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 102 wind turbine generators (WTGs), of which up to 93 will ultimately be constructed. There are no neighboring wind farms or solar farms near the Project.

There were 44 receptors, representing inhabited residences, identified within 5,003 feet (1,525 m) of a Project turbine, which is the equivalent of ten tip heights of the WTG.

While there are no regulatory limits regarding shadow flicker directly applicable to the Project, the Customer has voluntarily kept annual shadow flicker durations under 30 hours per year at non-participant receptors without a waiver, which is the industry standard, as recommended by American Wind Energy Association (AWEA). In the current model, all receptors respect the 30-hour limit, regardless of participant or waiver status.

Receptor 475 is predicted to experience the most shadow flicker per year (expected case), with a total of 27 hours. This is a participating receptor. 40 of the 44 receptors included in this assessment have predicted annual shadow flicker durations under 10 hours, which is well under the recommended annual limit.

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 102 GE 2.8-127 wind turbine generators with a hub height of 292 ft (89 m). The turbine layout was provided by the Customer [1] and modified as requested by the Customer. Only up to 93 of the 102 turbines in this analysis are planned to be constructed.

The GE 2.8-127 has a maximum blade tip height of 500 feet (152.5 m), a hub height of 292 feet (89 m), and a rotor diameter of 417 feet (127 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 Wishek, North Dakota.

2.2 Wind farm layout and turbine model

The current Project layout consists of 102 GE 2.8-127 WTGs. Ultimately, up to 93 of these turbines will be constructed. The turbine layout was provided by the Customer [1] and modified as requested by the Customer.

The GE 2.8-127 has a maximum blade tip height of 500 feet (152.5 m), a hub height of 292 feet (89 m), and a rotor diameter of 417 feet (127 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 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. DNV completed a desktop review of these receptor locations in November 2023 and identified one additional location.

Of the total number of identified receptors, results for 44 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.

In 2020, the American Wind Energy Association (AWEA) issued a publication [5] recommending 30 hour per year limits for shadow flicker duration, based on the “expected” or “realistic” case,

Additionally, the 2022 PSC order states: *The Project will comply with Badger Wind’s voluntary commitment of 30 hours per year or less of shadow flicker at all residences, absent a waiver.*

The Customer continues to voluntarily apply this shadow flicker duration limit at all inhabited participating and non-participating receptors, absent a waiver.

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 and windows 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]. Similarly to the UK standard, the common approach for US projects is to use 10 rotor diameters. However, 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.

The annual hours of shadow flicker at receptors have been calculated in two steps:

1) A “worst case” or astronomical worst-case, which represents the number of hours of annual shadow flicker that does not take into account attenuating factors, such as cloud cover or the site-specific wind rose.
2) An “expected case” that considers cloud cover and the site-specific wind rose in order to get a more realistic 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.

In the case of this Project, 10 x (hub height + rotor radius) is equal to 5,003 feet (1,525 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 [6] 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 [7]. 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 [7]. 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 [6].

