



Research article

What drives social acceptance of energy infrastructure? Comparing the expansion of wind, PV, and grid

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ABSTRACT

The transformation of energy systems requires not only technical and economic planning but also public acceptance. However, the social dimension of energy infrastructure planning has often been overlooked, although public acceptance can significantly influence the feasibility and pace of renewable energy expansion. This study investigates public acceptance of the expansion of 3 key energy transition technologies in the context of the German energy transition (*Energiewende*): wind power, photovoltaic (PV) systems, and transmission lines. Using a survey-based approach, we examined acceptance levels and identified predictors across social, spatial, and individual dimensions in a German lay sample ($N = 146$). PV systems were most widely accepted, while transmission lines encountered the greatest skepticism. These differences are linked to perceived intrusiveness, ownership structures, and environmental framing. Technological self-efficacy and employment in the energy sector predicted acceptance of wind and grid infrastructure, but not of PV. The findings underline the need for technology-specific strategies to foster public acceptance. Future research should adopt system-level perspectives, explore regional differences, and investigate the temporal stability of acceptance.

1. Introduction

Germany's energy system is undergoing profound change in the wake of the global climate crisis. Transformation of the electricity system is critical to achieving climate neutrality by 2045 [1]. Wind and solar energy in particular will play a key role as their expansion will contribute significantly to decarbonization. Among the most widely deployed renewable energy generation technologies in Germany, wind power and photovoltaic (PV) systems account for a substantial share of green electricity production and are therefore central to achieving national climate targets [2–4]. German legislation calls for an increase to 80% of electricity generated from renewable sources in gross consumption by the year 2030 [5]. This will entail a geographical change and an expansion of wind power and PV systems, which will place new demands on the infrastructure of the electricity grid. Decentrally generated electricity must be transported safely and efficiently, which requires extensive grid expansion [6]. Although electricity grids do not generate energy themselves, they are a functional prerequisite for integrating renewable energy sources into the electricity system and thus an indispensable component of the energy transition [4,7].

In addition to technical and economic factors, social acceptance is a prerequisite for the implementation of the energy transition. Resistance to infrastructure projects poses a challenge to renewable energy

implementation [8] and has the potential to delay or prevent the expansion of renewable energy [9]. Despite their different functional roles, with wind and PV representing 2 dominant visible renewable energy generation technologies and electricity grids serving as the primary visible distribution infrastructure, all 3 technologies share key characteristics relevant to social acceptance: they are large-scale, spatially extensive infrastructures implemented in public spaces and experienced externally by the general population, together representing the generation-to-distribution chain of the energy transition.

Over the past decade, research has increasingly addressed the social acceptance of energy technologies [10]. Existing studies have examined Renewable Energy Technologies (RET) in general [11–13], as well as the acceptance of specific technologies, including wind power [14–17], PV systems [17,18], and electricity grids [19,20]. Despite this growing body of research, comparative studies that systematically analyze acceptance across different types of energy infrastructure within the same empirical framework remain limited. Such comparative approaches are needed to identify both shared and technology-specific acceptance-impacting factors, thereby providing a more nuanced understanding of public support for renewable energy infrastructure. This study therefore analyzes which determinants influence the acceptance of the expansion of wind energy, PV systems, and electricity grids, and the extent to which these determinants differ between technologies.

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2. Social acceptance of energy infrastructure planning

This section reviews theoretical frameworks and empirical findings on the social acceptance of energy infrastructure. Drawing on a growing body of research [10–13], the following paragraphs synthesize key influence factors across psychological, environmental, and procedural dimensions.

