Appendix O

Shadow Flicker Modeling

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Memorandum

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Subject	**Tatanka Ridge Wind Project Shadow Flicker Modeling**
Attention	Jesse Bermel/Avangrid Renewables, LLC.
From	Mark Bastasch/Jacobs Engineering Group, Inc.
Date	April 29, 2019

This memorandum provides the predicted duration of shadow flicker for the Tatanka Ridge Wind Project (Project) proposed by Tatanka Ridge Wind, LLC (Tatanka Ridge) a subsidiary of Avangrid Renewables, LLC (Avangrid Renewables). This analysis is based on 62 wind turbine locations (55 primary locations and 7 potential alternate locations). Figure 1 (attached) presents the Project's proposed wind turbine layout and the predicted duration of flicker based on the analysis described herein, as well as the residences that have been identified by Avangrid Renewables. Deuel County's zoning ordinance limits shadow flicker to no more than 30 hours annually at existing residences. Modeling of the Project found that the highest predicted hours of expected shadow flicker per year is approximately 15 hours at a nonparticipating dwelling and approximately 28 hours at a participating dwelling. Therefore, the predicted duration of shadow flicker associated with the Project's proposed wind turbine layout satisfy the Deuel County zoning ordinance requirements.

1. Background

Shadow flicker is a term used to refer to the alternating changes in light intensity that can occur at times when the rotating blades of wind turbines cast moving shadows on the ground or on structures. Shadow flicker occurs only when the wind turbines are operating during sunny conditions, and is most likely to occur early and late in the day when the sun is at a low angle in the sky. The intensity of shadow flicker is defined as "the difference or variation in brightness at a given location in the presence or absence of a shadow" (National Research Council, 2007). The intensity of the shadows cast by moving blades of wind turbines, and thus the perceived intensity of the flickering effect, is determined by the distance of the affected area from the turbine, with the most intense, distinct, and focused shadows occurring closest to the turbine (Department of Energy & Climate Change, 2009). The frequency of shadow flicker is a function of the number of blades making up the wind turbine rotor and rotor speed. Shadow flicker frequency is measured in terms of alternations per second, or hertz (Hz).

There are two kinds of concerns that have been raised about shadow flicker in severe cases. One is that shadow flicker could have the potential to trigger epileptic seizures, and the other is that shadow flicker could become a source of annoyance to residents living near wind turbines. The Epilepsy Foundation notes that for a small minority (about 3 percent) of the 3 million people in the United States who are affected by epilepsy, there is a potential for epileptic seizures to be triggered by flashing light. These seizures have the potential to be triggered when the light flashes are in the range of 5 to 30 Hz. Because the frequency of the shadow flicker created by modern wind turbines is below this range of (typically less than 1.0 Hz), the shadow flicker effects created by wind turbines do not have the potential to trigger epileptic seizures (Epilepsy Foundation, 2008).

The issue of annoyance is more subjective and addressed by the limits established in the Deuel County zoning ordinance. There could be cases in which shadow flicker cast on residences located very close to

wind turbines could be enough of a distraction for residents to be considered an annoyance. The Project has mitigated this risk by selecting turbine locations that comply with the Deuel County requirements.

2. Regulatory Requirements and Modeling Methods

Deuel County's Zoning Ordinance Section 1215.03(13)(b) states that the "*Limit for allowable shadow flicker at existing residences to no more than 30 hours annually*." To evaluate the potential levels of shadow flicker an analysis for the proposed Project was conducted using the SHADOW calculation module of the WindPRO 3.2 software. WindPRO is a comprehensive software package developed for the design, development, and assessment of wind farm projects, as well as for the evaluation of energy, environmental, visual, electrical, and economic effects of wind energy projects. To calculate shadow flicker levels at nearby residences and other structures, referred to as receptors, the WindPRO SHADOW calculation module takes into account the location of each receptor, the orientation of each side of the receptor, the location of each wind turbine, turbine hub height, turbine rotor diameter, turbine blade width, latitude and longitude, elevation data of the specific analysis area, and data on the sun's path through the sky on each day of the year (EMD International A/S [EMD], 2008). The locations of proposed wind turbines as well as the residences were provided by Avangrid Renewables for the analysis. The shadow flicker model made use of topographic data to account for the minor elevation differences and topographic features potentially in the line of sight when turbines are viewed from a receptor. For the area within the Project and its vicinity, the U.S. National Elevation Dataset incorporated in WindPro was used.

