In the Shadow of Wind Energy

Predicting community exposure and annoyance to wind turbine shadow flicker in the United States

Please Note:
- All participants will be muted during the webinar
- Please submit questions via the chat window
- This webinar will be recorded

LBNL Paper Release Webinar
March 11, 2022

RSG
the science of insight

BERKELEY LAB

VERA Renewables

This work was funded by the U.S. Department of Energy Wind Energy Technologies Office, under Contract No. DE-AC02-05CH11231.

Disclaimer

Copyright Notice

Project Team

Ben Hoen*

bhoen@lbl.gov

Joe Rand

jrand@lbl.gov

Ryan Haac

Ryan.Haac@rsginc.com

Ken Kaliski

Ken.Kaliski@rsginc.com

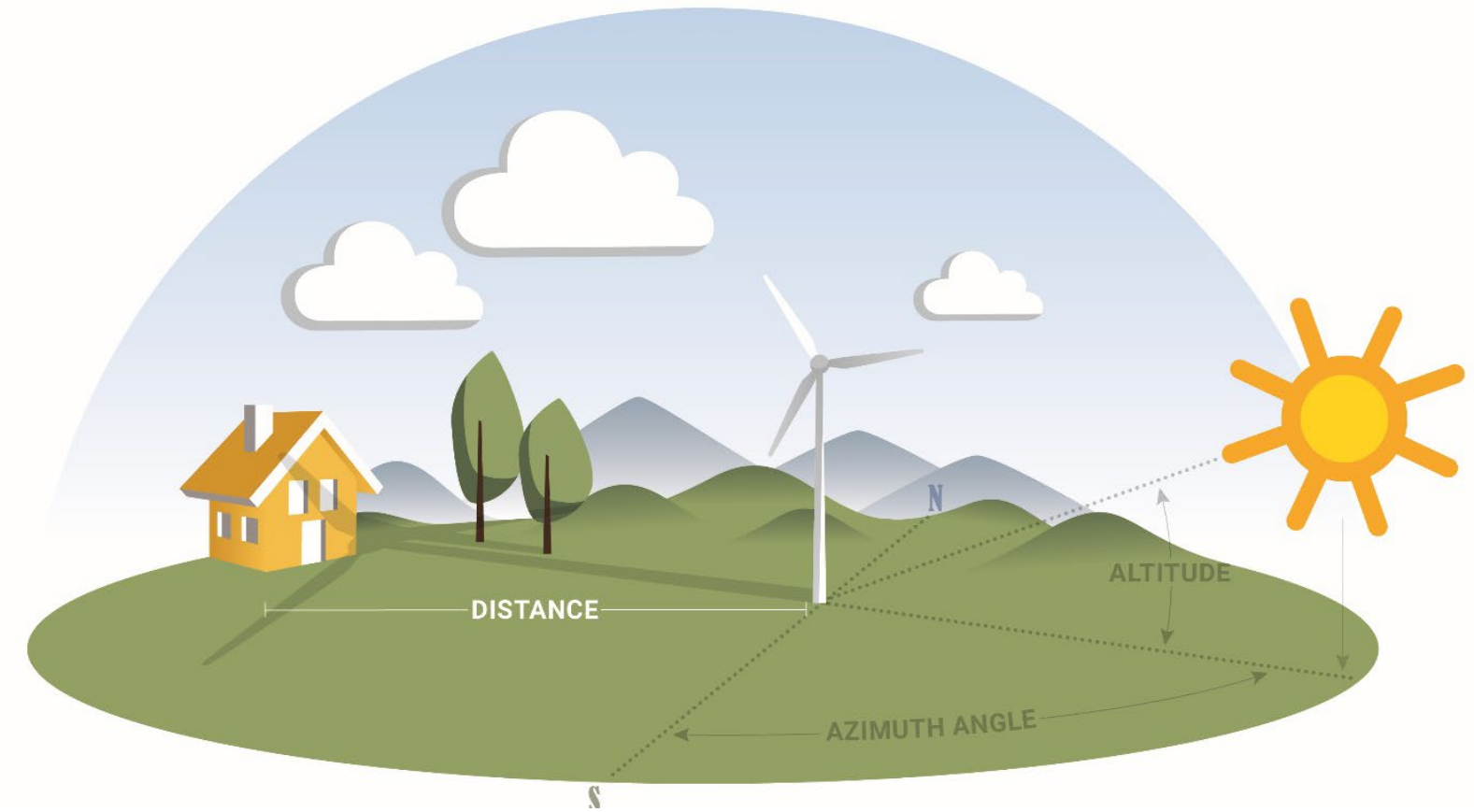
Ryan Darlow

ryand@verarenewables.com

* Corresponding author: 1 Cyclotron Drive, Berkeley, CA, 94720 | (845) 758-1896

Outline

- Background
- Data
- Methods
- Results
- Discussion



Background

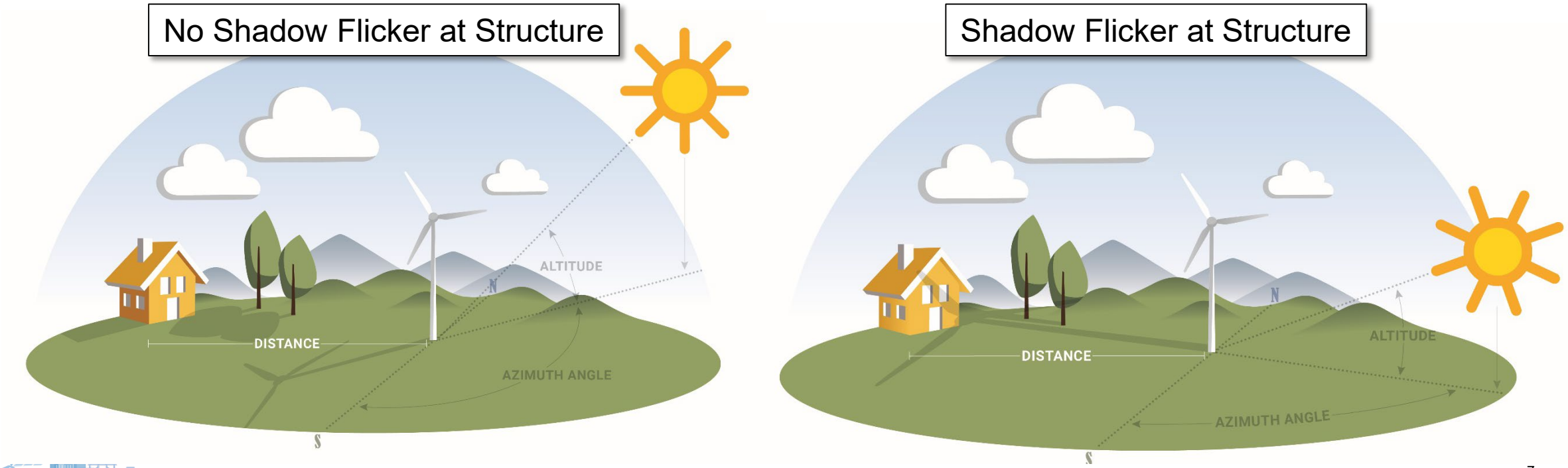
What is Shadow Flicker?

- Shadow flicker (SF) is an effect of pulsating light and shadow caused by the sun shining through rotating wind turbine blades
- SF is most common in the morning and evening hours to the west and east of the turbine
- SF can cause annoyance due to the flickering lights—like driving with the sun flickering in the side window
- Prior research has not found a link between SF and health impacts

NYS Video, 2021, “Wind Turbine Shadow Flicker,” https://www.youtube.com/watch?v=NeVWhxs7Ljo

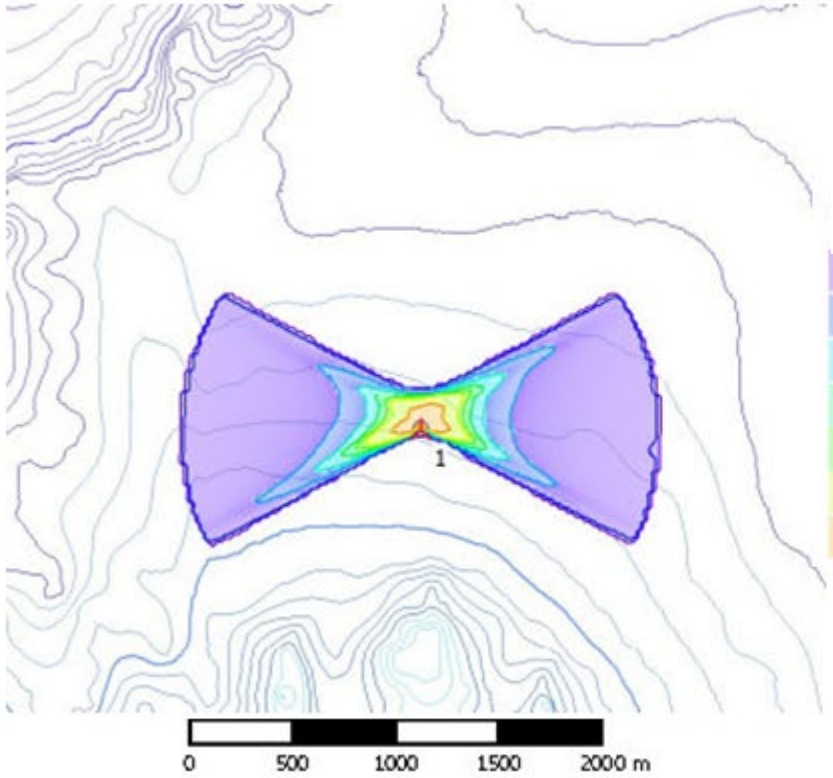
How is Shadow Flicker Generated?

