Estimating annoyance to calculated wind turbine shadow flicker is improved when variables associated with wind turbine noise exposure are considered

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The *Community Noise and Health Study* conducted by Health Canada included randomly selected participants aged 18–79 yrs (606 males, 632 females, response rate 78.9%), living between 0.25 and 11.22 km from operational wind turbines. Annoyance to wind turbine noise (WTN) and other features, including shadow flicker (SF) was assessed. The current analysis reports on the degree to which estimating high annoyance to wind turbine shadow flicker (HA_{WTSF}) was improved when variables known to be related to WTN exposure were also considered. As SF exposure increased [calculated as maximum minutes per day (SF_m)], HA_{WTSF} increased from 3.8% at $0 \leq SF_m < 10$ to 21.1% at $SF_m \geq 30$, $p < 0.0001$. For each unit increase in SF_m the odds ratio was 2.02 [95% confidence interval: (1.68,2.43)]. Stepwise regression models for HA_{WTSF} had a predictive strength of up to 53% with 10% attributed to SF_m. Variables associated with HA_{WTSF} included, but were not limited to, annoyance to other wind turbine-related features, concern for physical safety, and noise sensitivity. Reported dizziness was also retained in the final model at $p = 0.0581$. Study findings add to the growing science base in this area and may be helpful in identifying factors associated with community reactions to SF exposure from wind turbines. [http://dx.doi.org/10.1121/1.4942403]

[JFL] Pages: 1480–1492

I. INTRODUCTION

There are a growing number of studies that have assessed community annoyance to wind turbine noise (WTN) exposure using modeled WTN levels and/or proximity to wind turbines (WTs) (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2007; Pedersen *et al.*, 2009; Pedersen, 2011; Verheijen *et al.*, 2011; Pawlaczyk-Łuszczyńska *et al.*, 2014; Tachibana *et al.*, 2014). Adding to these findings are the results from the Health Canada *Community Noise and Health Study* (CNHS) where it was found that the prevalence of self-reported high annoyance to several WT features, including noise, vibrations, visual impact, blinking lights, and shadow flicker (SF) increased with increasing exposure to modeled outdoor A-weighted WTN levels (Michaud *et al.*, 2016b).

This suggests that in addition to providing an estimate of WTN annoyance, modeled WTN levels could also be used to estimate annoyance from other WT-related variables. Although there is a benefit to using WTN to estimate multiple community reactions, the advantages of a more parsimonious exposure assessment may not necessarily be the best approach for estimating annoyance responses that are based on visual

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perception. These reactions may be estimated with more accuracy with an exposure model that estimates the visual exposure that is presumably causing annoyance. In this regard, there was an opportunity in the CNHS to investigate the prevalence of high annoyance to wind turbine shadow flicker (HA_{WTSF}) using a commercially available model for SF exposure.

WT SF is a phenomenon that occurs when rotating blades from a WT cast periodic shadows on adjacent land or properties [Bolton, 2007; Department of Energy and Climate Change (DECC), 2011; Saidur *et al.*, 2011]. The occurrence of SF is determined by a specific set of variables that include the hub height of the turbine, its rotor diameter and blade width, the position of the Sun, and varying weather patterns, such as wind direction, wind speed, and cloud cover [Harding *et al.*, 2008; Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH), 2012; Katsaprakakis, 2012]. As the onset of shadow flickering will only occur when the WT blades are in motion, it will always be associated with at least some level of WTN emissions. When studying the effects of SF, it is therefore important to also consider personal and situational variables that have been assessed in relation to WTN annoyance. These include, but are not limited to, noise sensitivity, concern for physical safety, reported health effects, property ownership, presence of WTs on property, type of dwelling, personal benefit, etc. (Michaud *et al.*, 2016a). Unlike annoyance reactions, conceptually, "*concern for physical safety*" from having WTs in the area was not considered to necessarily be a response to operational WTs. Rather, this is more likely to reflect an attitudinal variable that could exert an influence on the response to SF. This would align with the research that has repeatedly demonstrated that "*fear of the source*," but not its associated noise, has been found to have an influence on noise annoyance (Fields, 1993).

The current analysis follows the approach presented by Michaud *et al.* (2016a). Two multiple regression models are provided for HA_{WTSF}. The first model is *unrestricted*, with variables retained in the model based solely on their statistical strength of association with HA_{WTSF}. In contrast, the second model can be viewed as *restricted*, insofar as variables that are *reactions* to WT operations are not considered. The rationale for two models is that while the unrestricted model reports on all of the variables that were found to be most strongly associated with HA_{WTSF} in the current study, the restricted model may yield information that could be used to identify annoyance mitigation measures and other methods of accounting for HA_{WTSF}, over and above reducing SF exposure levels.

II. METHODS

A. Sample design

1. Target population, sample size and sampling frame strategy

A detailed description of the study design and methodology, the target population, final sample size, and allocation of participants, as well as the strategy used to develop the sampling frame has been described by Michaud *et al.* (2013) and Michaud *et al.* (2016b). Briefly, the study locations were drawn from areas in southwestern Ontario (ON) and Prince Edward Island (PEI) having a relatively high density of dwellings within the vicinity of WTs. Preference was also given to areas that shared similar features (i.e., rural/semirural, flat terrain, and free of significant/regular aircraft exposure that could confound the response to WTN). There were 2004 potential dwellings identified from the ON and PEI sampling regions which included a total of 315 and 84 WTs, respectively. The WT electrical power outputs ranged between 660 kW and 3 MW, with hub heights that were predominantly 80 m. To optimize the statistical power[1] of the study in order to detect an association between WTN and health effects, all identified dwellings within 600 m from a WT were sampled, as occupants in these dwellings would be exposed to the highest WTN levels. Dwellings at further distances were randomly selected up to 11.22 km from a WT. This distance was selected in response to public consultation, and to ensure that exposure-response assessments would include participants unexposed to WTN. The target population consisted of adults aged 18 to 79 yrs.

This study was approved by the Health Canada and Public Health Agency of Canada Review Ethics Board (Protocol Nos. 2012-0065 and 2012-0072).

B. Data collection

1. Questionnaire content and administration

A detailed description of the questionnaire content, pilot testing, administration, and the approaches used to increase participation have been described in detail by Michaud *et al.* (2016b), Michaud *et al.* (2013), and Feder *et al.* (2015). Briefly, the questionnaire instrument included modules on basic demographics, noise and shadow annoyance, health effects (e.g., tinnitus, migraines, dizziness), quality of life, sleep quality, perceived stress, lifestyle behaviours, and chronic diseases.

Data were collected by Statistics Canada who communicated all aspects of the study as the CNHS. This was an attempt to mask the study's true intent, which was to assess the community response to WTs. This approach is commonly used to avoid a disproportionate contribution from any group that may have distinct views toward the study subject. Sixteen (16) interviewers collected study data through in-person interviews between May and September 2013 in southwestern ON and PEI. Once a roster of all adults aged 18 to 79 yrs living in the dwelling was compiled, a computerized method was used to randomly select one adult from each household. No substitution was permitted under any circumstances.