The primary wind turbine specifications that influence shadow flicker are the hub height, blade length, and blade width. Avangrid Renewables provided this information for the General Electric turbines. The WindPRO SHADOW calculation model was run based on the project layout identified in Table 1.

Table 1. Modeled Turbine Locations

Source ID	Turbine Manufacturer	Rotor Diameter (m)	Hub Height (m)	Coordinates		
				Easting (m)	Northing (m)	Z (m)
A1	GE	127	88.6	690,799	4,939,136	585
A2	GE	127	88.6	691,407	4,939,152	580
B1	GE	127	88.6	690,097	4,940,133	590
B2	GE	127	88.6	691,218	4,940,385	568
B3	GE	127	88.6	691,615	4,940,639	571
C5	GE	127	88.6	689,357	4,940,791	590
E1	GE	116	90	684,544	4,942,375	613
E2	GE	116	90	685,022	4,942,384	609
E3	GE	116	90	685,724	4,942,474	611
E4	GE	127	88.6	686,854	4,941,987	605
E5	GE	127	88.6	687,711	4,942,510	592
E6	GE	127	88.6	688,223	4,942,843	590
F1	GE	127	88.6	687,280	4,943,515	587
F2	GE	127	88.6	688,033	4,944,395	582
F4	GE	127	88.6	689,608	4,943,698	570
G1	GE	116	90	684,078	4,943,490	610
G2	GE	116	90	684,583	4,943,517	612
G3	GE	116	90	685,040	4,943,455	612
H1	GE	127	88.6	681,030	4,944,127	608

Table 1. Modeled Turbine Locations

Source ID	Turbine Manufacturer	Rotor Diameter (m)	Hub Height (m)	Coordinates		
				Easting (m)	Northing (m)	Z (m)
H2	GE	127	88.6	681,471	4,944,211	613
H3	GE	127	88.6	681,931	4,944,224	615
H4	GE	127	88.6	682,427	4,943,501	612
H5	GE	127	88.6	682,765	4,943,922	615
I2	GE	127	88.6	682,410	4,945,098	609
I3	GE	127	88.6	683,048	4,944,921	609
I4	GE	127	88.6	683,432	4,944,956	609
I5	GE	127	88.6	685,151	4,945,281	598
J1	GE	127	88.6	684,023	4,945,449	601
J2	GE	127	88.6	684,389	4,945,846	593
K0	GE	127	88.6	676,230	4,943,117	580
K1	GE	127	88.6	676,670	4,943,472	588
K2	GE	127	88.6	677,108	4,943,724	589
K3	GE	127	88.6	677,637	4,943,726	590
K4	GE	127	88.6	678,278	4,943,221	594
K5	GE	127	88.6	678,736	4,943,263	595
K6	GE	127	88.6	679,281	4,943,157	599
K7	GE	127	88.6	679,879	4,943,079	601
K8	GE	127	88.6	680,365	4,943,168	600
L1	GE	127	88.6	675,295	4,946,281	588
L10	GE	127	88.6	679,680	4,944,655	603
L11	GE	127	88.6	680,314	4,944,999	613
L2	GE	127	88.6	676,183	4,946,247	591
L3	GE	127	88.6	676,798	4,946,277	598
L4	GE	127	88.6	677,113	4,946,511	583
L5	GE	127	88.6	677,560	4,945,484	597
L6	GE	127	88.6	678,208	4,945,420	599
L7	GE	127	88.6	678,716	4,945,435	605
L8	GE	127	88.6	679,174	4,945,757	606
L9	GE	127	88.6	679,657	4,946,274	592
O3	GE	127	88.6	683,641	4,940,587	601
O4	GE	127	88.6	682,854	4,940,037	590
O5	GE	127	88.6	683,275	4,939,446	591
P1	GE	127	88.6	680,174	4,941,593	588
P3	GE	127	88.6	680,988	4,942,323	603
P4	GE	127	88.6	681,515	4,942,260	603
P5	GE	127	88.6	681,693	4,941,514	597
P6	GE	127	88.6	682,544	4,941,503	597

Table 1. Modeled Turbine Locations

Source ID	Turbine Manufacturer	Rotor Diameter (m)	Hub Height (m)	Coordinates		
				Easting (m)	Northing (m)	Z (m)
P7	GE	127	88.6	682,938	4,942,691	609
P8	GE	127	88.6	683,589	4,941,798	606
S5	GE	127	88.6	676,976	4,948,113	591
S6	GE	127	88.6	677,460	4,948,073	597
S8	GE	127	88.6	677,815	4,948,173	594

Notes:
GE = General Electric
ID = identifier
m = meter(s)

As the sun approaches the horizon, sunshine becomes less intense, and, therefore, the shadow influence is reduced. To take this phenomenon into account, the standard practice in shadow flicker analysis is to calculate shadow flicker for only the times when the sun is at an angle of 3 or more degrees above the horizon (EMD, 2008; Osten and Pahlke, 1998). In conducting this analysis, the 3-degree threshold was observed.