- Shadow flicker exposure is a function of
  - Solar angle (azimuth) and elevation (zenith or altitude)
  - Distance the home is from the wind turbine
  - Sunlight intensity and, by extension, cloud cover
  - Obstructions, including buildings and vegetation



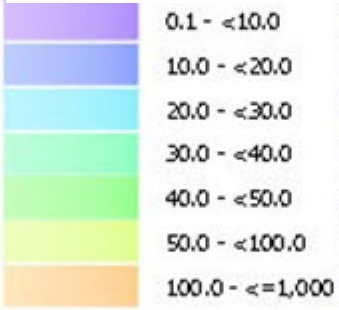
Models Are Used to Predict Amounts of Shadow Flicker a Home near a Wind Project Will Receive

- SF is usually expressed as either the maximum number of hours/year or minutes/day

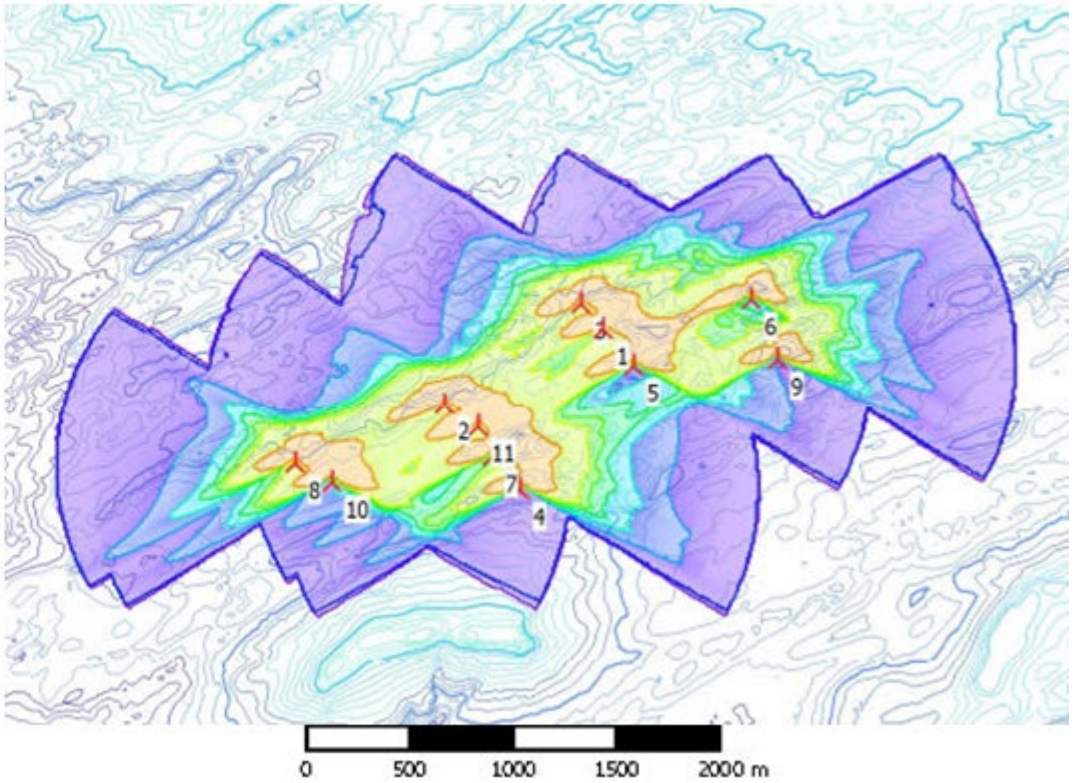


Single Wind Turbine

Modeled Shadow Flicker



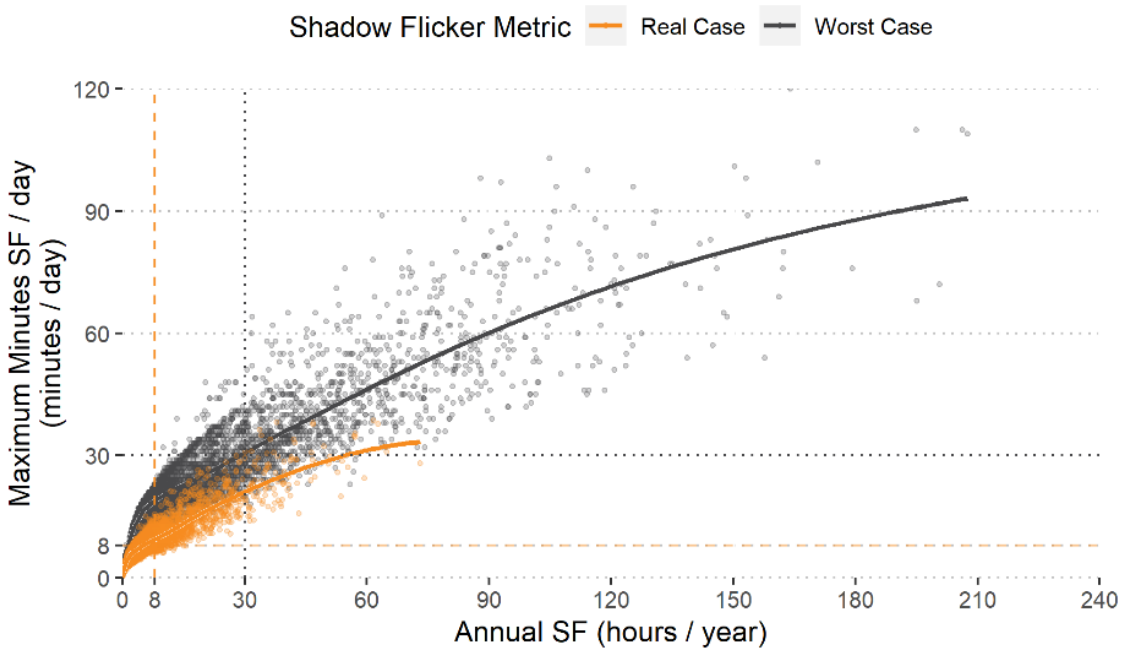
Hours per year (Real Case)



Multiple Wind Turbines

Two Common Ways to Model Shadow Flicker: "Worst" Case and "Real" Case

- "Worst" Case (also called Astronomical Case)
  - Assumes turbines are always operating (rotating) and there is no cloud cover
- Real Case
  - More realistic approximation of actual conditions experienced by wind project neighbors
  - Adjusts for actual conditions
    - Meteorology (cloud cover), turbine operational factors (downtime), wind speed and direction, and sometimes landcover
  - Each adjustment is a reduction from worst case levels
- Worst Case to Real Case Ratio
  - 30 hours Worst Case ≈ 8 hours Real Case (or approximately 3:1)
  - Ratio applies to both hours/year and minutes/day, which are often used interchangeably
- Real Case is the primary metric used in our analysis



What is Annoyance?

- Lindvall et al. 1973 define annoyance as

  "[A] feeling of displeasure associated with any agent or condition believed to affect adversely an individual or group."

- Annoyance is not necessarily pathogenic and may or may not result in negative health consequences

- In this study, we focus on self-reported annoyance on a five-point scale, with the highest annoyance category being "very annoyed"

- Our Five-Point Self-Reported Annoyance Scale:
  Not at all (0), slightly (1), somewhat (2), moderately (3), and very (4)

What Has Been Done to Assess Shadow Flicker Perception and Annoyance?

- Verkuijlen et al. 1984 found that no epileptic, nausea, seizures should occur below 60 RPM
  - Modern turbines average 17.4 RPM
- Pohl et al. 1999 evaluated the relationship between shadow flicker exposure duration and annoyance in Germany
  - No significant correlation was found, except when weighted for the number and types of rooms exposed in each home
- Health Canada found a correlation between shadow flicker exposure and annoyance, albeit weak when subjective variables were included (Voicescu et al., 2016)
- The LBNL team has already evaluated wind turbine noise perception and annoyance; team has found perception of noise is significantly predicted by modeled levels of noise, but annoyance was better predicted by subjective factors (Haac et al., 2019) (see more on this later)

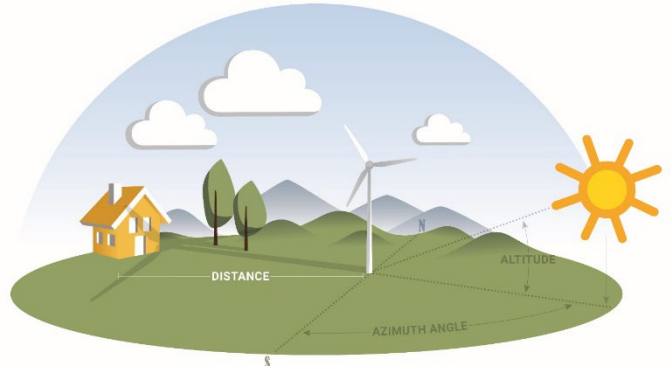
Project Summary

Title: Analysis of Shadow Flicker Perception and Annoyance Using Modeled Shadow Flicker Exposure and Survey Data

Motivation: There is an absence of comprehensive recent data on shadow flicker exposure, perception and annoyance, especially in the US context. Further, there are few examples of attempts to predict shadow flicker perception and annoyance. Finally, a review of population-level shadow flicker exposure as well as shadow flicker ordinances has not been conducted.

Project: To explore how well modeled shadow flicker exposure predicts levels of shadow flicker perception and annoyance at 61 U.S. wind projects across 17 states. To review population-level shadow flicker levels around these sites as well as the in-place shadow flicker regulations and ordinances.

Funder: Wind Energy Technologies Office of US DOE



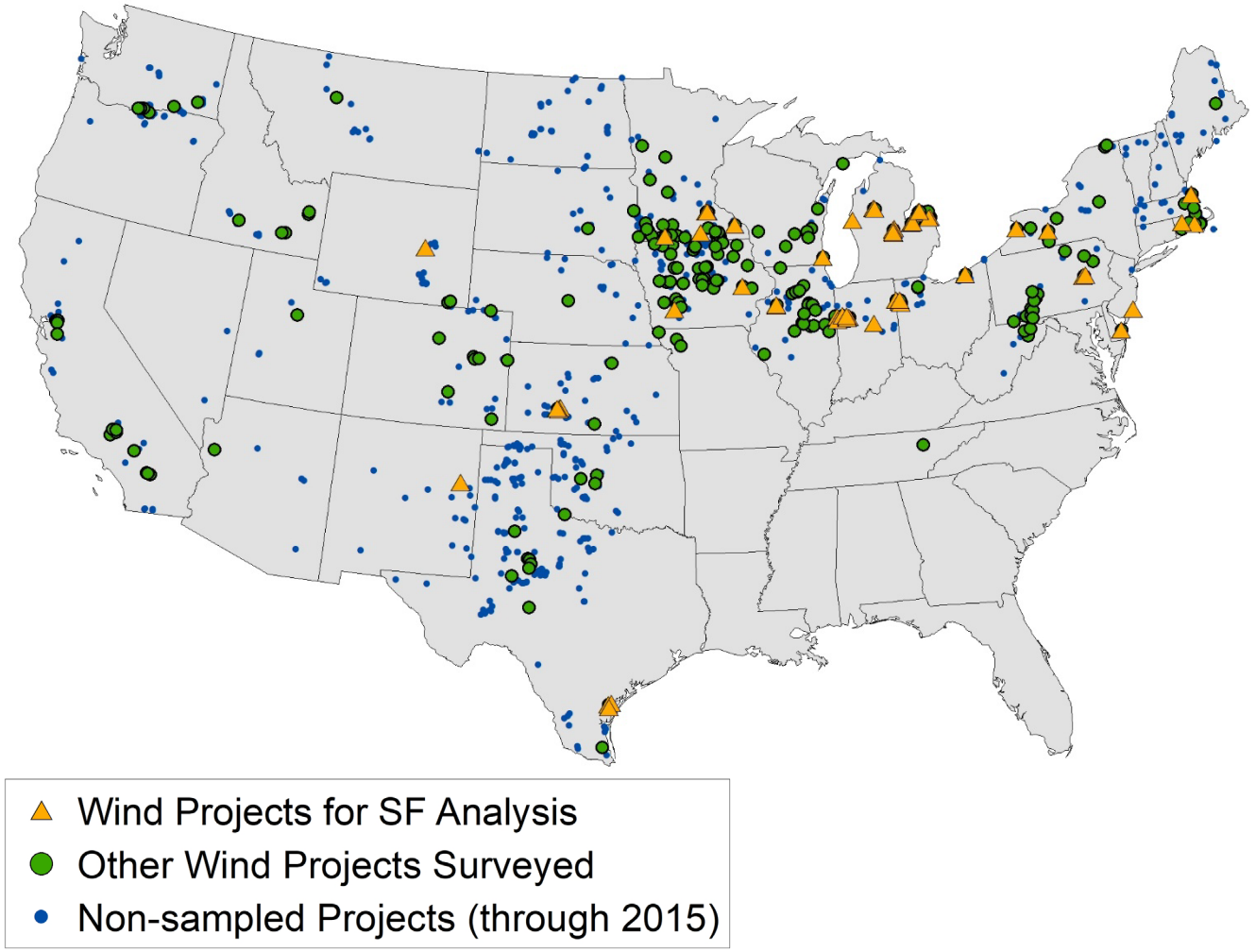
BERKELEY LAB

RSG
the science of insight

VERA
Renewables

In 2016, 1,705 Wind Neighbor Survey Responses Collected

747 were near 61 wind projects across 17 states where shadow flicker was modeled



Random sample of residences within 5 miles of a modern wind turbine

- >= 364 feet tall
- >= 1.5 MW

Oversampled

- close to (<1.6 km) turbines
- large projects (>10 turbines)

