Subject: Shadow-Flicker Modeling
Dairy Hills Wind Farm, NY.

Customer: Horizon Wind Energy
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Project type: Modeling

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1. Introduction

This is an update (rev. 3) of the Shadow-Flicker Briefings dated Dec. 16, 2005 (rev. 0), Mar. 8, 2006 (rev. 1) and Jun. 6, 2006 (rev. 2). Revision 0 provided a brief explanation of the shadow-flicker phenomenon, the modeling approach employed and relevant explanations and results.
This Briefing (rev. 3) is a complete update of turbine layout and receptor changes. Compared to revision 0, this briefing also contains an evaluation of the shadow-flicker intensity.
The turbine applied to the model is the Gamesa G90 (90 meter rotor diameter) at 78 meter hub height.
The shadow-flicker results have been modeled using two sets of assumptions, standard assumptions and a scenario where shadow-flicker intensity is sought clarified.

2. Shadow-Flicker Background

Shadow-flicker from wind turbines is defined as alternating changes in light intensity caused by the moving blade casting shadows on the ground and stationary objects, such as a window at a dwelling. No shadow will be cast when the sun is obscured by clouds/fog or when the turbine is not operating.
Shadow-flicker can occur in project area homes when the turbine is located near a home and is in a position where the blades interfere with very low-angle sunlight. The most typical effect is the visibility of an intermittent light reduction in the rooms of the residence facing the wind turbines and subject to the shadow-flicker. Such locations are here referred to as shadow-flicker receptors. Obstacles such as terrain, trees, or buildings between the wind turbine and a potential shadow-flicker receptor significantly reduce or eliminate shadow-flicker effects.

The spatial relationships between a wind turbine and receptor, as well as wind direction are key factors related to shadow-flicker time (hours per year). General industry practices place turbines at least 1000 ft from sensitive receptors. At these distances shadow flicker usually only occurs at sunrise or sunset when the cast shadows are sufficiently long. For situations where the rotor plane is in-line with the sun and receptor (as seen from the receptor), the cast shadows will be very narrow (blade thickness), of low intensity, and will move quickly past the stationary receptor. When the rotor plane is perpendicular to the sun-receptor "view line", the cast shadow of the blades will move within a circle equal to the turbine rotor diameter. Shadow flicker intensity is defined as the difference in brightness at a given location in the presence and absence of a shadow. Shadow flicker intensity diminishes with greater receptor-to-turbine separation distance and low visibility weather conditions, such as haze, or fog.

Part of the analysis performed for this project evaluates the shadow flicker intensity. Normally, a shadow-flicker analysis is limited to focus on the total amount of time (hours and minutes/year) that shadow flicker can potentially occur at receptors regardless of whether the shadow flicker is barely noticeable or clearly distinct. There are two input parameters in the model that can be set at various values in order to make an intensity evaluation possible. One parameter is the sun's minimum angle over the horizon. This parameter is normally set to 3 degrees which means that no shadow-flicker is "counted" at lower angles than 3 degrees. The rationale here is that a combination of the sun's size (as seen through the atmosphere) and intensity makes the cast shadows less distinct. At sunset and sunrise the shadows from large objects are theoretically of infinite length whereas a shadow from a thin flagpole will dissipate within a few feet. This 3 degree parameter however, is not adjusted for the purposes of evaluating the intensity. The parameter that is adjusted is the maximum distance between a turbine and a receptor for shadow-flicker to be "counted". The normal maximum distance used for the model is 1,000 or 1,500 meters (3,300 or 4,900 feet). At distances from 1,000 to 1,500 meters between the turbine and a receptor there will be virtually no distinct "chopping" of the sun-light. Only in rare occasions like in a dark room with a single window facing the turbine will it be possible to identify faint shadow-flickering on the opposite wall. At distances from 500 to 1,000 meters the flickering will be more distinct and may be possible to identify in rooms with more windows (more light) and may also be possible to identify outside on patios etc. By comparing results from two model runs with this maximum distance set at i.e. 1,500 and 1,000 meters the conclusion can be made as to how many hours of shadow-flicker may be noticeable – as opposed to how many hours shadow-flicker may be barely noticeable.

It is likely that receptors will experience less shadow-flicker impact than modeled and reported, especially those that are at greater distances from turbines. It is emphasized the marginally affected receptors may not be able to identify shadow-flicker at all.

