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How do residents perceive energy-producing kites? Comparing the community acceptance of an airborne wind energy system and a wind farm in Germany

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ABSTRACT

Airborne wind energy (AWE) is an emerging renewable energy technology that uses kites to harvest winds at higher altitudes than wind turbines. Understanding how residents experience a local AWE system (AWES) is important as the technology approaches commercialization. Such knowledge can help adjust the design and deployment of an AWES to fit locals' needs better, thereby decreasing the technology's burden on people. Although the AWE literature claims that the technology affects nature and residents less than wind turbines, empirical evidence has been lacking. This first community acceptance study recruited residents within a 3.5 km radius of an AWE test site in Northern Germany. Using structured questionnaires, 54 residents rated the AWES and the closest wind farm on visual, sound, safety, siting, environmental, and ecological aspects. Contrary to the literature's claims, residents assessed the noise, ecological, and safety impacts similarly for the AWES and the wind farm. Only visual impacts were rated better for the AWES (e.g., no shadows were perceived). Consistent with research on wind turbines, residents who rated the site operation as fairer and the developer as more transparent tended to have more positive attitudes towards the AWES and to experience less noise annoyance. Consequently, recommendations for the AWE industry and policymakers include mitigating technology impacts and implementing evidence-based strategies to ensure just and effective project development. The findings are limited to one specific AWES using soft-wing kites. Future research should assess community responses across regions and different types of AWESs to test the findings' generalizability.

1. Introduction

Considerably more renewable energy is needed to limit global warming to below two degrees [1,2]. As a result, many more renewable power plants have to be built, also close to residential areas. The deployment of sustainable energy must consider how humans perceive and respond to those innovations to reduce the impact on residents and avoid local opposition slowing down the expansion of renewables [3,4,5].

The evolution of new energy technologies offers the opportunity to consider social needs, concerns, and values already in the development phase. One such emerging technology is airborne wind energy (AWE). AWE uses tethered flying devices to harvest higher-altitude winds not accessed by wind turbines (WTs). A recent report commissioned by the industry estimates that by 2035, 5 GW of AWE could be commercially deployed, increasing to 177 GW by 2050 [6]. According to the International Renewable Energy Agency, AWE has the potential to contribute to decarbonizing the energy sector successfully alongside established

Abbreviations: AWE, airborne wind energy; AWES, airborne wind energy system; AWESs, airborne wind energy systems; WT, wind turbine; WTs, wind turbines.

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wind energy technology, especially offshore [7].

While researchers and developers worldwide have worked on AWE prototypes for over two decades, the technology is still in its infancy, with only a few pilot projects [6]. The early development stage offers opportunities for assessing the technology's social impacts ahead of time so they can be considered in the design phase before the technology is fully matured [8,9]. It is necessary to understand the technology's key features to examine the social implications of AWE. There are different implementations of AWE, but generally, a distinction can be made between ground-gen(eration) and fly-gen(eration) concepts [10]. During ground-gen, the lift forces of the kite are converted into electricity by flying the kite at an increasing altitude in a programmed trajectory, such as figures-of-eight or circles (Fig. 1). As the ascending kite pulls the tether from the drum, the generator attached to the rotating drum is powered. When the kite reaches the end of the tether, it is automatically depowered and reeled back in so that the energy generation phase can start anew. This results in a continuous cycle of reel-out and reel-in, referred to as the pumping cycle. More energy is generated during the reel-out than is consumed during the reel-in, leading to a positive net power outcome [11].

A specific subtype of ground-gen systems does not generate energy through reeling out and reeling in. These rotational systems instead use multiple rotors connected by tethers that are kept in the air with a lifter kite (Fig. 1) [13]. While keeping the system of tethers tensioned, the entire structure rotates. The torque of the rotation is then converted into electricity by a generator on the ground. Kites used for ground-gen are usually soft-wing kites made from flexible membrane wings or fixed-wing kites that consist of carbon fiber-reinforced polymers (Fig. 1). Sometimes hybrid-wing kites are used that combine a rigid support structure with a textile canopy. For fly-gen, the other operational type, the kite carries small onboard wind turbines that produce electricity in the air (Fig. 1). The electricity is then transmitted through a conducting tether to the ground. Current fly-gen concepts exclusively use fixed-wing kites because attaching an onboard wind turbine to a soft-wing kite is difficult.

While there are more than two decades of technical research on AWE, it has yet to be empirically investigated how people view the technology [14]. Despite the lack of research, the AWE literature is optimistic about the acceptability of the technology. Specifically, in the literature, five factors are assumed to influence the social acceptance of the technology: visual impacts, sound emissions, ecological impacts, safety, and geographical sites [14]. Visual impacts are expected to be lower for an AWE system (AWES) compared to a WT due to the higher operational altitude, the absence of a tower, less shadow-casting, and the possibility of retrieving the kite in low wind. Sound emissions and ecological impacts are also expected to be weaker for an AWES than a WT. These three impact factors are thus presumed to influence the social acceptance of AWE positively compared to WTs. Only safety concerns about the technology, aviation collisions, and presently lacking regulations are recognized as possible bottlenecks for acceptance. Certain sites, such as densely populated regions, are also seen as potentially detrimental to the acceptance of the technology.

However, the AWE literature does not back up these claims with evidence. Further, it disregards individual preferences, experiences, and perceptions and assumes that humans assess AWE entirely rationally [14]. Social psychological research and studies on established renewables demonstrate that people's assessments are intertwined with their experiences with a given technology or energy plant. For example, research has repeatedly shown that residents' experience of the planning process and the distribution of benefits is related to their acceptance of a local energy project [15,16,17,18,19,20,21] and how they perceive the project's impacts [22,23]. The lack of knowledge about which factors influence the acceptance of AWE, combined with the persistent, unfounded assumptions in the AWE literature, can lead to a distorted understanding of the technology's social impacts [14]. As a result, policy and deployment decisions could be misinformed, increasing the chance that the technology will burden people disproportionately. Furthermore, potentially resulting widespread opposition would cause rising implementation costs, dwindling political support, and limit AWE's contribution to renewable energy targets [24]. Empirical social science studies are thus needed to help understand people's perceptions of and responses to AWE better. This increased understanding can help identify relevant factors that should be addressed in the technology's development or deployment to facilitate its introduction into society [25,26].

The present study aims to address this knowledge gap by testing the literature's assumptions regarding the visual impacts, sound emissions, ecological impacts, safety, and siting of AWE. Specifically, we empirically test the following six hypotheses: (1) residents have a more positive attitude towards AWESs than WTs; residents rate (2) visual, (3) noise, and (4) ecological impacts more positively for AWESs than WTs; (5) safety perceptions are highly relevant to the acceptance of AWESs; (6) remote sites are more acceptable for AWESs [14]. While there are no commercial AWESs in Europe yet, certain impacts, such as noise and obstruction lights, will only be perceptible in the direct vicinity of an AWES. Therefore, we decided to evaluate the literature's assumptions at a test site of AWE, thus focusing on the community acceptance of the technology at the local level [27]. In line with past research, community acceptance was operationalized as residents' attitudes towards the AWES [15].

2. Method

Residents living up to 5 km from an AWE test site in Northern Germany were recruited. Consistent with standard practices in community acceptance research, residents' evaluations of the AWES and the WTs were assessed through a structured questionnaire with open- and closed-ended questions [18,21]. Next to measuring respondents' attitudes towards local renewable energy projects, the questionnaire mainly focused on visual, noise, ecological, and safety impacts of the AWES and the WTs to test the study's hypotheses. During in-person appointments,

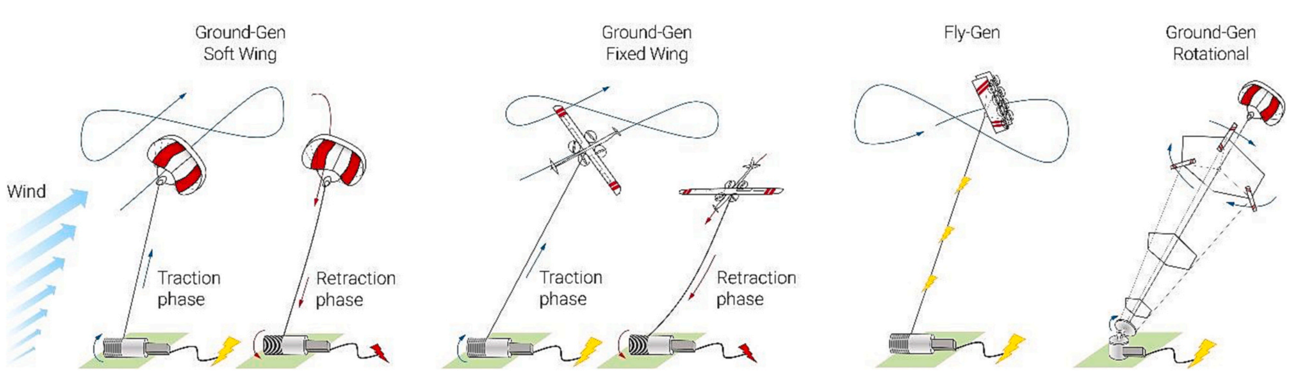

Fig. 1. Overview of ground- and fly-gen airborne wind energy systems in operation (adapted from [12]).

fifty-five residents answered the questionnaire online or in vivo, of which one respondent had to be excluded. We analyzed the resulting quantitative and qualitative data through standard statistical procedures and thematic coding, respectively. In the following, we provide more details about four main components of the method: the research context, the participant recruitment, the data collection, and the statistical analyses. The institutional review board of Delft University of Technology gave ethics approval for the research.