The acceptance of RET is shaped by a range of environmental, technical, economic, and social factors [21] and encompasses forms ranging from passive tolerance to active advocacy [10,22]. Although the absence of support does not necessarily signify an absence of acceptance, active participation of the population is considered conducive to the successful expansion of large infrastructure elements [12]. Acceptance can also be defined as a behavioral reaction whereby support is expressed, for example, in financial participation in the construction of wind farms, while resistance can become visible through protests [23]. Further clarification of the concept of acceptance is provided by Wüstenhagen et al. [11]. They conceptualize acceptance at the socio-political, community, and market level. Transferred to the specific case of RET, socio-political acceptance refers to the general acceptance of energy technologies and the political measures taken to implement such technologies [14]. Community acceptance, on the other hand, refers to the acceptance of regional energy projects by residents and local stakeholders. Market acceptance refers to the willingness of consumers and investors to invest in a technology [17]. While market acceptance is particularly important for energy technologies at the household level, it plays a subordinate role for large-scale infrastructure expansion [11]. Thus, in this study, we focus on general, i.e., socio-political acceptance and its influencing factors, to compare these across wind power plants, PV systems, and transmission lines. This focus was chosen because socio-political acceptance operates at a general level that is comparable across technologies, whereas community acceptance is inherently tied to specific local projects and affected populations, which would have introduced context-specific confounds incompatible with a comparative design. While community acceptance and the local resistance it may generate are of undeniable practical importance, socio-political attitudes provide the broader societal baseline within which local conflicts are politically situated.

A useful basis for structuring these diverse influence factors is provided by Huijts et al. [23], who proposed a comprehensive psychological framework for the acceptance of sustainable energy technologies. Their model synthesizes insights from multiple theoretical traditions, identifying perceived costs and benefits, affective responses, feelings of trust and fairness, and perceptions of personal control as core psychological determinants. Importantly, the framework highlights that acceptance is shaped by both cognitive evaluations — such as assessments of risks and benefits — and affective responses, suggesting that neither rational calculation nor emotional reaction alone accounts for public attitudes [23]. This integrative perspective informs the structure of the literature review below.

Previous acceptance studies of RET have often identified technology-specific factors linked to acceptance, whereby the predictors for grid acceptance often differ from those for the acceptance of expanding wind power and PV [24,25]. Besides project-related and local ties, personal factors can also contribute as an explanation for both acceptance and rejection [26]. However, Batel [27] has argued that acceptance research needs to move beyond treating acceptance as a binary outcome to be achieved — whether expressed as support or resistance. Rather, acceptance should be understood as a complex, dynamic, and politically embedded process. Public resistance to energy projects should not be dismissed as irrational opposition or reduced to 'Not in my backyard' (NIMBY) related behavior; instead, it reflects legitimate concerns about procedural fairness, distributional justice, and power asymmetries in planning and governance. Furthermore, [27] emphasizes the need to consider not only current public responses but also historical and social contexts that shape why people accept or reject

particular technologies. This critical perspective enriches the study of acceptance factors by highlighting that identifying predictors is only one part of a broader analytical picture.

Against this backdrop, the following paragraphs focus on the empirical predictors most consistently identified in prior research. A personal trait that was found by previous research to have a positive impact on support for sustainable energy infrastructure such as PV and wind energy is the level of knowledge or awareness about energy (infrastructure) [28,29]. Expert knowledge (e.g., through an occupation in the energy sector) is also an aspect that has a potential influence, as risk perception by laypeople and experts differs, for example, with regard to the energy grid [30]. Furthermore, both environmental and technology-related attitudes have a measurable impact on the acceptance of energy infrastructure. Studies show that greater environmental awareness and a greater degree of technological self-efficacy (reflecting a person's confidence in using technology) have a positive influence on the acceptance of energy and infrastructure technologies [31,32]. Heightened environmental awareness is furthermore linked to higher levels of risk perception for conventional energy technologies [33]. Corroborating and extending these findings, a recent global meta-analysis by Eppe et al. [34] identified personal norms, positive attitudes towards technologies, and perceived behavioral control as the strongest psychological predictors of sustainable energy technology adoption. Perceived monetary costs and risk perceptions act as relevant barriers. Notably, the positive influence of environmental concern on adoption was found to grow stronger over time, suggesting an increasing alignment between pro-environmental values and openness toward sustainable energy technologies [34].