Survey Asked about Perception of and Annoyance to Shadow Flicker (Among Other Possible Nuisances)

21. Do the blades of a wind turbine ever cast a shadow on your property, but outside your home?

- ○ Yes
- ○ No
- ○ Don't Know

Skip to #22

21a. Do the blades of a wind turbine ever cast a shadow in your home?

- ○ No
- ○ Yes
- ○ Don't Know

The next set of questions asks about any effects the local wind project has had on you. For these questions, think about the experiences you have had over the past year.

24. To what extent do you feel annoyed by each of the following effects of the local wind project?	**Not at All**	**Slightly**	**Somewhat**	**Moderately**	**Very**	**Don't Know**
a. Change to the landscape	1	2	3	4	5	○
b. Wind turbine lighting	1	2	3	4	5	○
c. Shadow flicker	1	2	3	4	5	○
d. Sound of the wind project	1	2	3	4	5	○

If your answer to #24d (Sound of the wind project) was…

Slightly (2), **Somewhat** (3), **Moderately** (4), or **Very** (5) → Answer **#25** & **#26**

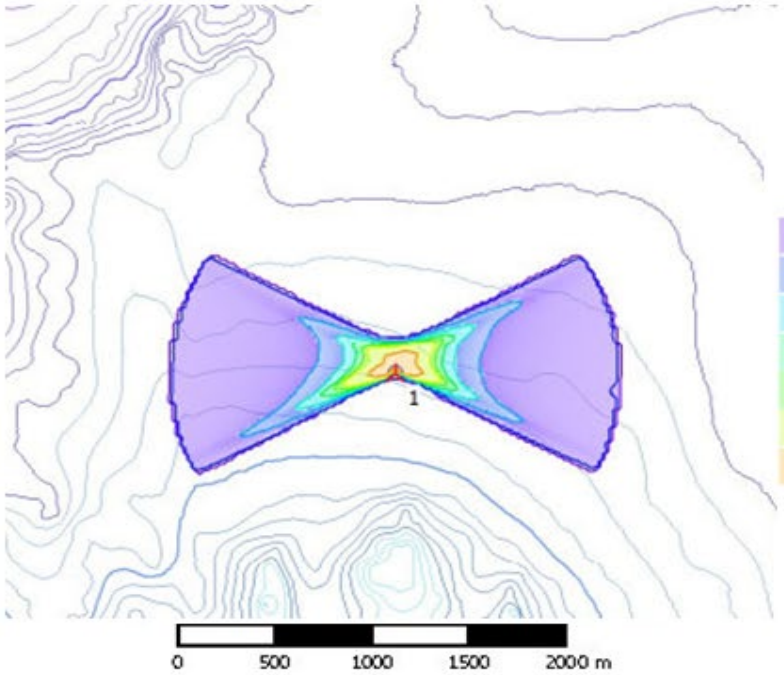
Not at All (1) or **Don't Know** → Skip to **#27**

Shadow Flicker Modeling Results

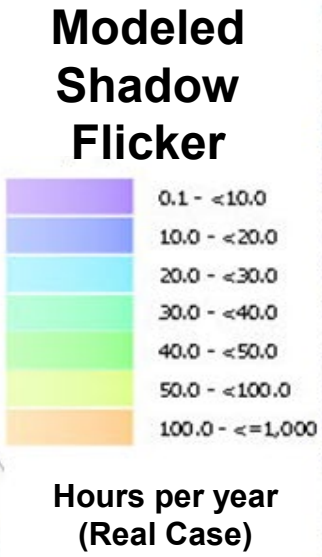
Team Modeled Shadow Flicker around the 61 Wind Projects

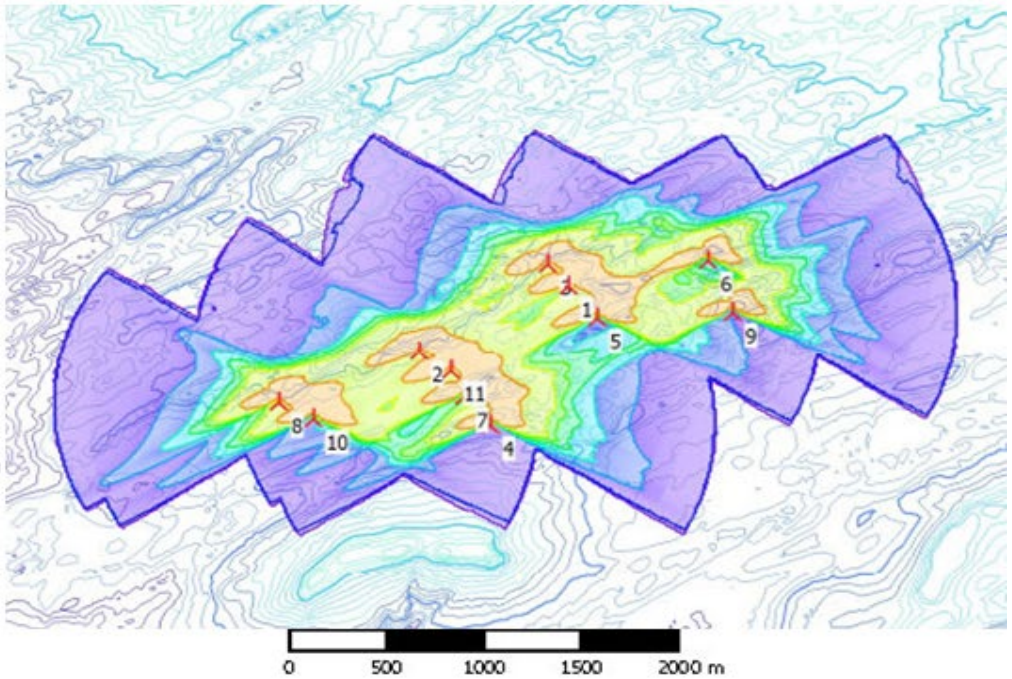
Shadow flicker was modeled for all residences within 2 kilometers of a turbine

- 34,950 residences, 747 of which were survey respondents; 2,982 wind turbines



Single wind turbine



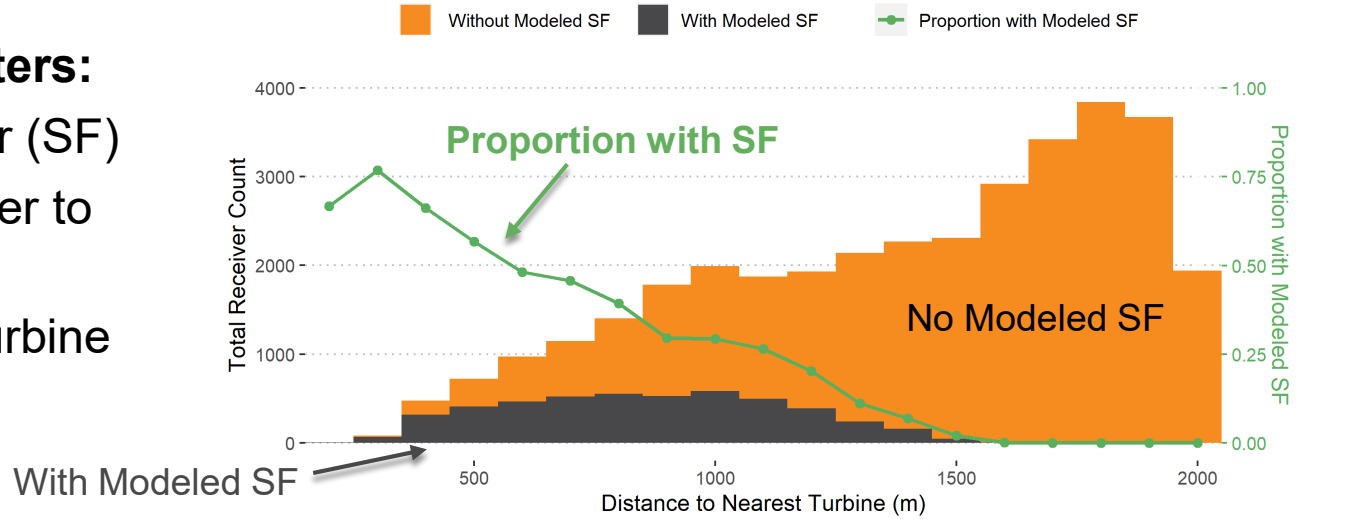


String of wind turbines

Shadow Flicker Exposure Increases the Closer Homes Are to Turbines, but Most Homes within 2 Kilometers Experience No or Very Low Amounts

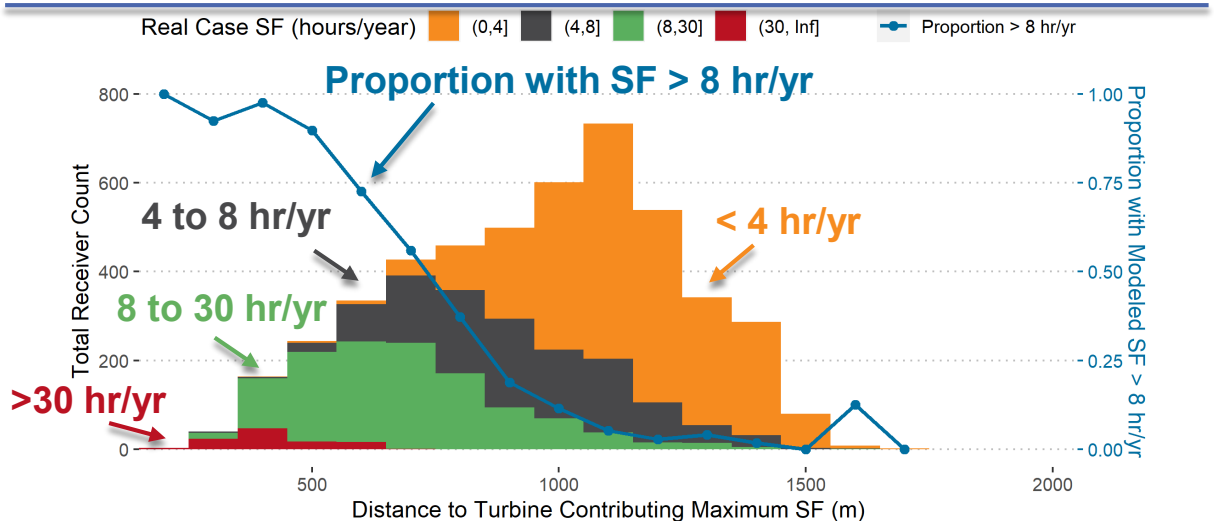
For all homes within approximately 2 kilometers:

