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Public receptiveness of vertical axis wind turbines

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ABSTRACT

Most of the scholarly focus to date has been on large horizontal axis rather than vertical axis wind turbines. It may be possible to improve the efficiency of vertical axis wind technology by deploying turbines in clusters. There might also be advantages to deploying vertical axis turbines at a smaller scale in urban or suburban areas and in places where the risk of bird damage is highest. Would these features increase public acceptance of new wind turbine installations and possibly open up new areas for wind energy development?

We conducted a public opinion poll in California to examine public receptiveness. We used experimental design to assess the willingness to accept vertical axis turbines in certain urban settings. We find that the visual differences between the vertical and conventional wind turbines did not matter very much in any of the hypothetical settings in which we placed them. However, the prospect of killing fewer birds registered strongly with our survey respondents, though it could be outweighed by concern for cost. We also show that certain segments of the population, particularly those who are more educated, may be open to a more extensive deployment of vertical axis turbines in urban communities.

1. Introduction

The extensive deployment of wind energy in many parts of the world has taught us a great deal about public attitudes towards wind turbines. Public understanding about wind energy in the United States remains superficial (Klick and Smith, 2010). While some members of the public are unalterably opposed to wind turbines for ideological or aesthetic reasons (Devine-Wright, 2004; Padersen and Larsman, 2008; Johansson and Laike, 2007; Ellis et al., 2007), the views of many others depend on various qualifications such as how close the wind farm facility is to their home (Jones and Eiser, 2010; Swofford and Slattery, 2010), its likely impact on birds (Drewitt and Langston, 2006; Smallwood and Thelander, 2008), the level of turbine noise and its impact on health (Bolin et al., 2011; Salt and Kaltenbach, 2011), the perception of shadow flicker (Eltham et al., 2008), the concern for spoiled scenery (Devine-Wright and Howes, 2010), community ownership (Warren and McFadyen, 2010), or perceived need for wind power (Devlin, 2005). Some of these objections have been met by siting wind farms in remote places and away from environmentally sensitive areas, while others have been met by technological advances (e.g. noise reduction). Nonetheless, as new developments may disrupt pre-existing emotional attachments and threaten place-related identity processes (Devine-Wright, 2009; Pasqualetti, 2011), wind farm proposals still encounter many objections from citizens and stakeholder groups, even in places where the majority of citizens are committed to meeting the challenges of climate change (Bell et al., 2005).

Most of the scholarly focus to date has been on large horizontal axis rather than vertical axis wind turbines. Vertical wind turbines have been less popular for various reasons, but especially because they have been less reliable than horizontal axis turbines, and current commercially available versions do not produce as much energy per unit as the horizontal turbines (Gipe, 2004). It may be possible to improve the efficiency of vertical axis wind technology, e.g. by deploying turbines in clusters (Dabiri, 2011). There might also be advantages to deploying vertical axis turbines at a smaller scale in urban or suburban areas and in places where the risk of bird damage is highest. Would these features

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increase public acceptance of new wind turbine installations and possibly open up new areas for wind energy development? The goal of this study is to test these propositions in order to give an old technology a new look, and see whether vertical wind technologies might be an underutilized option.

Our data is drawn from a California sample. California is particularly relevant since it has ambitious state goals for reducing greenhouse gases but at the same time has encountered problems in deploying new wind farms due to public concerns about siting and impact on wildlife. In the sections that follow, we set out some hypotheses about why the public might prefer vertical to horizontal axis turbines and tested them with an experimental public opinion survey design. We also use this experimental design to assess the willingness to accept vertical axis turbines in certain urban settings. In general, we find that the visual differences between the two types of turbines did not matter very much in any of the hypothetical settings in which we placed them. The prospect of killing fewer birds registered strongly with our survey respondents, though it could be outweighed by concern for cost. We also show that certain segments of the population, particularly those who are more educated, may be open to a more extensive deployment of vertical axis turbines in urban communities.

2. Vertical axis wind turbines

In contrast to horizontal axis wind turbines, in which a set of airfoil blades rotate around a horizontal axis like a propeller, vertical axis wind turbines are characterized by blade rotation around an axis perpendicular to the ground. This design obviates the need for a mechanism to orient the turbine in the direction of the oncoming wind, which enables the turbine to function in complex wind conditions such as those that are prevalent close to the built environment. It also facilitates installation of the generator and other components closer to the ground, potentially simplifying operations and maintenance. Current commercially available implementations of the vertical axis design use a simple permanent magnet generator to create electricity, which eliminates the need for a gearbox or other complex mechanical transmission as is found in conventional horizontal axis wind turbines.

The overall simplicity of the vertical axis wind turbine design should present a commercial advantage in terms of cost and the range of wind conditions in which the technology could be deployed. However, the development of vertical axis wind turbines has significantly lagged behind horizontal axis wind turbines since the mid-1980s, when horizontal axis turbines became the industry standard due to their higher efficiency of power conversion and better record of reliability. The past decade has seen a resurgence of interest in the vertical axis wind turbine platform, in part due to new research showing the possibility of improved overall wind farm performance from favorable aerodynamic interactions between closely spaced vertical axis turbines (Dabiri, 2011, 2014; Araya et al., 2014; Brownstein et al., 2016). This is in contrast to the reduced performance of horizontal axis turbines when placed in proximity within a farm (Hau, 2005). The data in Dabiri (2011) support the possibility of increasing the footprint power density from 2 to 3 W/m^2 for horizontal wind turbine farms to 20–30 W/m^2 for vertical wind turbine farms. The number of turbines involved in either scenario is proportional to the individual unit power. Current large horizontal wind turbines are typically 2–3 MW individually, whereas the vertical wind turbines would be 5–50 kW (0.005–0.05 MW) individually. The hub height deficiencies can be compensated by the increase in turbine efficiency due to collective behavior (e.g. Brownstein et al., 2016). In addition, the vertical wind turbine start wind speed is lower than that of the horizontal turbine.

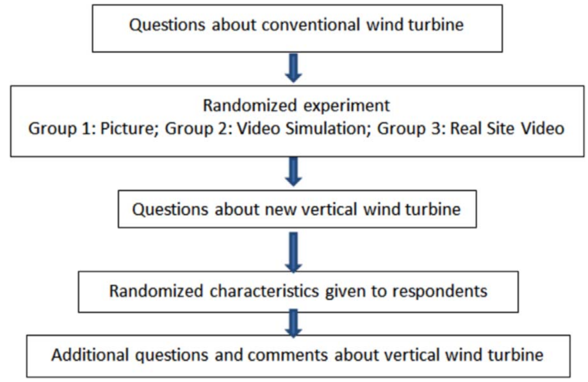

Fig. 1. Research design and embedded experiments.

An increased awareness of avian impacts from horizontal axis wind turbines has also encouraged the exploration of vertical axis wind turbines as a more environmentally-friendly alternative. Indeed, the lower operating speeds of the vertical-axis wind turbine blades, their different visual signature, and their typical implementation at lower heights than horizontal axis wind turbines suggest that they should have a more limited impact on birds and bats. Anecdotal evidence supports this view; however, controlled studies of avian impacts of vertical axis wind turbines have not been conducted to date.

3. Public opinion and technology preferences

Public opinion research has repeatedly shown that there are important limitations in what the public knows and cares about. In the area of economic policy, for instance, voters tend to react more to perceived conditions than to specific arguments about the merits of monetary versus fiscal strategies (Fiorina, 1981; Kinder and Kiewiet, 1981). Or when faced with choices about taxes and expenditures, many people lack the basic facts about which programs are the most expensive or have inconsistent views about what they are willing to pay for the services they believe that the government should provide (Converse, 1962). Hence, one might be skeptical about whether public input is valuable when it comes to choosing between different strategies and technologies for generating more alternative energy.