Shadow flicker intensity is defined as the difference in brightness at a given location in the presence and absence of a shadow. The intensity of shadow flicker tapers off with increasing distance from the turbine. Generally, shadow flicker is most intense and noticeable within 1,000 meters (3,274 feet) of the turbine. With increased distance from the turbine, the shadow flickering becomes less perceptible. Research has established that the threshold at which shadow flicker is no longer pronounced is the point at which less than 20 percent of the sun would be covered by the blade (EMD, 2008; Osten and Pahlke, 1998). The distance threshold defining the area within which 20 percent or more of the sun is covered is determined by WindPRO based on the width of the blades.

The orientation of each receptor was set on “greenhouse mode” for the model, which makes the assumption that the receptor has windows on all of its sides and, therefore, would be affected by shadow flicker that falls on any side of the structure; the “greenhouse mode” represents a worst-case indoor scenario for each receptor.

An important variable that the WindPRO Shadow calculation model takes into account is the probable hours when the sunny conditions required for shadows to be created will be present in the Project area. To generate the data that the model requires to account for hours of sunshine, Jacobs reviewed the meteorological data from nearby weather stations to identify the available data on cloud coverage and used it to calculate the percentage of sunny days by month. The most representative meteorological station where the appropriate data are collected is located at the Watertown Regional Airport, located approximately 30 miles northwest of the Project’s northern edge. To calculate the monthly probabilities of sunshine, hourly observations of cloud cover were obtained from the National Weather Service (NWS) Watertown Regional Airport meteorological monitoring station (Weather-Bureau-Army-Navy #14946).

The monthly probabilities of sunshine were calculated using hourly data from the 2007 through 2018. The AERMET meteorological data processor, developed by the U.S. Environmental Protection Agency to read and extract parameters from NWS data and process for the purposes of air dispersion modeling, was used to calculate the monthly probabilities of sunshine. For this analysis, AERMET (Version 18181) extracted the fraction of cloud cover for each hour and calculated the convective mixing height based on the station latitude and time zone. The total daytime hours for each month were determined based on the convective mixing height, which is generated only during daytime hours. For each valid hour, a cloud cover of 0.7 and below was considered sunny. The total number of sunny hours (or sun hours) was divided by the total number of valid daytime hours in the month to determine each month’s sunshine

probability. The monthly sunshine probabilities derived through this analysis and used in calculating the Project's adjusted shadow flicker effects are summarized in Table 1.

Table 2. Average Sunshine Probability per Month (Recorded Sun Hours/Possible Sun Hours)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.56	0.58	0.55	0.63	0.66	0.76	0.87	0.80	0.75	0.64	0.62	0.50

Based on the analysis of the available cloud cover data, the sun would be unobstructed by clouds long enough to have the potential to permit shadow flicker effects to be created anywhere from 50 to 87 percent of the time during daylight hours on a monthly basis. Meteorological data were provided by Avangrid Renewables to incorporate the annual operational hours for each wind direction into the shadow flicker analysis. The wind direction determines how much of the time the blades are turned in a direction that would cast shadows on the receptors being evaluated. These statistics are summarized in Table 3:

Table 3. Average Annual Operational Hours per Wind Direction

N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
814	564	389	383	500	654	1,197	844	542	739	874	805

Other factors that could also affect the total amount of predicted shadow flicker, but were not taken into account in the modeling include the following:

- Presence of haze or particulate matter in the air that tends to reduce the intensity of light and reduce distances at which shadows can be cast.
- Potential structures and vegetation located between receptors and the turbines, which would block shadows created by the rotating turbine blades and thus prevent shadow flicker from occurring at receptors.
- The model assumes that the receptors are in the "greenhouse mode," in which the receptor is assumed to be all windows—a worst-case scenario. Receptors normally have much less window than wall space on any given side.