- Only 14% have *some* modeled shadow flicker (SF)
- Proportion with shadow flicker increases closer to the nearest turbine
- Over 50% within 550 meters of the nearest turbine have modeled shadow flicker



For those homes with <u>some</u> shadow flicker:

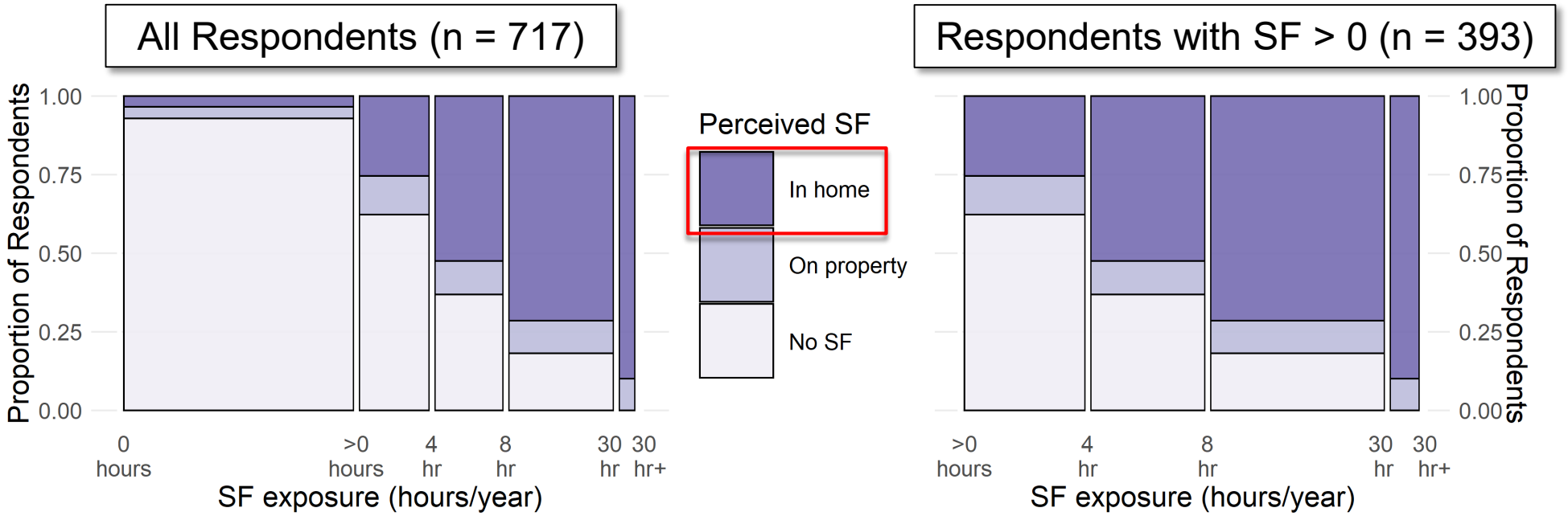
- Most have relatively low levels of shadow flicker
- Of homes within 550 meters of nearest turbine
  - Nearly all have shadow flicker above 8 hours/year
  - 20% have shadow flicker above 30 hours/year



Basic Two-Way Comparison Results

Perceived Shadow Flicker among Survey Respondents Was Correlated with Modeled Shadow Flicker Exposure Levels

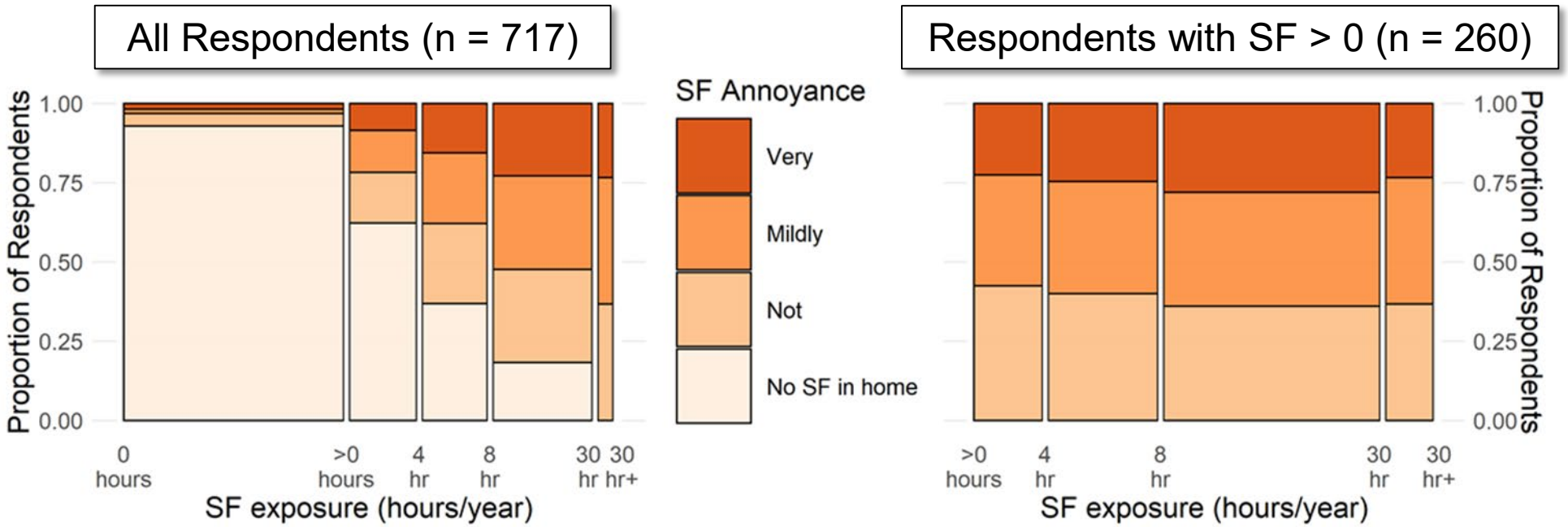
- The proportion of respondents that notice (i.e., perceive) shadow flicker in their homes increases as exposure increases, implying a dose-response relationship
- With exposure of:
  - 4 to 8 hours/year, ~ 50% perceive shadow flicker in their home
  - 8 to 30 hours/year, ~ 75% perceive shadow flicker in their home
  - >30 hours/year, more than 90% perceive shadow flicker in their home



Note: bar widths represent proportion of sample represented in each modeled shadow flicker exposure bin

Annoyance To Shadow Flicker among Survey Respondents Was Not Correlated with Exposure

- 50% of respondents had no shadow flicker exposure, thus could not be annoyed by it
- Of those with some exposure, there is no evidence of a dose-response relationship between exposure and annoyance
  - Annoyance levels were similarly distributed among not-at-all, mildly, and very annoyed despite different levels of exposure

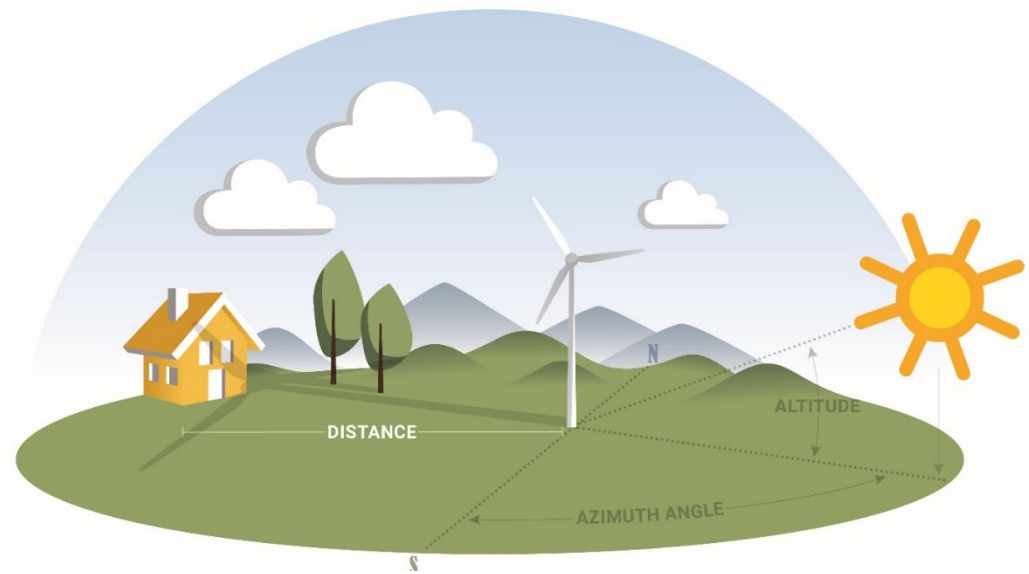


Note: bar widths represent proportion of sample represented in each modeled shadow flicker exposure bin

Regression Model Methods

Perceived Shadow Flicker and Annoyance Is Predicted Using Regression Models

- Team implemented ordinal logistic regression models to predict perception and annoyance
- These models allow examination if independent variables are uniquely correlated with (i.e., predict) the outcome variables
- The two dependent variables are:
  - Perceived shadow flicker (Perceived SF)
  - Shadow flicker annoyance (SF Annoyance)
- The sets of independent variables are discussed on the next slide



Three Sets of Independent Variables (IV) Were Used to Predict Shadow Flicker Perception and Annoyance

- **Basic Variables**
  - Modeled shadow flicker (hours per year)
  - Project participation (respondent received payments)
  - Distance home is from nearest turbine
- **Observable Variables**
  - Project/turbine characteristics:
    - hub height, rotor diameter, rotor tip speed, project age
  - Number of turbines in view
  - Resident moved in after wind project construction
- **Subjective Variables**
  - Average annoyance to typical community stressors, which include:
    - Motor vehicle traffic, including cars and trucks; streetlights; agricultural machinery; and lawnmowers, snow blowers, or leaf blowers
  - Does respondent like the look of the project?