2.1. The research context

The AWES operated at a test site of a German AWE developer in a rural, flat area in Schleswig-Holstein, Northern Germany (Fig. 2). In 2017, the local council permitted the site. The permit was initially issued for a research project from 2018 until 2022 [28]. In agreement with the municipality, the developer decided to inform residents once the testing activity increased and became more noticeable. Thus, about a year after the operation began in December 2019 [28], the developer informed residents in two of the four adjacent municipalities about the purpose and the impacts of the site by letter. Half a year later, the developer invited the same households for an open day. An official public participation process did not occur and was not legally mandated for this temporary, non-commercial site. At the end of the research project, the permit was extended until autumn 2024 [28].

Since the start of the operation, the developer has tested different prototypes, all ground-gen concepts using a soft-wing kite with a wing surface area between 40 and 160 m^2 [28]. The kite's flight altitude was approximately 200 to 400 m, and the rated cycle power was up to 200 kW. The AWES did not operate continuously, and for organizational reasons, most of the flights since 2019 took place during the day between Mondays and Fridays [28]. Continuous overnight flights also occurred for testing purposes [28].

We chose this site because the deployed AWES has the most operation hours worldwide, according to the developer [28]. This enabled us to identify a sufficient number of residents familiar enough with the AWES to evaluate it. Moreover, Schleswig-Holstein's high density of WTs [29] allowed us to compare residents' perceptions of the AWES with their evaluations of WTs in the vicinity.

2.2. Participant recruitment

All residents, 18 years or older at the time of the study, who lived up to 5 km from the AWES, could participate if they knew the site. The recruitment of respondents followed eight steps: (1) we identified all 1152 addresses in a 2.5 km radius around the AWES through public online map services (i.e., https://www.google.com/maps; https://danord.gdi-sh.de); (2) we sent letters to all addresses; (3) one week later, we called all the addresses, for which the phone numbers could be identified in public online telephone directories; (4) we shared study invitations with local organizations and institutions via mail or social media (e.g., sports club; community supported agriculture organization; one local church); (5) the local newspaper published an announcement; (6) study invitations were placed on the hosting municipality's website and Facebook page and in three local Facebook groups; (7) recruitment posters were hung in the local area; (8) one day before the start of the data collection, we distributed leaflets to addresses in just under a 2 km radius around the AWES. In addition, the developer of the AWE test site emailed a research invitation to residents who had attended the open day at the site in the previous year. Due to the recruitment via multiple and partially indirect channels, it is difficult to report a total response rate. Therefore, Table 1 provides an overview of the successes and failures per recruitment channel. The questionnaire results later showed that most respondents had become aware of the study through the letters (66.7 %), followed by the phone calls (33.3 %), other channels like a

Fig. 2. The researched test site featured a ground-gen airborne wind energy system with a soft-wing kite. In the background, one of the many nearby wind farms is visible (Courtesy of the SkySails Group).

Table 1
An overview of the used recruitment channels and the associated success rates.

Recruitment channel	Number of addressees	Success rate
Sending letters within a 2.5 km radius	1152	40 letters were returned as undeliverable.
Calling within a 2.5 km radius	244	94 households (38.5 %) answered the phone, of which 23 (24.5 %) agreed to participate.[a]
Distributing leaflets in a < 2 km radius	~400	All leaflets were delivered.
Contacting local organizations	8	Three responded, and one confirmed to have shared the study invitation with their members.

[a] Not all the initially scheduled appointments took place due to cancellations.

neighbor or family member or the leaflet in the mailbox (20.4 %), the newspaper article (13 %), local organizations (7.4 %), and, finally, the AWE developer (3.7 %). The percentages reflect that some respondents heard of the study via multiple channels.

2.3. Data collection

Guided by the study hypotheses, we determined relevant constructs by checking available literature reviews on the acceptance of wind energy (e.g., [15,21]) and AWE [14]. The constructs we identified from the literature are attitudes towards local energy projects and energy technologies in general, attitudes towards the energy transition, perceptions of the planning process and the developer, social norms around local energy projects, perceived impacts of local energy projects on people and the environment and corresponding annoyance (i.e., landscape impact and fit, noise, shadow flicker, obstruction lights, economic and ecological impacts), safety concerns regarding local energy projects, and site preferences for AWE. To assess these constructs, we used measurement scales from questionnaires of research groups with long-standing experience and an established publication record in wind energy acceptance research [18,21]. The same questions and answering scales were used for WTs and AWE, where applicable; for the topic of AWE, only the phrasing was slightly adapted to fit. The answering scales were either dichotomous (yes/no), bipolar – ranging from −3 (negative dimension of the attribute) to +3 (positive dimension of the attribute) –, or unipolar – ranging from 0 (not at all) to 4 (very). Bipolar scales have been widely used in psychological research, such as in the prominent theory of planned behavior [30], because they are better suited for constructs that can be rated either positively or negatively (e.g., attitudes). However, unipolar scales were needed for the other constructs that were not two-dimensional (e.g., the extent to which respondents are annoyed).

Additionally, due to the lack of social science research on AWE, we consulted with experts in the field of AWE to make out constructs we had overlooked. This led to the identification of the following constructs: general and visual impressions of AWE (open questions), perception of AWE compared to other renewables (open question), likes and dislikes of AWE (open questions), perceived advantages and disadvantages of AWE (e.g., climate mitigation effect, material consumption, impact on aviation), and knowledge of AWE and WTs. We could not identify validated measurement scales for these constructs and developed our own items – one item per construct to keep the questionnaire to a reasonable length. In doing so, we used the same answering scales for the closed questions as for the remainder of the questionnaire to keep it consistent (i.e., yes/no, 0 to 4, or −3 to +3). In designing the open questions, we adhered to the following principles: using clear and accessible language, making questions specific but open enough to allow for different responses, and avoiding double-barreled questions that ask about multiple concepts at once.

Furthermore, some questions on the preferences for the commercialization of AWE were included for a Master thesis project (e.g., the impact of kite size, hybrid AWE development, and sole night operation on support for commercialization) [31]. The final questionnaire contained 124 items, covering a wide range of acceptance-related aspects, but in the following, we only briefly describe the items analyzed for this article. We present the bipolar-scaled items that might be more difficult to understand in Table 2. The codebook file in the associated database provides an overview of the questions asked.

Perceptions and attitudes: a) Perceptions: Respondents were asked nine open-ended questions about their perception of and experiences with the local AWES and conditions for commercializing it, e.g., "How and when did you first hear of the AWES?" or "What would you change about the AWES, if you could?". Additionally, respondents were asked to state how often they perceived the AWES on a 5-point scale (from "every day" to "less than every couple of months").

b) Attitudes: Respondents were asked about their attitudes towards (1) WTs and AWESs in general, as well as (2) concerning the local AWES and the wind farm they perceived to be closest to their home. Table 3 presents the details of the wind farms respondents referred to.

Technology impacts: a) Visual impacts: To assess the visual impacts of the closest wind farm and the AWES on residents, respondents stated whether they had a view of the wind farm and the AWES from home, perceived shadow-casting and obstruction lights, and how much they were annoyed by perceived shadow-casting and obstruction lights. Annoyance was rated on a 5-point scale from 0 ("not at all") to 4 ("very"). Further, respondents answered two bipolar questions each about the impact of the AWES and the wind farm on the landscape (Table 2).

Table 2
Overview of constructs rated on bipolar scales.

Topic	Item/question	Rating scale
General attitudes	Attitude towards wind farms in general	The attitude was assessed by two pairs of adjectives on bipolar scales ranging from −3 ("bad"/"useless") to +3 ("good"/ "useful"). The average across both items is used as the attitude score.
	Attitude towards AWE in general	Same as above
Project attitudes	Attitude towards the closest wind farm	The attitude was assessed by two pairs of adjectives on bipolar scales ranging from −3 ("bad"/"useless") to +3 ("good"/ "useful"). The average across both items is used as the attitude score.
	Attitude towards the AWES	Same as above
Landscape impact	"The wind farm..."	−3 to +3 {−3 = Compromises the landscape very much; −2 = Compromises it somewhat; −1 = Compromises it slightly; 0 = Neither nor; 1 = Makes the landscape slightly attractive; 2 = Makes it somewhat attractive; 3 = Makes it very attractive}
	"The AWES..."	Same as above
Landscape fit	"The wind farm is..."	−3 to +3 {−3 = Very unfitting for the regional landscape; −2 = Somewhat unfitting; −1 = Slightly unfitting; 0 = Neither nor; 1 = Slightly fitting the regional landscape; 2 = Somewhat fitting; 3 = Very fitting}
	"The AWES is..."	Same as above
Ecological impacts	"The wind farm..."	−3 to +3 {−3 = Compromises nature very much; −2 = Compromises nature somewhat; −1 = Compromises nature slightly; 0 = Neither nor; 1 = Supports nature slightly; 2 = Supports nature somewhat; 3 = Supports nature very much}
	"The AWES..."	Same as above

Note. Respondents had to complete the items in quotation marks with one of the provided answer options.

Table 3
Characteristics of wind farms closest to respondents' homes at the time of the study.