2. Defining percent highly annoyed by SF exposure

As part of the household interview, participants were asked if they could see WTs from anywhere on their property. Participants that indicated they could see WTs were then asked to rate their magnitude of annoyance with "*shadows or flickers of light*" (hereafter referred to as SF annoyance) from WTs by selecting one of the following categories: "*not at all*," "*slightly*," "*moderately*," "*very*," or "*extremely*." Consistent with the approach recommended in ISO/TS-15666 (2003), the top two categories were collapsed to create a "*highly annoyed*" group (i.e., HA_{WTSF}). This group was compared to a group defined as "*not highly annoyed*" which consisted of all other categories, including those who did not see WTs. The same approach was taken for defining the percentage highly annoyed by WTN (Michaud *et al*., 2016a).

C. Modeling WT SF

SF exposure was calculated for all dwellings with WindPro v. 2.9 software (EMD International®, 2013a,b). The model estimated SF exposure from all possible visible WTs from a particular dwelling. WindPro sets the maximum default distance that is used to create this exposure area to be 2 km from a WT, based on available German nationwide requirements (German Federal Ministry of Justice, 2011; EMD International®, 2013a,b). Beyond this distance, the model assumes that shadow exposure will dissipate before reaching dwellings. At 2 km an object must be at least 17.5 m wide to be able to fully cover the Sun's disk and thus cause a maximum variation in light intensity. As WT blades are much narrower, the sunlight will only be partially blocked and the variation in light intensity will be considerably decreased. Other calculation parameters were set for the astronomical maximum shadow durations (i.e., worst case) including: solar elevation angles greater than 3° above the horizon; no clouds; constant WT operation; and rotor and dwelling facade perpendicular to the rays of the Sun (German Federal Ministry of Justice, 2011). Base maps set within the appropriate UTM grid zones for the studied areas were fitted with local height contours and land cover data for forested areas (Natural Resources Canada, 2016). Average tree heights for the most common tree species were estimated for both provinces (Gaudet and Profitt, 1958; Peng, 1999; Sharma and Parton, 2007; Schneider and Pautler, 2009; Ontario Ministry of Natural Resources, 2014) as vegetation can block the line of sight of a turbine and thus may reduce SF exposure [Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH), 2012; EMD International®, 2013a,b]. The model calculates SF exposure at the dwelling window, which factors in window dimensions, window height above ground, and window distance from room floor for all dwellings. In the current study, the WindPro default window dimension (1 m × 1 m) and distance from the bottom of the window to the room floor (1 m) were considered to be representative of the dwellings in the CNHS. With regards to dwelling height, the default value in WindPro is 1.5 m from the ground; however, in order to be consistent with modeled WTN and standard practice in Canada (ONMOE, 2008; Keith *et al*., 2016), a dwelling height of 4 m was chosen. The "*greenhouse*" mode for SF exposure calculation was used, which considers that the dwelling window can be affected by SF from all possible directions by all WTs within the line of sight of a dwelling. As a result, the calculations provided worst-case SF exposure for all dwelling windows from each facade.

As mentioned above, SF occurs together with noise emissions. Therefore, WTN levels considered in this analysis are based on the calculations presented by Keith *et al*. (2016).

D. Model uncertainties

There are some limitations associated with the current available SF calculation models, which may have an influence on the analysis of the study responses. With regards to this particular model, there are uncertainties regarding the specific distance from a WT where SF ceases to be visible, when the worst-case scenario method is employed (EMD International, 2013a,b). However, when applying Weber's Law of Just Noticeable Difference (Ross, 1997) to the turbines in this study, the distance at which the shadow flickering ceases to be noticeable falls within the 2 km exposure range, which is in line with the software default parameters. Even the combined uncertainty of ±55 m that is associated with using GPS to estimate the location of the dwellings and the location of the WTs in the study (Keith *et al*., 2016), is not likely to have a large impact on SF exposure near the WindPro 2 km default exposure limit. The impact of this uncertainty increases with decreasing distance between the dwelling and WT (Fig. 1). This is especially the case in the North to South orientation relative to the WT (e.g., dwelling H, Fig. 1). In a worst case scenario, due to the nature of SF exposure, at close distances to the WT it is possible that dwellings could be misclassified as having no exposure when they may in fact receive high levels of SF exposure or vice-versa (e.g., dwelling E, Fig. 1).

Shadow areas as well as turbine and dwelling points were plotted using WindPro v. 3.0 (EMD International®, 2015) and Global Mapper v.14 (Blue Marble Geographics®, 2012). These plots indicate that approximately 10% of the dwellings included in the analysis are at risk of being misclassified with regards to their respective SF exposure groups (Sec. II E).

E. Statistical analysis

The analysis for categorical outcomes follows very closely the description as outlined in Michaud *et al*. (2013). SF exposure groups were delineated in the following manner:

- in hours per year (SF_h): (i) $0 \le SF_h < 10$, (ii) $10 \le SF_h < 30$, and (iii) $SF_h \ge 30$;
- in days per year (SF_d): (i) $0 \le SF_d < 15$, (ii) $15 \le SF_d < 45$, and (iii) $SF_d \ge 45$;
- in maximum minutes per day (SF_m): (i) $0 \le SF_m < 10$, (ii) $10 \le SF_m < 20$, (iii) $20 \le SF_m < 30$, and (iv) $SF_m \ge 30$.

The Cochran-Mantel-Haenszel (CMH) chi-square test was used to detect associations between sample characteristics and SF exposure groups while controlling for province. As a first step to develop the best predictive model, univariate logistic regression models for HA_{WTSF} were fitted, with SF_m categories as the exposure of interest, adjusted for province and a predictor of interest. It should be emphasized that potential predictors considered in the univariate analysis have been previously demonstrated to be related to the modeled endpoint and/or considered by the authors to conceptually have a potential association with the modeled endpoint. In the absence of other possibly important predictors, the interpretation

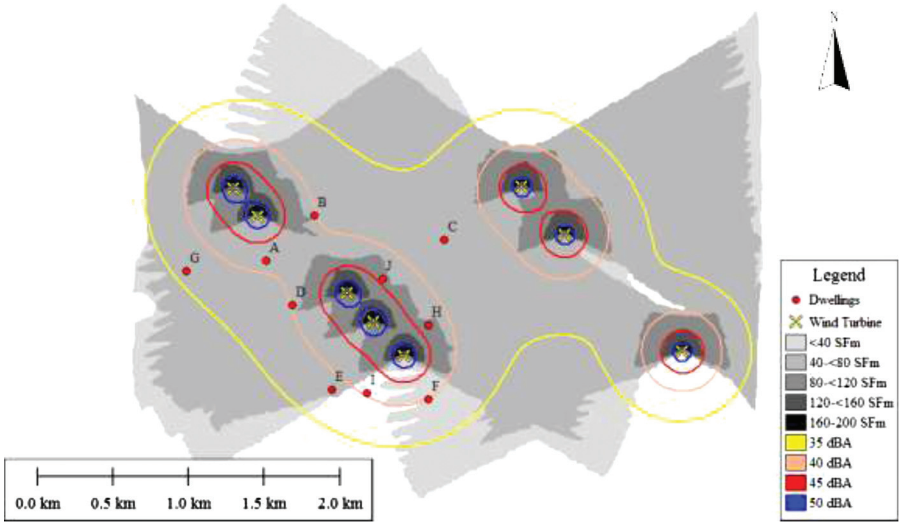

FIG. 1. A theoretical illustration of co-exposure to modeled WT SF and WTN levels. This figure presents a simulation of SF and noise exposure generated by eight WTs on flat terrain, with shadow coverage and WTN level contours described by the sequential color palettes in the legend box. The particular shape of the shadow coverage is created as the Sun moves behind the turbines throughout the day, generating a bowtie-shaped coverage area that is due to longer shadows at sunrise and sunset and shorter shadows at mid-day. In an actual WT park, dwellings are exposed to the combination of SF exposure from multiple turbines, as illustrated in this figure. As can be seen in the case of dwelling I, it is theoretically possible for a dwelling to be located relatively close to a WT, where WTN levels exceed 40 dBA, but outside the SF exposure area. For this demonstration, calculations were carried out with WindPro 3.0 (EMD International®, 2015) and projected with Global Mapper v.14 (Blue Marble Geographics®, 2012). WindPro 3.0 is used here in order to simultaneously present both WTN levels and shadow exposure. Shadow exposure is quantified in SF_m, while WTN noise levels are expressed in A-weighted decibels (dBA).

of any individual relationship in the univariate analysis must be made with caution as it may be tenuous.