The shadow-flicker frequency is related to the rotor speed and number of blades on the rotor. The modeling results presented are based on a wind turbine with a 3-bladed, 90 meter diameter rotor, 78 meter hub height and a nominal rotor speed of 16.7 RPM which translates to a blade pass frequency of 0.8 Hz (less than 1 alternation per second). Health wise, such low frequencies are harmless. Frequencies higher than 3 Hz but below 10 Hz are widely used in discotheques and the Epilepsy Foundation has made a statement that frequencies below 10 Hz are not likely to trigger epileptic seizures.

3. Modeling Approach

A near worst case approach has been adopted for reporting the shadow-flicker results. Additional general site and receptor-specific assessments such as obstacles, diurnal and seasonal cloud and fog patterns may further reduce the reported shadow flicker impacts. The analysis assumes windows are situated in direct alignment with the turbine to sun line of sight. Even when windows are so aligned, the analysis does not account for the difference between windows in rooms with primary use and enjoyment (e.g. living rooms) and other less frequently occupied rooms.

The shadow-flicker model uses the following input:

- Turbine locations (coordinates)
- Shadow Flicker receptor (residence) locations (coordinates)
- USGS 1:24,000 topographic and USGS DEM (height contours)
- Turbine rotor diameter
- Turbine hub height
- Joint wind speed and direction frequency distribution
- Sunshine hours (long term monthly reference data)

The model calculates detailed shadow-flicker results at each assessed receptor location and the amount of shadow-flicker time (hours/year) everywhere surrounding the project (on an iso-line plot). A receptor in the model is defined as a 1 m^2 area 1 meter above ground level. This omni-directional approach produces shadow-flicker results at a receptor regardless of the direction of windows and provides similar results as a model with windows on various sides of the receptor.

The sun's path with respect to each turbine location is calculated by the software to determine the cast shadow paths every 2 minutes, every day over a full year.

The turbine run-time and direction (seen from the receptor) are calculated from the site's long-term wind speed and direction distribution.

Finally, the effects of cloud cover are calculated using long term reference data (monthly average sunshine hours) to arrive at the projected annual flicker time at each receptor.

Output from the model includes the following information:

- Calculated shadow-flicker time at selected receptors
- Tabulated and plotted time of day with shadow flicker at selected receptors
- Map showing turbine locations, selected shadow-flicker receptors and iso-line contours indicating projected shadow-flicker time (hours per year).

4. Conclusion

The shadow-flicker model assumptions applied to this project are very conservative and as such, the analysis is expected to over-predict the impacts. Additionally, many of the modeled shadow flicker hours are expected to be of very low intensity.

The results are therefore prudent projections of the anticipated shadow flicker levels that would be experienced at the nearby residences. The modeled results have been summarized below.

Receptor name	Shadow hours per year (worst case) [hh:mm / year]	Shadow days per year [days / year]	Max shadow hours per day [hh:mm / day]	Shadow hours per year (real) [hh:mm / year]
537	110:50	214	0:52	39:15
653	109:44	192	1:14	37:03
221	108:52	216	1:06	36:06
226	93:34	151	1:04	33:28
599	91:52	210	0:58	30:05
101	103:22	205	0:48	29:37
639	105:54	262	0:48	29:29
640	107:16	253	0:48	29:08
228	80:42	143	0:52	29:05
603	121:08	204	1:00	28:41
638	105:22	225	0:44	27:42
598	94:30	173	1:06	27:31
013	74:28	123	0:58	26:47
100	98:44	205	0:58	26:19
651	118:46	161	1:28	26:16
600	91:24	184	0:50	26:14
555	95:06	187	1:02	26:08
052	98:00	104	1:38	25:07
650	120:08	154	1:26	25:02

Fig. 1. Shadow-flicker listing, 25 hours and above.

The overall statistics are outlined below:

Cumulative shadow-flicker time	Number of receptors	--of which receive extreme low intensity
Total	332	
>0 hours	244	63
>10 hours	102	28
>15 hours	51	10
>20 hours	28	2
>25 hours	19	5

Fig. 2. Overall statistics, all receptors.