In addition to attitudinal factors, studies on RET also highlight the relevance of perceived environmental impacts, in particular aspects of spatial planning and climate compatibility [35]. These include objectively measurable factors, such as land use, as well as subjective variables such as perceived aesthetic changes in the landscape [36]. The evaluation of environmental impacts of RET is complex, as it can vary depending on season, climate, location, and specific technology [37]. Although scientific evidence indicates that the ecological footprint of RET is generally low [37,38], concerns about nature conservation remain prevalent. For example, while wind turbines are often criticized for endangering birds and bats, studies show that their contribution to overall mortality rates is relatively small compared to other human-related causes [37,39]. Nevertheless, concern alone is often sufficient to affect public attitudes [40].

These concerns are particularly salient in the case of wind power, where the direct environmental impacts, such as visual intrusion or effects on local wildlife, are weighed against the more indirect environmental benefits, such as reductions in greenhouse gas emissions or compensation measures [41]. However, these indirect benefits are often less tangible to residents, leading to ambivalent perceptions and local opposition. This is sometimes referred to as a 'green-on-green' conflict [42]. Consequently, the net effect of environmental considerations on acceptance remains uncertain [43]. A systematic review of 141 studies on public acceptability and perceived impacts across eleven energy sources and mitigation technologies by Görsch et al. [44] confirms that perceived environmental, community, and health impacts are among the most frequently studied and influential factors shaping public evaluations. While renewable energy sources — including solar and wind — are generally evaluated more positively than fossil fuel and nuclear technologies with respect to environmental benefits, they can still elicit mixed evaluations regarding aesthetic and local impacts, particularly at the project level. Critically, Görsch et al. [44] highlight that acceptability tends to be lower for specific local projects than for general evaluations of the same technology, underscoring the role of spatial proximity and local context — a finding that is directly relevant to the present study, in which all 3 technologies are evaluated as types of infrastructure physically present in people's environments. In a similar vein, research on place-related beliefs shows that the perceived fit

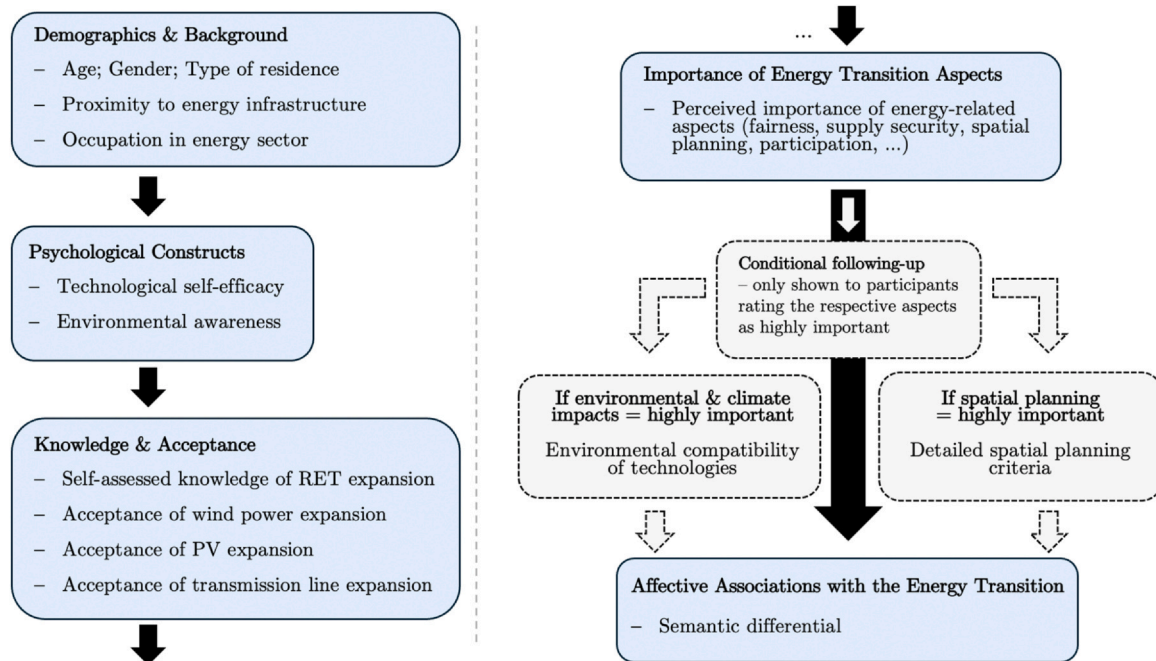


Fig. 1. Design of the survey structure. Dashed borders indicate conditional modules shown only to participants rating the respective aspects as highly important.

between energy infrastructure and its contextual environment — including local landscape values and place attachment — can independently influence acceptance [45].