Location	Sample percentage referring to wind farm	*M* living distance in m (*SD*)	Start operation	Number of turbines	Turbine type(s)	Hub height (m)	Total wind farm capacity (MW)	Shareholders
Bosbüll/ Klixbüll	48.1 %	1481 (436)	1994	6	2 Siemens SWT-3.6-107; 1 Enercon E-70 E4 2.3; 1 Senvion MM82; 2 Enercon E-92	59–104	16.2	Residents/landowners in Klixbüll; municipality of Klixbüll
Klixbüll	24.1 %	1487 (637)	2014	8	Siemens SWT-3.0-113	92.5	24	Residents/landowners in Klixbüll; municipality of Klixbüll; two public regional bodies responsible for monitoring and managing water
Braderup	20.4 %	1022 (336)	1995	8	4 Siemens SWT-3.6-107; 4 Siemens SWT-2.3	80	23.6	Residents/landowners in Braderup; municipality of Braderup
Risum-Lindholm	3.7 %	3297 (1667)	2014	11	Vestas V112–3.075	94	33.8	Residents/landowners in Risum-Lindholm; municipality of Risum-Lindholm; local church
Niebüll	3.7 %	3528 (342)	2011	5	Vestas V112–3.075	84–94	15.4	Residents/landowners in Niebüll

Note. *M* living distance refers to how far away respondents who referred to a given wind farm lived, on average, from the closest turbine of that farm. *SD* denotes the standard deviation.

b) Noise impacts: Respondents stated whether they heard sounds from the wind farm and the AWES, and if so, how annoyed they were by them. Annoyance was rated on a 5-point scale from 0 ("not at all") to 4 ("very"). Additionally, respondents were asked to describe the sounds they heard.

c) Ecological and environmental impacts: Respondents answered one bipolar question each about the impacts of the AWES and the wind farm on nature and wildlife (Table 2). For the AWES, respondents were asked to name their ecological concerns if they scored minus one or lower. Because the expected carbon footprint of AWE might also be relevant to people's acceptance of the technology [14], respondents were asked to rate the extent to which AWE is more sustainable than WTs due to a lower material consumption on a 5-point scale from 0 ("not at all") to 4 ("very").

d) Safety: Respondents rated their concerns about the safety of the wind farm and the AWES on a 5-point scale from 0 ("not at all") to 4 ("very"). Respondents who scored at least one were asked to describe their concerns.

e) Planning process: Respondents were asked whether the planning process for the wind farm had proceeded fairly, whether the developer had been open and transparent during the process, and how satisfied they were with the developer's efforts to inform about the project (5-point scales from 0 "not at all" to 4 "very"). The same was asked for the AWES, but the first two questions related to the ongoing operation of the test site because no public planning process had taken place.

f) Siting: Respondents stated which sites they found most acceptable for commercial use of AWE (e.g., agricultural areas, offshore). Questions about siting were only asked for AWE as much less is known about it than for WTs, and the questionnaire had to be kept to a reasonable length.

Demographics: Basic sociodemographic information, such as age, gender, and educational background, were gathered. Respondents were further asked if they had financial benefits from local WTs and what the closest wind farm was in their perception. Living distances from the mentioned wind farm and the AWES were determined for each participant in Google Maps by using the geographical coordinates of the ground station of the AWES, the closest WT, and residents' addresses.

Three trained researchers administered the questionnaire in German to residents at home during one week in June 2022. For nine participants, this was done through Microsoft Teams video calls for scheduling reasons. Administering the questionnaire took between 30 and 100 min, averaging 64 min. One researcher conducted 51.9 % of the appointments, and the other two carried out 29.6 % and 18.5 %, respectively. While a small number of the appointments were done with couples from the same household and once with a group of four neighbors, most were done with one resident at a time (55.6 %). When two or more respondents participated simultaneously, respondents still answered each question for themselves.

2.4. Analyses

For the inferential statistics, non-parametric tests were applied because the data was not normally distributed (see Appendix for the supporting evidence). Where applicable, r was calculated as an approximate effect size. As explained under Data Collection, both unipolar and bipolar scales were used in this study, but the only inferential tests that included data from both scale types were bivariate correlations. When one variable takes only positive values and the other takes positive and negative values, the correlation is still computed as usual [32]. Therefore, the combination of unipolar and bipolar scales did not cause any statistical problems. SPSS Version 28 was used to carry out all statistical analyses. Respondents' answers to the open questions were recorded in bullet points by themselves or the interviewer. The resulting qualitative data was analyzed through an iterative process of open and axial coding until distinct themes emerged. The first author, as the principal researcher, did all the qualitative coding to ensure consistency, but the progress and outcome of the coding process were regularly discussed with the other authors to ensure quality.

3. Results

3.1. Sample characteristics

Fifty-five residents participated in the study. However, one respondent was excluded from all subsequent analyses because there was strong evidence that the person could not properly understand and answer the questions. About one-fourth (24.1 %) lived in Klixbüll, where the AWES was located, and 42.6 %, 20.4 %, and 13 % of respondents were from the neighboring municipalities Niebüll, Bosbüll, and Risum-Lindholm, respectively. The respondents ranged in age from 34 to 85, averaging 61 years ($SD = 12.29$). Almost equally as many women (48.1 %) as men (51.9 %) participated in the research. By comparison, data from the regional statistical bureau suggests that 51.6 % of the entire population across the four municipalities ($N = 15.411$) is female, and the average age for the adult population is around 53 years ($n = 12.844$) [33]. The sample's educational background was relatively high: 37 % of respondents had completed an apprenticeship, 16.7 % held a college or bachelor's degree, and 20.4 % had a master's degree. On average, the respondents lived in a two- or three-person household. When the AWE site was first approved at the end of 2017, the vast majority (87 %) had lived in their home already.

Respondents lived between 1085 and 3575 m from the AWES's ground station, a standard shipping container that housed the generator and the tether drum ($M = 1987.35$, $Mdn = 1989.50$, $SD = 406.74$). It should be noted that the kite could fly up to around 680 m closer to houses than the ground station was located. The majority (77.8 %) saw the AWES from home. Most respondents (53.7 %) reported noticing the AWES weekly, 16.7 % monthly, 14.8 % daily, 13 % every few months, and 1.9 % less than every few months, suggesting that many respondents had sufficient exposure to the AWES to evaluate its impacts. By comparison, respondents lived between 641 and 4475 m from the nearest turbine of the respectively closest wind farm ($M = 1531.98$, $Mdn = 1355$, $SD = 762.34$). The majority (83.3 %) saw the closest wind farm from home.

Respondents were asked if they worked in the wind energy sector and received any financial benefits from local WTs to assess response bias. Because only a few respondents (3.7 %) worked in the wind energy industry, it is highly unlikely they strongly biased the sample responses and were, therefore, not removed from the study. While one-third of respondents (33.3 %) had financial benefits from local WTs, mainly in the form of ownership shares, there were no differences in attitudes towards the respectively closest wind farm between respondents who benefited financially and those who did not (Mann-Whitney U test: $M = 2.56$ vs. $M = 2.15$; $p = .133$, $n = 54$). Thus, financial compensation is unlikely to have unduly influenced evaluations of the closest wind farm.

Because no background information, especially about renewable energy attitudes, could be obtained from existing data sources on all residents living in the 5 km radius around the AWES, we compared respondents to non-respondents in the study to estimate selection bias. The non-respondents were thirty-two residents contacted via phone during the recruitment who did not want to participate in the entire survey but agreed to answer a few questions over the phone. Importantly, non-respondents did not differ significantly from the respondents in their age (Mann-Whitney U test: $M = 66.00$ vs. $M = 60.87$; $p = .119$, $n = 82$), gender distribution (Pearson chi-square test: 48.4 % male vs. 51.9 % male; $p = .758$, $n = 85$), and attitudes towards the AWES (Mann-Whitney U test: $M = 1.26$ vs. $M = 1.89$, $p = .310$, $n = 81$) and the closest wind farm (Mann-Whitney U test: $M = 1.41$ vs. $M = 2.02$, $p = .302$, $n = 81$). Non-respondents' average level of education was significantly lower compared to respondents' (Fisher's Exact test: 29.6 % with college/ university degree vs. 40.8 %; $p = .006$, $n = 81$), and non-respondents had noticed the AWES significantly less often than respondents (Fisher's Exact test: 16 % had never seen the AWES vs. 0 % $p = .010$, $n = 85$). In fact, a common reason why non-respondents did not want to participate in the study was that they believed they had had too little exposure to the AWES.

In the following, reported results refer to the local projects (i.e., the AWES and the closest wind farm) unless stated otherwise. The results are presented in the order of the hypotheses, integrating quantitative and qualitative findings for each hypothesis. The results for the AWES and the wind farm are compared to each other per hypothesis. The key descriptive values are presented in Table 4.

3.2. Attitudes and perceptions

Average attitudes were positive for WTs in general ($M = 2.39$, $SD = 1.24$) and for AWESs in general ($M = 2$, $SD = 1.30$). For the closest wind farm, average attitudes were also positive ($M = 2.29$, $SD = 1.26$), and for the local AWES, they were somewhat positive to positive ($M = 1.87$, $SD = 1.33$). The general attitudes towards WTs and AWESs were not significantly different (Wilcoxon-signed rank test: $p = .062$), nor were the attitudes concerning the local projects (Wilcoxon-signed rank test: $p = .051$). However, there were discrepancies in the correlational results across the wind farm and the AWES. Attitudes towards the AWES correlated positively with participants' satisfaction with the developer's efforts to inform about the project, perceived developer transparency, and site operation fairness (Table 5). For the wind farm, only information satisfaction was significantly positively correlated to attitudes (Table 5).