2.1.1 Conclusions

The shadow flicker modeling results for the all identified receptors are presented in tabular format in Table 4. These results present the expected annual hours of shadow flicker for 62 wind turbines which is 7 more than the Project's stated maximum buildout of 55 locations. As turbine technology continues to evolve, Tatanka Ridge intends to obtain multiple bids for the Project and evaluate multiple technologies. The final turbine locations will be selected based on a subset of the 62 locations identified in this analysis. These results are based on the historical average meteorological conditions identified in this analysis. All receptors are identified with an identification that corresponds to the receptor locations labeled in Figure 1. The information provided on Figure 1 consists of butterfly diagrams that indicate the 30 hour per year potential shadow flicker contour around each turbine, and the locations of the receptors in the Project area in relationship to this contour. A review of the annual shadow flicker exposure data indicates that the receptors with the potential to experience shadow flicker effects could experience from 1 minute up to approximately 28 hours per year of shadow flickering. These results do not exceed the 30 hours per year limit established by Deuel County.

Table 4. Expected Annual Hours of Flicker

Receiver ID	Receiver Status	Easting [m]	Northing [m]	Z [m]	Expected Shadow Hours per Year [h/year]
H86	Participating	684,161	4,944,755	613	28:29

Table 4. Expected Annual Hours of Flicker

Receiver ID	Receiver Status	Easting [m]	Northing [m]	Z [m]	Expected Shadow Hours per Year [h/year]
H89	Participating	679,515	4,945,123	609	27:24
H75	Participating	681,840	4,942,678	602	27:03
H146	Participating	676,373	4,947,953	576	25:10
H76	Participating	680,833	4,942,902	605	22:32
H155	Participating	678,585	4,942,822	596	21:45
H81	Participating	678,919	4,943,688	596	20:59
H72	Participating	682,934	4,941,994	598	20:19
H156	Participating	676,014	4,943,529	582	20:16
H74	Participating	683,780	4,942,251	611	17:51
H145	Participating	676,613	4,947,704	570	17:44
H158	Participating	678,182	4,946,033	605	16:57
H45	Nonparticipating	682,524	4,939,180	579	14:51
H58	Participating	682,263	4,940,123	584	14:27
H71	Participating	686,229	4,941,921	610	14:17
H163	Participating	675,547	4,946,765	598	13:45
H117	Participating	678,375	4,948,421	601	13:05
H147	Participating	677,166	4,948,738	583	12:11
H87	Nonparticipating	688,741	4,944,987	571	11:37
H53	Participating	689,381	4,939,944	596	11:18
H144	Nonparticipating	676,071	4,947,608	563	11:16
H77	Participating	681,688	4,942,911	603	10:51
H60	Participating	688,637	4,940,736	595	10:05
H157	Nonparticipating	675,808	4,944,069	583	9:39
H83	Nonparticipating	685,334	4,944,133	605	9:09
H85	Participating	687,326	4,944,518	588	8:57
H137	Nonparticipating	674,779	4,945,951	583	8:15
H160	Participating	675,633	4,946,794	595	7:55
H67	Participating	688,636	4,941,413	593	7:45
H65	Participating	679,189	4,941,266	567	7:09
H78	Nonparticipating	689,062	4,942,941	575	7:02
H50	Participating	684,050	4,939,765	596	6:15
H88	Nonparticipating	687,136	4,945,116	586	6:14
H63	Participating	680,616	4,941,080	594	5:36
H64	Nonparticipating	684,540	4,941,185	611	4:34
H80	Participating	688,300	4,943,646	587	3:49
H43	Participating	683,463	4,939,028	585	0:00
H161	Participating	676,584	4,947,413	567	0:00
H159	Participating	675,799	4,945,577	583	0:00
H68	Participating	685,385	4,941,463	610	0:00