In addition, opportunities for participation have been shown to play a significant role in shaping public acceptance of RET projects [46]. In the context of wind energy expansion, political participation, such as involvement in decision-making processes, is often perceived as more desirable than financial participation, which typically refers to the opportunity to invest in or benefit financially from energy projects [14,47]. Furthermore, involving trusted actors such as scientists and civil society organizations alongside the implementation of inclusive planning processes can enhance both public trust and the long-term acceptance of RET [48,49]. The importance of these relational and affective factors is further underscored by a meta-analysis by Milani et al. [50], which identified perceived benefits and positive emotional responses as the strongest predictors of social acceptability across renewable and sustainable energy technologies, followed by perceptions of fairness and trust in decision-makers. In contrast, negative emotional responses emerged as the strongest single barrier [50]. These findings confirm that social acceptance is deeply shaped by affective and relational factors alongside cognitive assessments of costs and benefits.

Taken together, these findings suggest that public acceptance is shaped by a combination of environmental, procedural, and attitudinal factors that may differ across technologies. Consequently, a one-size-fits-all model does not seem appropriate, as the drivers and barriers to social acceptance may be technology-specific. Therefore, the present study focuses on comparing key determinants of social acceptance that have been identified in previous research as particularly influential across different types of RET. These include the perceived importance of spatial planning, occupation in the energy sector, environmental awareness, self-assessed knowledge of energy infrastructure, technological self-efficacy, perceived environmental compatibility of technologies, and the desire for political participation. To provide a comprehensive picture of public attitudes, the present study follows a stepwise approach. We first examine how citizens affectively and cognitively perceive the energy system transformation (RQ 1), then identify which aspects of the transition they consider most important (RQ 2), and finally analyze which factors are connected to the technology-specific acceptance of wind power, PV, and grid expansion (RQ 3). By moving

from general perceptions to evaluative priorities and finally to statistical predictors, we aim to contextualize the acceptance patterns identified in the regression analyses within the broader attitudinal landscape of the energy transition.

- **RQ 1: How do citizens perceive the transformation of the electricity system towards a green energy system?** This question explores general public perceptions and spontaneous associations, providing insight into whether the transformation is viewed as desirable, feasible, or contentious.
- **RQ 2: What factors do citizens consider important in the transition to a green energy system?** This question investigates the evaluative criteria and priorities people apply when forming opinions about energy infrastructure, helping to reveal underlying value orientations.
- **RQ 3: What factors are linked to the acceptance of wind power, PV, and grid expansion?** This question focuses on identifying key factors associated with acceptance for each technology. Comparison across technologies aims to highlight both common and specific patterns, contributing to more targeted strategies to promote acceptance.

3. Materials and methods

The survey instrument was developed in an iterative process, informed by insights from qualitative interviews conducted during an informative pre-study on perceptions of energy system transformation alongside validated measures from prior research. The structure of the survey, the data analysis, the methods used to analyze the data, and the sample are described below.

3.1. Survey design

In the first part of the survey (Fig. 1), participants were asked for *demographic information* such as their age, gender, place of residence (city center, suburb, or village), and the proximity of their place of residence to energy infrastructure. Participants were also asked to indicate their *technical self-efficacy* [51] and their *environmental awareness* [52]. In the second part, participants were asked to rate their level of

awareness regarding the expansion of RET as well as their attitudes and degree of acceptance (adapted from [22]) toward the development of PV systems, wind power plants, and transmission lines. The third part of the questionnaire, including items on the perceived importance of various energy-related issues and spatial preferences, was developed on the basis of the qualitative pre-study mentioned above. Only participants who had previously rated the environmental and climate impacts of the energy system and/or the spatial planning of energy infrastructure as highly important were presented with follow-up item sets designed to capture more nuanced assessments of these specific issues. Finally, affective associations with the transformation of the energy system were surveyed by means of a semantic differential including sets of opposites that measured dimensions identified in the qualitative pre-study. All items were measured using a Likert scale, with responses ranging from 1 (strong disagreement) to 6 (strong agreement). Items within a block of questions were randomized.

