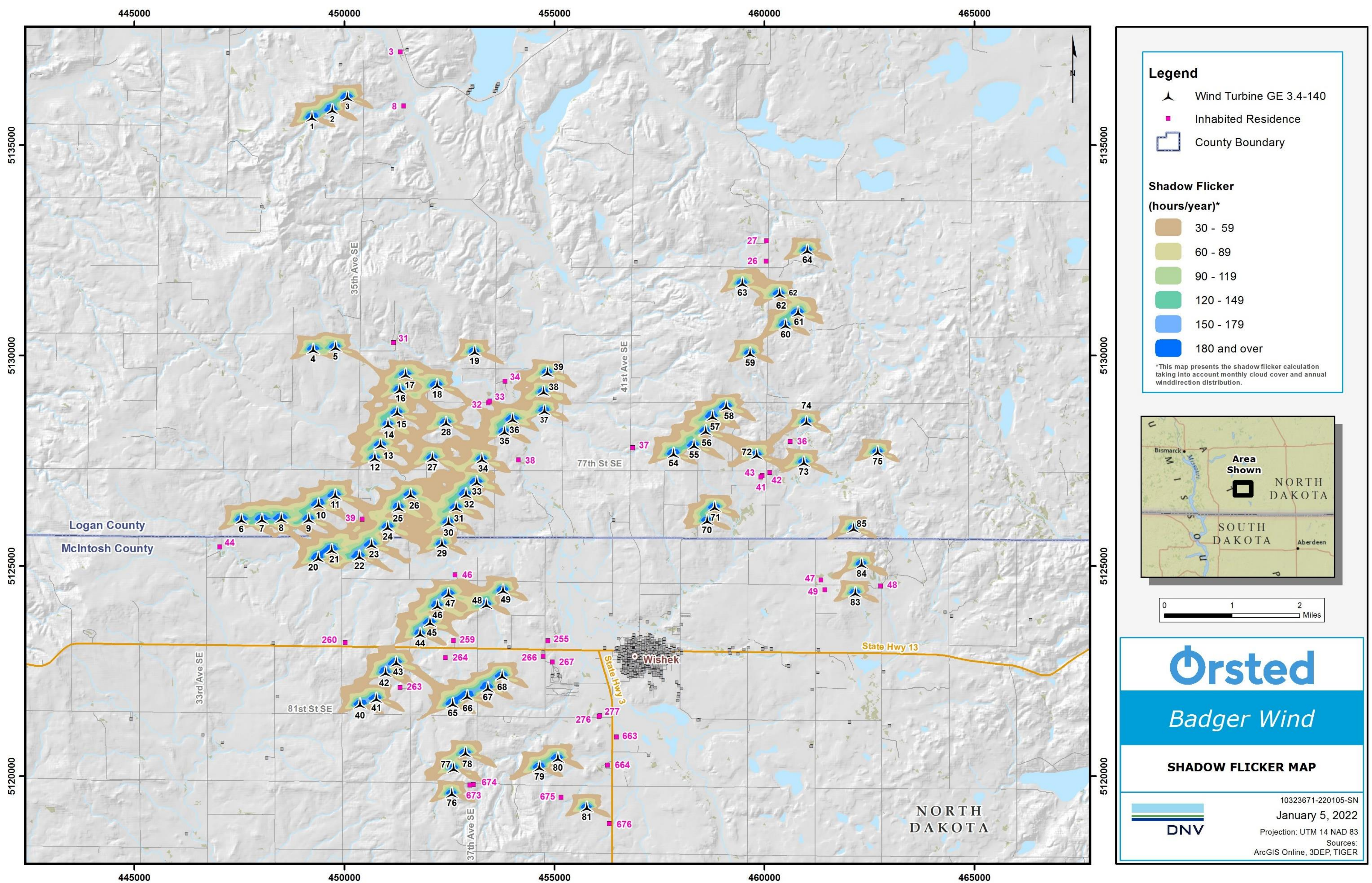

Figure 4-1 Modeled hours of shadow flicker (Expected Case)

5 REFERENCES

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[4] Receptor locations sent by email, by Orsted to DNV on 23 September 2021, "*Badger_ReceptorSurvey_FieldVerify.zip*""

[5] Annual site-specific wind direction distribution for Badger Wind sent by email, by Orsted to DNV on 22 September 2021, "*M2000_WindRose_12sector.xlsx*"

[6] Freud H-D, Kiel F.H., "Influences of the opaqueness of the atmosphere, the extension of the sun and rotor blade profile on the shadow impact of wind turbine", DEWI Magazine No. 20 pp 43-51, February 2002.