The qualitative data indicated that respondents with somewhat positive to very positive attitudes to the local AWES (‘supporters’) viewed the technology differently from respondents with neutral to very negative attitudes (‘critics’). ‘Supporters’ found AWE interesting, unusual, and innovative, emphasizing the renewable character of the technology. They believed that AWE could help to become independent from nuclear energy and fossil fuels, also mentioning that AWE has fewer impacts on residents and nature than existing renewables. In contrast, ‘critics’ tended to be indifferent or dismissive towards AWE, saw the local AWES as a test project, even as play, and did not believe that AWE could contribute to the energy transition. However, even among ‘supporters’, there were uncertainties about how much energy could be produced with AWE.

3.3. Evaluation of visual impacts

While the attitude results were relatively congruent across the wind farm and AWES, the following five main differences were found regarding visual impacts: (1) the landscape impact (-3 to $+3$) was rated more positively for the AWES; (2) developer transparency and planning process fairness positively correlated with landscape impact and fit for the wind farm only; (3) no shadow-casting was reported for the AWES but for the wind farm it was; (4) more respondents perceived obstruction lights of the wind farm than of the AWES; (5) and a higher percentage was annoyed by the wind farm's obstruction lights than the AWES's lights. We will illustrate each difference in more detail next.

Firstly, landscape impacts, scored on a bipolar scale from -3 to $+3$, were rated for the AWES, on average, neutral to somewhat enhancing the landscape ($M = 0.71$, $SD = 1.59$) and for the wind farm neutral to somewhat compromising the landscape ($M = -0.64$, $SD = 1.63$). The difference was statistically significant (Wilcoxon signed-rank test: $z = 4.32$, $p < .001$, $r = 0.50$; medium effect size; Fig. 3). The landscape fit, scored on a bipolar scale from -3 to $+3$, was rated on average, as somewhat fitting for the AWES ($M = 1.06$, $SD = 1.67$) and as neutral to somewhat fitting for the wind farm ($M = 0.64$, $SD = 1.96$). However, this difference was not statistically significant (Wilcoxon signed-rank test: $p = .143$). The qualitative data showed that despite overall positive landscape impact and fit ratings for the AWES, even respondents with a more positive attitude towards the AWES were concerned about how

Table 4
Descriptives of key independent variables.

	AWES				Wind farm			
	M	*Mdn*	*SD*	*n*	*M*	*Mdn*	*SD*	*n*
General attitude*,†	2	2.50	1.30	54	2.39	3	1.24	54
Attitude to local project*	1.87	2.50	1.33	54	2.29	3	1.26	54
Landscape impact*	0.71	0	1.59	53	−0.64	0	1.63	53
Landscape fit*	1.06	1	1.67	53	0.64	1	1.96	53
Shadow-casting annoyance	[a]	[a]	[a]	[a]	0.80	0	1.21	15
Obstruction light annoyance	0.45	0	1.18	22	0.66	0	1.28	41
Noise annoyance	1.32	1	1.25	19	1.08	1	1.09	26
Ecological impact*	0.26	0	1.21	53	−0.13	0	1.47	53
Safety concern	0.57	0	0.95	53	0.49	0	0.82	53
Living distance (m)	1987.35	1989.50	406.74	54	1531.98	1355	762.34	54
Information satisfaction	1.36	1	1.34	47	2.38	3	1.50	37
Developer transparency	2.20	3	1.34	44	3.06	3	1.19	32
Fairness of site operation/planning process	2.49	3	1.25	45	2.69	3	1.15	32

Note. M, *Mdn*, *SD*, and *n* refer to the mean, median, standard deviation, and sample size, respectively.
* Scales marked with an asterisk range from −3 to +3; all remaining scales range from 0 to 4, except for distance.
† General attitudes refer to AWESs in general and WTs in general.
[a] Shadow-casting annoyance was only measured for the wind farm because no respondent perceived a shadow of the AWES at home.

Table 5
Kendall's Tau-b correlations between attitudes towards the local projects and key independent variables.

	Attitude wind farm	Attitude AWES
	τ (*p*)	τ (*p*)
Information satisfaction	**0.42** (0.002) $n = 37$	**0.38** (0.002) $n = 47$
Developer transparency	0.28 (0.068) $n = 32$	**0.47** (0.001) $n = 44$
Fairness of site operation/planning process	0.21 (0.172) $n = 32$	**0.35** (0.004) $n = 45$
Landscape impact*	**0.34** (0.002) $n = 53$	**0.31** (0.005) $n = 53$
Landscape fit*	**0.49** (<0.001) $n = 53$	**0.42** (<0.001) $n = 53$
Obstruction light annoyance†	−**0.38** (0.007) $n = 41$	−**0.50** (0.009) $n = 22$
Noise annoyance†	−**0.53** (0.002) $n = 26$	−**0.44** (0.020) $n = 19$
Ecological impact*	**0.39** (<0.001) $n = 53$	**0.40** (<0.001) $n = 53$
Safety concerns	−**0.27** (0.029) $n = 53$	−0.15 (0.201) $n = 53$
Living distance (m)	−0.06 (0.584) $n = 54$	0.06 (0.548) $n = 54$

Note. r, *p*, and *n* refer to the correlation coefficient, *p*-value, and sample size, respectively. Correlations printed in bold are significant at the $p = 0.05$ level.
* Scales marked with an asterisk range from −3 to +3; all remaining scales range from 0 to 4, except for distance.
† Only respondents reporting perceiving the impact at home were asked to rate their annoyance with that impact.

more than one AWES in the same location would affect the landscape.

Secondly, attitudes towards the AWES and the wind farm correlated positively with the respective landscape impact and fit (Table 5). In other words, the more respondents indicated that the local project enhanced the landscape or fitted the regional landscape, the more positive their attitude tended to be towards the project. However, characteristics of the planning process correlated only with landscape ratings of the wind farm. For the wind farm, developer transparency and process fairness were correlated positively with landscape fit ($\tau = 0.40$, $p = .008$, and $\tau = 0.32$, $p = .029$, respectively) and process fairness with landscape impact ($\tau = 0.32$, $p = .031$). For the AWES, neither transparency nor fairness were significantly related to landscape impact or fit (all *p*'s > .220).

Thirdly, no respondents perceived a shadow from the AWES on their property or inside the house. In contrast, over a quarter of respondents (27.8 %) reported experiencing shadow-casting of the wind farm at home (Table 6). On average, those affected by the wind farm's shadow-casting were between not and slightly annoyed by it ($M = 0.80$, $SD = 1.21$). It should be noted that the AWES casts a very irregular and faint shadow [34] when compared to WTs, and respondents lived significantly further from the AWES than the wind farm (Sign test: $M = 1987.35$ vs. $M = 1531.98$; $z = -4.49$, $p < .001$).

Fourthly, more respondents perceived the wind farm's obstruction lights than the AWES's lights at home (75.9 % vs. 40.7 %; Table 6). Like WTs, the AWES has obstruction lights on the kite and the ground station that warn airspace users at night [28]. Fifthly, while the average level of obstruction light annoyance was between none and slight for both the wind farm ($M = 0.66$, $SD = 1.28$) and the AWES ($M = 0.45$, $SD = 1.18$), more respondents were annoyed by the obstruction lights of the wind farm than of the AWES (14.8 % vs. 5.6 %; Table 6). Following conventions in the literature, residents were characterized as annoyed when they reported at least a score of two [35]. Attitudes towards the AWES and wind farm correlated negatively with the corresponding obstruction light annoyance (Table 5).

It is noteworthy that the wind farm was more perceptible than the AWES (Table 6) because a majority of those who could see the AWES from home (71.4 %) only noticed it when the kite was visible in the sky (note: 19 % did not state when they could see the AWES). In other words, while WTs are always present in the landscape, the AWES is often only visible when in operation. Besides, the qualitative data revealed that respondents associated the operating kite with positive leisure and childhood activities, such as flying a kite, kitesurfing, paragliding, sailing, or being at the beach. Seeing the kite fly reminded respondents that it produces renewable energy or made them wonder how the technology works. The kite's movements tended to be experienced as playful, calming, and soft, especially in contrast to the nearby static energy plants. However, it was also reported that the flying kite creates unrest and is harder to get used to than the steadier movements of WTs.

3.4. Evaluation of noise impacts

Similar to the result patterns for visual impacts, four differences emerged for noise impacts across the AWES and wind farm: (1) the wind farm was heard more often at home than the AWES; (2) a slightly higher proportion was highly annoyed by the WT noise than the AWES noise; (3) WT and AWES sounds were experienced rather differently; (4) and perceived process fairness and developer transparency negatively correlated with noise annoyance for the AWES only. Each difference will be described in more detail in the following.