The instrument was examined by the “Interfaculty Ethics Committee of RWTH Aachen University” with regard to ethical harmlessness and was assessed as ethically unobjectionable.

3.2. Data cleaning and statistical analysis

Data were analyzed using descriptive and inferential statistics. To ensure response quality, data cleaning was conducted in several sequential steps: incomplete cases ($n = 52$), 1 speeder (completion time below 7.0 min, i.e., one third of the median completion time of 21.0 min among complete cases), 3 participants under 18 years of age, and 6 cases with implausible response patterns (e.g., full agreement with contradictory statements) were removed. All remaining participants passed the attention check item, yielding a final analytic sample of $N = 146$ from an initial 208 respondents. After testing for sufficient internal consistency using Cronbach's alpha ($\alpha > .7$) [53], and after reversing the polarity of the negatively worded items, construct formation was carried out by calculating the mean value across the included items (see Table 1 for construct formation).

The level of significance was set at 5%. Although no formal a priori power analysis was conducted prior to data collection, post-hoc power evaluation using G*Power 3.1 [54] confirms that the sample size was adequate for all analyses. For the repeated-measures analyses of variance (ANOVA), a minimum of 28 participants was required to detect a medium effect ($f = .25$) at $\alpha = .05$ with 80% power; the observed effect was large ($\eta_p^2 = .37$), rendering the sample of $N = 146$ more than sufficient. For the multiple linear regression models with 7 predictors, a minimum of 103 participants was required to detect a medium effect ($f^2 = .15$) at $\alpha = .05$ with 80% power. The obtained effect sizes ($f^2 = .35-.61$) substantially exceeded this threshold, confirming adequate statistical power across all models.

ANOVA with repeated measures was used to determine whether there were differences in the acceptance of wind power, PV systems, and grid expansion. Multiple linear regressions were calculated to determine which factors are associated with attitudes towards energy

infrastructure. Before conducting regression analyses, key assumptions of linear regression were tested: linearity, homoscedasticity, multicollinearity, and normality [55]. Additionally, frequency distributions were examined, and the reliability of the construct scales was assessed. Pearson's correlations indicated that there was no critical multicollinearity among the factors. This was further confirmed by collinearity diagnostics, with variance inflation factors (VIF) ranging from 1.2 to 2.2, well below the critical threshold of 10 [55]. The Durbin-Watson statistic suggested no substantial autocorrelation of residuals (wind power plants: 2.40, PV systems: 1.99, transmission lines: 1.91), supporting the assumption of independent errors. Finally, differences in siting preferences for wind power and PV were determined using paired t -tests.

3.3. Sample

Following data cleaning, the final sample comprised 146 participants. Of these, 58.2% identified as female, 41.1% as male, and 0.7% as non-binary. Participants' age ranged from 18 to 90 years ($M = 34.99$, (standard deviation) $SD = 16.47$). According to the International Standard Classification of Education [56], the majority of respondents (56.2%) reported a high level of education, 40.4% reported a medium level, and 3.4% reported a low level. Therefore, the sample deviates from the general German population, which is comprised of 50.7% women and 49.3% men [57] as well as of 22% of people with low, 48% with medium, and 30% with a high level of education [58].

While the majority of respondents (78.8%) indicated that they did not work in an energy-related field, 22.2% of the sample worked in the energy industry (e.g., energy engineering or electrical engineering). The majority of the participants lived in the city center (43.8%) and almost as many in the suburbs (38.4%). 17.8% of the sample reported living in the countryside or in a village. In general, just over half (51.3%) of the participants stated that they had installed a PV system on their own property or lived in close proximity to installed PV systems. In addition, 15.8% of the respondents reported living close to a wind power plant and 19.2% close to a transmission line.