Table 4. Expected Annual Hours of Flicker

Receiver ID	Receiver Status	Easting [m]	Northing [m]	Z [m]	Expected Shadow Hours per Year [h/year]
H98	Nonparticipating	682,904	4,946,155	604	0:00
H66	Participating	691,388	4,941,342	558	0:00
H93	Nonparticipating	682,055	4,945,939	607	0:00
H36	Participating	690,696	4,938,383	593	0:00
H162	Nonparticipating	678,852	4,947,413	594	0:00
H101	Participating	683,599	4,946,691	587	0:00
H102	Nonparticipating	684,074	4,946,851	589	0:00
H62	Participating	687,368	4,941,026	611	0:00
H69	Nonparticipating	690,352	4,941,587	567	0:00
H54	Nonparticipating	688,658	4,939,959	592	0:00
H104	Nonparticipating	680,692	4,947,086	607	0:00
H55	Nonparticipating	681,031	4,940,013	583	0:00
H40	Participating	692,283	4,938,611	572	0:00
H33	Nonparticipating	691,948	4,938,171	579	0:00
H154	Nonparticipating	675,757	4,941,934	568	0:00
H132	Nonparticipating	674,929	4,944,253	575	0:00
H59	Nonparticipating	686,562	4,940,149	606	0:00
H25	Nonparticipating	690,715	4,937,792	598	0:00
H52	Participating	687,955	4,939,871	604	0:00
H105	Nonparticipating	684,957	4,947,425	580	0:00
H106	Nonparticipating	684,194	4,947,619	592	0:00
H108	Nonparticipating	681,028	4,947,822	598	0:00
H49	Nonparticipating	686,281	4,939,710	611	0:00
H28	Participating	683,448	4,937,988	575	0:00
H152	Nonparticipating	676,826	4,941,169	561	0:00
H133	Nonparticipating	674,171	4,945,237	575	0:00
H26	Participating	682,715	4,937,976	568	0:00
H116	Nonparticipating	677,958	4,949,878	587	0:00
H92	Nonparticipating	688,489	4,945,892	565	0:00
H95	Nonparticipating	687,770	4,946,076	572	0:00
H109	Nonparticipating	683,484	4,947,898	597	0:00
H141	Nonparticipating	674,202	4,947,455	582	0:00
H23	Participating	691,912	4,937,732	593	0:00
H41	Nonparticipating	685,817	4,938,898	610	0:00
H37	Nonparticipating	685,209	4,938,467	601	0:00
H142	Nonparticipating	674,195	4,947,534	582	0:00
H38	Nonparticipating	688,821	4,938,498	605	0:00
H46	Participating	687,223	4,939,256	604	0:00
H153	Nonparticipating	675,873	4,941,177	555	0:00

Table 4. Expected Annual Hours of Flicker

Receiver ID	Receiver Status	Easting [m]	Northing [m]	Z [m]	Expected Shadow Hours per Year [h/year]
H24	Participating	692,163	4,937,775	591	0:00
H96	Nonparticipating	688,841	4,946,145	564	0:00
H150	Participating	678,221	4,939,683	550	0:00
H17	Nonparticipating	684,084	4,937,488	592	0:00
H34	Nonparticipating	688,367	4,938,286	602	0:00
H128	Participating	678,716	4,939,141	554	0:00
H151	Nonparticipating	677,418	4,939,868	548	0:00
H20	Participating	681,578	4,937,615	564	0:00
H30	Nonparticipating	680,611	4,938,073	568	0:00
H130	Nonparticipating	675,574	4,940,786	551	0:00
H32	Nonparticipating	686,745	4,938,142	606	0:00
H14	Nonparticipating	690,508	4,937,083	599	0:00
H136	Nonparticipating	673,228	4,946,679	590	0:00
H94	Nonparticipating	690,052	4,945,991	558	0:00
H99	Nonparticipating	689,630	4,946,277	558	0:00
H134	Nonparticipating	673,086	4,945,901	576	0:00
H18	Nonparticipating	688,764	4,937,521	607	0:00
H119	Participating	680,671	4,937,573	563	0:00
H138	Nonparticipating	673,333	4,947,545	582	0:00
H135	Nonparticipating	672,956	4,945,917	575	0:00
H121	Nonparticipating	679,979	4,937,635	563	0:00
H9	Participating	682,277	4,936,774	573	0:00
H118	Participating	681,391	4,936,894	572	0:00
H114	Participating	682,887	4,936,492	579	0:00
H124	Nonparticipating	679,249	4,937,641	557	0:00
H129	Nonparticipating	677,481	4,938,248	549	0:00
H122	Participating	680,705	4,936,501	565	0:00
H123	Nonparticipating	679,220	4,936,990	564	0:00
H126	Nonparticipating	677,489	4,937,617	550	0:00
H139	Nonparticipating	672,465	4,948,293	563	0:00
H140	Nonparticipating	672,468	4,948,419	564	0:00
H125	Nonparticipating	677,541	4,936,351	547	0:00