Firstly, more respondents reported hearing the wind farm (48.1 %)

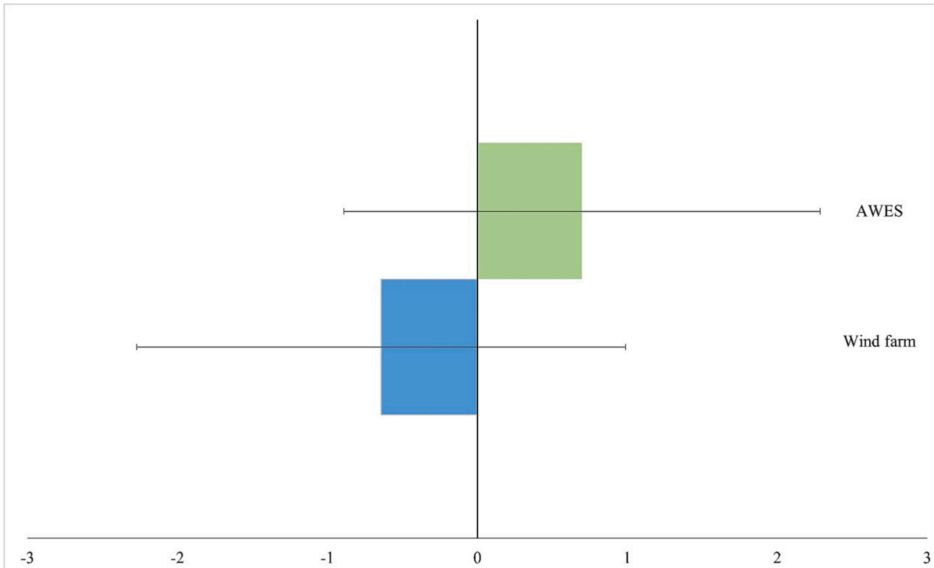

Fig. 3. Mean values for landscape impact for the wind farm and the AWES ($n = 53$; scale range: -3 to $+3$). The error bars represent the standard deviations.

Table 6
Perception of visual impacts at home and prevalence of annoyed residents.

	AWES	Wind farm
	Percentage (number)	
Local project visible at home*	77.8 % (42)	83.3 % (45)
Shadow perception	0 % (0)	27.8 % (15)
Annoyed by shadow-casting†	–	3.8 % (2)
Obstruction light perception	40.7 % (22)	75.9 % (41)
Annoyed by obstruction lights†	5.6 % (3)	14.8 % (8)

Note. *The local project is visible outside on one's property or from inside the house. †Residents are characterized as annoyed when they score two or higher (scale range: 0–4). Only respondents reporting perceiving a given visual impact at home were asked to rate their corresponding annoyance.

than the AWES (35.2 %) at home. The average level of noise annoyance was slight for both the wind farm ($M = 1.08$, $SD = 1.09$) and the AWES ($M = 1.32$; $SD = 1.25$), but the subgroups were too small to verify if there was no significant difference. Secondly, a slightly higher percentage of residents could be characterized as highly annoyed by the wind farm, meaning they scored at least three on the noise annoyance scale (Table 7).

Thirdly, WT and AWES sounds were described differently. WT sounds were characterized as droning, beating, swishing, and whirring or were compared to a wind gust. The rhythmic nature of the sounds was noted, too. In contrast, for the AWES, the tether's sound was described as howling but also as whistling, whirring, or hissing. The kite was reported to make a fluttering sound. When asked what annoyed them about the AWES sound, respondents mentioned its irregularity and unpredictability, making it hard for them to get used to. The type of sound and the pitch were also reported to be annoying. Respondents noted that the sound is most perceptible when the kite changes direction, consistent with the AWE developer's noise impact assessment [28]. Interestingly, respondents' familiarity with and exposure to the AWES sound at home seemed to have influenced their evaluation: More than half of the respondents (53.7 %) had not heard the AWES at home or near the site. When responding to the open questions, they tended to assume that the AWES is quiet, especially compared to WTs, which all respondents had heard before.

Table 7
Perception of noise at home and prevalence of annoyed and highly annoyed residents (scale range: 0–4).

	Noise perceptible at home	Prevalence of noise annoyance	
		Annoyed residents (score ≥ 2)	Highly annoyed residents (score ≥ 3)
		Percentage (number)	
AWES	35.2 % (19)	13.1 % (7)	7.5 % (4)
Wind farm	48.1 % (26)	11.1 % (6)	11.1 % (6)

Note. Noise is perceptible on one's property or inside the house with open or closed windows. Only respondents perceiving noise at home were asked to rate their noise annoyance.

Lastly, noise annoyance was negatively correlated with attitudes (Table 5) and uncorrelated with living distance for the AWES and the wind farm (p = .270 and p = .690, respectively). However, noise annoyance was only significantly negatively correlated with perceived fairness and developer transparency for the AWES ($\tau = -0.42$, $p = .048$ and $\tau = -0.50$, $p = .016$, respectively; $n = 17$) but not for the wind farm ($p = .434$ and $p = .955$, respectively; $n = 15$).

3.5. Evaluation of ecological and environmental impacts

For the ecological impact scale, ranging from -3 to $+3$, a significant difference was found across the AWES and wind farm (Wilcoxon-signed rank test: $z = 2.08$, $p = .038$; Fig. 4). On average, respondents perceived that the impact of the AWES on nature and species conservation was neutral ($M = 0.26$, $SD = 1.21$), but the wind farm's expected impact was rated between neutral and slightly compromising ($M = -0.13$, $SD = 1.47$). When respondents who reported at least somewhat negative impacts of the AWES ($n = 5$) were asked about their ecological concerns, they mentioned bird impacts, such as birds colliding with the tether or getting irritated by the kite, potentially because the shadow looks like that of a predatory bird. The same respondents also worried that the loud and irregular sounds could disturb animals, including birds. However, generally, respondents disclosed that they found it difficult to rate the ecological impacts because they lacked knowledge about AWE. For both the AWES and the wind farm, ecological impact ratings were positively correlated with attitudes to the respective local project (Table 5). That is, respondents who perceived a more positive impact of the project on nature and species conservation tended to have a more positive attitude towards the project.

Apart from ecological impacts, respondents rated the sustainability

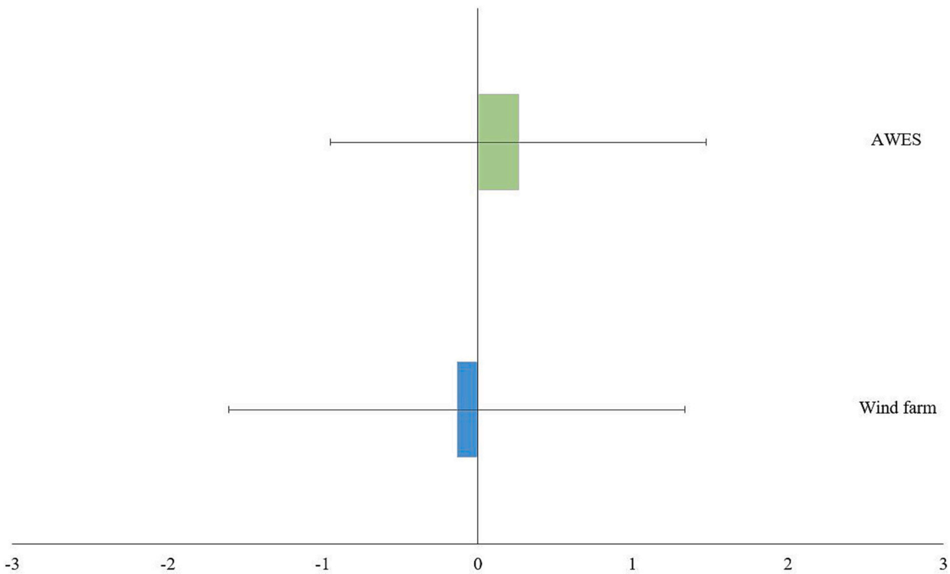

Fig. 4. Mean values for the ecological impact of the wind farm and the AWES (n = 53; scale range: −3 to +3). The error bars represent the standard deviations.

of materials for AWE compared to WTs [14]. On average, respondents agreed somewhat to moderately that future commercial AWESs would be more sustainable than WTs because of lower material consumption ($M = 2.84$, $Mdn = 3.00$, $SD = 1.19$, $n = 51$). The lower material use as an advantage of AWE over WTs was also mentioned in response to the open questions, next to the lack of fundaments and the resulting easier decommissioning of an AWES. However, respondents disagreed about the space requirements for AWE; some mentioned it requires less space than WTs, while others believed it needed more.

3.6. Evaluation of safety

Consistent with the previous pattern of rather slight differences between AWE and WTs, only two differences were detected regarding safety concerns. Respondents were not at all to slightly concerned about safety, with no significant difference across the AWES ($M = 0.57$, $SD = 0.95$) and the wind farm ($M = 0.49$, $SD = 0.82$; Wilcoxon signed-rank test: $p = .830$). However, a difference emerged in the relationships between safety concerns and attitudes towards the local projects. While safety concerns about the wind farm correlated negatively with attitudes to the wind farm, safety concerns about the AWES were uncorrelated with attitudes to the AWES (Table 5). Interestingly, concerns about the AWES' safety did negatively correlate with general attitudes to AWESs, as did concerns about the wind farm's safety with general attitudes to WTs ($\tau = -0.33$; $p = .006$ and $\tau = -0.29$; $p = .020$, respectively, $n = 53$).

A qualitative difference emerged regarding the nature of safety concerns. For the wind farm, respondents were concerned about fire, ice throw, and parts falling off, such as rotor blades. For the AWES, respondents were worried that the tether would snap and the kite would take off, that the kite would crash, or that it would collide with an aircraft. Worries also existed about the kite colliding with cars, distracting oneself while driving, or making other drivers slow down unexpectedly upon spotting the kite and creating a traffic hazard. Regarding aviation risks, respondents criticized that the AWES was built in the approach path of the local emergency helicopter. They might have been unaware that a no-fly zone and a range of other safety measures were active during the operation of the AWES [28]. Respondents especially recognized the safety risks of AWE in more densely populated regions. The safety radius of the local AWES was therefore appreciated, although it was not liked that the access roads were sometimes blocked during operation [28].