The unrestricted and restricted multiple logistic regression models for HA_{WTSF} were developed using stepwise regression with a 20% significance entry criterion for predictors (based upon univariate analyses) and a 10% significance criterion to remain in the model. The stepwise regression was carried out in three different ways: (1) the base model included exposure to SF_m categories and province; (2) the base model included exposure to SF_m categories, province, and an adjustment for participants who reported receiving personal benefit from having WTs in the area; and (3) the base model included exposure to SF_m categories and province, conditioned on those who reported receiving no personal benefit. In all models, SF_m categories were treated as a continuous variable. The unrestricted model aimed to identify variables that have the strongest overall association with HA_{WTSF}. In the restricted model, the variables not considered for entry were those that were subjective responses to WT operations, such as high annoyances to visual, blinking lights, noise, vibrations, the World Health Organization (WHO) domain score, as well as the two standalone WHO questions (Quality of Life and Satisfaction with Health) and the perceived stress scale (PSS) scores.

Exact tests were used in cases when cell frequencies were <5 in the contingency tables or logistic regression models (Stokes *et al.*, 2000; Agresti, 2002). All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. Since the interaction between modeled SF exposure and province was never statistically significant, province was treated as a confounder in all of the regression models. The Nagelkerke pseudo R^2 and Hosmer-Lemeshow (H-L) p-value are reported for all logistic regression models. The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable. When the p-value from the H-L goodness of fit test is >0.05, it indicates a good fit.

Statistical analysis was performed using Statistical Analysis System (SAS) version 9.2 (2014). A 5% statistical significance level was implemented throughout unless otherwise stated. In addition, Bonferroni corrections were made to account for all pairwise comparisons to ensure that the overall Type I (false positive) error rate was less than 0.05.

III. RESULTS

A. Response rates, WT SF and WTN levels at dwellings

Of the 2004 potential dwellings, 1570 were valid dwellings[2] and 1238 individuals agreed to participate in the study (606 males, 632 females). This produced a final response rate of 78.9%. Table I presents information about the study population by the SF_m categories, as this exposure parameter was found to be the most strongly associated with HA_{WTSF} when compared to shadow exposure in hours per year (SF_h) and total shadow days per year (SF_d) (see Sec. III B). The majority of respondents were located in the two lowest SF exposure groups, i.e., $0 \leq SF_m < 10$ ($n = 654$, 53.0%) and $10 \leq SF_m < 20$ ($n = 233$, 18.9%), and the least number of respondents ($n = 161$, 13.1%) were situated in areas where $SF_m \geq 30$. Employment ($p = 0.0186$), household annual income ($p = 0.0002$), and ownership of property in PEI ($p < 0.0001$) were significantly related to SF categories (Table I). Participants receiving personal benefits from having WTs on their properties were not equally distributed between SF categories ($p < 0.0001$) with the greatest proportion of these participants situated in areas with $SF_m \geq 20$. Self-reported prevalence of health effects such as migraines/

TABLE I. Sample characteristics by SF exposure.

Variable	Shadow flicker exposure (SF_m) $0 \le SF_m < 10$	$10 \le SF_m < 20$	$20 \le SF_m < 30$	$SF_m \ge 30$	Overall	CMH p-value[a]
n	657[b]	234[b]	185[b]	162[b]	1238[b]	
SF_h min–max[c]	0–4.5	1.67–24.10	6.07–62.65	15.05–136.67		
SF_d min–max[d]	0–62	14–133	28–228	39–242		
Distance between dwellings and nearest WT (km) min–max	0.40–11.22	0.44–1.46	0.33–1.18	0.25–0.84		
Distance between dwellings and nearest WT (km) 50th, 95th percentiles	1.38, 8.54	1.02, 1.38	0.81, 1.05	0.60, 0.78		
WTN level (dB) min–max	<25–43	29–43	32–45	35–46		
WTN level (dB) 50th, 95th percentiles	33, 41	36, 41	38, 42	40, 45		
Do not see WT n (%)	133 (20.3)	11 (4.7)	3 (1.6)	2 (1.2)	149 (12.1)	
Highly annoyed to WTSF[e] n (%)	25 (3.8)	12 (5.2)	25 (13.5)	34 (21.1)	96 (7.8)	<0.0001
Highly annoyed by WTN (either indoors or outdoors)[e] n (%)	38 (5.8)	14 (6.0)	18 (9.7)	19 (11.8)	89 (7.2)	0.0013
Highly annoyed by WTN indoors[e] n (%)	20 (3.1)	10 (4.3)	6 (3.2)	11 (6.8)	47 (3.8)	0.0275
Highly annoyed by WTN outdoors[e] n (%)	44 (6.7)	15 (6.4)	22 (11.9)	21 (13.0)	102 (8.3)	0.0012
Highly annoyed by WT blinking lights[e] n (%)	54 (8.3)	21 (9.0)	26 (14.1)	21 (13.0)	122 (9.9)	0.0033
Highly annoyed visually by WT[e] n (%)	70 (10.7)	33 (14.1)	30 (16.2)	26 (16.2)	159 (12.9)	0.0054
Highly annoyed by WT vibrations[e] n (%)	8 (1.2)	0 (0.0)	5 (2.7)	6 (3.8)	19 (1.5)	0.0147
Sex n (%males)	318 (48.4)	120 (51.3)	95 (51.4)	73 (45.1)	606 (49.0)	0.9432
Age mean (SE)	51.91 (0.71)	50.71 (1.13)	50.44 (1.21)	51.01 (1.25)	51.61 (0.44)	0.5854[f]
Marital Status (PEI) n (%)						0.0724[g]
Married/Common-law	73 (60.3)	16 (80.0)	29 (87.9)	38 (71.7)	156 (68.7)	
Widowed/Separated/Divorced	22 (18.2)	2 (10.0)	1 (3.0)	8 (15.1)	33 (14.5)	
Single, never been married	26 (21.5)	2 (10.0)	3 (9.1)	7 (13.2)	38 (16.7)	
Marital Status (ON) n (%)						0.1939 [g]
Married/Common-law	371 (69.5)	137 (64.0)	110 (72.8)	74 (67.9)	692 (68.7)	
Widowed/Separated/Divorced	103 (19.3)	38 (17.8)	21 (13.9)	20 (18.3)	182 (18.1)	
Single, never been married	60 (11.2)	39 (18.2)	20 (13.2)	15 (13.8)	134 (13.3)	
Employment n (%employed)	359 (54.7)	149 (63.7)	111 (60.0)	103 (63.6)	722 (58.4)	0.0186
Agricultural employment n (%)	50 (14.0)	25 (16.9)	6 (5.5)	17 (16.7)	98 (13.7)	0.6272
Level of education n (%)						0.8435
≤High School	357 (54.4)	130 (55.6)	100 (54.1)	91 (56.2)	678 (54.8)	
Trade/Certificate/College	254 (38.7)	87 (37.2)	72 (38.9)	56 (34.6)	469 (37.9)	
University	45 (6.9)	17 (7.3)	13 (7.0)	15 (9.3)	90 (7.3)	
Household income (×$1000) n (%)						0.0002
<60	300 (53.3)	111 (55.5)	70 (45.5)	50 (37.3)	531 (50.5)	
60–100	155 (27.5)	56 (28.0)	43 (27.9)	46 (34.3)	300 (28.5)	
≥100	108 (19.2)	33 (16.5)	41 (26.6)	38 (28.4)	220 (20.9)	
Property ownership (PEI) n (%)	83 (68.6)	20 (100.0)	31 (93.9)	48 (90.6)	182 (80.2)	<0.0001[e]
Property ownership (ON) n (%)	471 (87.9)	188 (87.9)	134 (88.2)	101 (92.7)	894 (88.4)	0.5419[e]
Receive personal benefits n (%)	37 (6.0)	19 (8.4)	23 (12.6)	31 (19.5)	110 (9.3)	<0.0001