However, when energy technologies have tangible effects on people's lives or on their immediate environment, public attitudes can be more definitive and strongly held. At the same time, permitting procedures at the state and federal level for new energy facilities have been democratized, giving individual citizens, neighborhood groups, NGOs, and the like many opportunities to weigh in on the decision of whether and how to site new utility-scale thermal, solar, or wind turbine energy facilities. This in effect has given groups organized around specific wildlife causes such as protecting birds the ability to delay or hold up the permitting processes of new wind turbine deployments over possible bird deaths. If this problem is not addressed, it could limit the supply of an important source of alternative energy.

We can divide the determinants of public attitudes about wind turbines into three categories. First, there are factors that do not hinge on any specific features of technical design. These include climate skepticism and partisan polarization. Climate skeptics and those who support fossil fuels for partisan reasons are more likely to be unalterably opposed to new wind facilities, regardless of any new design features or carefully planned siting decisions. Political scientists have

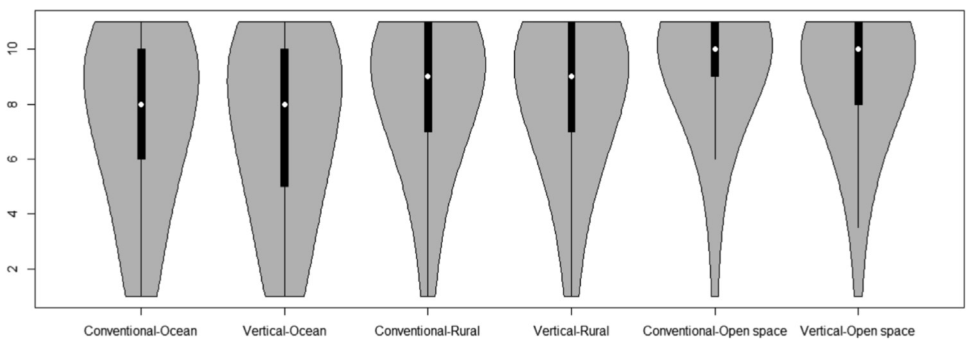

Fig. 2. Three pairwise location comparisons. Note: The boxplots contrast the favorability of pairwise comparisons between conventional and vertical wind turbine system in three locations, namely ocean, rural setting with sparse population and open space. Ocean setting is the least desired location while open space is the most preferred. The favorability of the vertical system, overall, is roughly comparable to that of conventional system.

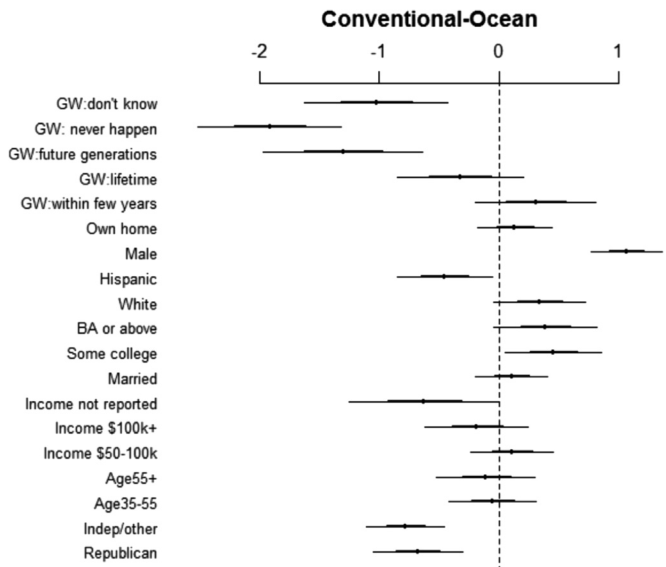

Fig. 3. Support for conventional wind turbine in ocean setting. Note: The dots display linear regression coefficients and the lines delineate 95% and 90% confidence intervals. The dependent variable ranges from 0 to 10, where higher number indicates stronger support. Attitude toward global warming (GW) is the strongest predictor. Respondents who believe global warming will never happen are the least likely to support installation of conventional wind turbine in our hypothetical offshore location.

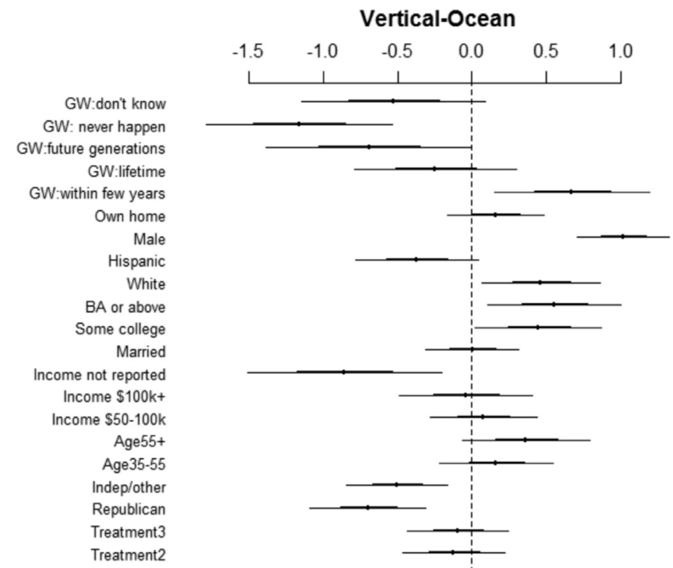

Fig. 4. Support for vertical wind turbine in ocean setting. Note: The dots display linear regression coefficients and the lines delineate 95% and 90% confidence intervals. Regardless of the form of communication, respondents who were skeptical of climate change remain more resistance toward vertical wind turbine compared to those who believed global warming is happening.

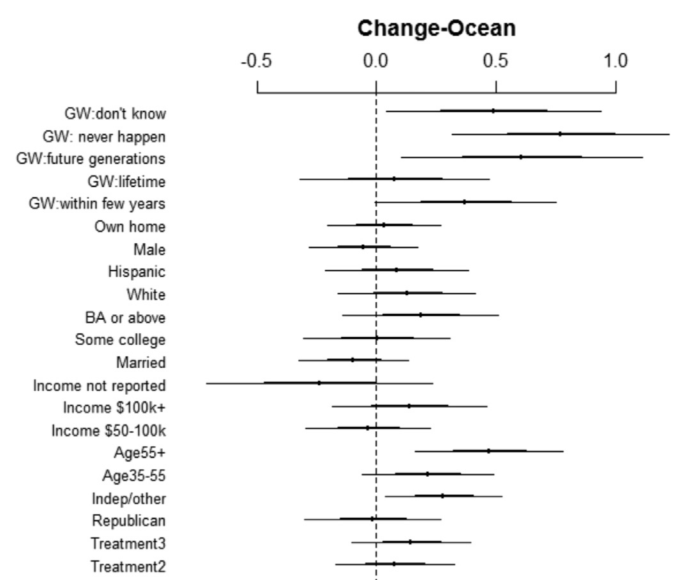

Fig. 5. Change in support in ocean setting. Note: Results from linear regression. Dependent variable is the change in score (i.e. support for vertical system minus that for conventional system). Positive coefficients indicate support in favor of the vertical system. Two groups show the biggest change ($p < 0.05$), namely climate skeptics and respondents who are above age 55.

been tracking the rise of partisan polarization for several decades (Poole and Rosenthal, 1984; McCarty et al., 2016). We know that partisanship can create a filter that shapes both what seems important to individuals and their willingness to accept evidence as credible to them (Enns et al., 2012; Iyengar and Valentino, 2000). It can even affect the credibility of scientific information if people believe that the science itself is influenced by ideology (Pornpitakpan, 2004). While this is not the focus of our research, it means that our models must control for such predispositions.

The second type of attitudes deals with trade-offs. These are features of turbine design that offer linked advantages and disadvantages. While it is likely advantageous that vertical turbines are smaller and less visible on the horizon, it is likely disadvantageous that in order to compensate for their lower efficiency in producing energy, a vertical design requires more units and, at least in a first implementation of the new technology, could initially cost more per kilowatt-hour than the conventional horizontal turbine. Clearly, we must take these trade-offs into account in any assessment of how people compare vertical and horizontal designs.