Note: Demographic and stratification variables included in all regressions

Two Main Regression Model Statistics Are Used to Examine Importance of Each IV and Overall Explanatory Power of the Model

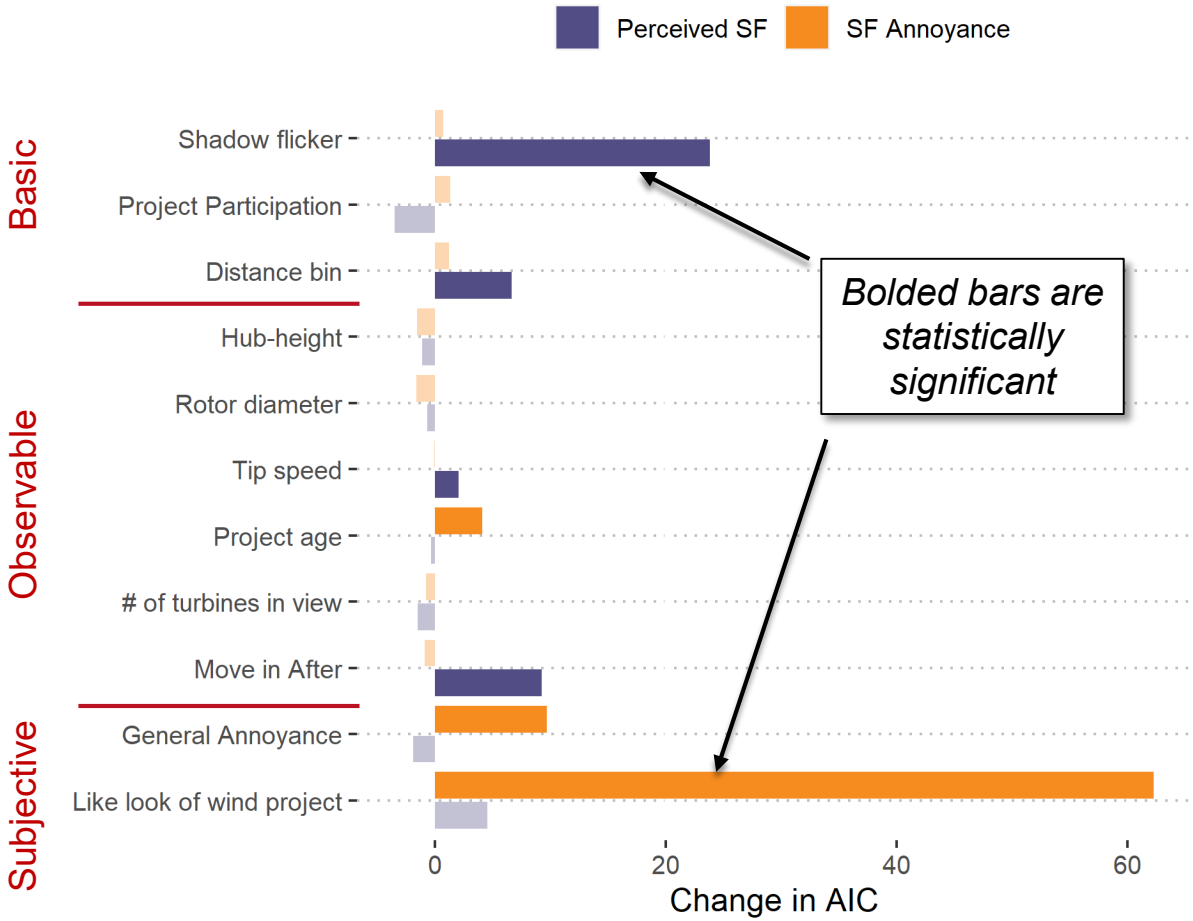
- **Independent Variable Importance Is Assessed Using ΔAIC**
  - The Akaike Information Criterion (AIC) of a particular variable represents the impact on the model fit when it is removed from the regression
  - Higher AIC values signify stronger predictors
  - For categorical variables, the AIC measure is particularly useful in that it shows the strength of the whole variable rather than the influence of the categorical variable's individual levels

- **Model Explanatory Power Is Evaluated Using Leave One Out Cross Validation**
  - For each sample, the regression model is calculated without that individual sample; the goal is to see if the model correctly predicts the sample that was "left out"
  - The results of the validation are expressed as the proportion of samples that were correctly predicted for each level of the response variable

Regression Results

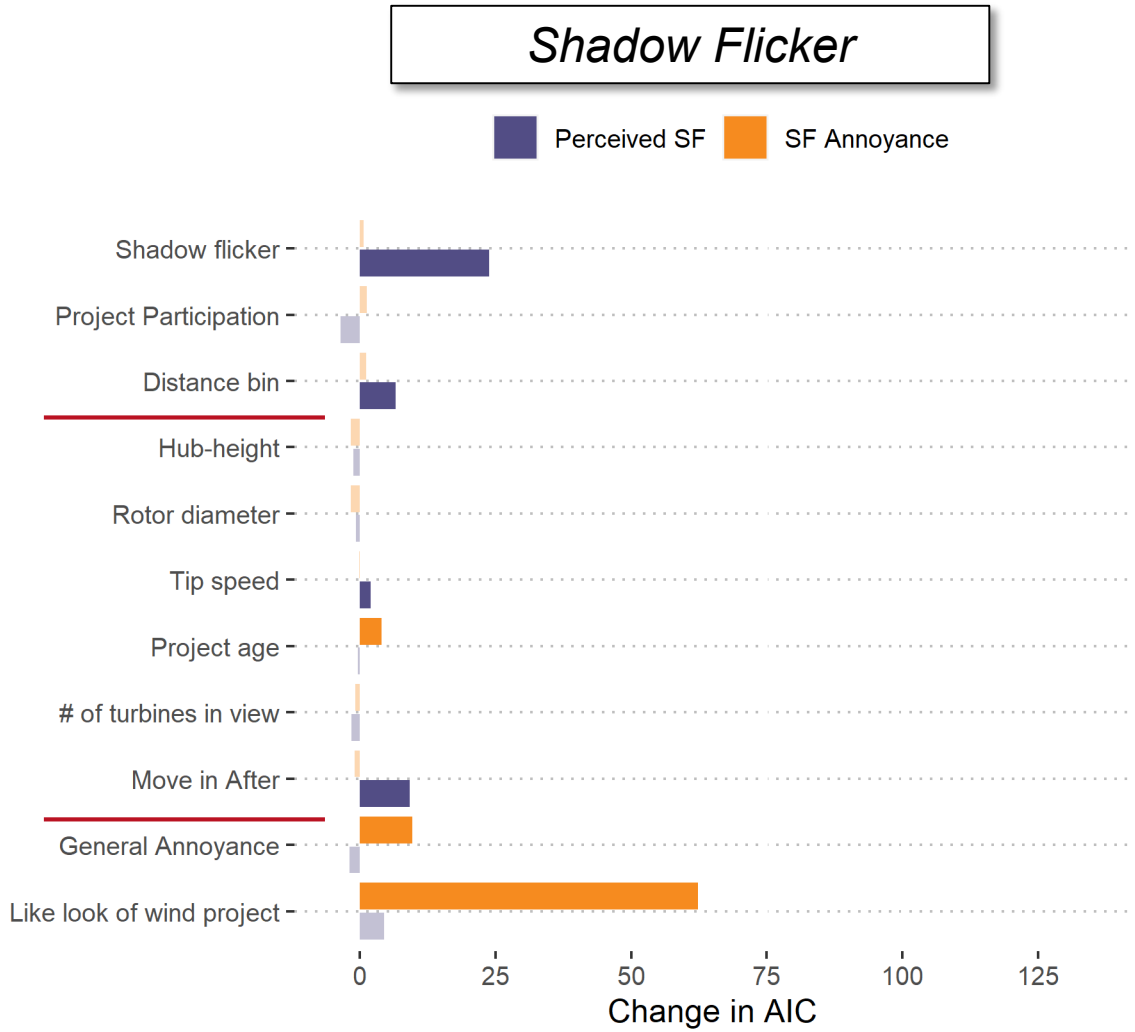
Shadow Flicker Regression Model Results

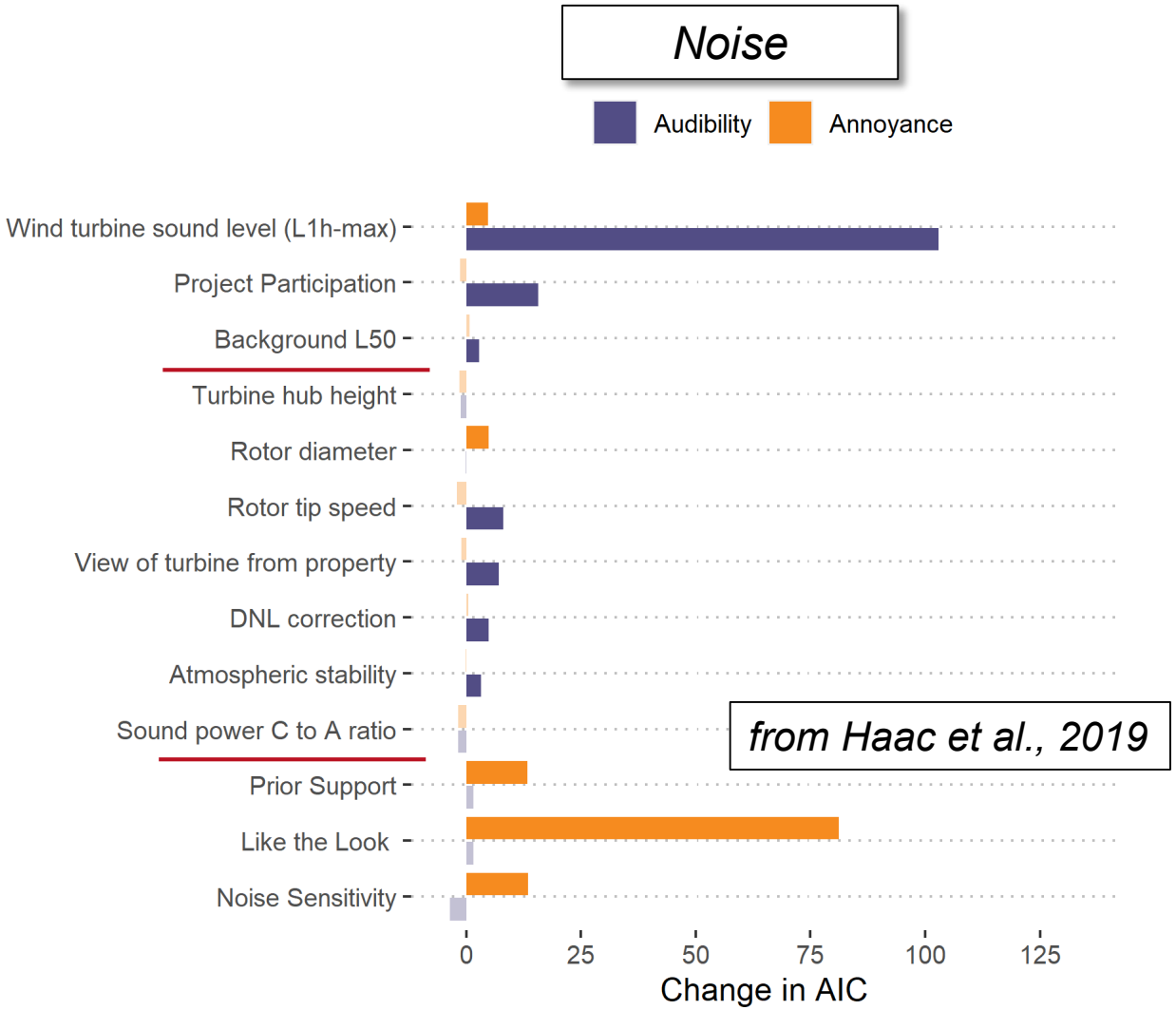
- **For Perceived SF:**
  - Statistically significant basic and objective variables
    - Modeled SF, moved in after project was built, and distance from nearest turbine
  - Subjective variables were not statistically significant
- **For SF Annoyance:**
  - Other than project age, none of the basic or objective variables were statistically significant, including modeled shadow flicker
  - However, subjective variables were statistically significant
    - If respondent liked the way the project looked and general annoyance to other community stressors were strong predictors
- **Explanatory power was relatively high**
  - Perceived SF responses predicted correctly: 70%
  - SF Annoyance responses predicted correctly: 65%