Both technological self-efficacy ($M = 4.47$, $SD = 1.09$) and environmental awareness ($M = 4.93$, $SD = 0.80$) were relatively high on average. Respondents reported feeling only moderately informed about the expansion of energy infrastructure ($M = 3.22$, $SD = 1.28$). However, their self-assessed knowledge of PV systems ($M = 3.53$, $SD = 1.41$) was higher than their level of knowledge of wind power plants ($M = 3.28$, $SD = 1.38$; $t(145) = -3.57$, $p < .001$, $d = .84$), and also higher than that of transmission line expansion ($M = 2.84$, $SD = 1.43$; $t(145) = 5.55$, $p < .001$, $d = .95$). In addition, subjective knowledge about PV systems was significantly higher than that about electricity grids ($t(145) = 6.89$, $p < .001$, $d = 1.20$).

4. Results

The following section is structured according to the research questions. First, we analyze affective and evaluative associations with the energy system transformation (RQ 1) to establish the general attitudinal context. Building on this, we examine which aspects of the transition citizens consider most important (RQ 2), thereby identifying the evaluative criteria that may underlie technology-specific attitudes. Finally, we turn to the core analytical question (RQ 3) and present acceptance levels as well as multiple regression models identifying technology-specific factors for wind power, PV, and grid expansion.

4.1. Analysis of associations with the energy system transformation (RQ 1)

To better understand how people emotionally and cognitively perceive the transition to a green electricity system, we included a set of bipolar adjective pairs capturing affective as well as process-related aspects of the energy transition (Fig. 2). These pairs were designed to

Table 1
Cronbach's alpha and descriptive statistics for computed constructs

Construct	Items	Cronbach's α	M	SD
technological self-efficacy	4	0.89	4.47	1.09
environmental awareness	8	0.82	4.93	0.80
importance of spatial planning	4	0.80	4.42	0.95
political participation	4	0.70	3.70	0.60
self-assessed knowledge of RET	3	0.90	3.22	1.28
environmental compatibility	4	0.81	5.14	0.87

RET = renewable energy technologies; SD = standard deviation.

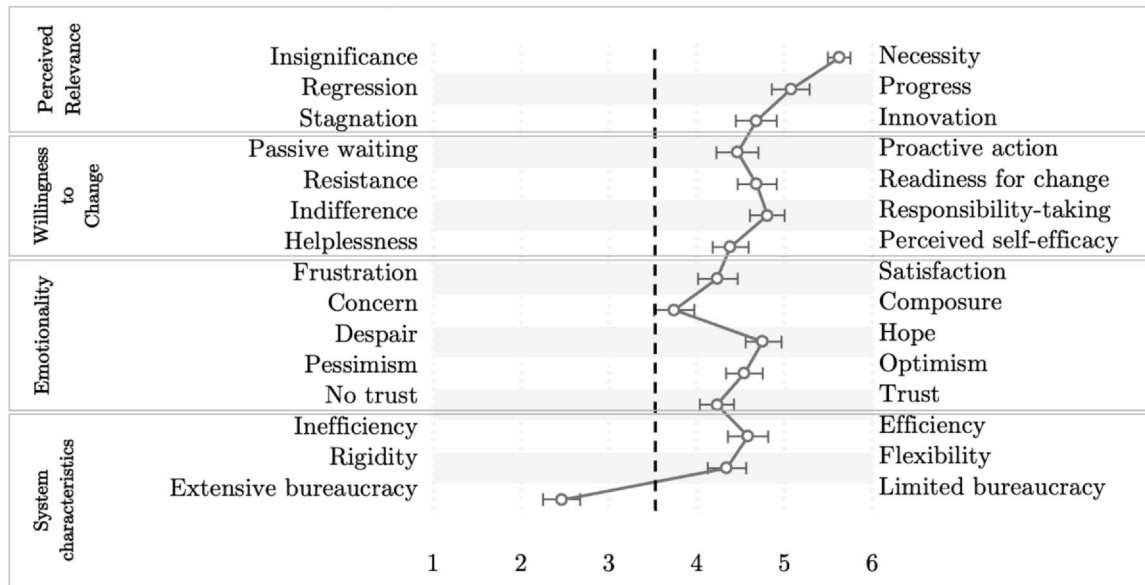


Fig. 2. Mean agreement of associations on the transformation of the energy system (semantic differential). Dots represent means; whiskers show 95%-CI; n = 146.