Finally, there are the specific features of vertical turbine designs that might cause individuals to prefer them to the horizontal turbines. For the purposes of this paper, we are not going to enter the debate as to whether the claims are proven or not, but rather on whether any of

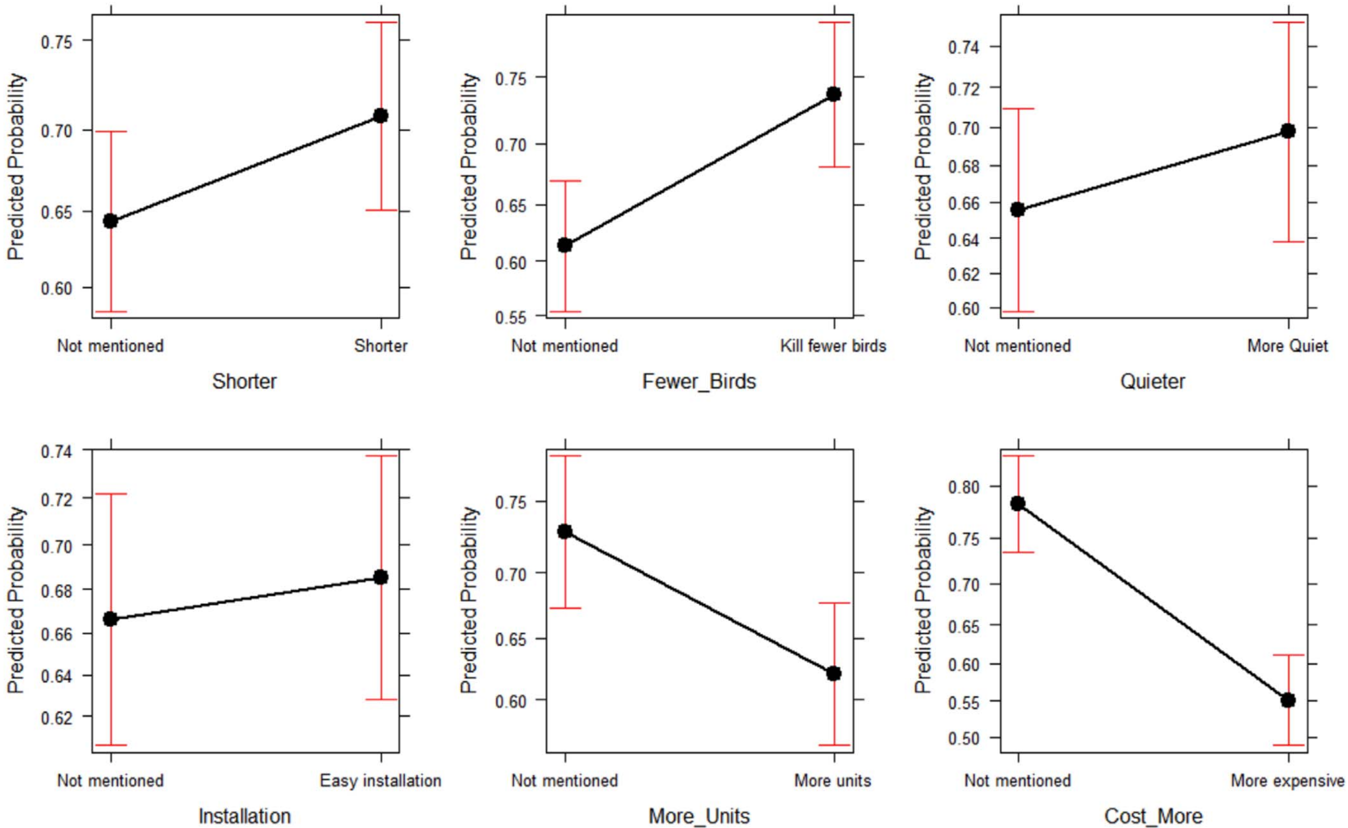

Fig. 6. Trade-offs among pros and cons. Note: Dependent variable is binary (1 = prefer the vertical system over the conventional one; 0 = otherwise). We plot the predicted probabilities for each statement associated with the support of the vertical system. Among our six features, killing fewer birds and bats is seen as the most positive feature and higher cost is seen as the biggest disadvantage.

these features, if true, would lead individuals to prefer the vertical to the horizontal design. The three that we focus on are lower height, less noise, and potentially killing fewer birds. Lower height may matter because we know from previous research that some people object to the appearance of the large horizontal turbines, especially close to where they live or travel regularly. Noise also matters to those who live near wind farm installations. But above all, we are interested in the potential bird deaths, as that has been a particularly salient and vexing problem in California. Efforts to limit bird deaths by technological means (e.g. smart blades) have been mixed at best with respect to horizontal turbines (Drewitt and Langston, 2006; Smallwood and Thelander, 2008). Nor has it been effective to try to argue that the bird deaths from climate change would likely exceed those from large wind turbines. However, the vertical design has a much better chance of succeeding and we are interested in discovering whether it could lessen resistance to new deployments.

4. Research design and data

4.1. Data

For this research, we devised an online opt-in public opinion survey that included two embedded experiments as well as a number of closed- and open-ended questions. We used Qualtrics, a survey company, to recruit about 2000 adults who were at least 18 years old and resided in California.[1] Respondents could complete the survey either with a computer or a mobile device. They were given a unique identification in order to prevent them from answering the same survey twice. Their responses, however, remain anonymous. Using the latest demographic statistics from the Census Bureau as reference, we conducted quota sampling based on gender, age and Hispanic origin to make our sample comparable to the general population in the state. In Appendix Table A1, we contrast the main characteristics of our sample to that in the population. The main differences are that our respondents are more educated and have higher income than the general population.

While our sample is not a probability sample, its diversity is comparable to that observed in the general population. Besides, some of our analyses are based on experiments. Random assignment to treatment conditions ensures our treatments are independent from respondents' observed and unobserved characteristics. Hence, our conclusions drawn from randomized experiments are empirically vigorous despite not having a probability sample.

4.2. Research design and methodology

We present our research design in Fig. 1. Our survey is divided into three main parts. Part 1 compares the new technology with the conventional wind turbine design. It includes a randomized experiment that tests three communication strategies that introduce the vertical wind turbine to the respondents. Part 2 explores the strengths and weaknesses of the new technology. It embeds another randomized experiment to test how respondents react to different qualities of the vertical wind turbine. Part 3 further studies the siting and pricing of the new technology and how it compares to alternative energy sources.

[1] The full survey is available here: https://irishuipolsci.weebly.com/research.html.

