

**Appendix E – Crocker Wind Farm Shadow
Flicker Assessment**



METEOROLOGY & ENERGY ASSESSMENT

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SHADOW FLICKER ASSESSMENT CROCKER WIND PROJECT CLARK COUNTY, SOUTH DAKOTA



METEOROLOGY & ENERGY ASSESSMENT

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1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

Crocker Wind Farm, LLC ('Crocker') is developing the Crocker Wind Farm ('Project') in eastern South Dakota with a nameplate capacity of approximately 400 megawatts. Currently, the Project is proposed to consist of either:

- 200 Vestas V110-2.0 turbines on towers up to 95 meters tall
- 160 GE 2.5-116 turbines on towers up to 90 meters tall
- 152 Gamesa G126-2.625 turbines on towers up to 84 meters tall
- 116 Vestas V136-3.45 turbines on towers up to 82 meters tall

To support the development of the Project, Geronimo Energy, LLC ('Geronimo') completed – on behalf of Crocker - a shadow flicker analysis to estimate levels of flicker potentially associated with the operation of the Project.

1.2 DESCRIPTION OF SHADOW FLICKER AND MODELING

Rotating wind turbine blades may cast shadows during periods when the sun is shining and the turbine is operating. Such shadows may occasionally fall upon homes or other occupied structures (known as receptors) in and near the wind farm area. Expected shadow flicker impacts of the Project have been evaluated by the WindPRO software package, which incorporates the proposed turbine layout, 70 receptors (identified via a combination of aerial imagery and site visits), and site-specific meteorological data.

2. SHADOW FLICKER – DEFINITION AND CHARACTERISTICS

Like any tall structure, wind turbines will cast a shadow when the sun is visible. As wind turbines rotate, a flickering or flashing effect may occur when the shadows of the rotating blades cause rapid changes in light intensity at stationary locations such as homes (referred to as receptors). This change in light intensity is known as shadow flicker. Shadow flicker at a receptor occurs only when the following four conditions are met:

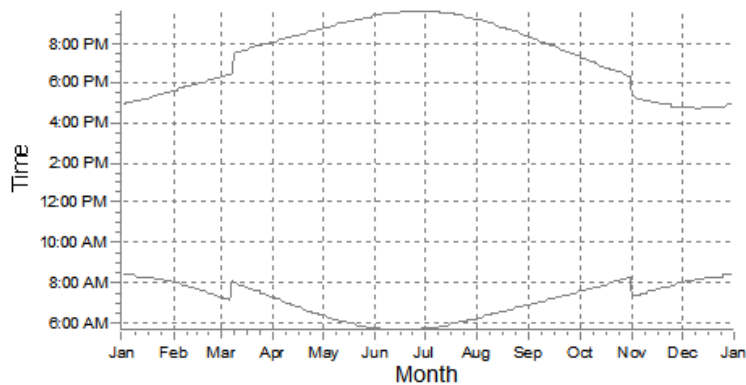
- The sun is shining with no cloud cover present;
- The turbine is operating;
- The turbine blades are positioned on a line between the sun and the receptor; and
- The receptor is close enough to the turbine to distinguish the shadow created by the blades.

Shadow flicker intensity and frequency of occurrence at a given receptor are determined by several factors:

- **Cloud Cover and Visibility:** If the sun is obscured by clouds, the solar disk is not prominent enough to perceive shadow flicker. Similarly, atmospheric phenomena such as haze, fog, or smoke which would limit visibility also reduce the intensity of shadow flicker because it diffuses the light from the sun.
- **Local Topography:** Elevation differences between the receptor and the turbine location can either increase or decrease frequency of shadow flicker, compared to flat terrain. For example, a receptor may be shielded from the turbine by a prominent hill, wind break, or by other nearby buildings.
- **Wind Speed:** Shadow flicker will only occur if the turbine is operating, as discussed previously. Turbines are designed to operate above a specific wind speed (cut-in speed, generally 3 – 4 m/s for modern wind turbines) and below another specific wind speed (cut-out speed, generally 20 – 25 m/s for modern wind turbines).
- **Wind Direction:** Upwind wind turbines like those proposed at the Project seek to maximize energy production by orienting themselves with blades facing into the wind. The area affected by shadow flicker depends on the orientation of the plane of blade rotation relative to a line between the receptor and the sun. If the other conditions are such that shadow flicker is possible and the plane is close to parallel to the receptor-sun

line, the generation of flicker is negligible at the receptor. Alternatively, if the plane is close to perpendicular the generation of flicker at the receptor may be noticeable.