Of the 19 receptors potentially receiving more than 25 hours:
14 of them will potentially receive between 25 and 30 hours per year
2 of them will potentially receive between 30 and 35 hours per year
1 will potentially receive 36 hours and 6 minutes per year
1 will potentially receive 37 hours and 3 minutes per year
1 will potentially receive 39 hours and 15 minute per year

In general, receptors that receive relatively many hours of shadow-flicker receive it at noticeable intensity. This is quite logical in that turbines close to a receptor cast shadows for relatively longer time. The largest departures from this normal is when turbines far away from a receptor contribute with many hours of (low intensity) shadow-flicker. Below in fig. 3 is listed how many hours (approximately) the receptors in fig. 1 receive extreme low intensity shadow-flicker:

Receptor	Shadow hours per year (real) [hh:mm / year	Approximate hours with extreme low intensity
537	39:15	2.0
653	37:03	0.5
221	36:06	0.5
226	33:28	0.5
599	30:05	2.0
101	29:37	0
639	29:29	2.0
640	29:08	2.5
228	29:05	0.5
603	28:41	1.0
638	27:42	0.5
598	27:31	2.0
013	26:47	2.0
100	26:19	0
651	26:16	0.5
600	26:14	2.0
555	26:08	1.5
052	25:07	0.5
650	25:02	0.5

Fig. 3. Shadow-flicker listing, hours of extreme low intensity.

The list of receptors receiving shadow-flicker in the category “noticeable” and “more than 25 hours” contain hereafter only 14 receptors (see fig. 4).

Receptor name	Shadow hours per year (worst case) [hh:mm / year]	Shadow days per year [days / year]	Max shadow hours per day [hh:mm / day]	Shadow hours per year (real) [hh:mm / year]
537	104:08	183	0:52	37:09
653	107:46	171	1:14	36:24
221	106:26	216	1:06	35:42
226	90:18	151	1:04	32:50
101	103:22	205	0:48	29:37
228	79:02	143	0:52	28:42
599	85:22	184	0:58	27:56
639	94:52	195	0:48	27:39
603	116:50	198	1:00	27:28
638	104:26	225	0:44	27:23
640	95:50	189	0:48	26:42

100	98:44	205	0:58	26:19
598	89:14	147	1:06	25:50
651	117:24	145	1:28	25:48

Fig. 4. Shadow-flicker listing, 'noticeable' and above25 hours.

Receptors 537 and 226 are analyzed further below – mainly to show how the various charts and plots in the detailed shadow-flicker reports can be read.

Receptor 537:
The detailed shadow-flicker contour around receptor 537 is seen below in fig. 5.

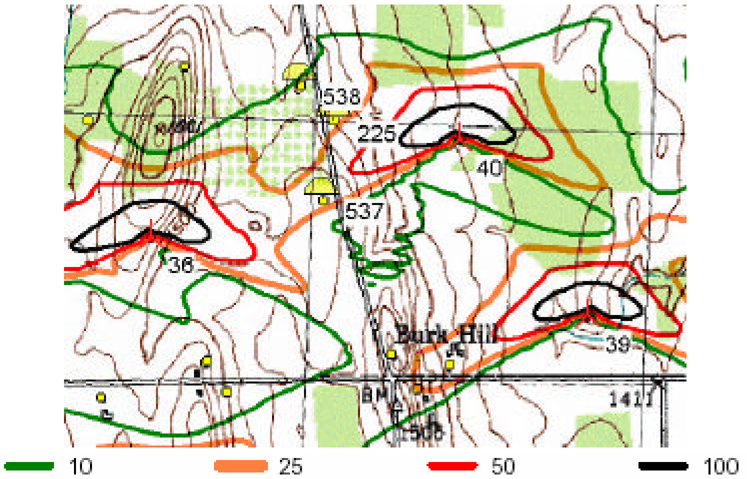

Fig. 5. Shadow-flicker contours around receptor 537.