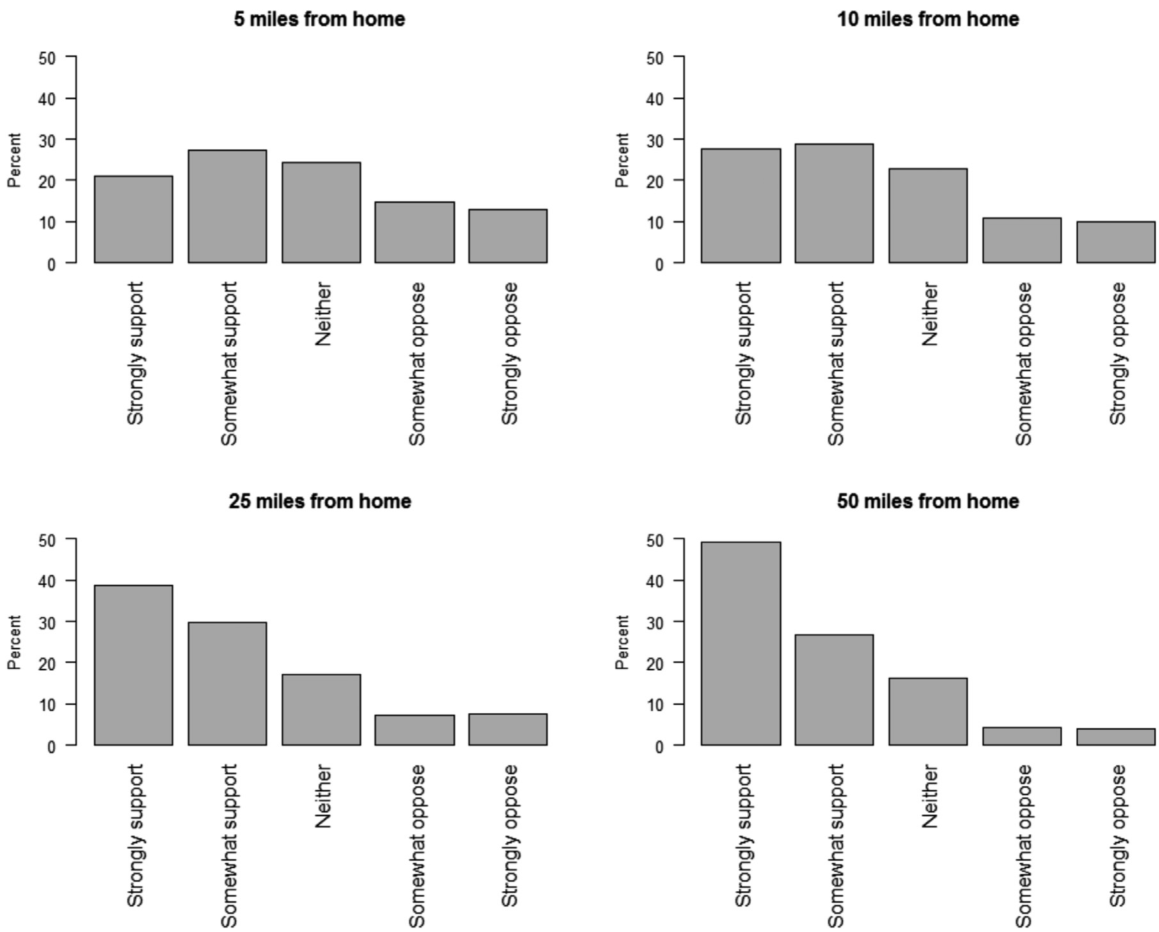

Fig. 7. Distance and home and support for vertical wind turbine. Note: Bar-plots show NIMBY thinking dominates. There is stronger support for sites further away from one's residence.

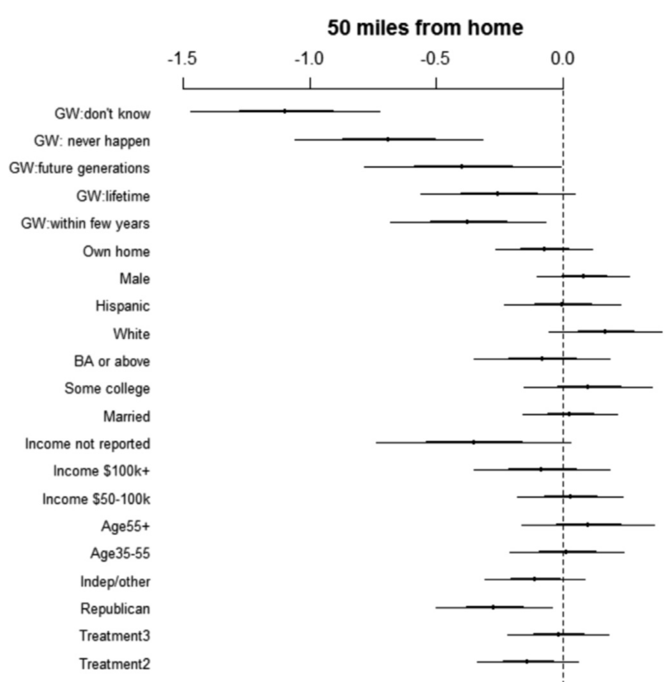

Fig. 8. Support for vertical wind turbine, 50 miles from home. Note: Coefficients from linear regression analysis. Less than half of our respondents support installing vertical system within 50 miles from their home. Climate skeptics and Republican identifiers are less likely to support the idea.

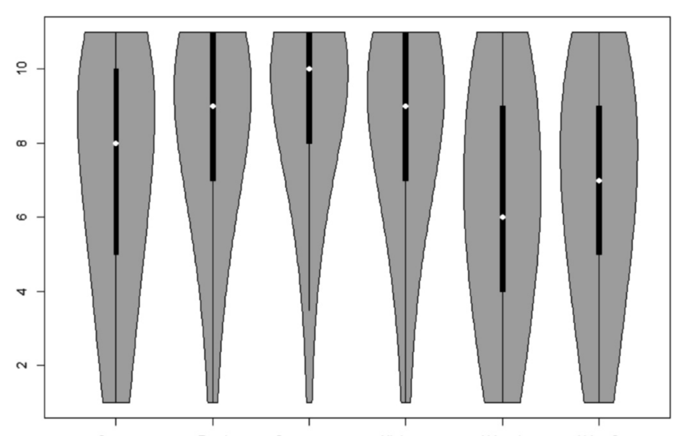

Fig. 9. Support for vertical wind turbine in six locations. Note: The boxplots contrast the favorability of vertical axis wind turbine in six different locations. The two urban scenarios are the least preferred by respondents.

4.2.1. Part 1: contrast new and conventional design

To establish a baseline for the support of the existing wind turbine technology, we began the study by asking all respondents to rate, on a scale from 0 to 10, whether they support installing the conventional wind turbine in three hypothetical scenarios. These three scenarios, namely, ocean, rural area with sparse settlement, and open space, are

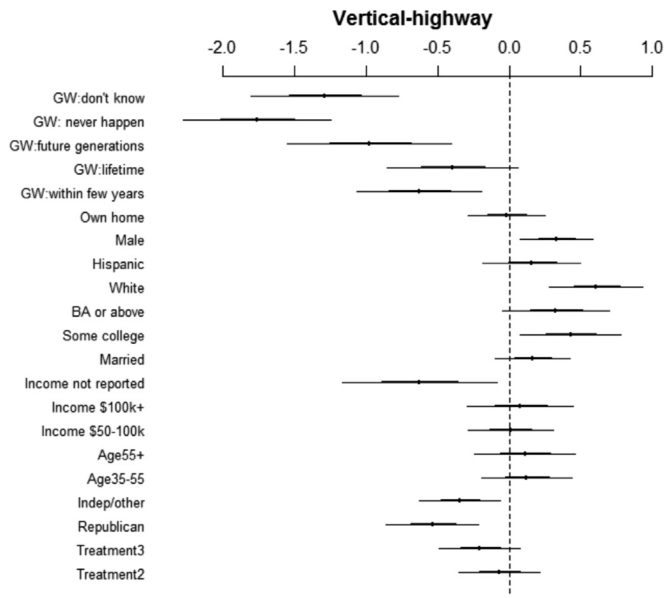

Fig. 10. Support for vertical wind turbine – along highway. Note: Coefficients from linear regression analysis. Support for installing a vertical system along highway varies by demographic. Self-identified Republicans and independents are less likely to rally behind the idea, same for climate skeptics.

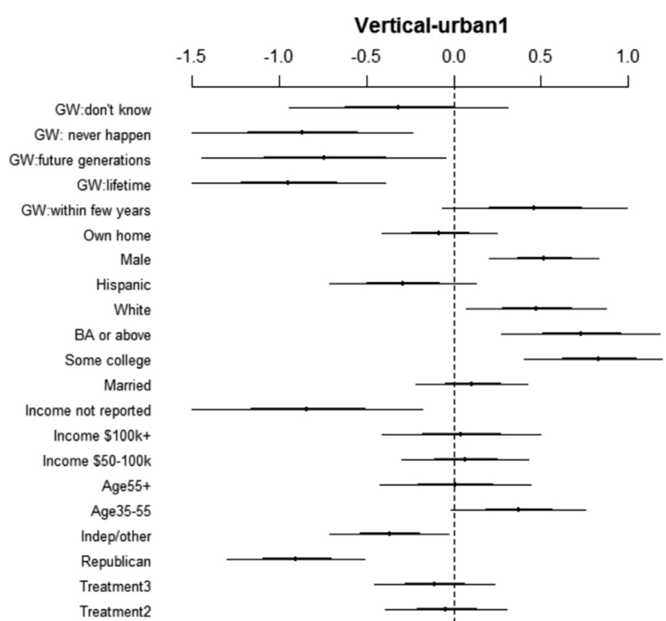

Fig. 11. Support for vertical wind turbine – in urban setting 1. Note: Coefficients from linear regression analysis. Support for installing a vertical system that integrates into urban setting varies by demographic. Self-identified Republicans, independents, females are less likely to rally behind the idea, same for climate skeptics.