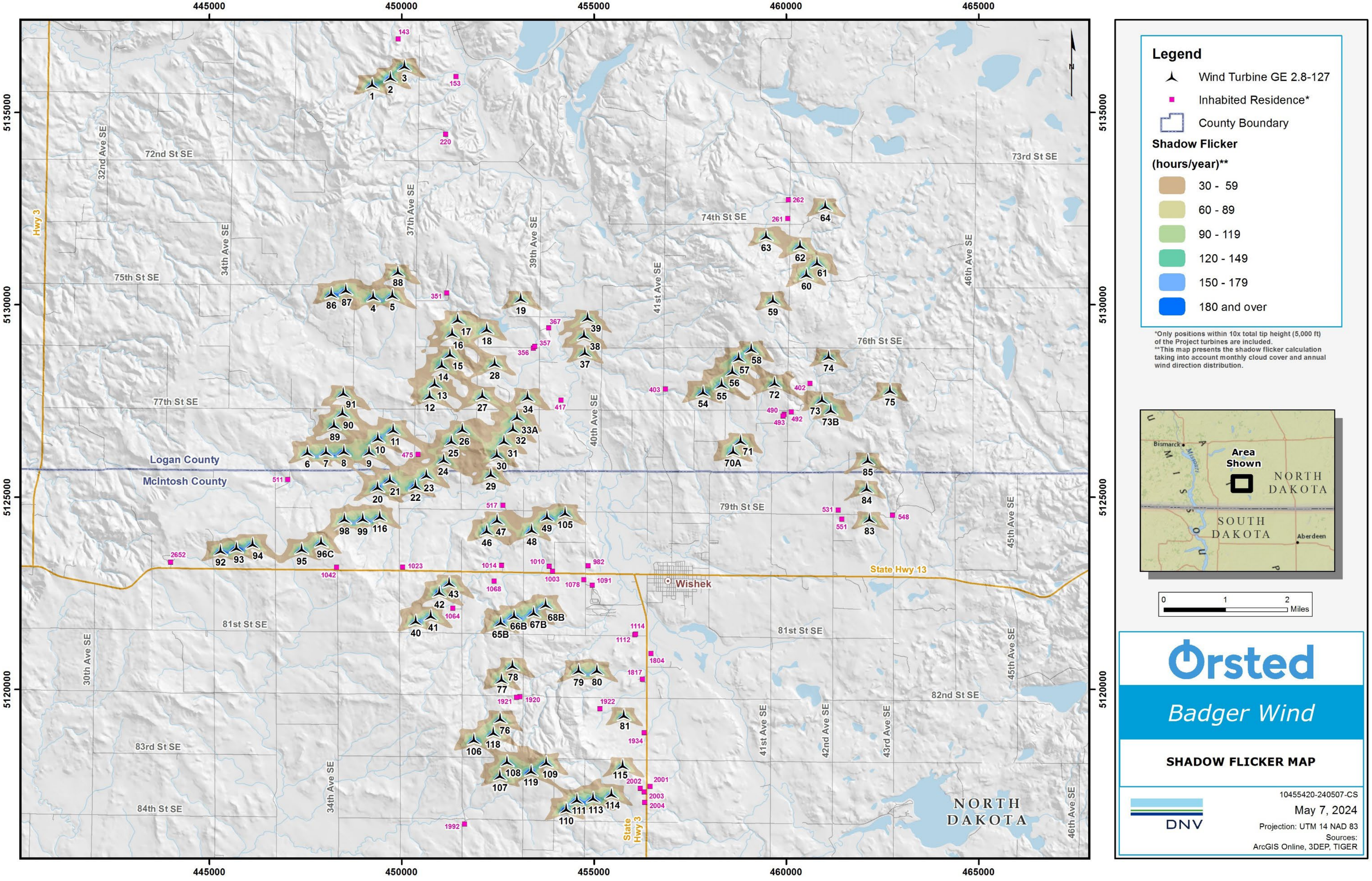
A detailed map illustrating predicted “expected case” shadow flicker duration at receptors lying within 5,003 feet (1,525 m) of the Badger Wind Farm are presented in Figure 4-1. The map takes into account average monthly cloud cover and annual wind direction distribution. Shadow flicker is shown in isopleths of 30 hours per year or more.

While there are no regulatory limits regarding shadow flicker directly applicable to the Project, the Customer has voluntarily kept annual shadow flicker durations under 30 hours per year at non-participant receptors without a waiver, which is the industry standard, as recommended by AWEA. Additionally, the 2022 PSC order states: *The Project will comply with Badger Wind’s voluntary commitment of 30 hours per year or less of shadow flicker at all residences, absent a waiver.* In the current model, all receptors respect the 30-hour limit, regardless of waiver status.

Receptor 475 is predicted to experience the most shadow flicker per year (expected case), with a total of 27. This is a participating receptor. 40 of the 44 receptors included in this assessment have predicted annual shadow flicker durations under 10 hours, which is well under the recommended annual limit.

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 up to 93 of the 102 turbines included in this analysis will be built. Results may be overestimated in areas where turbines may not end up being constructed.

The astronomical worst case represents a theoretical, extreme situation in which no cloud cover occurs at any point during the year. Furthermore, it assumes that all turbine rotors are always perpendicular to any given receptor, which is unfeasible. As a result, the astronomical worst case can be assumed to be an extreme, theoretical example which is extremely unlikely to occur, and can be considered informative.



*Only positions within 10x total tip height (5,000 ft) of the Project turbines are included.
**This map presents the shadow flicker calculation taking into account monthly cloud cover and annual wind direction distribution.

Ørsted

Badger Wind

SHADOW FLICKER MAP

DNV

10455420-240507-CS
May 7, 2024
Projection: UTM 14 NAD 83
Sources:
ArcGIS Online, 3DEP, TIGER

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

5 REFERENCES

[1] Badger Wind Turbine locations received 9 November 2023

[2] Department for Business Enterprise & Regulatory Reform, UK, “Onshore Wind: Shadow Flicker”, http://webarchive.nationalarchives.gov.uk/20090609003228/http:/www.berr.gov.uk/whatwedo/energy/sources/renewables/planning/onshore-wind/shadow-flicker/page18736.html . Accessed December 2021.

[3] Danish Wind Industry Association, "Shadow variations from Wind turbines", http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/env/shadow/shadow2.htm . Accessed December 2021.

[4] Receptor locations sent by Orsted to DNV, “Receptors_Badger_230724.shp” with some subsequent minor updates based on a field verifications performed in August 2023.