- **Maintenance:** It is occasionally necessary to shut down wind turbines for maintenance, during which time the turbine will not produce shadow flicker.
- **Sun Angle and Path:** On a given day, shadows cast by the sun are longest during the periods around sunrise and sunset and shortest during mid-day hours. Shadows are also longer in the summer than the winter, with the longest shadows occurring on the summer solstice and shortest shadows occurring on the winter solstice, as seen in the image below:



- **Position of Turbines Relative to Receptors:** The frequency of shadow flicker at a receptor decreases as the distance between the receptor and a wind turbine increases. The frequency is also affected by the location of a wind turbine relative to the receptor. For example, a wind turbine will never cast a shadow on a receptor located directly to its south, since it is never possible for the turbine to lie between the receptor and the sun. A receptor located to the west of the turbine, however, may experience shadow flicker during the early morning hours when the sun is in the eastern sky and low to the ground provided other conditions are met.
- **Distance from Turbines to Receptors:** It is generally accepted that shadow flicker from wind turbines is not perceptible beyond distances of 1500 meters (4921 feet), because the shadow is sufficiently diffuse that the shadow is not seen as a solid obstruction.

Currently, shadow flicker impacts are not regulated by state and federal law; however, a general threshold of 30 hours of shadow flicker exposure is often used as a reference within the wind industry based on a standard goal which has been derived from a German court case in which it was determined that 30 hours of actual observed shadow flicker at a neighbor's property was tolerable [1].

3. SHADOW FLICKER MODELING

Computer models are frequently employed to predict the expected amount of shadow flicker at locations within or around a wind farm. One such model is built into EMD WindPRO 2.9.285, an industry standard software package for the design, assessment, and optimization of wind farms. The WindPRO SHADOW module is able to incorporate the sun’s position, topography of the wind farm site, locations of receptors, wind turbine specifications, and the observed wind direction distribution to calculate shadow positions and orientations at one-minute intervals for a calendar year.

3.1 MODEL INPUTS

Crocker has identified 205 positions for turbine placement in the Project area. Figure 1 displays the proposed turbine positions within the wind farm area as well as the receptor locations. Due to siting and setback requirements, some positions are not viable with larger rotor diameter turbines and have been removed from the layout in the model runs corresponding to that turbine. Appendix A provides the turbine coordinates, and indicates which positions are included in each model run. The total number of turbines included in each run of the model was 200 Vestas V110, 160 GE 2.5-116, 152 Gamesa G126-2.625, and 116 Vestas V136-3.45.

Possible receptor locations were identified from 2015 aerial imagery provided by the Farm Service Agency’s (FSA) National Agricultural Imagery Program (NAIP). The locations were further refined by field visits to determine if the buildings were still occupiable and to identify any new buildings since the 2015 photo was taken. A total of 70 receptors were identified within one mile of the project, as seen in Figure 1.

Historical sunshine frequencies (in terms of mean sunlight hours per day) for each calendar month were provided by the WindPRO station database. The nearest site in the database to the Crocker Project is at the National Weather Service (NWS) weather station at Huron, SD. Table 1 lists the percentage of possible sunshine hours that was used in the shadow flicker modeling.

Table 1 – Percent of possible sunshine hours per month at Huron, SD

Average Sunshine Hours Per Day											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
52%	54%	58%	63%	65%	66%	74%	78%	68%	59%	51%	51%

Wind direction data collected by an on-site meteorological tower was used in the analysis. The wind direction observations were binned into twelve 30-degree sectors to determine the relative frequency of wind direction at the site. Table 2 below shows the hourly distribution for the 12

sectors and their number of corresponding hours per direction on an annual basis that was used by the shadow flicker model.