Regression Results Considering Noise and Shadow Flicker

Shadow Flicker and Noise Perception and Annoyance Have Similar Patterns: Perception Is Objective; Annoyance Is Subjective





Shadow Flicker Ordinances

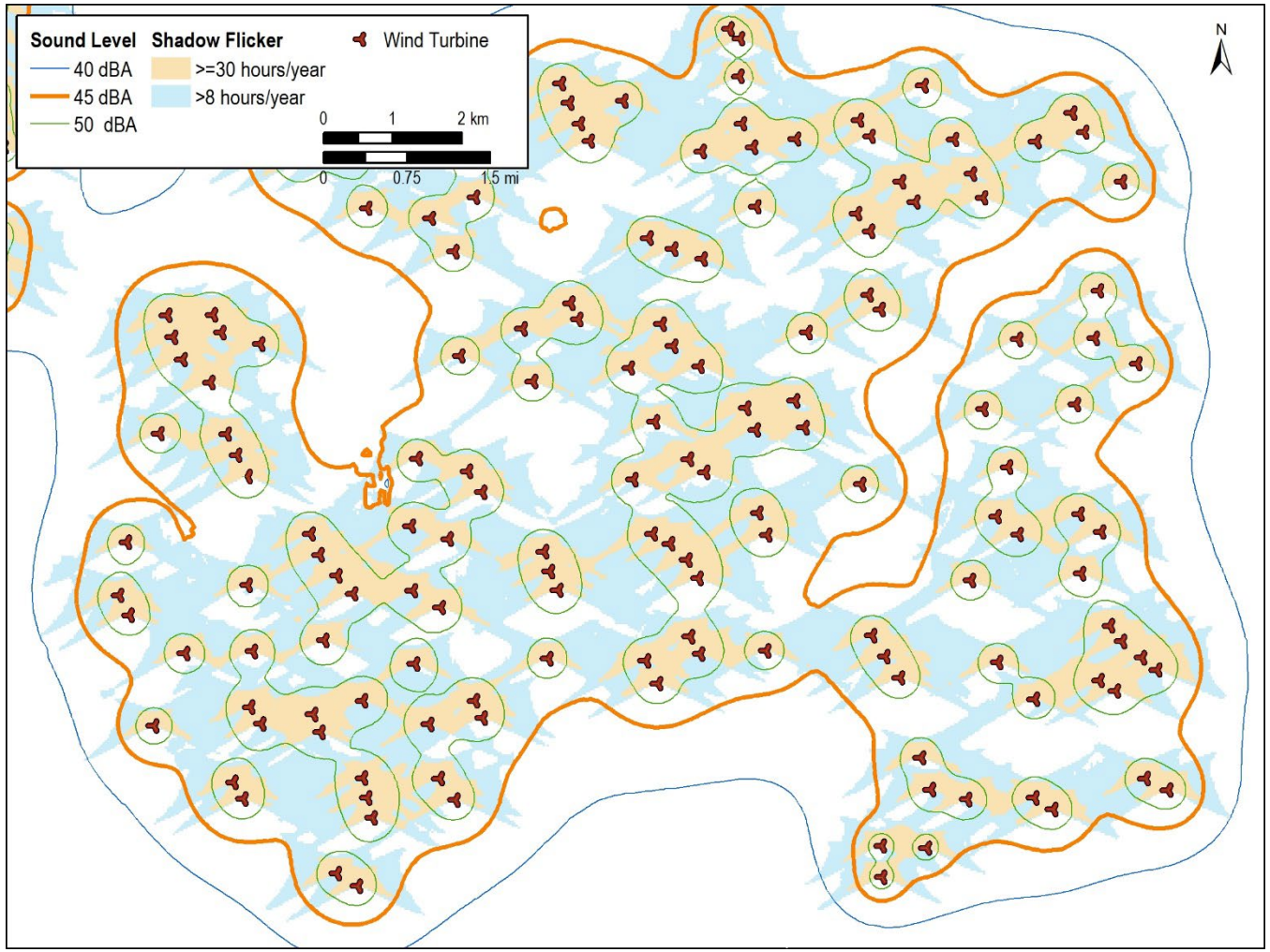
Team Reviewed Shadow Flicker Siting Ordinances For 70 US Counties across 17 States

Findings:

- Most counties (62%) do not enforce any limit on shadow flicker
  - Two states (New York and Ohio) have statewide shadow flicker limits (30 hours/year)
  - 13 county-level ordinances were identified
- 30 hours/year was by far the most common limit
- Of those that have a limit, only two specify which model to use: real or worst case
  - As discussed, real case is roughly one-third of worst case
  - Significant room for interpretation exists
  - In most circumstances, based on author experience in the US, real case is used for the 30 hours/year limit, equating to roughly 90 hours of worst case

So, what can be done in the absence of regulation in most jurisdictions?
A solution is likely already in use.

Sound Limits Can (And Likely Do) Serve as Proxies for Shadow Flicker Limits



- Sound and shadow flicker exposure are related
- A sound limit of 45 dBA (L_{1h}) is largely protective of 30 hours/year real-case shadow flicker exposure
- A sound limit of 40 dBA (L_{1h}) is largely protective of 8 hours/year real-case shadow flicker exposure
- The opposite is not true
  - **Shadow flicker limits are not necessarily protective of noise exposure**

Map on left shows wind turbine with 107 dBA sound power, 100-meter hub height, and 90-meter rotor

Summary and Conclusions

- Shadow flicker is annoying to some people around wind projects and is a design constraint for developers
- This study looked at homes near wind projects and developed models to predict residents' perception and annoyance to shadow flicker
- A relatively small portion of the population near turbines experience any shadow flicker, and those that do are close to the turbines
- Perception of shadow flicker was most strongly correlated with shadow flicker exposure
- Annoyance to shadow flicker was most strongly correlated with perceptions of wind project aesthetics and general annoyance to other (non-turbine) factors
  - Shadow flicker exposure was not a significant predictor of shadow flicker annoyance when subjective factors were included
- Shadow flicker limits are rarely defined and, if they are, "real" or "worst" case is almost never clarified
- Sound-level limits might serve as an adequate proxy for shadow flicker limits in their absence

ELECTRICITY MARKETS & POLICY

Questions?

Contacts

Ben Hoen, bhoen@lbl.gov
Joe Rand, jrand@lbl.gov
Ryan Haac, Ryan.Haac@rsginc.com
Ken Kaliski, Ken.Kaliski@rsginc.com
Ryan Darlow, ryand@verarenewables.com

For more information

Download publications from the Electricity Markets & Policy: https://emp.lbl.gov/publications
Sign up for our email list: https://emp.lbl.gov/mailing-list
Follow the Electricity Markets & Policy on Twitter: @BerkeleyLabEMP

Acknowledgements

This work was funded by the U.S. Department of Energy Wind Energy Technologies Office, under Contract No. DE-AC02-05CH11231.

Summary of previous research

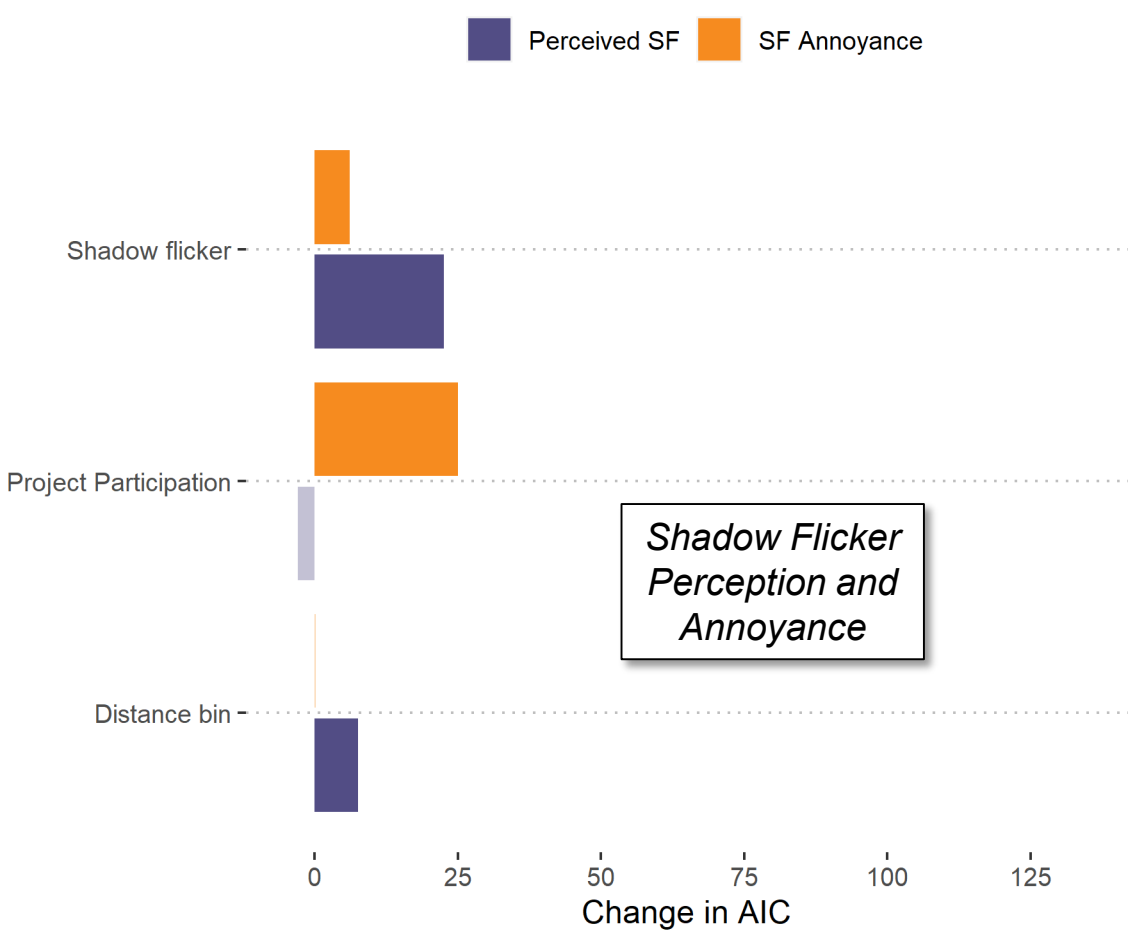
- Firestone, J., Hoen, B., Rand, J., Elliot, D., Hubner, G., & Pohl, J. (2018) **"Reconsidering Barriers to Wind Power Projects: Community Engagement, Developer Transparency and Place"**, Journal of Environmental Policy & Planning, 20(3): 370-386, DOI: https://doi.org/10.1080/1523908X.2017.1418656
- Haac, R., Kaliski, K., Landis, M, Hoen, B., Rand, J., Firestone, J., Elliot, D., Hubner, G., & Pohl, J. (2019) **"Wind Turbine Audibility and Noise Annoyance in a National U.S. Survey: Individual Perception and Influencing Factors"**, Journal of the Acoustical Society of America, 146, 1124, https://doi.org/10.1121/1.5121309
- Hoen, B., Firestone, J., Rand, J., Elliot, D., Hubner, G., Pohl, J., Wiser, R., Lantz, E., Haac R., Kaliski, K. (2019) **"Attitudes of U.S. Wind Turbine Neighbors: Analysis of a Nationwide Survey"**, Energy Policy, 134, 110981, https://doi.org/10.1016/j.enpol.2019.110981
- Hubner, G., & Pohl, J., Hoen, B., Firestone, J., Rand, J., Elliot, D., Haac, R. (2019) **"Monitoring Annoyance and Stress Effects of Wind Turbines on Nearby Residents: A Comparison of U.S. and European Samples"**, Environment International 132, 105090, https://doi.org/10.1016/j.envint.2019.105090
- Rand, J and Hoen, B. (2017) **"Thirty Years of North American Wind Energy Acceptance Research: What Have We Learned?"** Energy Research and Social Science, 29, 135-148, https://doi.org/10.1016/j.erss.2017.05.019
- Firestone, J. and Kirk, H. (2019) **"A Strong Relative Preference for Wind Turbines in the United States Among Those that Live Near Them"**, Nature Energy, 4, 311-320, https://doi.org/10.1038/s41560-019-0347-9
- Russell, A., Firestone, J., (2021) **What's love got to do with it? Understanding local cognitive and affective responses to wind power projects**. Energy Research & Social Science, Volume 71, 101833, https://doi.org/10.1016/j.erss.2020.101833