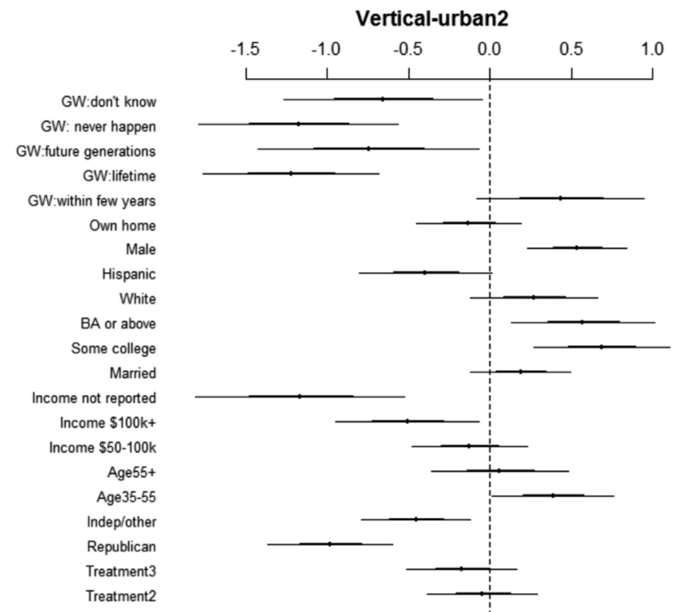

Fig. 12. Support for vertical wind turbine – in urban setting 2. Note: Coefficients from linear regression analysis. Support for installing a vertical system that integrates into urban setting varies by demographic. Similar to elf-identified Republicans, independents, females are less likely to rally behind the idea, same for climate skeptics.

examples of sites where conventional wind turbines are either currently installed or being discussed as a policy option.

In our first embedded experiment, we tested three different communication strategies and examined whether the introduction of the vertical system would change respondents' receptiveness toward wind turbines. Respondents were randomly assigned into one of the three treatment groups. In the first strategy, respondents were presented a picture (as shown in Appendix Fig. A1a) that highlights the height and size difference between the conventional turbine and vertical turbine systems. In the second and third communication strategies, respondents were shown two different videos. The two videos were both about 50 s in length. Respondents were required to watch the video before proceeding with the survey. The former video presented a computer simulation of the spinning action of the vertical turbine system and the latter featured the system in an actual site (screen-captures from videos are shown in Appendix Fig. A1b and c).

Respondents were presented with three paired scenarios. They were first asked to rate, from a scale of 0–10, how much they support installing the conventional turbine system in ocean (location 1), rural area (location 2) and open space (location 3) settings. After our experimental treatments, they were asked to rate a parallel set of photos with the same background but featuring the vertical turbine system. The photos used in the experiment are displayed in Appendix Figs. A2, A3 and A4.

We also explored which sub-groups in the sample were more susceptible to changing their opinion in favor of the vertical turbine system. We ran three sets of separate linear regression models with the dependent variable ranging from 0 to 10, where a higher score indicates stronger support. The dependent variables for the three models are support for the conventional wind turbine, support for the new design, and change in support between the conventional and new design. We controlled for demographic factors and treatment conditions in these regression models.

4.2.2. Part 2: strengths and weaknesses

In our second embedded experiment, we tested the impact of communicating different qualities of the new system. Respondents were told that, compared to the conventional wind turbine, the new system:

- is 90% shorter (i.e. 1/10 of the height);

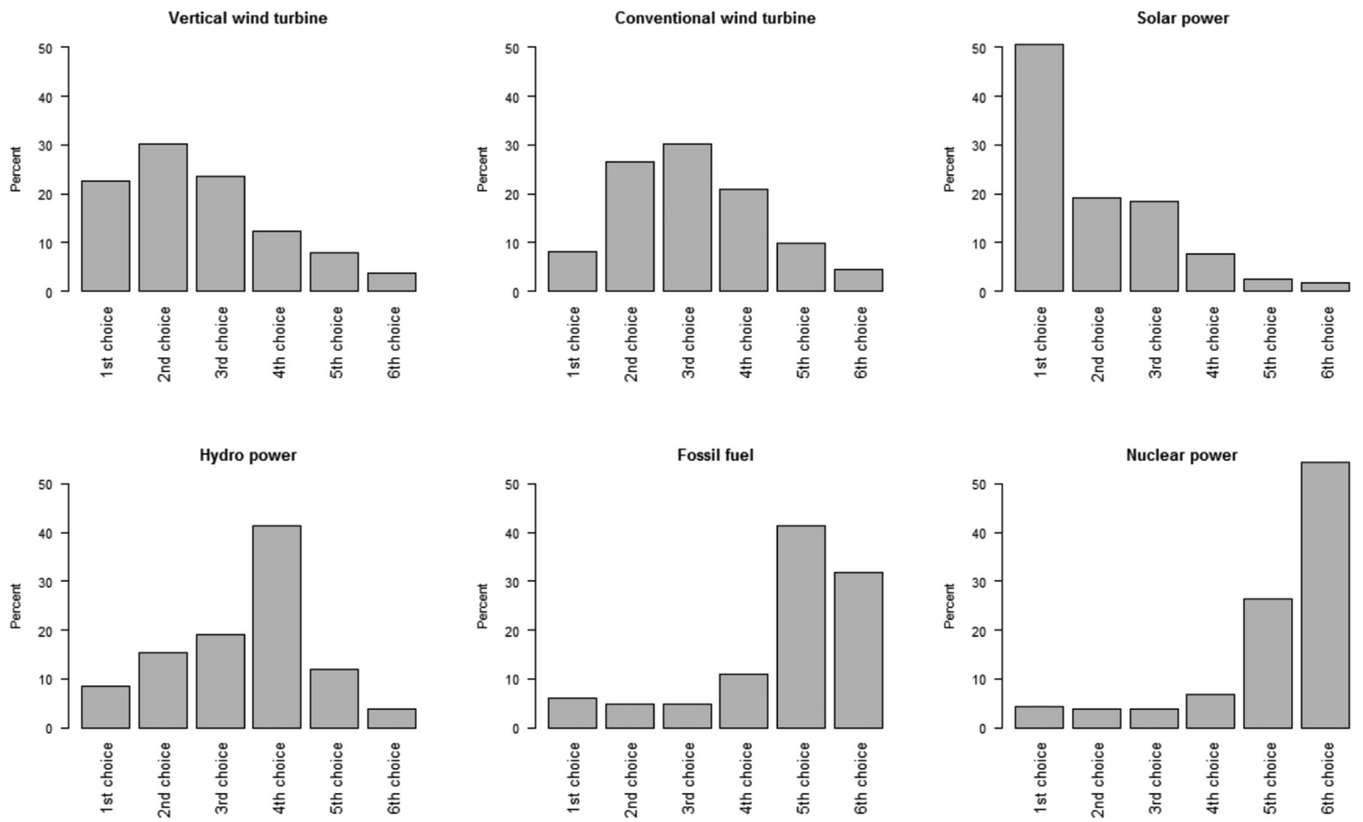

Fig. 13. Preference among six energy sources. Note: Bar-plots show the preferences among six energy sources. Solar energy is more preferred to wind energy. Between the two types of wind energy, vertical system commands slightly stronger support than conventional system.

- may kill 90% fewer birds and bats;
- is 50% quieter;
- can be installed without specialized equipment;
- would require more units to generate power (i.e. smaller turbines but more numerous);
- per kilowatt-hour electricity cost may be 25% more expensive.