assess associations regarding the expansion of RET. The results indicate a consistently positive evaluation. Nearly all items were rated clearly above the neutral midpoint of the scale (3.5), suggesting that participants predominantly associate the transition with desirable qualities. The strongest agreement was found for the necessity of the transformation ($M = 5.62$, (confidence interval) $CI[5.49, 5.75]$), followed by notions of progress and responsibility-taking. The pair ‘concern - composure’ ($M = 3.74$, $CI[3.51, 3.97]$) was rated close to the midpoint, indicating a rather neutral perception of emotional composure in the context of the grid transition. In contrast, only the association with extensive bureaucracy ($M = 2.46$, $CI[2.25, 2.67]$) fell below the midpoint, suggesting that administrative burdens are viewed more critically. Overall, the polarity profile points to a broadly supportive affective and evaluative stance, in which the energy transition is not only perceived as necessary but also associated with optimism, trust, and efficiency.

4.2. Perceived relevance of energy transition aspects (RQ 2)

In order to gain insight into the normative expectations that influence public opinion regarding the transformation of the energy system, participants were asked to evaluate the importance of various transition-related aspects (Fig. 3). The results show that all of the assessed aspects were rated above the midpoint of the scale, indicating a generally high level of perceived relevance. The fairness of supply ($M = 5.55$, $CI[5.44, 5.67]$), the security of energy supply ($M = 5.51$, $CI[5.40, 5.62]$), and the environmental and climate compatibility of the energy system ($M = 5.38$, $CI[5.25, 5.52]$) were rated particularly high. Geographical and political factors such as spatial planning ($M = 4.99$, $CI[4.84, 5.13]$) and public participation ($M = 4.77$, $CI[4.58, 4.95]$) were rated comparatively less important, but still important.

As set out in the survey design, participants were only asked to assess the items presented in Fig. 4 if they had rated the climate impacts and/or spatial planning of RET as highly important, in order to gain a deeper understanding of how these factors are perceived. Overall, all aspects received ratings above the scale’s midpoint. Nevertheless, a difference emerged between the 2 dimensions: items addressing climate-related impacts were consistently evaluated as more important than those concerning spatial planning. Among the climate-related criteria, the sustainable and clean production of renewable energy systems received the highest importance rating ($M = 5.36$, $CI[5.22, 5.50]$). In contrast, aspects of spatial planning, such as ensuring a

sufficient distance from residential areas ($M = 4.22$, $CI[4.02, 4.45]$) and landscape protection in Germany ($M = 3.90$, $CI[3.67, 4.12]$) were perceived as comparatively less important. However, the difference in importance ratings between the 2 dimensions should not be overstated. For example, there was no significant difference between the lowest-rated climate-related item — protection of flora during the construction of energy infrastructure ($M = 5.04$, $CI[4.86, 5.22]$) — and the highest-rated spatial planning item — avoidance of infrastructure in ecologically or culturally sensitive areas ($M = 4.96$, $CI[4.79, 5.13]$; $t(133) = 0.92$, $p = .18$, $d = .08$).

4.3. Factors linked to the acceptance of energy system expansion (RQ 3)

To further investigate which factors influence acceptance across technologies, the following section identifies key factors for each case. All respondents provided acceptance ratings for the expansion of wind power plants, PV systems, and transmission lines. Accordingly, technology was treated as a within-subject factor, and differences between technologies were analyzed using repeated-measures ANOVA. As this was an exploratory study, no directional hypotheses regarding differences between technologies were specified a priori. Bonferroni-adjusted post hoc tests were therefore used to examine pairwise differences between technologies.