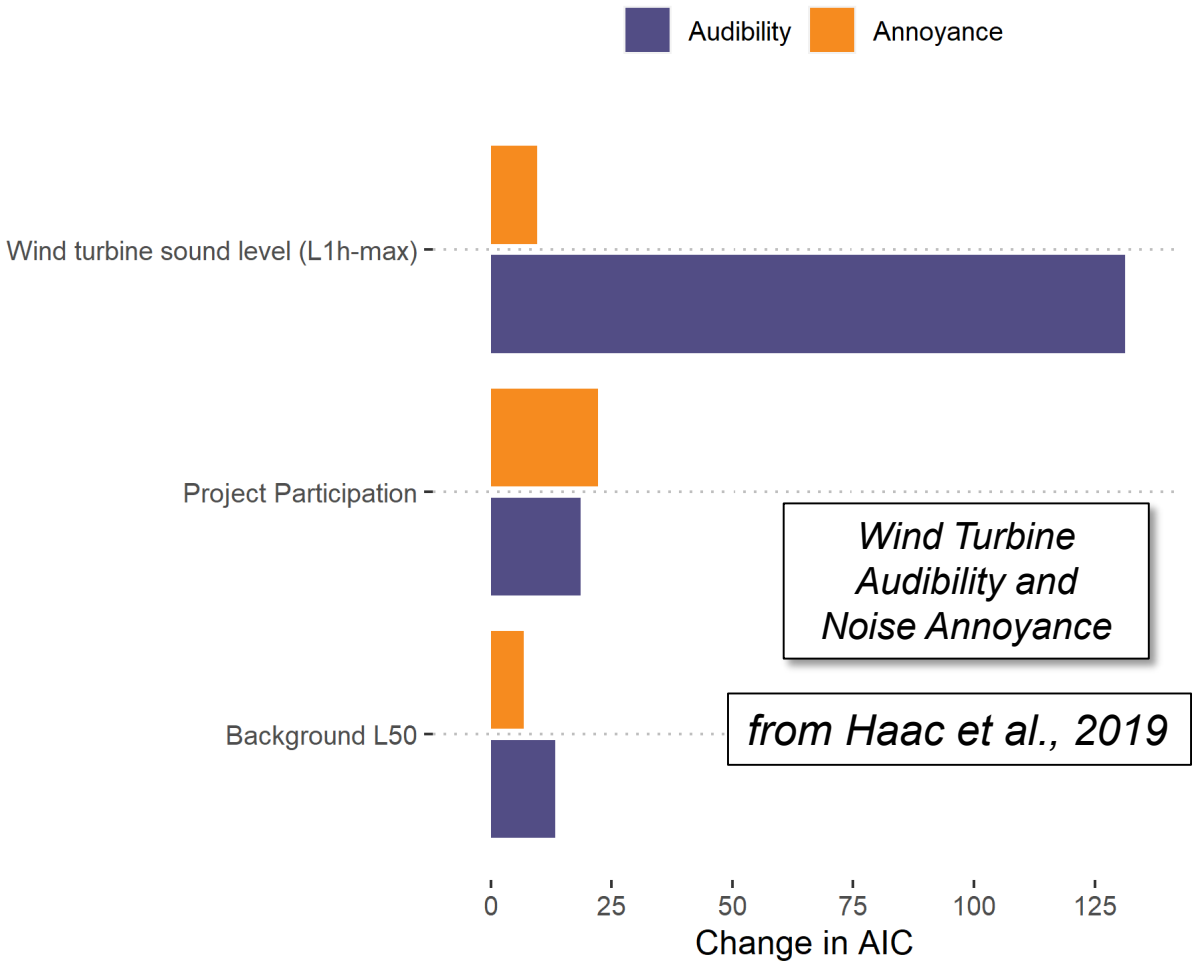
Supplemental Slides

Our review of the 60 locations modeled in this study found 13 applicable SF regulations

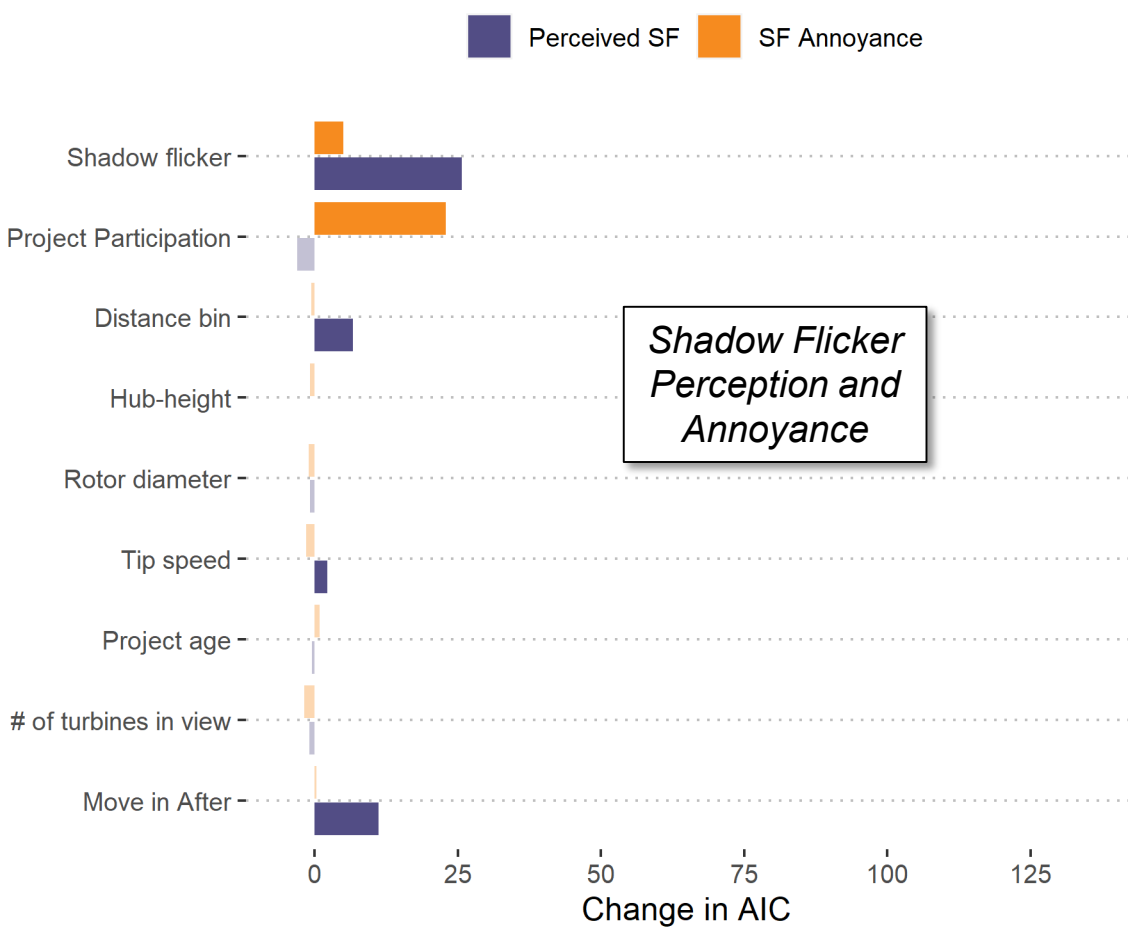
SF Duration	Unit	Metric (Real/Worst)	Location at which standard is met
30	hr/year & min/day (both)	Worst case	“Observer"
30	hr / yr	Unspecified	Non-participating residence
40	hr / yr	Real case	Dwellings, or road intersections (see text)
30	hr / yr	Unspecified	Occupied Building
30	hr / yr	Unspecified	Non-participating dwelling
30	hr / yr	Unspecified	Occupied Building
30	hr / yr	Unspecified	Unspecified
30	hr / yr	Unspecified	Participating and non-participating inhabited structure
30	hr / yr	Unspecified	Unspecified
30	hr / yr	Unspecified, no landcover	Homes and roads
30	hr / yr	“Potential and realistic”	Homes
30	hr / yr	Unspecified	Non-participating sensitive receptor within 1km
30	hr / yr	Unspecified	Window of existing, non-hosting, residential structure