[a]The CMH chi-square test is used to adjust for province unless otherwise indicated.
[b]Totals may differ due to missing data.
[c]SF_h, maximum number of hours of SF in hours per day.
[d]SF_d, maximum amount of SF exposure in days per year.
[e]Highly annoyed includes the ratings *very* or *extremely*.
[f]Two-way analysis of variance adjusted for province.
[g]Chi-square test of independence.

headaches, chronic pain, dizziness, and tinnitus were all found to be equally distributed across SF categories (data not shown). The corresponding A-weighted WTN levels and proximity to the nearest WT are also shown in Table I.

B. Percentage highly annoyed by SF exposure from WTs

Regardless of the parameter used to quantify SF exposure, in all cases the predictive strength of the base model was statistically weak. Nevertheless, an analysis based on SF_m had the largest R^2 ($R^2 = 11\%$, compared to 10% for SF_h and 8% for SF_d; data not shown). Therefore, results are presented for HA_{WTSF} with respect to SF_m.

A statistically significant exposure-response relationship was found between SF_m and reporting to be HA_{WTSF}. As such, the prevalence of HA_{WTSF} increased from 3.8% in the lowest modeled SF exposure group ($0 \le SF_m < 10$) to 21.1% when modeled shadow exposure was above or equal to 30 min per day, which represents almost a six-fold increase in the prevalence of HA_{WTSF} from the lowest exposure category to the highest. In comparison to an exposure duration of $0 \le SF_m < 10$, the OR for HA_{WTSF} was statistically similar to

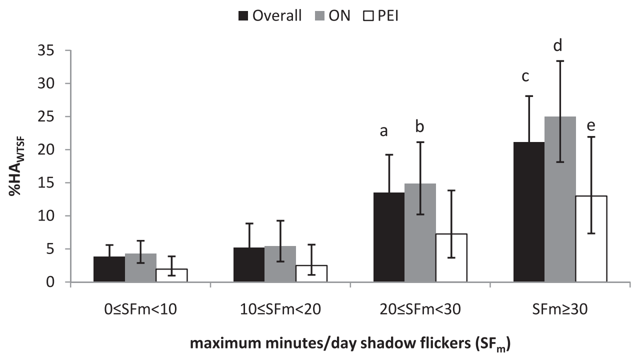

FIG. 2. Illustrates the percentage of participants that reported to be either very or extremely (i.e., highly) bothered, disturbed, or annoyed over the last year or so while at home (either indoors or outdoors) by shadows or flickers of light from WTs. Results are presented by province and as an overall average as a function of modeled SF exposure time (SF_m). Fitted data are plotted along with their 95% CIs. The models fit the data well (H-L test p-value >0.9). Bonferroni corrections were made to account for all pairwise comparisons. [(a), (b), (c)] Significantly different from $0 \le SF_m < 10$ and $10 \le SF_m < 20$; respective p-values for pairwise comparisons, $p \le 0.0138$, $p \le 0.0012$, and $p < 0.0006$. (d) Significantly different compared to all other categories, $p \le 0.0126$; (e) Significantly different compared to $0 \le SF_m < 10$, $p = 0.0162$.

that for $10 \le SF_m < 20$ [1.29, 95% confidence interval (CI): (0.50, 3.33)]; and then significantly increased with increasing SF_m from 3.94 [95% CI: (1.80, 8.63)] at $20 \le SF_m < 30$ to 7.51 [95% CI: (3.54, 15.96)] for $SF_m \ge 30$. Significant increases were also observed between the two highest SF exposure groups ($20 \le SF_m < 30$, $SF_m \ge 30$) and those exposed to $10 \le SF_m < 20$ (see Fig. 2).

1. Univariate analysis of variables related to HA_{WTSF}

Several variables were considered for their potential association with HA_{WTSF} (see Table II). A cautious approach should be taken when interpreting univariate results as these models do not account for the potential influence from other variables. The base model had an R^2 of 11%, compared to a base model of 10% when modeled using outdoor A-weighted WTN as a surrogate of SF exposure (data not shown). Prior to adjusting for other factors, the prevalence of HA_{WTSF} was significantly higher in ON ($p = 0.0193$). As WTN exposure and SF can occur simultaneously, the interaction between WTN levels and SF_m was also tested to assess the possible influence that such an interaction may have on HA_{WTSF}. As can be seen from Table II, the interaction between WTN levels and SF exposure was statistically significant ($p = 0.0260$), and increased the R^2 to 15%. This is somewhat better than the 11% obtained from the base model.

Factors beyond SF and WTN exposure were also considered for their potential influence on HA_{WTSF}. Participants who owned their property had 6.38 times higher odds of reporting HA_{WTSF} compared to those who were renting property [95% CI: (1.54, 26.39)]. Those who did not receive a personal benefit from having WTs in the area were found to have 4.03 times higher odds of being HA_{WTSF} compared to those who did receive personal benefits [95% CI: (1.42, 11.44)]. Those who reported to have migraines, dizziness, and tinnitus had 3 times higher odds of reporting HA_{WTSF} compared to those who did not report these health conditions. Participants that reported having chronic pain, arthritis, or restless leg syndrome had at least one and a half times the odds of reporting HA_{WTSF} compared to those who did not report suffering from these conditions (Table II). Participants who self-identified as being highly sensitive to noise had 3.49 times higher odds of being HA_{WTSF} compared to those who did not self-identify as being highly sensitive to noise [95% CI: (2.14, 5.69)]. Those who reported that WTs were audible had 10.68 times higher odds of HA_{WTSF} compared to those who could not hear WTs [95% CI: (5.07, 22.51)]. This variable was further categorized into the length of time that the participant heard the WT (do not hear, <1 year, ≥1 year); it was found that both those who heard WTs for less than 1 year and 1 year or greater had higher odds of being HA_{WTSF} compared to those who could not hear the WTs. Furthermore, there was no statistical difference in the proportion HA_{WTSF} among those who heard the WTs for less than 1 year or greater than or equal to 1 year ($p = 0.0924$). People who did not have a WT on their property had higher odds of reporting HA_{WTSF} compared to those who had at least one WT on their property [OR = 11.07, 95% CI: (1.49, 82.14)]. Annoyance variables were significantly correlated (Table III) and participants who were highly annoyed to any of the aspects of WT (noise, blinking lights, visual, and vibrations) tended to be also HA_{WTSF}.