Each respondent would receive *three* randomly assigned statements. Our goal is twofold. Through random assignment, we can identify the impact of each statement on the support for the new design, as well as the trade-offs among our criteria.

4.2.3. Part 3: siting, pricing and other energy sources

In contrast to the conventional system, the vertical turbine system is compact and has the potential advantage of integrating into densely populated urban space. We tested the public receptiveness toward having the vertical system in an urban setting. We featured three additional hypothetical scenarios (photos are shown in Appendix Fig. A5). The first scenario is adjacent to a highway, and the second and third scenarios are as part of an urban garden and along urban coast, respectively. Lastly, we further explore whether the communication strategies and mention of qualities affect respondents' reactions to different siting and pricing and preference toward various energy alternatives. We ran linear regression models to explore how the socio-demographic characteristics of respondents correlate with their reactions.

5. Results

5.1. Contrast conventional and vertical system

Fig. 2 shows six violin plots to display the distribution of scores in each scenario. Among all three locations, ocean is the least preferred and open space is the most preferred. The means for vertical turbine system are slightly lower than the conventional system. In the ocean scenario, the mean for former is 7.2 and 7.5 for latter (*t*-test difference in means, $p = 0.003$); in the rural area scenario, the means are about the same at 8.4; and in the open space scenario, the means are 9.1 for the vertical system and 9.4 for the conventional system ($p < 0.001$). The boxplots, however, reveal that the differences are substantially small.

5.1.1. Sub-groups that are susceptible to change

We tested three different communication strategies and explored how the introduction of the vertical wind turbine system would change minds, especially among skeptics. We ran a linear regression model with the dependent variable ranging from 0 to 10, where a higher score indicates stronger support. Fig. 3 shows how various sub-groups support the conventional wind turbine in the first hypothetical site – ocean (location 1). Respondents who self-identified as Republican, independent, or with a third political party are less likely to support the idea than Democrats. Gender and ethnicity play a role as well. Female respondents and Hispanic respondents are less supportive of the idea. The biggest contrast is found between climate change believers and skeptics. We included a question in our survey, "which of the following statements reflect your view of when the effects of global warming will begin to happen?" Those who said global warming "will never happen", or it "will not happen within (their) lifetime but will affect future generations", or "don't know" are substantially less likely to support the installation of conventional wind turbines offshore than the reference category, that is, those who believe global warming is happening now. These groups comprise about 15% of the sample.

Fig. 4 shows the same coefficient plot, except the dependent variable is switched to support for the installation of vertical wind turbines offshore. We find that the impacts of our three communication strategies, as indicated by the dummy variables, Treatment 2 and Treatment 3, are not statistically distinguishable. That is, whether respondents were shown a picture or a simulation or an actual site does not affect their perception of the vertical turbine. The finding removes any concerns that our results may be biased by the way the vertical turbine system was introduced to the respondents.

Compared to climate change believers, those who were skeptical of climate change remain less likely to support the vertical design. Similarly, self-identified Republicans and independents are less likely to rate the vertical system favorably compared to Democrats. Gender (male respondents), race (white respondents) and education (those with at least a bachelor degree) are positively associated with the support for the vertical system in ocean setting.

Fig. 5 shows the changes in opinion between vertical and conventional wind turbine. Positive coefficients indicate a change in favor of the vertical wind turbine design in location 1. Two groups show notable improvement. The first are respondents who are above the age of 55, the second are respondents who are climate skeptics. The increase in support is about half a point on the dependent variable. Both groups become slightly more receptive toward installing a vertical turbine system in the sea.

We conducted similar analyses for the other two hypothetical locations, namely, rural area with sparse population (location 2) and open space (location 3). Because the support for these locations was initially high, there was little change in opinion when the vertical turbine system was introduced. The results are reported in our Online Appendix and are not shown here.

5.2. Receptiveness toward strengths and weaknesses

Our second embedded experiment focuses on the qualities of the vertical wind turbine system. As discussed, respondents received three out of six items from the list randomly. They were then asked if they would prefer the vertical system over the conventional one. The dependent variable is binary, where 1 indicates in favor of the vertical system and 0 otherwise. In Fig. 6, we compare the predicted probability of each statement on the support for the vertical system. Among our six items, killing fewer birds and bats is the most desirable feature, closely followed by smaller size and less noise. Killing fewer birds garnered an increase of about 13% points in the probability of support for the vertical system. Easy installation generates little excitement as this advantage of the vertical system is less relevant to consumers. While each individual vertical turbine is shorter and smaller in size, requiring more units to generate the same level of electricity is also seen as a disadvantage. As expected, cost is a primary concern among respondents. When respondents were told the vertical system could generate energy that cost 25% more per kilowatt, support dropped by over 20% points. The potential increase in cost offset the pros of the system.

5.3. Siting

Since the vertical turbine system is shorter and more compact, we examined if respondents would be receptive toward installing a system close to their residence. Respondents were asked, "would you support installing the new vertical wind turbine system if it would be placed within 5, 10, 25 and 50 miles from your home?" Fig. 7 shows the distribution of preferences. Our finding corroborates one established finding in the literature – when it comes to siting, not-in-my-back-yard (NIMBY) tendency remains strong. Support tends to grow with increasing distance from sites (Jones and Eiser, 2010). About 75% of respondents would support installing a vertical system 50 miles away from home. The coefficient plot, Fig. 8, from regression analysis shows that climate skeptics and self-identified Republicans remain less likely to support a new vertical wind turbine even if it is installed 50 miles away from home.

5.3.1. Receptiveness toward Installing the vertical system in urban settings

The vertical wind turbine system has the advantage of integration in densely populated areas. Respondents were shown three additional hypothetical scenarios, near a highway and integrated into urban settings. Fig. 9 compares the distribution of preferences among all our hypothetical scenarios.

Although there are several sites that feature the conventional system along California highways, the support for that lags behind support for the system in rural settings or in open space. As for our two urban settings, our respondents only show lukewarm support.

The coefficient plots in Figs. 10–12 show the variation in support among our respondents. Respondents with higher educational attainment are more open to installing the vertical system in integrated urban settings. We also included population density as a proxy for urbanity in the models. We did not find significant variation in preference across geographic location; that is, urban residents were no more likely to support or oppose installing the vertical system. Hence, we did not include that result here.

5.4. Alternative energy sources

Lastly, we explore the desirability of the vertical wind turbine system relative to the conventional wind turbine system and other energy sources. Respondents were asked to rank six energy options in order of their preference to generate electricity. Fig. 13 shows that solar power is the most preferred energy source in California. Wind energy comes in a close second. Perhaps because of the priming effect of getting information about the features of different types of wind turbines, respondents in our survey showed a slight preference in favor of the vertical over the conventional horizontal wind turbine system. We suspect that because of the recent drought experienced in the state, respondents were hesitant to rely on hydro power. Fossil fuel, a non-renewable source, and nuclear power, deemed a risky source by the general public, rank last in preference among the six sources.

6. Discussion

Our survey experiment results consistently show no substantial difference in preference for vertical over horizontal wind turbines in various settings. This holds true no matter whether the respondents come to learn about the system through a picture, a computer simulation video, or an actual site video; i.e. the mode of introduction does not affect the pattern of responses. It may also mean that any of these modes of conveying information can effectively work as a means of public education about the wind turbine system.[2]

Our evidence suggests that Californians have already developed a

[2] Because the Internal Review Board requirement, respondents were informed, at the beginning of the survey, that the public opinion study was conducted by the Bill Lane Center for the American West at Stanford University. The effect of identifying the university this way is unknown, but was unavoidable.

general acceptance for large centralized horizontal wind generation away from populations at the lowest cost. Do vertical wind turbines offer features that the public might prefer over the conventional system? The survey results indicate that many see a shorter, quieter system as an advantage, though that could be off-set by requiring more units to generate the same energy as the horizontal system. Easier installation is seen as an advantage for the vertical system. It is, however, less relevant from consumers' perspective. Killing fewer birds is seen as a desirable feature regardless of the type of system. This will be seen as an added advantage if the vertical system is proven to kill fewer birds than conventional turbines.