Table 2 - Wind turbine operating hours by direction, Crocker Wind Farm

Operating Hours by Direction													
Sector	1	2	3	4	5	6	7	8	9	10	11	12	Total
Frequency (%)	8.9	6.1	5.3	6.6	8.2	10.7	15.2	8.1	5.1	5.8	9.1	11.0	100
Hrs/Year	776	534	460	582	721	938	1329	712	443	511	793	960	8760

Finally it was assumed that no shadows would be cast if the sun angle was less than 3 degrees above the horizon, since the depth of the atmospheric column at these angles substantially increases scattering of solar radiation and renders shadows, like those analyzed in this report, incoherent.

Geronimo assessed the wind turbine/receptor interaction using two methods – an expected case and a conservative case – each using the following assumptions:

- Receptors assumed to be transparent in all directions (known as ‘greenhouse’ mode);
- Flat terrain without obstacles which would reduce shadow flicker occurrences;
- Obstructions such as trees and outbuildings not considered; and
- Turbines were assumed to always operate regardless of wind speed conditions

In the ‘conservative case’ model, further conservative assumptions were made beyond those listed above:

- Turbines were assumed to be always oriented perpendicular to the receptors; and
- Skies were assumed to be clear at all times regardless of observed sunshine frequency.

3.2 MODEL RESULTS

Summary statistics are as follows, for participating and non-participating landowners:

Table 3 - WindPRO shadow flicker results, conservative case

Hours / Year, Conservative Case	Vestas V110	GE 2.5-116	Gamesa G126	Vestas V136
Average - Participant	65.9	55.9	53.4	43.5
Average - Non Participant	10.3	8.6	8.2	6.7
Max - Participant	255.0	223.1	267.2	252.9
Max - Non Participant	57.6	56.2	40.2	43.6

Table 4 - WindPRO shadow flicker results, expected case

Hours / Year, Expected Case	Vestas V110	GE 2.5-116	Gamesa G126	Vestas V136
Average - Participant	18.9	15.8	13.7	10.7
Average - Non Participant	9.8	9.2	9.9	8.5
Max - Participant	101.0	90.6	110.0	104.1
Max - Non Participant	21.9	19.0	14.1	13.1

Calculated flicker impacts for each receptor are provided in Appendix B. The model predicts no non-participating residences to receive shadow flicker in excess of 30 hours per year. The model does suggest several participants will receive in excess of 30 hours per year of shadow flicker, but the impacts are primarily due to turbines located on their land and these landowners are less likely to perceive this as a nuisance.

4. MITIGATION

Due to the conservative nature of the shadow flicker modeling, the results presented here are likely in excess of the amount of flicker that will be observed in operation. In the event that Crocker receives complaints about flicker from the Project, impacts can be re-evaluated and mitigation measures will be taken if necessary. Such mitigation measures include but are not limited to planting of additional vegetation near receptors and installation of curtains or blinds in the windows of affected receptors.

Crocker plans to address any post-construction shadow flicker concerns on a case-by-case basis. If shadow flicker concerns are reported to Crocker, project representatives will implement the following procedure:

- Log the contact in Crocker's complaint database to track resolution efforts;
- Prepare site-specific assessment of shadow flicker impacts, noting the time of day, season, and expected duration of future flicker impacts;
- Meet with landowner to discuss site-specific assessment, educate landowners on landowner driven mitigation strategies (e.g. modification of interior lighting) and discuss concerns;
- Assess the residence to determine if on-site mitigation measures, including but not limited to, installation of exterior or interior screening, are appropriate for the level of impact and effectively address the concern;
- Work with landowner to develop a mitigation plan; and
- Implement the mitigation plan.

Crocker's goal is to resolve all flicker related complaints the project may receive satisfactorily. Crocker has preference for the least intrusive methodology for mitigating any effects first by engaging with the landowner through education, and will go to more intrusive measures in the event that education is not sufficient in resolving the matter with the landowner.



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5. CONCLUSION

An analysis of potential shadow flicker impacts from the Crocker Wind Farm on nearby receptors indicates that the effects are expected to be minor and well within tolerances that do not present concerns for nuisance. No non-participating residences are expected to experience over 30 hours per year of shadow flicker, and though some participants may experience over 30 hours per year, these impacts are predominantly due to turbines on their own property and less likely to be perceived as a nuisance.

6. REFERENCES

1. WindPower. 2003. Danish Wind Industry Association. Shadow Casting From Wind Turbines. <http://guidedtour.windpower.org/en/tour/env/shadow/index.html>. Accessed 20 June 2013.