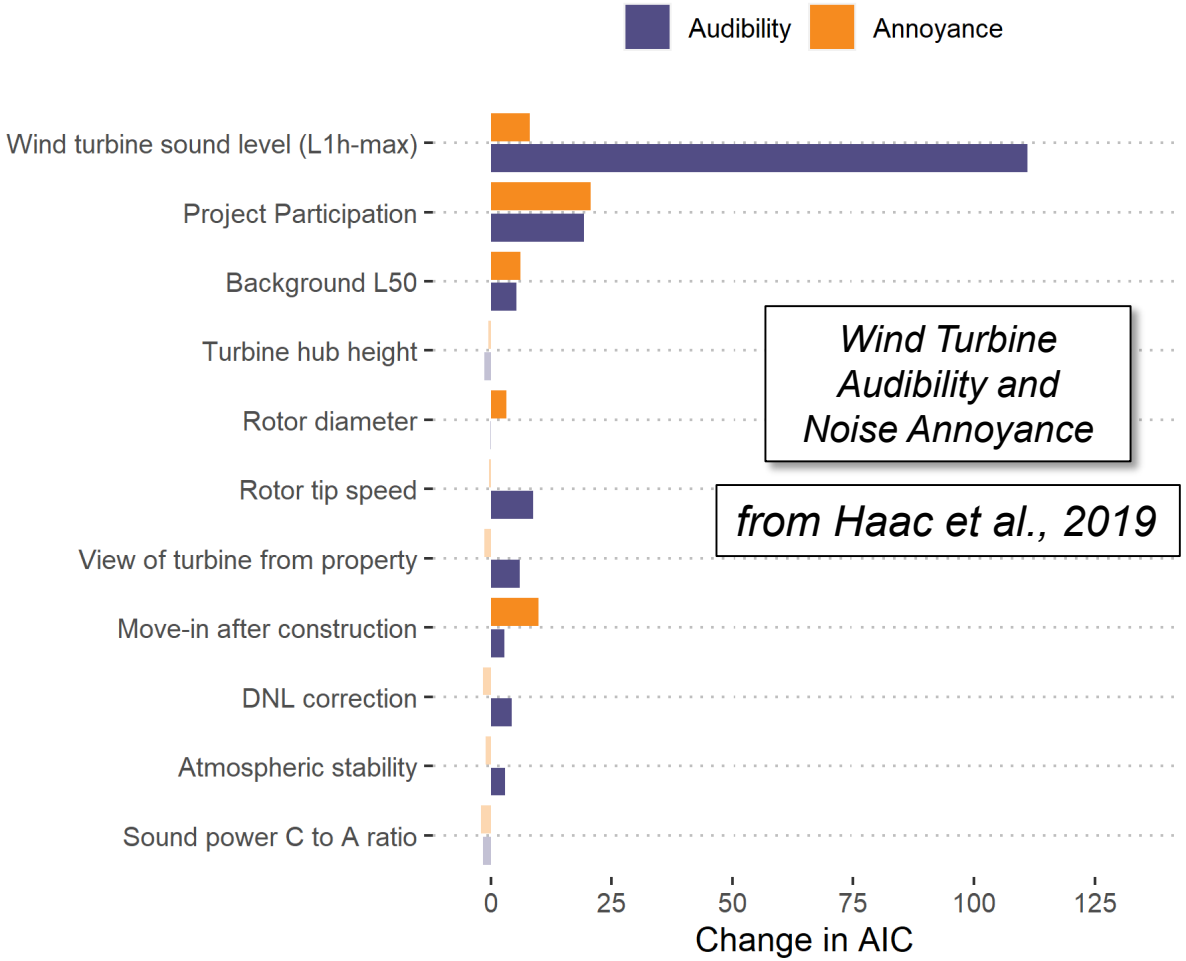
Shadow Flicker and Noise Perception and Annoyance Have Similar Patterns: Basic Variables



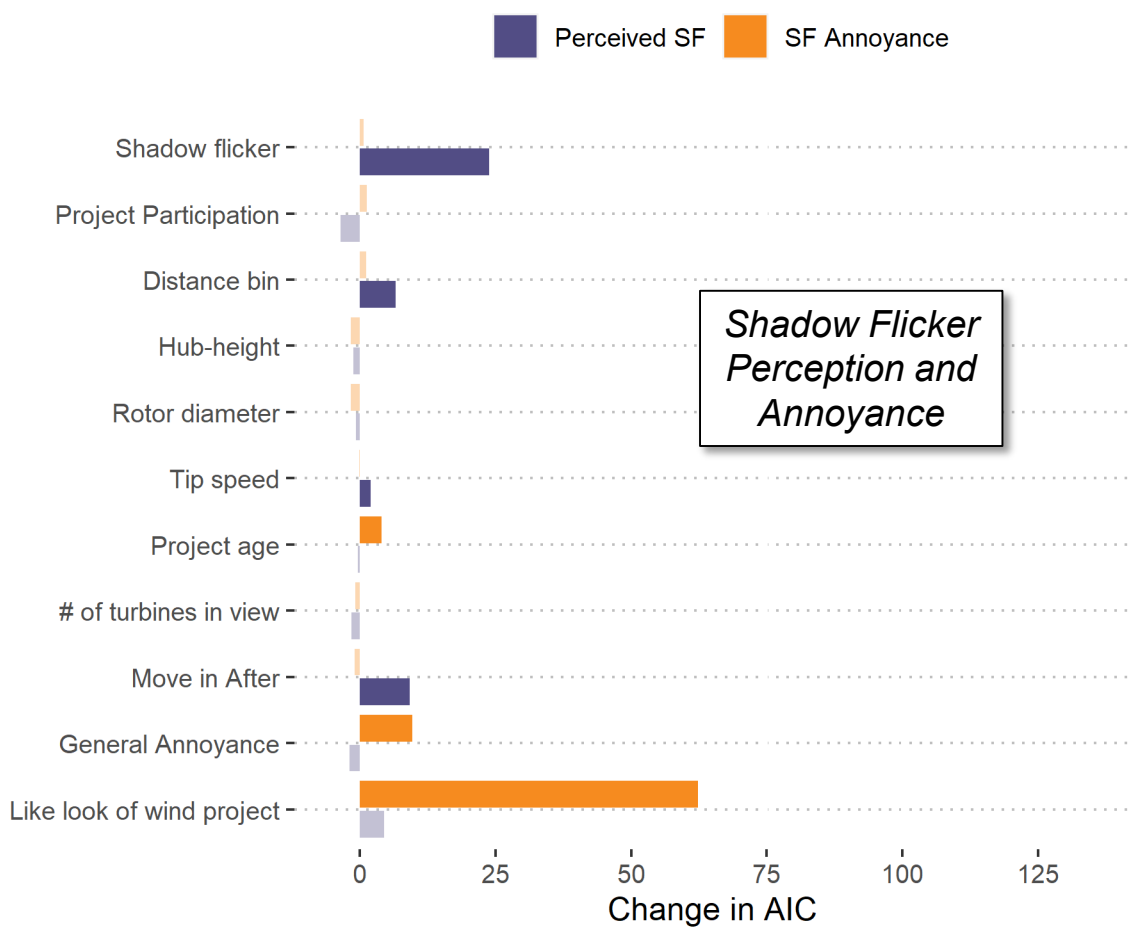


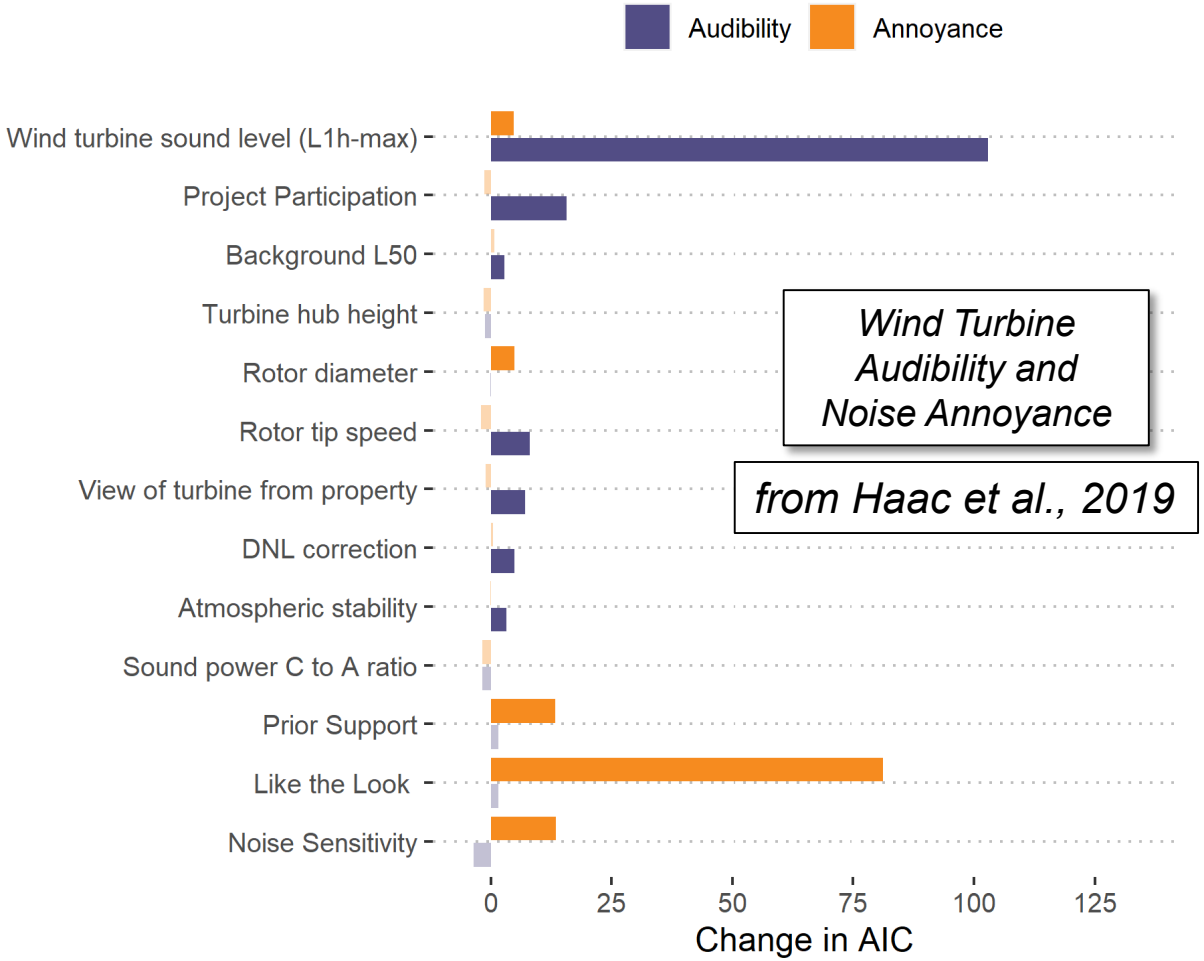
Shadow Flicker and Noise Perception and Annoyance Have Similar Patterns: Observable Variables





Shadow Flicker and Noise Perception and Annoyance Have Similar Patterns: Subjective Variables





Comparison of Noise And Shadow Flicker

- For homes with modeled wind turbine sound level 40 dBA or below, 98% do not exceed the 8-hour real case SF limit, while between 40 and 45 dBA, 90% do not exceed the limit. Alternatively, for those between 45 and 50 dBA or greater than 50 dBA, only 40% and 25% are below the 8-hour real case SF limit, respectively.