[5] AWEA, *Wind Turbines and Shadow Flicker: Facts and Proven Mitigation Strategies.* November 2020

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

[7] 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]
1	449232	5135638
2	449714	5135812
3	450071	5136111
4	449260	5130118
5	449758	5130152
6	447550	5126069
7	448035	5126080
8	448497	5126098
9	449154	5126084
10	449386	5126438
11	449781	5126652
12	450728	5127537
13	450860	5127853
14	451041	5128333
15	451256	5128620
16	451315	5129160
17	451460	5129521
18	452210	5129270
19	453099	5130065
20	449376	5125160
21	449699	5125356
22	450359	5125200
23	450646	5125478
24	451091	5125879
25	451295	5126363
26	451577	5126666
27	452097	5127541
28	452421	5128376
29	452323	5125495
30	452479	5126004
31	452664	5126361
32	452894	5126680
33A	453003	5126987
34	453276	5127510
37	454764	5128664
38	454742	5129112
39	454835	5129566
40	450370	5121682
41	450760	5121822
42	450982	5122434
43	451235	5122676
46	452216	5124027
47	452481	5124306
48	453381	5124054
49	453778	5124395
54	457834	5127638
55	458325	5127835
56	458601	5128175
57	458765	5128525
58	459094	5128759
59	459656	5130026
60	460523	5130695
61	460803	5130994
62	460359	5131441
63	459474	5131693
64	461020	5132473
65B	452574	5121646
66B	452928	5121822
67B	453431	5121899
68B	453743	5122114
70A	458619	5126099
71	458816	5126367
72	459697	5127871
73	460934	5127435
73B	461159	5127167
74	461104	5128566
75	462699	5127679
76	452565	5119147
77	452596	5120163
78	452882	5120526
79	454604	5120400
80	455082	5120401
81	455774	5119232
83	462165	5124334
84	462095	5125131
85	462125	5125862
86	448174	5130196
87	448552	5130291
88	449901	5130762
89	448243	5126773
90	448461	5127094
91	448482	5127610
92	445292	5123520
93	445705	5123590
94	446125	5123690
95	447398	5123549
96C	447909	5123733
98	448512	5124333
99	448991	5124344
105	454252	5124496
106	451880	5118601
107	452555	5117661
108	452740	5118025
109	453762	5118008
110	454279	5116798
111	454557	5117036
113	454981	5117083
114	455457	5117189
115	455748	5117927
116	449433	5124398
118	452384	5118784
119	453366	5117786

APPENDIX B – RECEPTOR LOCATIONS & RESULTS

Receptor ID	UTM Easting [m]	UTM Northing [m]	Total Hours in Year [hrs/yr]		Closest Turbine		
			Astronomical Worst Case	Expected Case with Monthly Cloud Cover and Wind Rose	Distance [ft]	Distance [m]	Turbine ID
475	450426	5126113	110	27	2204	672	23
261	460040	5132243	57	12	2587	789	63
367	453827	5129394	47	12	3140	957	38
1064	451329	5122110	48	11	1558	475	42
357	453463	5128918	38	9	3854	1175	28
492	460131	5127219	34	9	2568	783	72
356	453428	5128874	32	8	3686	1123	28
1922	455159	5119498	32	8	2200	671	81
548	462767	5124527	35	8	2073	632	83
1068	452406	5122819	32	7	3692	1125	66B
417	454147	5127522	33	7	2858	871	34
517	452631	5124788	29	7	1652	504	47
1042	448303	5123172	23	7	2250	685	96C
490	459950	5127152	29	7	2501	762	72
2004	456317	5117069	26	7	2848	868	114
493	459917	5127112	29	7	2592	790	72
551	461444	5124433	26	6	2389	728	83
2001	456463	5117481	25	6	2764	842	115
1023	450024	5123180	24	6	3984	1214	42
531	461350	5124665	25	5	2884	879	84
2002	456205	5117426	23	5	2224	678	115
403	456860	5127809	19	5	3246	989	54
2003	456305	5117334	18	4	2670	814	115
351	451171	5130311	14	4	2760	841	17
402	460620	5127961	15	4	2007	612	73
1078	454738	5122856	19	3	4070	1241	68B
262	460052	5132724	12	3	3281	1000	64
1817	456265	5120265	9	3	3750	1143	81
153	451414	5135938	7	2	4440	1353	3
1091	454957	5122712	8	2	4436	1352	68B
2652	443993	5123311	6	2	4317	1316	92
1920	453076	5119807	10	1	1960	597	77
1934	456308	5118878	8	1	2101	640	81
1804	456482	5120937	5	1	4917	1499	80
1014	452598	5123225	5	1	2681	817	46
511	447037	5125452	4	1	2635	803	6
1921	452989	5119794	0	0	1768	539	77
143	449910	5136911	0	0	2675	815	3
1010	453837	5123201	0	0	2590	789	48
1003	453922	5123072	0	0	3086	941	68B
982	454849	5123219	0	0	4628	1411	105
1112	456064	5121418	0	0	4635	1413	80
1114	456081	5121438	0	0	4721	1439	80
1992	451637	5116504	0	0	4848	1478	107
220	451142	5134435	0	0	6515	1985	T2

[1] Receptor 220 has been included in the Shadow Flicker Assessment, however it falls outside of the 5000 foot calculation domain.

APPENDIX C - SHADOW FLICKER PER DAY RECEPTOR RESULTS

About DNV