At the same time, it will be important to make new versions of vertical wind turbine systems as cost-effective as possible since there is clear evidence that potential higher costs are viewed negatively. We explored precisely how price-sensitive respondents were by asking them about their exact willingness to pay for the energy generated by vertical wind turbine. The result is reported in our Online Appendix. We find that just a $5 increase in monthly electricity bills would deter half of the respondents in supporting the vertical wind turbine system. The result suggests respondents are highly sensitive to pricing.

Similar to other studies on wind turbines, we find strong levels of NIMBY-ism even in our hypothetical scenarios. About a quarter of our respondents still express reluctance even if the vertical wind system is installed 50 miles from their homes. While our sample captures the diversity of opinions among Californian residents and shows how support varies across multiple segments of the population, it can by no means fully predict who would become politically active in rallying against the system in reality. This is because political activism around wind turbine is often a function of siting. General support for wind energy may not translate into support for a particular wind mill project (Wolsink, 2000). Residents who are generally supportive of wind energy may become defensive if the actual site is too close to home or disrupts their familiar landscape. Similarly, opponents of wind energy may not voice any adamant opposition if the site is in a remote location.

In this survey, we have tested several dimensions of the vertical system, including appearance, siting, costs, and environmental impact. One important dimension that we have not explored is noise. In theory, we could incorporate sound in our experiment. In practice, it is hard to control the quality and experience of such an experiment. Respondents may not turn on the volume, or have the volume too high or too low, and respondents who wear headphones may have different experiences than those who listen through a speaker.

Due to space limitations, we have only tested six different sitings for the vertical system. There are other possibilities. For example, given the compact size, the vertical system can be co-located underneath the existing conventional wind turbine system, or the vertical system can replace sites with the obsolete conventional wind turbine system. Such placement may garner stronger support as the installation would not take up new land.

7. Conclusion and policy implications

How can this evidence inform policy-making with respect to wind turbines? We would argue that rather than seeing horizontal and vertical wind turbines as competing technologies serving identical functions, they should be seen as potentially complementary. Vertical wind turbines may be more suitable in some areas than others and vice versa for horizontal wind turbines. For instance, it is possible that vertical wind turbines may be a better solution in sensitive wildlife areas if they do less damage to birds. If this proves to be true, it could neutralize the strong objections of bird-oriented stakeholder groups and help states with ambitious sensitive habitation protection and greenhouse gas reduction goals to move forward.

It is also possible that vertical wind turbines could be placed in certain urban settings where horizontal wind turbines would be too intrusive. Rodman and Meentemeyer (2006) have evaluated the wind conditions in nine counties in the San Francisco Bay Area. They identified numerous locations in the Bay Area for placement of smaller-scale wind turbine systems. The vertical axis wind turbine system is physically more compact and has the potential to be integrated into more urban settings. While average public receptiveness to this idea is lukewarm, the equation results in Fig. 11 show a higher receptivity to the idea among highly educated individuals who are committed to the goal of reducing global warming. This profile fits many cities in the Bay Area of California, for instance, suggesting that these communities might be open to vertical wind turbine projects in the future.

With respect to implications for future research, an important next step in the development of vertical axis wind turbines is to rigorously characterize avian impacts, so that the anecdotal observations of reduced harm can be supported by quantitative data. Those results can play an important role in both local permitting discussions and broader policy implementation in the state. Moreover, the imperative revealed in this study to achieve costs comparable to existing wind technology should motivate specific research and development to identify areas for cost reduction, e.g. via streamlined manufacturing and supply chain integration.

In addition to the effect of NIMBYism on siting, McClachlan (2009) argues that people's reaction to renewable energy can be in part related to interpretations of what the technology and the location are seen to represent or symbolize. Further qualitative research in the form of in-person interviews would be useful in understanding the symbolism related to vertical and conventional wind turbines. Interviews can explore how these two systems are seen to be congruent with landscape and how perception of 'fit' can be improved, especially for vertical wind turbines in urban settings.

Perhaps the most important cost component of vertical axis wind turbines that requires further attention is the economic toll of their relatively low reliability. The reliability issues for horizontal wind turbines have been addressed through decades of concerted research. A similar level of research has not occurred for vertical wind turbines. That situation is changing as academic researchers are increasingly studying vertical axis wind turbines. For example, the number of annual journal citations to vertical axis wind turbines has increased from 14 in 2006 to 1600 in 2016; the number of published articles has increased by a similar factor. However, it will still be essential to resolve those technical issues in order to achieve cost-effective energy production from vertical axis wind turbines.

Finally, it is worth noting that even more unconventional wind-generating devices, including airborne kites, waving structures that resemble trees, and devices with no moving parts, are all currently at various stages of development. The present work provides a framework for evaluation public opinions regarding those technologies in the future.

Appendix A

See Appendix Figs. A1–A5
See Appendix Table A1

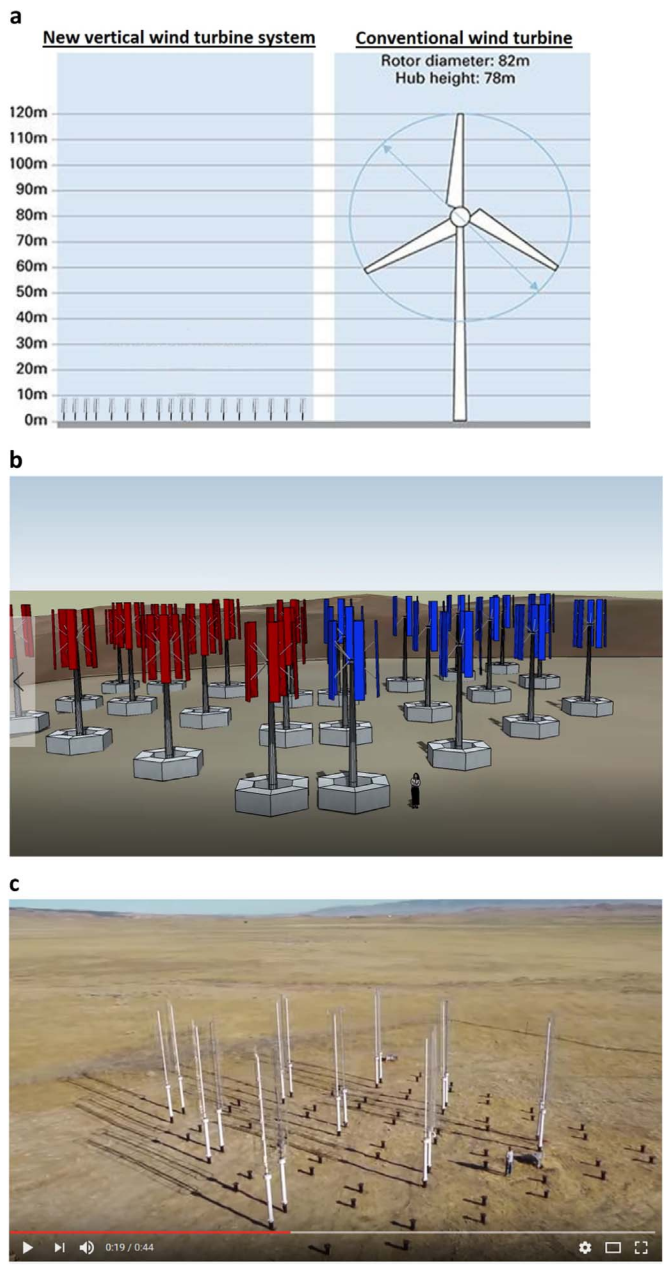

Fig. A1. a: Experimental Cue #1 (Picture). b: Experimental Cue #2 (Computer Simulation). c: Experimental Cue #3 (Actual Site).