The OR for these annoyances ranged from 13 to 34, with annoyance to vibrations and blinking lights having the lowest and highest OR, respectively. Concern for physical safety due to the presence of WTs in the studied communities (i.e., *concern for physical safety* variable) was also highly associated with HA_{WTSF}; participants who were highly concerned about their physical safety had 14.15 times higher odds of HA_{WTSF} compared to those who were not highly concerned about their physical safety [95% CI: (8.17, 24.53)]. Those who identified that their quality of life was "*Poor*" or were "*Dissatisfied*" with their health had 2 times higher odds of reporting HA_{WTSF} compared to their counterparts. Both the physical health domain and the environmental domain from the abbreviated World Health Organization Quality of Life questionnaire were negatively associated with being HA_{WTSF} (Feder *et al.*, 2015). That is to say that as the domain value increased (indicating an improved domain value), the prevalence of HA_{WTSF} decreased. Additionally, as the PSS scores of participants increased, so did the prevalence of HA_{WTSF} by 3% [95% CI: (1.00, 1.07)] (Table II).

2. Multiple logistic regression analyses of variables related to HA_{WTSF}

Table IV presents the unrestricted multiple logistic regression model for HA_{WTSF}. The first variable to enter the model was annoyance with WT blinking lights, which increased the R^2 from 11% at the base model level to 42%. This was followed by annoyance to WTN when outdoors, annoyance to the visual aspect of WTs, concern for physical safety, audibility of WTs, and annoyance to vibrations caused by WTs, which together increased the R^2 of the final model to 53%. Personal economic benefit associated with WTs has been found to have a strong impact on reducing

TABLE II. Univariate analysis of variables related to HA_{WTSF}.

Variable	Groups in variable[a]	Nagelkerke pseudo R^2	SF_m[b] OR (CI)[d]	SF_m[b] p-value	Explanatory variable OR (CI)[d]	Explanatory variable p-value	Province[c] OR (CI)[d]	Province[c] p-value	H-L test[e]
Base model[f,b]		0.11	2.02 (1.68, 2.43)	<0.0001			2.16 (1.13, 4.12)	0.0193	0.7699
SF_m × WTN level[g]		0.15	—[h]		—[h]		2.03 (1.04, 3.98)	0.0381	0.4851
Sex	Male/Female	0.11	2.02 (1.68, 2.43)	<0.0001	1.10 (0.72, 1.70)	0.6527	2.15 (1.13, 4.10)	0.0203	0.6015
Age group	≤24	0.12	2.03 (1.69, 2.45)	<0.0001	0.55 (0.15, 1.98)	0.3611	2.23 (1.17, 4.27)	0.0153	0.5879
	25–44				1.40 (0.74, 2.65)	0.3002			
	45–64				1.47 (0.83, 2.62)	0.1901			
	65+				reference				
Education	≤High School	0.11	2.02 (1.68, 2.43)	<0.0001	1.19 (0.48, 2.92)	0.7112	2.12 (1.11, 4.05)	0.0225	0.8936
	Trade/Certificate/College				1.40 (0.56, 3.50)	0.4695			
	University				reference				
Income (×$1000)	<60	0.12	1.99 (1.63, 2.44)	<0.0001	0.71 (0.39, 1.29)	0.2617	1.68 (0.85, 3.33)	0.1390	0.1722
	60–100				1.08 (0.59, 1.98)	0.8041			
	≥100				reference				
Marital Status	Married/Common-law	0.12	2.02 (1.68, 2.43)	<0.0001	1.76 (0.85, 3.65)	0.1274	2.20 (1.15, 4.21)	0.0169	0.5600
	Widowed/Separated/Divorced				1.21 (0.50, 2.97)	0.6746			
	Single, never been married				reference				
Property ownership	Own/rent	0.13	1.99 (1.65, 2.39)	<0.0001	6.38 (1.54, 26.39)	0.0105	2.11 (1.10, 4.04)	0.0246	0.8715
Type of dwelling	Single detached/Other	0.11	1.99 (1.65, 2.40)	<0.0001	1.67 (0.51, 5.52)	0.3969	2.10 (1.10, 4.02)	0.0246	0.6535
Employment	Employed/not employed	0.12	2.00 (1.67, 2.41)	<0.0001	1.43 (0.91, 2.26)	0.1247	2.18 (1.14, 4.16)	0.0183	0.3034
Type of employment	Agriculture/ Other	0.13	2.03 (1.61, 2.57)	<0.0001	0.95 (0.43, 2.12)	0.9017	3.27 (1.34, 7.98)	0.0094	0.8071
Personal benefit	No/Yes	0.13	2.09 (1.73, 2.52)	<0.0001	4.03 (1.42, 11.44)	0.0088	2.16 (1.13, 4.13)	0.0205	0.7111
Migraines	Yes/No	0.16	2.06 (1.70, 2.48)	<0.0001	3.15 (2.02, 4.94)	<0.0001	1.91 (1.00, 3.68)	0.0518	0.4864
Dizziness	Yes/No	0.15	2.03 (1.69, 2.45)	<0.0001	2.81 (1.79, 4.41)	<0.0001	2.19 (1.14, 4.20)	0.0190	0.6998
Tinnitus	Yes/No	0.15	2.09 (1.73, 2.52)	<0.0001	2.91 (1.85, 4.58)	<0.0001	2.21 (1.15, 4.25)	0.0170	0.6902
Chronic Pain	Yes/No	0.13	2.06 (1.71, 2.48)	<0.0001	2.16 (1.37, 3.42)	0.0010	2.01 (1.05, 3.84)	0.0355	0.5661
Asthma	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	1.19 (0.55, 2.60)	0.6606	2.16 (1.13, 4.12)	0.0194	0.6215
Arthritis	Yes/No	0.12	2.06 (1.71, 2.48)	<0.0001	1.57 (1.01, 2.45)	0.0461	2.20 (1.15, 4.21)	0.0170	0.5660
High Blood Pressure	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	0.90 (0.56, 1.45)	0.6710	2.17 (1.14, 4.14)	0.0186	0.3444
Medication for high blood pressure, past month	Yes/No	0.12	2.02 (1.68, 2.43)	<0.0001	0.74 (0.45, 1.21)	0.2251	2.20 (1.15, 4.19)	0.0171	0.3238
History of high blood pressure in family	Yes/No	0.11	2.02 (1.67, 2.44)	<0.0001	1.03 (0.67, 1.60)	0.8926	2.03 (1.06, 3.88)	0.0334	0.7739
Chronic bronchitis/ emphysema/ COPD	Yes/No	0.11	2.01 (1.67, 2.42)	<0.0001	0.55 (0.16, 1.82)	0.3240	2.18 (1.14, 4.16)	0.0178	0.8001
Diabetes	Yes/No	0.12	2.02 (1.68, 2.44)	<0.0001	0.61 (0.25, 1.45)	0.2587	2.12 (1.11, 4.05)	0.0227	0.6111
Heart disease	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	1.22 (0.56, 2.68)	0.6137	2.15 (1.13, 4.10)	0.0198	0.7954
Diagnosed sleep disorder	Yes/No	0.12	2.02 (1.68, 2.43)	<0.0001	1.57 (0.82, 2.98)	0.1716	2.11 (1.11, 4.03)	0.0236	0.7696
Restless leg syndrome	Yes/No	0.13	2.01 (1.67, 2.42)	<0.0001	2.12 (1.26, 3.55)	0.0044	2.01 (1.05, 3.85)	0.0342	0.5256
Sensitivity to Noise	High/Low	0.15	2.04 (1.69, 2.46)	<0.0001	3.49 (2.14, 5.69)	<0.0001	2.03 (1.06, 3.91)	0.0335	0.4659
See WT	Yes/No	0.14	1.88 (1.56, 2.27)	<0.0001	>999.999 (< 0.001, > 999.999)	0.9658	2.06 (1.08, 3.92)	0.0290	0.7480
Audible WT	Yes/No	0.23	1.66 (1.37, 2.02)	<0.0001	10.68 (5.07, 22.51)	<0.0001	2.42 (1.26, 4.67)	0.0083	0.7198
Number of years turbines audible	less than 1 year	0.23	1.66 (1.37, 2.02)	<0.0001	5.04 (1.56, 16.25)	0.0068	2.51 (1.30, 4.85)	0.0063	0.8472
	1 year or more				11.51 (5.45, 24.33)	<0.0001			
	Do not hear WTs				reference				