3.7. Evaluations of siting aspects

The main finding from the qualitative data is that regardless of their attitude towards the local AWES, respondents generally preferred AWESs to be placed further away from houses. Specifically, respondents with a more negative attitude towards the AWES tended to think that AWE uses too much space and should not be commercially deployed in a densely populated country like Germany, partially because of potential noise and obstruction light annoyance. As a result, respondents affected by the impacts of the AWES advocated restricting operation to the daytime if AWESs were placed in populated areas. While respondents with a more positive attitude towards the local AWES were less likely to think that AWE takes up too much space, they still tended to prefer deployment sites away from settlements. Contradictorily, the quantitative results showed that respondents' attitudes towards the local AWES were unrelated to the living distance, meaning that living further from the AWES was not necessarily linked to a more positive evaluation of the local AWES (Table 5).

When asked which sites they found most acceptable for commercial deployment, respondents rated agricultural areas highest, followed by offshore sites, natural areas that are neither protected nor farmed, and the edges of settlements (Table 8). Alternative sites that respondents (n = 22) suggested were mainly remote places, such as deserts, mountains, forests, unpopulated strips of coastline, and regions in between settlements. Areas where other renewable energy plants cannot be installed and the integration of AWE into existing solar farms were also proposed. Four respondents suggested rooftops, especially of high-rise buildings. However, none of them saw the obstruction lights of the local AWES at home, and only one had heard the AWES before outside his house. The

Table 8
Percentage of respondents approving of a site for commercial AWE deployment.

Site	Percentage (number)
Agricultural areas	69.2 % (36) $n = 52$
Offshore sites	64.7 % (33) $n = 51$
Unprotected, unfarmed natural areas	40.4 % (21) $n = 52$
Edges of settlements	25 % (13) $n = 52$

Note. Residents were asked to select all that apply from a list of the four sites.

fact that they were not affected by the impacts of the AWES might explain why they were open to installing it in cities.

4. Discussion

Airborne wind energy (AWE) is an emerging renewable energy technology that aims to produce electricity by harvesting higher-altitude winds with kites. While AWE has not yet been commercially deployed, except for a recently launched project in Mauritius [36], initial projections suggest that AWE could substantially contribute to the future renewable energy mix [6]. As with any energy technology, AWE will impact people and nature to some extent once deployed. If human responses to the technology are understood early in development, AWE could be designed and deployed with people's needs and values in mind. This would help minimize negative impacts and facilitate introducing the technology into society. Despite the high relevance, how humans perceive and respond to AWE has not been investigated before.

Notwithstanding the lack of research, the AWE literature persistently claims that the technology impacts people and nature significantly less than wind turbines (WTs) and will, therefore, be more socially acceptable. If wrong and unchallenged, these assumptions could lead to misguided policies and development and deployment practices, which potentially increase the technology's burden on people and harm the long-term success of the technology. To better understand the social impacts of AWE and scrutinize the literature's assumptions, we surveyed residents living up to 3.5 km from an AWE system (AWES) in Germany. The following six hypotheses were tested: (1) residents have a more positive attitude towards AWESs than WTs; residents rate (2) visual, (3) noise, and (4) ecological impacts more positively for AWESs than WTs; (5) safety perceptions are highly relevant to the acceptance of AWESs; (6) remote sites are more acceptable for AWESs. Inconsistent with the hypotheses, the present results overall suggest that residents evaluate the noise, ecological, and safety impacts fairly similarly for the AWES and the wind farm. Only visual impacts were rated somewhat better for the AWES, as hypothesized. The results will be discussed in more detail in the following.

First, we will present and discuss the AWE results for the different impact categories. Then, where applicable, we will contrast the AWE and WTs findings per impact to assess the evidence for each hypothesis. In doing so, we will also compare the present WTs results with past research to check if they are similar. If the current WTs results are very different from past research, the comparison of AWE and WTs in this study is less generalizable.

Starting with the AWE findings, residents had, on average, positive attitudes towards AWESs in general and somewhat positive to positive attitudes towards the local AWES. Residents who had more positive attitudes towards the local AWES tended to be more satisfied with the developer's efforts to inform them about the project; they also tended to perceive the developer as more transparent and the site operation as fairer (moderate correlations). These findings align with previous research on WTs [15,16,17,37]. Interestingly, residents with more positive attitudes ('supporters') and residents with more negative attitudes towards the local AWES ('critics') focused on similar aspects of the technology but viewed them widely differently. Specifically, supporters appreciated that research is being done on AWE as a potential addition to existing renewables, while opponents questioned whether AWE would ever reach the technological standard of modern WTs.

Regarding the visual impacts, most residents who could see the AWES from home only noticed it when it was in operation (71 %). The AWES is not constantly in operation but only for limited periods, so the reduced visibility arguably lowers the perceived visual impact. The impact of the AWES on the landscape (bipolar scale) was rated, on average, as neutral to somewhat enhancing the landscape, and its fit into the regional landscape (bipolar scale) was rated, on average, as somewhat fitting. The more residents perceived that the AWES enhanced the landscape and fitted the regional landscape, the more positive their attitude tended to be towards the AWES (moderate correlations). These findings are consistent with research on WTs [15,18]. None of the respondents perceived a shadow of the AWES on their property, which was to be expected. Due to the changing flight altitude of the kite, an observer is highly unlikely to be hit by a shadow multiple times in a short time [34]. About 41 % noticed obstruction lights, and the average annoyance was lower than slight, with only about 6 % being at least somewhat annoyed. In line with WT research, the more annoyed residents were by the obstruction lights, the more negative their attitude tended to be towards the AWES (strong correlation) [38,39]. Initial evidence from WTs indicates that demand-based lights can somewhat decrease corresponding annoyance [39]. Demand-based obstruction lights only turn on when an aircraft approaches. They might become a requirement for AWE in the future as they have for WTs in Germany at the end of 2022 [40]. According to the developer of the researched site, prospective AWESs might require more intense lights due to airspace safety. Still, the use of demand-based obstruction lights is also conceivable, depending on the maturity of the AWE technology.

Regarding noise impacts, 35 % heard the AWES at home, and the average annoyance was slight, with about 13 % being at least somewhat annoyed. Residents who were more annoyed by the noise tended to have more negative attitudes towards the AWES and to perceive the site operation as unfairer and the developer as less transparent (moderate to strong correlations). This is in line with past research on WTs [22,23].

Concerning ecological impacts, residents reported, on average, that the impact of the AWES on nature and species conservation was neutral. Residents who perceived more negative ecological impacts tended to have more negative attitudes towards the AWES. Past research has also found that wildlife-related concerns affect people's attitudes towards wind energy and local WTs [41,42,43,44]. In this study, ecological impacts were more strongly related to respondents' attitudes towards the local AWES than expected by the AWE literature but less than factors like noise and obstruction light annoyance. By and large, residents overlook the general environmental benefits of wind energy over fossil fuel energies and focus more on local impacts like bird and bat strikes [37]. Indeed, the most common ecological concern regarding the AWES was how it would impact birds.

Regarding safety, residents were, on average, less than slightly concerned about the safety of the AWES. However, it became clear during the data collection that respondents had a varying understanding of the AWES's components, which will have influenced safety perceptions: A common misconception was that the kite only consists of fabric and thus would not cause any damage when crashing, although a heavy control unit is suspended underneath the kite. Interestingly, safety concerns were unrelated to respondents' attitudes to the local AWES but moderately correlated with attitudes towards AWESs in general. Concerned residents were mainly worried about accidents involving airborne components, such as the kite crashing down or colliding with someone or something. Informing the public about the actual likelihood of said accidents and the safety mechanisms in place (e.g., safety radius, no-fly zone, airspace observer) might help to reduce unnecessary worries.

Regardless of their attitude towards the local AWES, respondents generally preferred AWESs to be placed further away from dwellings. Respondents rated agricultural areas as most acceptable when provided with different options, followed by offshore sites, natural areas that are neither protected nor farmed, and the edges of settlements. However, the finding that remote locations are preferred should be interpreted cautiously because residents' attitudes towards the local AWES were unrelated to how far they lived from it. This aligns with past research on WTs: In hypothetical scenarios, such as choice experiments or proposals for regional wind energy development [45,46,47], respondents prefer WTs to be placed further away when given a choice. However, distance to existing wind projects has not been consistently related to attitudes towards the project, and typically, other factors are far more important to residents' project acceptance [15,18]. Furthermore, past research shows that the negative expectations people have, for example, regarding visual, noise, health, and wildlife impacts before a wind project is constructed [43,48] or before they have been virtually exposed to a WT [45], are often unmet. In other words, when people do not know the realities of a proposed energy development yet, they tend to assume 'the worst'. This might have also motivated respondents in this study to favor remote sites for future AWE projects despite a positive average attitude towards the existing AWES.