Notes:
h/year = hours per year
ID = identifier
m = meter(s)

3. References

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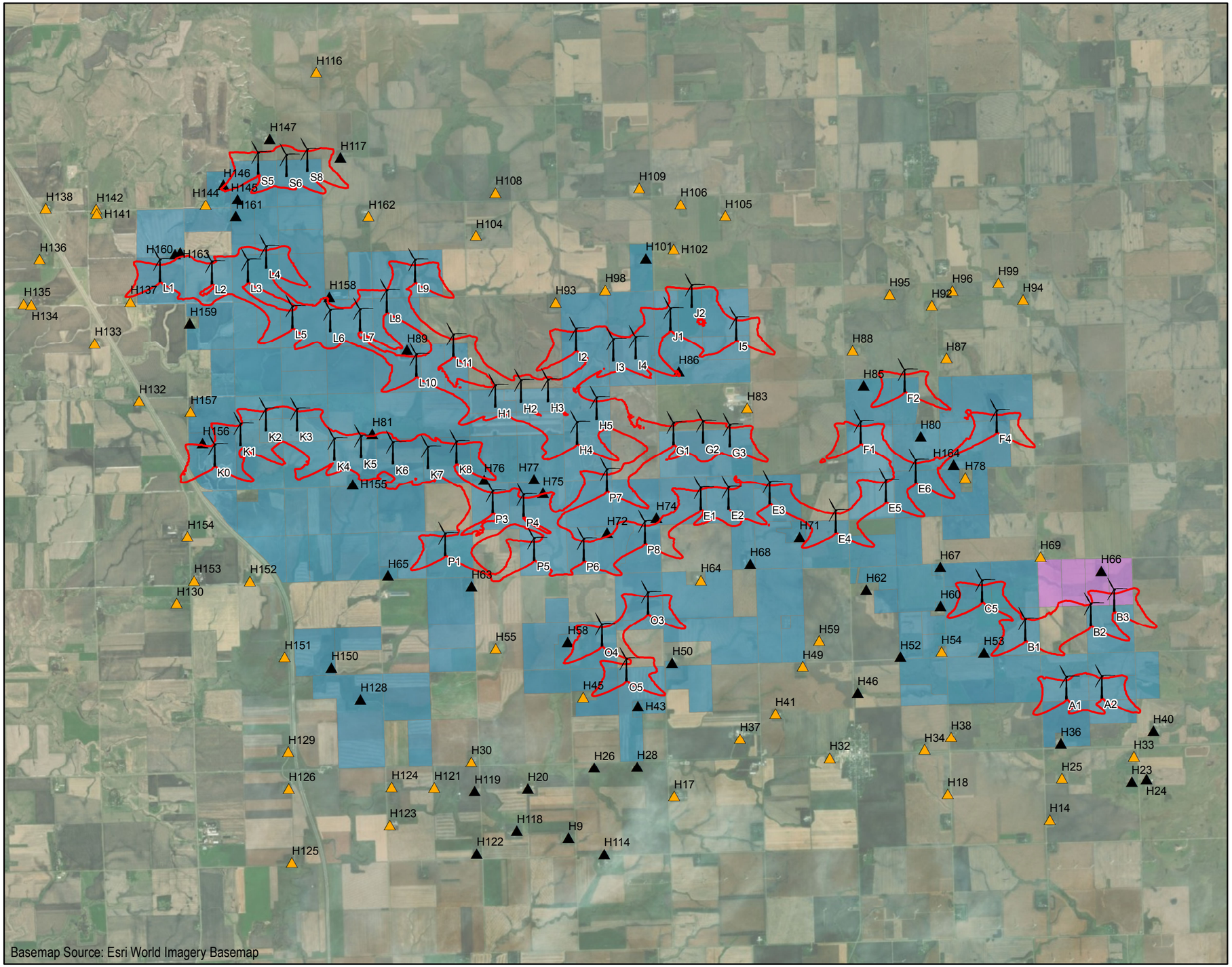
Figure



LEGEND

Turbine Location

Annual Hours of Shadow Flicker (30 hours)

Residence (Participating Status)

Participating

Nonparticipating

Property Agreement Status

Signed

Negotiating Transmission Line Easement

N

0 0.25 0.5 0.75 1 2

Miles

Figure 1
Predicted Shadow Flicker
Tatanka Ridge Wind Project

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