TABLE II. (*Continued.*)

Variable	Groups in variable[a]	Nagelkerke pseudo R^2	SF_m[b] OR (CI)[d]	SF_m[b] p-value	Explanatory variable OR (CI)[d]	Explanatory variable p-value	Province[c] OR (CI)[d]	Province[c] p-value	H-L test[e]
At least 1 WT on property	No/Yes	0.14	2.14 (1.77, 2.58)	<0.0001	11.07 (1.49, 82.14)	0.0187	2.07 (1.08, 3.95)	0.0279	0.4544
Visual annoyance to WTs	High/Low	0.37	2.17 (1.75, 2.71)	<0.0001	20.29 (12.24, 33.64)	<0.0001	1.68 (0.79, 3.56)	0.1785	0.9285
Annoyance with blinking lights	High/Low	0.42	2.22 (1.76, 2.80)	<0.0001	34.27 (19.68, 59.67)	<0.0001	1.23 (0.57, 2.66)	0.5984	0.7649
Annoyance to WTN	High/Low	0.30	2.02 (1.65, 2.48)	<0.0001	18.18 (10.58, 31.25)	<0.0001	1.72 (0.85, 3.48)	0.1336	0.3863
Annoyance to WTN from indoors	High/Low	0.23	2.05 (1.68, 2.50)	<0.0001	19.58 (9.80, 39.11)	<0.0001	1.65 (0.85, 3.21)	0.1388	0.4867
Annoyance to WTN from outdoors	High/Low	0.32	2.04 (1.66, 2.52)	<0.0001	19.49 (11.54, 32.93)	<0.0001	2.02 (0.99, 4.12)	0.0545	0.4643
Annoyance to vibrations/rattles	High/Low	0.16	2.01 (1.66, 2.43)	<0.0001	13.07 (4.71, 36.30)	<0.0001	2.07 (1.07, 4.01)	0.0309	0.9413
Concerned about physical safety	High/Low	0.26	1.92 (1.57, 2.34)	<0.0001	14.15 (8.17, 24.53)	<0.0001	2.09 (1.04, 4.18)	0.0379	0.6700
Quality of Life	Poor/Good[i]	0.12	2.04 (1.69, 2.45)	<0.0001	2.31 (1.14, 4.71)	0.0208	2.13 (1.12, 4.06)	0.0218	0.5909
Satisfaction with health	Dissatisfied/Satisfied[j]	0.12	2.04 (1.69, 2.45)	<0.0001	1.84 (1.07, 3.18)	0.0280	2.12 (1.11, 4.04)	0.0227	0.5133
Medication for anxiety/depression	No/Yes	0.11	2.02 (1.68, 2.43)	<0.0001	1.28 (0.62, 2.65)	0.5128	2.19 (1.15, 4.18)	0.0177	0.2842
Continuous scale explanatory variables									
Physical health domain (range 4–20)		0.13	2.06 (1.71, 2.48)	<0.0001	0.90 (0.85, 0.96)	0.0012	2.04 (1.07, 3.90)	0.0313	0.7547
Psychological domain (range 4–20)		0.11	2.02 (1.68, 2.43)	<0.0001	0.98 (0.90, 1.07)	0.6738	2.17 (1.14, 4.14)	0.0187	0.6490
Social relationships domain (range 4–20)		0.11	2.02 (1.68, 2.42)	<0.0001	0.98 (0.91, 1.06)	0.5701	2.14 (1.13, 4.09)	0.0205	0.7782
Environment domain (range 4–20)		0.13	2.05 (1.70, 2.47)	<0.0001	0.88 (0.80, 0.96)	0.0056	2.27 (1.19, 4.34)	0.0134	0.6815
Perceived stress scale (range 0–37)		0.12	2.01 (1.67, 2.42)	<0.0001	1.03 (1.00, 1.07)	0.0386	2.07 (1.08, 3.96)	0.0276	0.6513

[a]Where a reference group is not specified it is taken to be the last group.

[b]The exposure variable, SF_m, is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure.

[c]PEI is the reference group.

[d]Odds ratio (OR) and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.

[e]H-L test, $p > 0.05$ indicates a good fit.

[f]The base model includes the modeled shadow exposure (SF_m) and province.

[g]WTN level is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.

[h]The interaction between WTN levels and modeled shadow exposure was significant ($p = 0.0260$). When fitting separate logistic regression models to each shadow exposure group, it was observed that there was a positive significant relationship between high annoyance to SF and WTN levels only among those in the lowest shadow exposure group [OR and 95% confidence interval: 2.62 (1.64, 4.20)]. The relationship in the other three shadow exposure groups ($10 \leq SF_m < 20$, $20 \leq SF_m < 30$, and $SF_m \geq 30$) was not significant ($p > 0.05$, in all cases).

[i]"Poor" includes those that responded "poor" or "very poor."

[j]"Dissatisfied" includes those that responded "dissatisfied" or "very dissatisfied."

TABLE III. Spearman correlation coefficient (p-value) between annoyance variables.

Type of annoyance[a]	WTN inside	WTN outside	Visual	Blinking lights	SF	Vibrations inside
WTN in or out	0.98 ($p < 0.0001$)	0.99 ($p < 0.0001$)	0.49 ($p < 0.0001$)	0.48 ($p < 0.0001$)	0.51 ($p < 0.0001$)	0.25 ($p < 0.0001$)
WTN inside		0.98 ($p < 0.0001$)	0.46 ($p < 0.0001$)	0.46 ($p < 0.0001$)	0.50 ($p < 0.0001$)	0.23 ($p < 0.0001$)
WTN outside			0.49 ($p < 0.0001$)	0.48 ($p < 0.0001$)	0.51 ($p < 0.0001$)	0.25 ($p < 0.0001$)
Visual				0.79 ($p < 0.0001$)	0.70 ($p < 0.0001$)	0.19 ($p < 0.0001$)
Blinking lights					0.75 ($p < 0.0001$)	0.17 ($p < 0.0001$)
SF						0.18 ($p < 0.0001$)

[a]Participants were asked to indicate how bothered, disturbed, or annoyed they were over the last year or so while at home. Unless the participants' location was specified as indoors or outdoors, at home was defined as either indoors or outdoors. Vibrations were identified as being present during WT operations.

reported annoyance to WTN (Pedersen *et al.*, 2009). In the current study, directly or indirectly receiving personal benefit from having WTs in the area could include receiving payment, rent, or benefiting from community improvements ($n = 110$). When this variable was forced into the final model, it had no influence on the variables that entered the model, nor did it have any impact on the final R^2 (data not shown). Similarly, removing these participants had no influence on the strength of the overall final model (i.e., R^2 remained at 53%). The one change observed when participants receiving personal benefit were removed was that annoyance to vibrations was discarded and restless leg syndrome entered the model at a p-value of 0.0540 (data not shown). The statistically significant interaction between WTN levels and SF_m (see Sec. III B 1) was not found to be related to HA_{WTSF} after adjusting for the variables shown in Table IV.