Next, we will assess the evidence for the six study hypotheses while accounting for the generalizability of the findings. The first hypothesis that residents have a more positive attitude towards AWESs than WTs was not confirmed because there were no significant differences in attitudes across AWESs and WTs, neither in general nor concerning the local projects. Notably, attitudes towards the closest wind farm and WTs in general were more positive in this study than in previous research [18,22,37]. Thus, the finding that AWESs were rated equally to WTs might not generalize to other contexts where WTs are not evaluated as positively as in this study. The discrepancy in attitude levels across this and past research might be explained by the fact that all the wind farms respondents referred to in this study were owned by residents and local institutions (Table 3). Local ownership and financial benefits have been related to higher acceptance of wind projects, likely because, for locals, it tends to make the planning process and the distribution of project benefits fairer [15,49]. Familiarity could also explain the more positive attitudes towards wind energy in this study: As evidenced by the conversations with respondents, they had become used to WTs, which have been developed in the region for the past 30 years. Some evidence suggests that post-construction evaluations of low-carbon infrastructures are more positive [48,50] and that familiarity relates to a less negative assessment of project impacts like noise [51]. However, Rudolph and Clausen caution that "adaptation or familiarization should not be confused with (greater or regained) acceptance" (p. 65), as it can also be an expression of residents' apathy or resignation and residents' need to get used to the project "may point to inadequacies of the planning procedures to deal with certain issues" (p. 71) [52].

The second hypothesis that residents rate visual impacts more positively for AWESs than WTs was mainly supported: The influence on the landscape was rated significantly more positively for the AWES than the wind farm, no shadow-casting was reported for the AWES, and the obstruction lights of the AWES were perceived comparatively less, and almost three times fewer residents were annoyed by the lights of the AWES than of the wind farm. However, the fit of the AWES within the regional landscape was not rated significantly better, and the average obstruction light annoyance was not substantially lower than for the wind farm. It should be noted that the better landscape fit rating for the wind farm might have been influenced by residents' previously discussed familiarity with WTs in the region. Besides, the percentage of residents perceiving obstruction lights of the wind farm and the average annoyance were lower than in past research [38]. Regarding shadow-casting, none of the respondents reported noticing a shadow of the AWES at home due to the kite's changing flight altitude. In contrast, shadow-casting is a known problem for WTs. Still, it is surprising that more respondents perceived shadow-casting of WTs on their property than in past research, which found between 1.3 and 11 % of affected respondents. Nevertheless, the average level of shadow-casting annoyance for WTs was lower in this study [23,38]. This might be due to the introduction of regulations in Germany limiting the allowed shadow duration to a maximum of 30 min per day or 8 h per year [53]. If this threshold is exceeded, the turbines have to be temporarily shut down. The discrepancy with past research might further be explained by recent findings suggesting that subjective factors (e.g., perceptions of WT aesthetics and demographics) explain annoyance with shadow-casting beyond the mere perception of shadows [54].

The third hypothesis that residents evaluate the noise impacts of AWESs more positively than of WTs was only partly confirmed. While fewer residents heard the AWES than the wind farm at home, the prevalence and degree of noise annoyance appeared similar across the AWES and wind farm. However, the percentage of highly annoyed residents was slightly higher for the wind farm. It should be noted that, in general, the prevalence and the average level of annoyance from WT sounds were lower than in past research [22,23,38]. That the AWES was heard less than the closest wind farm might be explained by its limited operational time and the fact that residents lived on average further from the AWES than the wind farm rather than that the AWES is quieter, as claimed in the literature. Importantly, residents described the sounds of the AWES and WTs very differently, especially noting how annoying the irregularity of the AWES sound is. Past research suggests that noise quality is important in explaining noise annoyance for WTs [22,55,56]. Future studies should investigate to what extent the variability of the sound can explain annoyance to AWES sounds. Due to the early development stage of AWE, the industry has only just begun to study sound emissions, as will be elaborated on in the limitations.

Importantly, noise annoyance was not correlated to the living distance for the wind farm and the AWES. In past research, WT noise annoyance has been unrelated or minimally related to distance [22,23]. The effectiveness of emission regulations can explain this together with the greater influence of noise quality mentioned above and subjective factors on residents' experience of noise impacts. Subjective factors include experienced visual impacts [57,58] and the perception of the planning process and the responsible parties as fair and transparent [22,23]. Strikingly, noise annoyance was negatively correlated with the perceived fairness of site operation and the developer's transparency for the AWES but not for the wind farm. One reason the relationships were not significant for the wind farm might be that the closest wind farm for respondents was frequently in a neighboring municipality. As a result, they were not involved or informed during the planning process and, therefore, struggled to evaluate fairness and transparency. However, this would not explain why developer transparency and planning process fairness positively correlated with landscape ratings for the wind farm but not the AWES. In any case, while sound characteristics, such as the irregularity reported by residents, might partially explain annoyance with AWES noise, the experience of the planning process also seems to play a role. The present results on AWE noise impacts should be interpreted with caution because they rely on correlational data and are limited to the current early development stage of the technology, as will be discussed in the limitations.

The fourth hypothesis that residents assess ecological impacts more positively for AWE than WTs was again not supported. On average, residents rated the ecological impact of the AWES as neutral and not significantly different than for the wind farm. However, due to the lack of public awareness of AWE and the limited research on its ecological impacts [14], respondents found it difficult to evaluate what influence AWE has on the natural environment. In contrast, the wildlife impacts of WTs have been widely studied in the past decades [59], and the topic of birds has substantially shaped the public and political discourse about wind energy development and hindered proposed projects [60]. Comparing residents' evaluations of ecological impacts across WTs and AWE, therefore, suffers from an imbalance because the evidence bases and public discourses are differently developed.

The fifth hypothesis that safety perceptions are highly relevant to accepting AWESs was also not confirmed. Residents worried, on average, only slightly to not at all about the safety of the AWES, and their worries were not greater than for the safety of the wind farm. As previously explained, misconceptions about real safety risks likely shaped residents' safety perceptions. Furthermore, future research should investigate how important safety is to the technology acceptance of other actors and contexts beyond the local level (e.g., regulatory authorities and the general public).

In line with the sixth and last hypothesis, remote sites appeared more acceptable for AWESs. When asked about the placement of potential future AWE sites, residents generally preferred to place AWESs further from dwellings, independent of their attitude towards the local AWES.

However, respondents' attitudes towards the local AWES were not related to how far they lived from the AWES. In other words, residents who lived further away did not necessarily evaluate the AWES more positively, and residents who lived closer to the AWES did not consistently rate the AWES more negatively. This finding should, therefore, be interpreted cautiously, as previously explained.

Overall, the findings suggest there should be criteria other than remoteness for securing new AWE sites. The living distance was statistically unrelated to attitudes towards the local projects, but attitudes tended to be more negative when residents experienced more project impacts on themselves and nature and perceived the developer as less transparent and the process as less fair. Furthermore, when residents perceived less transparency and fairness, they tended to report more impacts (i.e., landscape impacts in the case of the wind farm and noise annoyance in the case of the AWES). This signals that how a project is implemented is linked to residents' experience of project impacts and their attitudes. Assuming at least some causal connectedness, developers should focus on facilitating a just and effective project implementation by being transparent and fair and minimizing impacts on nature (e.g., bird strikes) and residents (i.e., noise, obstruction lights, and landscape impacts), as further outlined in the recommendation section.

4.1. Limitations

There are at least five general limitations concerning the results of this study.

Firstly, the results are restricted to the prototypes tested by one developer at one site in Germany. Responses to the technology might differ across the various AWESs as visual, sound and other impacts can be expected to vary substantially for fly-gen vs. ground-gen concepts and soft-wing, fixed-wing-, and hybrid-wing kites (Section 1). Residents' evaluations of AWE might also change as the technology matures and mitigation measures for different impacts have been implemented (e.g., demand-based obstruction lights and noise mitigation methods).

Secondly, the results obtained for the closest wind farm in this study deviate from previous research, limiting the comparison with the AWES. Specifically, attitudes towards the wind farm were more positive, and reported annoyance by obstruction lights, shadow-casting, and noise was lower than in past research. Thus, the finding that AWE was rated relatively equally to WTs might not generalize to other contexts where WTs are not evaluated as positively as in this study.

Thirdly, the nominal power of the AWES was around 8 to 17 times smaller than that of the local wind farms residents referred to. It could, therefore, be argued that comparing the community acceptance of two energy infrastructures with such widely different power outputs is unrealistic. However, the purpose of the study was not to determine if residents would prefer to have an AWES in their vicinity instead of an entire wind farm. Rather, we wanted to explore how residents experience an AWE test site while considering their responses to local wind energy projects, for which community acceptance has been well-researched.

Fourthly, while the results shed some light on the factors intertwined with the community acceptance of AWE, we cannot conclude what caused respondents' attitudes due to the correlational nature of the data. We also did not investigate the contribution of each factor while controlling for the others. In other words, we have analyzed how isolated factors relate to respondents' attitudes towards AWE. Still, we do not know the weight of each factor in the context of all variables, as shown by a regression-based analysis [21]. Such an analysis could help distill the most influential determinants.

Fifthly, the sample size might have affected the statistical power. The present study represents a first attempt to understand the community acceptance of AWE better. However, the limited availability of long-operating AWE projects makes recruiting a large sample of residents difficult. Furthermore, we drew on a convenience sample without offering any compensation, which likely resulted in only highly motivated residents participating.