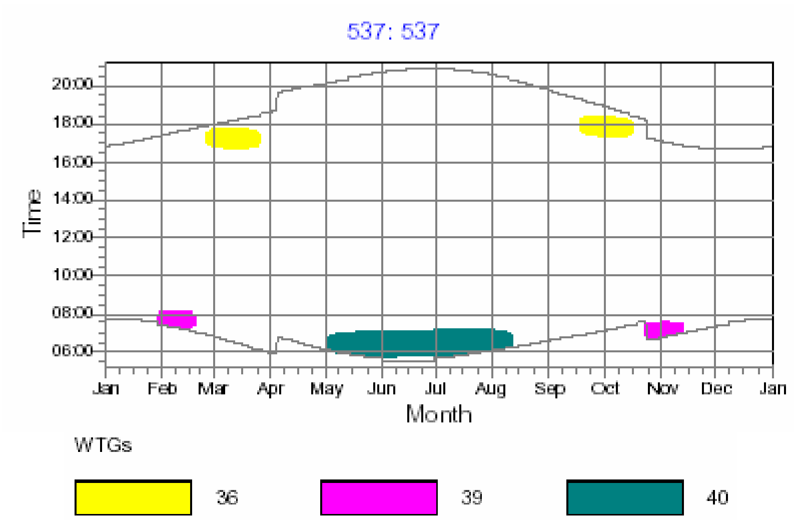

Fig. 6. Months and time of day with shadow-flicker for receptor 537.

The distance from receptor 537 to turbine 40 (and 36) is 440 meters (1,440 feet). Most of the shadow-flicker will potentially occur during summer mornings from turbine 40. Just how and how much this will affect receptor 537 depends on the design of the residence (windows, porch etc.), the immediate surroundings (obscuring garage, shadowing trees etc.), and on what activities take place at times with potential shadow-flicker.

Receptor 226:

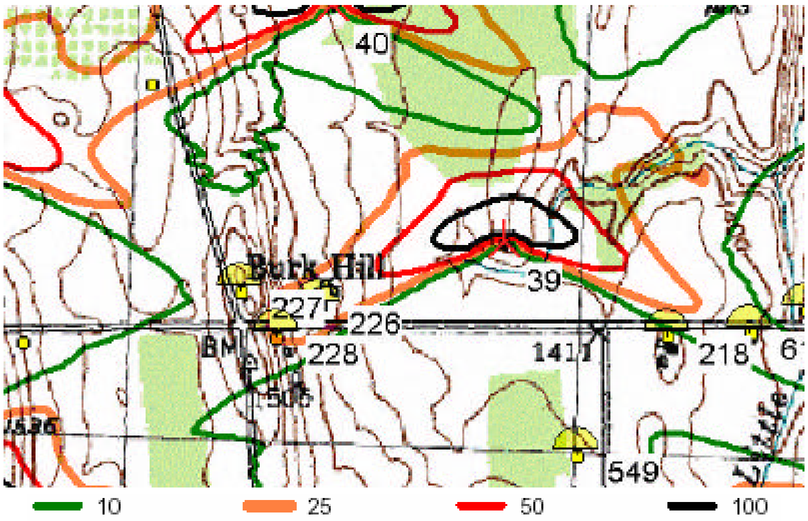

Fig. 5. Shadow-flicker contours around receptor 226.

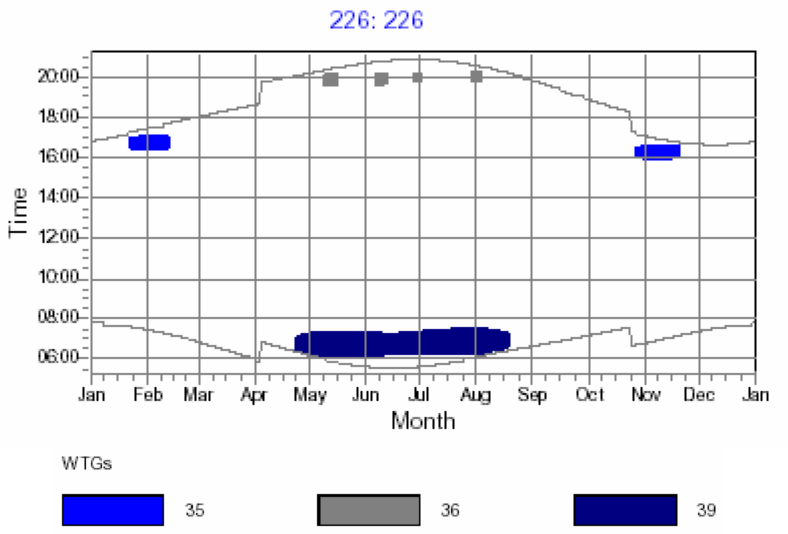

Fig. 7. Months and time of day with shadow-flicker for receptor 226.

It is seen that receptor 226 receive most of the shadow-flicker from turbine 39 which is also the closest turbine (highest intensity). Turbine 39 is also the only turbine that potentially contributes shadow-flicker summer mornings.

The number of shadow-flicker hours calculated and reported above in the tables is common and comparable to other wind power projects installed around the USA.

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