Table V presents the restricted multiple logistic regression model for HA_{WTSF}. In this restricted model, the first variable to enter the model was concern for physical safety, increasing the R^2 from 11% at the base model level to 26%. The following variables then entered the model: audibility of WTs, sensitivity to noise, having at least one WT on the property, property ownership, and dizziness. The overall fit of the final restricted model was 37%. The last three variables (having at least one WT on the property, property ownership, and dizziness) collectively contributed only an additional 2% to the overall model and were all only significant at the 10% level, and not at the 5% level. Receiving personal benefits does not enter the final model, due to its redundancy given the other variables that did enter the model. However, when it is forced into the model it is significant at $p = 0.0343$ level (data not shown). In this case, the variable "*is there at least one wind turbine on your property*" is dropped in place of "*employment status*," which comes into the model with a p-value of 0.0722 (data not shown). The overall fit of the model improves slightly to 38% (data not shown). Finally, when conditioning on only those who do not receive benefits, the overall fit of the model drops slightly to 36%, with neither of the "*employment status*" nor the "*is there at least one wind turbine on your property*" variables coming into the final model (data not shown).

IV. DISCUSSION

The accumulated research on the potential health effects associated with SF from WTs has concluded that SF from WTs is unlikely to present a risk to the occurrence of seizures, even among individuals that have photosensitive epilepsy (Harding *et al.*, 2008; Knopper *et al.*, 2014; Smedley *et al.*, 2010). The knowledge gap that persists is the extent to which WT SF causes annoyance. Also unknown is how this annoyance may result from an interaction between SF and WTN levels, given that SF and at least some level of WTN emissions occur simultaneously. To date, there have been very few assessments that have evaluated the effect of SF on community response. A German field study performed by Pohl *et al.* (1999) investigated methods for the evaluation of SF exposure, which ultimately led to current SF exposure

TABLE IV. Multiple logistic regression analysis (unrestricted) of variables related to HA_{WTSF}.

Variable	Groups in variable[a]	Stepwise Model 1		Order of entry into model: R^2 at each step
		OR (CI)[b]	p-value	
HA_{WTSF} versus not HA_{WTSF}		($n = 1147$, $R^2 = 0.53$, H-L $p = 0.7536$)		
SF_m[c]		2.04 (1.56, 2.66)	<0.0001	Base: 0.11
Province	ON/PEI	1.20 (0.50, 2.89)	0.6811	Base: 0.11
Annoyance with blinking lights	High/Low	7.67 (3.84, 15.34)	<0.0001	Step 1: 0.42
Annoyance to WTN from outdoors	High/Low	2.25 (1.09, 4.66)	0.0287	Step 2: 0.47
Visual annoyance to WT	High/Low	4.09 (2.09, 7.99)	<0.0001	Step 3: 0.50
Concerned about physical safety	High/Low	2.89 (1.39, 6.01)	0.0045	Step 4: 0.51
Audible WT	Yes/No	3.15 (1.35, 7.34)	0.0080	Step 5: 0.52
Annoyance to vibrations/rattles	High/Low	3.49 (1.00, 12.23)	0.0503	Step 6: 0.53

[a]Where a reference group is not specified it is taken to be the last group.
[b]OR and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c]The exposure variable SF_m is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure.

TABLE V. Multiple logistic regression analysis (restricted) of variables related to HA_{WTSF}.

Variable	Groups in variable[a]	Stepwise Model 1		Order of entry into model: R^2 at each step
		OR (CI)[b]	p-value	
HA_{WTSF} versus not HA_{WTSF}		($n = 1159$, $R^2 = 0.37$, H-L $p = 0.7294$)		
SF_m[c]		1.70 (1.37, 2.11)	<0.0001	Base: 0.11
Province	ON/PEI	2.07 (1.00, 4.27)	0.0494	Base: 0.11
Concerned about physical safety	High/Low	7.01 (3.90, 12.60)	<0.0001	Step 1: 0.26
Audible WT	Yes/No	6.33 (2.90, 13.81)	<0.0001	Step 2: 0.32
Sensitivity to noise	High/Low	2.81 (1.57, 5.05)	0.0005	Step 3: 0.35
At least 1 WT on property	No/Yes	6.87 (0.88, 53.73)	0.0663	Step 4: 0.36
Property ownership	Own/rent	4.78 (0.95, 24.01)	0.0574	Step 5: 0.37
Dizziness	Yes/No	1.68 (0.98, 2.86)	0.0581	Step 6: 0.37

[a]Where a reference group is not specified it is taken to be the last group.

[b]OR and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.

[c]The exposure variable SF_m is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure. Model is restricted insofar as variables that are reactions to WT operations are not considered.

limits in Germany, while a conference paper presented by Pedersen and Persson Waye (2003) assessed annoyance with SF as a function of modeled SF exposure. The conclusion from this conference paper was that modeled WTN levels were a better predictor of annoyance to SF from WTs than modeled SF exposure. A similar conclusion was reached in the current study wherein it was found that, regardless of how SF exposure was modeled, the R^2 for HA_{WTSF} by modeled SF was statistically weak and essentially the same as that found using WTN levels (i.e., 10% and 9%, respectively). Some improvement was found when the interaction between WTN levels and SF_m was considered, which increased the R^2 to 15%. However, after adjusting for other factors that were statistically related to HA_{WTSF}, this interaction was no longer significant in the final multiple regression models.

In spite of the obvious deficiencies in estimating HA_{WTSF} using either A-weighted WTN levels or SF_m alone (or together as an interaction term), a statistically significant exposure-response relationship was found between HA_{WTSF} and SF modeled as SF_m. The strength of the base model was markedly improved from 11% to 53% when adjusting for other factors. In this case, these other factors included those which are subjective and/or could be viewed as reactions to operational WTs (e.g., other annoyances). When the final model was restricted to variables conceptually viewed as objective and/or not contingent upon WT operations, the strength of the final model improved from 11% for the base model to 37%. Both of these models have merit, but as discussed below, the restricted model may be more valuable in situations where a wind farm is not yet operational.

It is not surprising that in the unrestricted model, the variables related to the visual perception of WTs were among those which had the strongest statistical association with $HA_{WTSF,}$ as these were found to be more highly correlated with each other than annoyance reactions mediated through tactile and/or auditory senses (see Table III). Their presence in the final model indicates that there were no issues related to multicollinearity. This should be interpreted to mean that each of these annoyance variables is a significant predictor of HA_{WTSF}. In this regard, most of the increase in the predictive strength of the model for HA_{WTSF} was observed once annoyance to blinking lights on WTs entered the model. This step increased the R^2 from 11% at the base level to 42%. Participants that reported being highly annoyed by blinking lights on WTs had almost 8 times higher odds of being HA_{WTSF}. In a study performed by Pohl *et al.* (2012), it was found that respondents were comparably as strongly annoyed by WT blinking lights as they were by SF, a finding which may also be reflected in this study. It is also worth mentioning that in the CNHS, annoyance to blinking lights on WTs was found to be related to actigraphy-measured sleep disturbance (Michaud *et al.*, 2016c). It is therefore possible that poorer sleep quality at night among these participants is associated with a heightened response to SF during the day.