Finally, there are a few specific limitations regarding the different technology impacts of AWE. Concerning the visual impacts, respondents evaluated one AWES against an entire wind farm (Table 3), with many more WTs nearby. The comparison of landscape impacts was, therefore, uneven, and it remains to be seen how residents would perceive the landscape impacts of multiple AWESs, maybe even an entire AWE park. Furthermore, the results on the perception of and annoyance by obstruction lights for the AWES should be interpreted cautiously because the AWES has only operated for a few nights.

The findings on noise impacts should also be interpreted in context. Firstly, as this study is the first of its kind, we assessed if residents are impacted at all by the sound of an AWES. Therefore, we only measured how annoyed they were by the noise and not if they experienced stress symptoms because of the noise. However, mental or physical symptoms, such as problems concentrating or sleeping, in combination with reported annoyance, are a more accurate measure of true stress levels [22]. To illustrate, in past research, 9.7 to 18.3 % of respondents reported being moderately to very annoyed by WT sounds, but only 1.1 to 9.9 % could be classified as strongly annoyed because they were at least somewhat annoyed and experienced at minimum one stress symptom at least once per month [22,23]. Thus, this study likely overestimated the percentage of residents substantially distressed by noise. Secondly, while the AWES complied with local noise regulations [28], it had yet to be optimized for noise impacts, unlike modern WTs. So far, the AWE industry has focused on increasing the reliability of AWESs and scaling them up rather than mitigating sound emissions. Developers are aware of the current noise impacts [28] and are starting to develop measurement methods and knowledge to reduce noise. For example, the developer of the researched site recognizes two main approaches to reducing noise impacts: (1) changes to the design, such as flying bigger kites at lower speeds or altering the design of the kite and support lines, and (2) changes to the operation like slowing the kite down at certain points during the flight path or adjusting the path to spare noise sensitive areas. Sound emissions generally drop as the flight speed decreases [61]. Lastly, the results are limited because the sound emissions measured for this AWES are specific to the site due to local conditions, such as topography and the existing sound environment [28]. In addition, sound emissions of AWESs can be expected to differ across ground- and fly-gen systems, flight trajectories, and soft-, hybrid- and fixed-wing kites. More research is needed on various AWESs at different stages of development and with more detailed annoyance and acoustic measures.

4.2. Future research

Building on the discussion of the results and the limitations, we have the following six research recommendations. Firstly, future research should conduct additional surveys on the acceptance of a local AWES, ideally across different types of AWESs and regions. This will help test the present findings' generalizability and examine similarities and differences in community responses to various AWESs. A challenge for this kind of field study is the limited availability of AWESs and, thus, the lack of affected communities to sample. While experimental research with members of the general public is less useful in studying the lived experience of communities around an AWES, experimental designs could be used to understand better how different design parameters of AWESs influence human responses to the technology. Both within-subjects and between-subjects experiments would work here. Participants could be exposed successively to multiple AWES designs that differ in generation mode (i.e., fly-gen vs. ground-gen) and kite type (i.e., soft-wing vs. hybrid-wing vs. fixed-wing kites) for a within-subjects design. An individual's attitudes or preferences would then be compared across the various designs to detect design-dependent differences. In a between-subjects design, participants would be assigned to one of the designs, and attitudes or preferences would be compared across rather than within participants. In further capitalizing on the early development stage of AWE, qualitative research, such as focus groups and interviews, can help to explore what needs and values different actors have regarding AWE and how design requirements can meet them.

Secondly, as the present study suggests that noise emissions of AWES impact residents, future research should assess the extent and source of noise annoyance to facilitate the development of mitigation measures. Experimental studies, such as laboratory listening experiments, could be used to identify which system components (e.g., tether, kite, generator) and sound properties contribute most to annoyance. By measuring annoyance levels in conjunction with experienced stress symptoms, field studies could help to estimate noise-related impairment among residents better and to develop suitable immission guidelines for AWE.

Thirdly, future research should aim to predict residents' attitudes to an AWES by using an acceptance model that considers the contribution of each predictor, such as visual, noise, and economic impacts, to attitudes while controlling for the other predictors [21]. Such research should account for the fact that the predictive validity of the model factors, especially perceived economic impacts, will likely depend on whether the project is commercial. However, even with commercial projects, the relevance of the factors can be expected to differ across the planning, construction, and post-construction phases [21]. It might, therefore, be interesting to compare data for AWE sites that differ in their degree of commericalization (e.g., test-site vs. semi-commercial vs. fully commercial). However, pooling data across sites would be useful in achieving larger samples, given the limited availability of AWESs, which tend to be located in sparsely populated areas.

Fourthly, tracking residents' perceptions of and attitudes towards an AWES over time, from pre-construction through operation and potentially until decommissioning, would help better understand how residents' experiences with a project causally influence their attitudes. Such research can also examine whether negative expectations or rather other factors motivate residents to prefer remote sites for hypothetical AWE developments.

Fifthly, the social acceptance of renewable energy technology is not limited to the community level but is influenced by actor positions and processes across the local, socio-political, and market dimensions [27]. Future research should also investigate AWE's socio-political and market acceptance as they will heavily influence the uptake and deployment of the technology. For example, while this study found that safety plays a minor role in the local acceptance of an AWES, it is most definitely important for some socio-political and market actors like regulatory authorities and investors [62,63]. Finally, on a more general note, we call for more interdisciplinary research collaborations of social, environmental, economic, and other relevant academic disciplines with the engineering-dominated field of AWE. Taking a holistic view of AWE at such an early stage offers a unique opportunity to integrate valuable research findings into the technology and industry development.

5. Conclusions and recommendations

This first community acceptance study of an AWES indicates that residents rate the visual impacts of a nearby AWES better than those of a wind farm. In contrast, noise, ecological, and safety impacts were rated similarly. The study further shows that many research findings from established renewables apply to this emerging technology. Specifically, impacts on nature and residents are related to lower acceptance, and residents' experience of the project implementation is linked to their evaluations of a local AWE project.

While much more research is needed to substantiate and extend the results, as outlined previously, the findings already imply two main recommendations for the industry. Firstly, the industry should identify ways to minimize impacts on residents and nature, especially while the technology is still more malleable. Potential technical solutions to reduce residents' annoyance include changing the design or operation of an AWES to mitigate sound emissions and implementing demand-based obstruction lights that only turn on when needed. Social science research can help to derive and evaluate suitable mitigation methods. For example, by increasing the understanding of the personal and contextual factors under which annoyance occurs, as is also done for WTs [64]. Furthermore, cameras could be used to detect birds and avoid collisions, thereby decreasing wildlife-related concerns. Secondly, the industry should use best practice strategies to engage communities better in test projects and future commercial sites because residents' experience of the project implementation is related to their acceptance, as shown in this and a wealth of previous research.

Both industry recommendations also illustrate the importance of policy for creating a legal framework that facilitates AWE's effective and socially just deployment. Particularly, immission regulations specifically for AWE are necessary because existing WT regulations only apply to a limited extent to this novel technology. It is not well understood yet what contributes to annoyance from AWE immissions. Experience with WTs shows that research into residents' perceptions of impacts can substantially help design more effective immission regulations. For example, studies into shadow-casting annoyance among WT neighbors [65] successfully led to the development of shadow exposure directives for WTs in Germany [53]. Moreover, regulations are required to integrate AWESs safely into the airspace, protecting people and property in the air and on the ground [66]. The regulatory and technical development should happen in parallel and feed into each other to make the process more efficient and effective and prevent the technology from being locked into a form incompatible with future regulations.

Furthermore, policymakers should capitalize on the early development stage of the technology to create conditions that not only make commercialization economically attractive, as demanded by the AWE sector [6], but also increase social justice. One possible way is to mandate (airborne) wind energy developers to consult with local communities more extensively throughout the planning and construction process to make locals a part of the project and improve social outcomes for the community [67]. Policies that require developers to offer financial participation or ownership to local communities to obtain a site permit could be implemented, as is the case for WTs in some countries [67]. Owning or at least benefitting financially from the project can make the planning process and the distribution of project benefits fairer, likely leading to higher project support [15,38]. If making these regulatory changes proves too difficult or slow, the AWE sector could develop its own quality mark that will be awarded to developers who are especially fair and transparent in their planning and community engagement processes. Such certificates exist in some regions for conventional wind energy developers [68].

However, the industry and developers' engagement processes should extend beyond local communities to include other relevant societal stakeholders, such as nature protection agencies, landowners, farmers, local authorities and businesses. While policymakers have been slow to respond to developments in the AWE sector [69], there are multiple efforts by the AWE industry and the international research community to promote policy development. For example, task forces have been established on policy-relevant topics like safety, and AWE was included in an EU-Horizon research project that aims to facilitate just and effective wind energy governance [70]. The research project seeks to encourage a dialogue between policymakers and other relevant stakeholders, such as the ones mentioned above, about how the different parties' interests can best be considered when deploying AWE. The emergence of AWE offers the opportunity to learn from the mistakes made while deploying established renewable energy technologies. It remains to be seen whether this opportunity will be seized.

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CRediT authorship contribution statement

Helena Schmidt: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Valentin Leschinger:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Florian J.Y. Müller:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Gerdien de Vries:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Reint Jan Renes:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Roland Schmehl:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Gundula Hübner:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Roland Schmehl reports a relationship with the Dutch airborne wind energy developer Kitepower B.V. that includes: board membership and equity or stocks.

Data availability

The dataset underlying the manuscript can be found online at https://doi.org/10.4121/fc1e49ca-08b6-435d-9888-a73f334edd92.

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Appendix A. Supplementary data

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