APPENDIX A – WIND TURBINE COORDINATES

ID	UTM Zone 14, NAD 83 Datum	
	Easting [m]	Northing [m]
T1	449232	5135639
T2	449715	5135813
T3	450072	5136112
T4	449261	5130118
T5	449789	5130171
T6	447551	5126070
T7	448036	5126080
T8	448497	5126099
T9	449154	5126085
T10	449387	5126438
T11	449782	5126653
T12	450729	5127537
T13	450861	5127853
T14	451042	5128333
T15	451257	5128621
T16	451315	5129161
T17	451454	5129529
T18	452210	5129271
T19	453100	5130066
T20	449377	5125160
T21	449699	5125357
T22	450360	5125201
T23	450646	5125479
T24	451033	5125893
T25	451295	5126363
T26	451577	5126667
T27	452098	5127542
T28	452421	5128376
T29	452324	5125495
T30	452479	5126005
T31	452664	5126362
T32	452894	5126680
T33	453151	5126962
T34	453276	5127510
T35	453813	5128161
T36	454004	5128462
T37	454764	5128664
T38	454742	5129113
T39	454835	5129567
T40	450371	5121682
T41	450761	5121823
T42	450983	5122435
T43	451235	5122677
T44	451804	5123359
T45	452037	5123629
T46	452217	5124027
T47	452482	5124307
T48	453381	5124054
T49	453779	5124395
T54	457835	5127638
T55	458325	5127835
T56	458602	5128176
T57	458765	5128526
T58	459095	5128759
T59	459657	5130026
T60	460506	5130695
T61	460804	5130994
T62	460359	5131442
T63	459474	5131694
T64	461020	5132473

ID	UTM Zone 14, NAD 83 Datum	
	Easting [m]	Northing [m]
T65	452577	5121697
T66	452929	5121877
T67	453416	5122072
T68	453759	5122358
T70	458635	5126052
T71	458816	5126368
T72	459815	5127608
T73	460934	5127436
T74	461003	5128392
T75	462699	5127680
T76	452558	5119564
T77	452597	5120163
T78	452882	5120526
T79	454642	5120186
T80	455082	5120402
T81	455774	5119232
T83	462165	5124334
T84	462316	5125016
T85	462125	5125862

APPENDIX B – RECEPTOR LOCATIONS & RESULTS

Receptor ID	UTM Easting [m]	UTM Northing [m]	Expected Case with Monthly Cloud Cover and Wind Rose [hrs/yr]	Closest Turbine		
				Distance [ft]	Distance [m]	Turbine ID
P39	450426	5126113	38	2119	646	24
33	453463	5128918	29	2320	707	36
32	453428	5128874	25	2320	707	36
P674	452989	5119794	16	1604	489	76
P34	453827	5129394	15	3114	949	36
P26	460040	5132243	15	2585	788	63
P263	451329	5122110	14	1558	475	42
P673	453076	5119807	13	1880	573	76
P47	461350	5124665	13	2887	880	83
259	452598	5123225	13	2267	691	45
675	455159	5119498	10	2198	670	81
P43	459917	5127112	10	1663	507	72
P48	462767	5124527	10	2073	632	83
P46	452631	5124788	10	1654	504	47
P38	454147	5127522	10	2369	722	35
P42	460131	5127219	9	1644	501	72
264	452406	5122819	8	2654	809	44
P36	460620	5127961	8	1893	577	74
P49	461444	5124433	8	2388	728	83
260	450024	5123180	7	3983	1214	42
P41	459950	5127152	7	1562	476	72
P37	456860	5127809	6	3245	989	54
P664	456265	5120265	4	3750	1143	81
266	454738	5122856	4	3606	1099	68
255	454849	5123219	4	4557	1389	68
P27	460052	5132724	4	3281	1000	64
267	454957	5122712	3	4098	1249	68
44	447037	5125452	3	2635	803	6
3	451335	5137218	2	5509	1679	3
8	451414	5135938	2	4439	1353	3
663	456482	5120937	2	4918	1499	80
676	456308	5118878	2	2100	640	81
P31	451171	5130311	1	2730	832	17
276	456064	5121418	0	4636	1413	80
277	456081	5121438	0	4721	1439	80
P7	449910	5136911	0	2674	815	3
45	447643	5124993	0	3543	1080	6
50	461281	5123004	0	5240	1597	83
257	453922	5123072	0	2402	732	68
258	453837	5123201	0	2779	847	68

Receptor IDs with a “P” prefix indicate a participating receptor.

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