In the current study, participants reported how annoyed they were by WTN while they were at home (either indoors or outdoors), indoors only, and outdoors only. Annoyance to WTN when inside does not make it into the final models; however, the finding that annoyance to WTN when outside had the stronger association with HA_{WTSF} seems to suggest that SF annoyance is more likely an outdoor phenomena. The results of the unrestricted multiple logistic regression model show that estimating HA_{WTSF} using SF_m can be significantly improved when considering these other annoyances.

Further improvements can be expected when concern for physical safety associated with having WTs in the area and the audibility of WTs are also accounted for. Although *concern for physical safety* may in some cases reflect a response to operational WTs, it could just as readily be treated as an attitudinal response triggered by the anticipated physical presence of industrial WTs. Although extremely rare, there have been reports of catastrophic failure that could exacerbate the level of concern for one's physical safety in the same way rare aircraft accidents are known to increase the fear of aircraft (Fields, 1993; Moran *et al.*, 1981; Reijneveld, 1994). As discussed below, concern for physical safety also appears in the restricted multiple regression model.

In the restricted model (see Table V), which only included variables that were not direct responses to WT operations, it was found that concern for physical safety was the variable that contributed the most to R^2, as it increased the base model R^2 from 11% to 26%. In this case, respondents that declared being highly concerned for their physical safety had, on average, 7 times higher odds of reporting HA_{WTSF}. The observation that this variable was present in both models suggests that actions taken to identify and reduce this concern at the planning stages of a WT facility may reduce HA_{WTSF}.

As already mentioned, exposure to SF from WTs will always occur with at least some level of WTN exposure. It is therefore not surprising that the audibility of WTs and noise sensitivity were also found to be statistically related to HA_{WTSF}. Noise sensitivity has long been known to have an influence on community noise annoyance. At equivalent noise levels, annoyance reactions are higher among people who report to be noise sensitive (Job, 1988).

Although property ownership, having a WT on one's property, and experiencing dizziness appear in the final model, together they only contribute an additional 2% to the overall strength of the model and all three variables are significant only at the 10% level. Therefore, only a very cautious interpretation of their influence on HA_{WTSF} can be made. Property ownership could reflect a greater attachment to one's property and heightened response to any exposure that is perceived to have negative impacts on one's property. The negative association between having a WT on one's property and HA_{WTSF} may be an indication that these participants are more likely to directly or indirectly benefit from having WTs in the area. While personal benefit does not enter any of the final multiple regression models, this is because only 110 participants received personal benefits. When considered alone, personal benefit had an influence on HA_{WTSF}. The presence of dizziness in the final model might be explained by the notion that dizziness can be a sensory-related variable and as such may have an influence on a visually-related parameter, such as HA_{WTSF}. Although both the unrestricted and restricted multiple regression models improved the strength of their corresponding base models substantially, their predictive strength for HA_{WTSF} was still rather limited.

Possible explanations for this limited predictive strength could stem from the uncertainties in the model used to quantify SF_m, as discussed in Sec. II D, or from additional limitations. First and foremost, it should be emphasised that the SF model employed for this study was developed to quantify SF exposure for a specific period of time. Therefore, there may have been a mismatch between the parameter used to quantify SF exposure (i.e., maximum minutes per day at the dwelling window) and the subjective perception of SF from WTs assessed in the current study. Annoyance to SF exposure is not limited to dwelling window façades. It is much more likely to reflect an integrated response to shadow over one's entire property, or to any location where SF is perceived. Additionally, the current SF model presents worst-case SF exposure. A more refined assessment that included precise meteorological conditions, such as cloud coverage as well as wind speed and wind direction, could provide a more accurate evaluation of WT SF exposure. This may in turn provide a stronger association with community response to this variable. Finally, it is important to mention that the SF model only accounts for SF duration, and not shadow intensity. An assessment of SF intensity could potentially strengthen the association between SF exposure and community annoyance.

A careful examination of the SF annoyance question in the CNHS questionnaire itself is also warranted. There was ambiguity in the question used to assess HA_{WTSF} that may have contributed to the weak association observed between SF_m and HA_{WTSF}. The question probed one's annoyance towards *shadows or flickers of light* from WTs while they are at home, where "*at home*" means either indoors or outdoors. This wording could have led the respondent to assess their annoyance from shadows caused by WTs with either stationary or rotating blades. By contrast, the wording of the question could also have led the respondent to assess their annoyance from flickers of light generated by rotating WT blades. However, the model used to quantify SF exposure only considers moving shadows and as such, there may have been a discrepancy between the modeled exposure, and the participants' response. Although improvements will only come as this research area matures, as a starting point the authors recommend that future research in this area refine the SF annoyance question to the following: *Thinking about the last year or so, while you are at home, how much do shadows created by rotating wind turbine blades bother, disturb or annoy you*?

V. CONCLUDING REMARKS

For reasons mentioned above, when used alone, modeled SF_m results represent an inadequate model for estimating the prevalence of HA_{WTSF} as its predictive strength is only about 10%. This research domain is still in its infancy and there are enough sources of uncertainty in the model and the current annoyance question to expect that refinements in future research would yield improved estimates of SF annoyance. In addition to addressing some of the aforementioned shortcomings, future research may also benefit by considering variables that were not addressed in the current study. These may include, but not be limited to, personality types, attitudes toward WTs, and the level of community engagement between WT developers and the community. In the interim, this study identifies the variables, that when considered together with modeled SF exposure, improve the overall estimate of HA_{WTSF}. The applicability of these variables to areas beyond the current study sample will only become known as this research area matures.

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[1]Overall statistical power for the CNHS was based on the study's primary objective to assess WTN associated impacts on sleep quality. Based on an initial sample size of 2000 potential dwellings, it was estimated that there

would be 1120 completed questionnaires. For 1120 respondents there should be sufficient statistical power to detect at least a 7% difference in the prevalence of sleep disturbances with 80% power and a 5% false positive rate (Type I error). There was uncertainty in the power assessment because the CNHS was the first to implement objectively measured endpoints to study the impact that WTN may have on human health in general, and on sleep quality, in particular. In the absence of comparative studies, a conservative baseline prevalence for reported sleep disturbance of 10% was used (Tjepkema, 2005; Riemann *et al.*, 2011). Sample size calculation also incorporated the following assumptions: (1) approximately 20%–25% of the targeted dwellings would not be valid dwellings (i.e., demolished, unoccupied seasonal, vacant for unknown reasons, under construction, institutions, etc.); and (2) of the remaining dwellings, there would be a 70% participation rate. These assumptions were validated (Michaud *et al.*, 2016b).

[2]Four hundred and thirty-four potential dwellings were not valid locations; upon visiting the address Statistics Canada noted that the location was inhabitable but unoccupied at the time of the visit, newly constructed not yet inhabited, unoccupied trailer in trailer park, a business, a duplicate address, an address listed in error, summer cottage, ski chalet, hunting camps, or a location where residents were all above 79 yrs of age. See Michaud *et al.* (2016b) for more details.

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