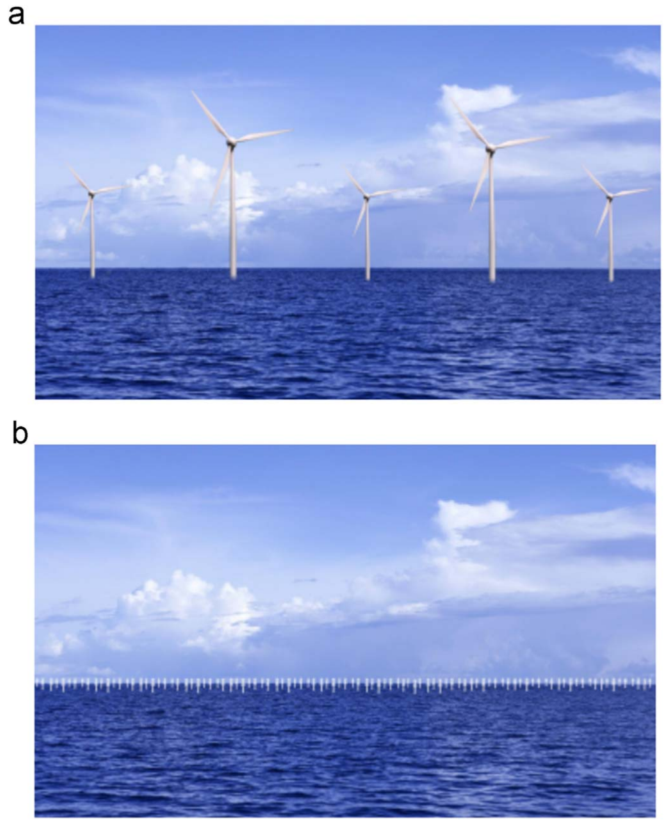

Fig. A2. Experimental Pair Comparion # 1 (Ocean).

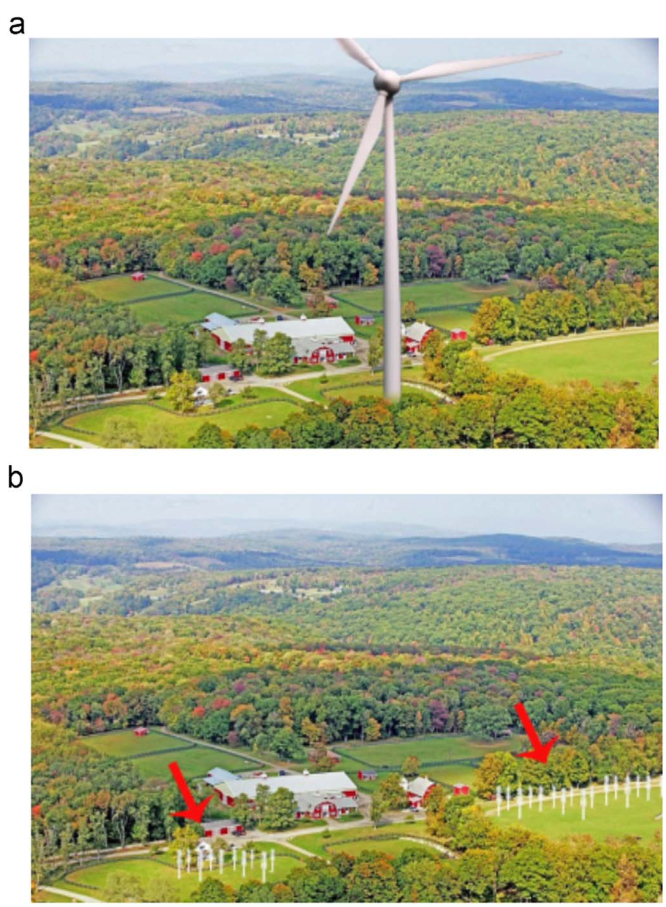

Fig. A3. Experimental Pair Comparion # 2 (Rural).

Fig. A4. Experimental Pair Comparion # 3 (Open Space).

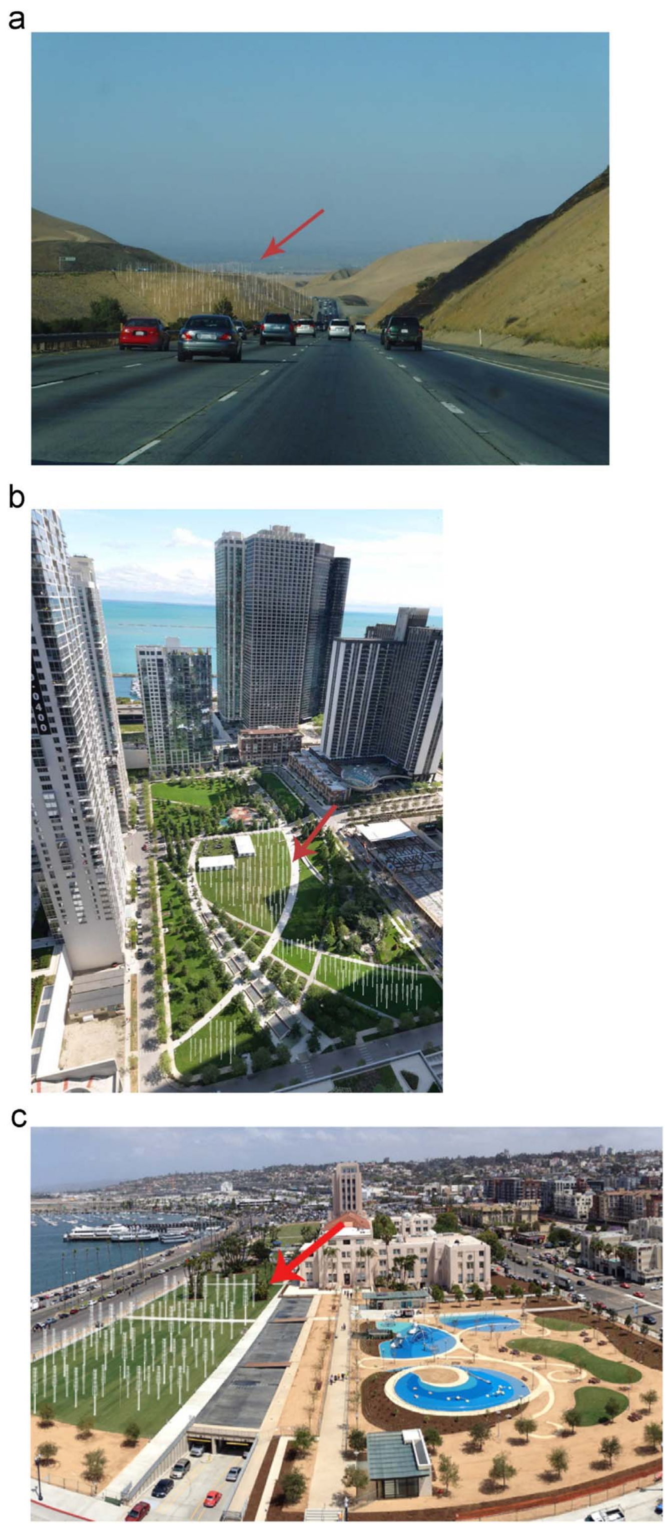

Fig. A5. a. Experimental Cue # 1 (Highway). b. Experiment Cue # 2 (Urban1). c. Experiment Cue # 3 (Urban2).

Table A1
Comparison between our sample and general population.

	Our sample	Population[a]
% Democrat	49%	44%
% Republican	22%	28%
% Independent/other party	30%	29%
% Age between 18–34	32%	33%
% Age between 35–54	38%	37%
% Age 55 or above	30%	30%
% Income < $50k	39%	47%
% Income $50k - < $100k	33%	33%
% Income over $100k	23%	20%
% Income not stated	5%	N/A
% Married	48%	48%
% White	56%	58%
%Hispanic origin	38%	38%
% High school or less	16%	43%
% Some college	37%	30%
% College or more	47%	27%
% Male	49%	50%
% Own home	56%	54%
Sample size	1965	

[a] Demographic statistics obtained from Census 2010 Summary File 1 and 3; Party registration statistics obtained from California Secretary of State, which is not a comparable but not identical comparison with party identification measured in our survey.

Appendix B. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2017.10.028.

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