An exploratory analysis of descriptive statistics for the acceptance of the expansion of wind power plants, PV systems, and transmission lines indicated differences between the technologies. The mean acceptance rating for PV expansion was 5.51 (95% – $CI[5.40, 5.63]$), indicating a high level of acceptance. The acceptance levels of wind power expansion ($M = 4.92$, 95% – $CI[4.75, 5.08]$) and transmission line expansion ($M = 4.57$, 95% – $CI[4.42, 4.71]$) were lower but still high on average. The sphericity assumption was met using the Mauchly sphericity test ($\chi^2(2) = 1.95$, $W = .99$, $p = .38$). The calculations revealed significant differences between the groups ($F(2, 290) = 86.17$, $p < .001$, $\eta_p^2 = .37$). Bonferroni-adjusted post hoc analysis showed that all pairwise comparisons were significant. The acceptance of the expansion of PV systems was significantly higher than that of wind power plants ($M_{Diff} = .60$, $p < .001$, 95% – $CI[.43, .77]$) and transmission lines ($M_{Diff} = .95$, $p < .001$, 95% – $CI[.76, 1.12]$). The final group comparison shows that the acceptance of the expansion of wind power plants was significantly higher than the acceptance of the expansion of transmission lines ($M_{Diff} = .35$, $p < .001$, 95% – $CI[.16, .54]$).

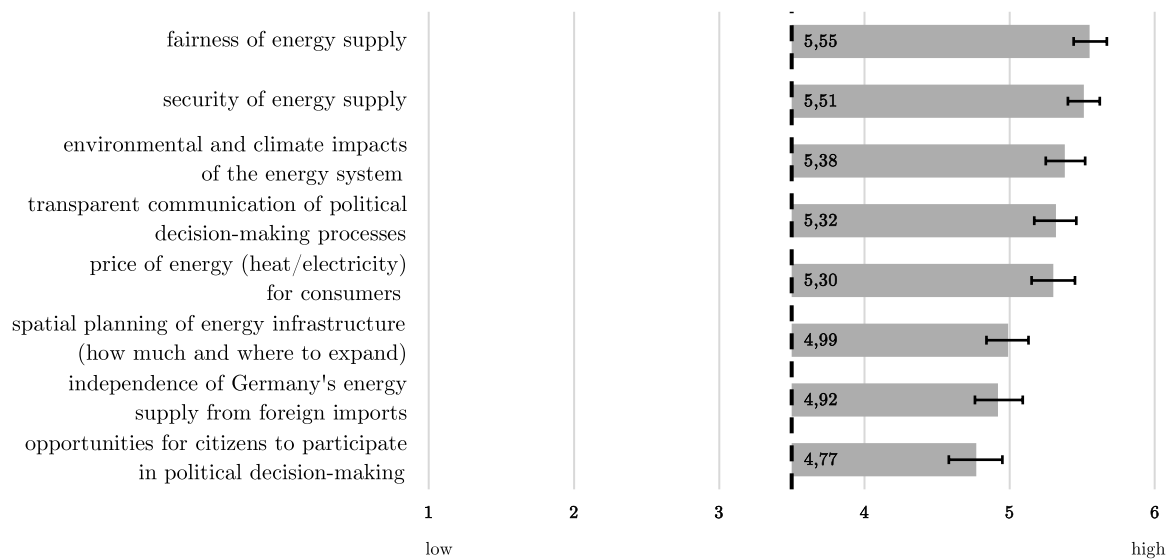


Fig. 3. Mean perceived importance of various aspects in relation to the energy system. Mean values on bars; whiskers show 95%-CI; n = 146.

4.3.1. Factors linked to the acceptance of wind power expansion

The predictors included in the model (Table 2) significantly explained the acceptance of wind power expansion ($F(7, 130) = 11.41, p < .001$). The R^2 for the overall model was .38 (adj. $R^2 = .35$), indicating a high goodness of fit [59]. The strongest regression variable, *perceived importance of spatial planning*, was associated with lower acceptance ($b = -.35, p < .001$), followed by *employment in the energy sector* ($b = .25, p = .004$) and *environmental awareness* ($b = .26, p = .007$), which were positively associated with acceptance. In addition, *technological self-efficacy* had a smaller acceptance-enhancing effect ($b = .15, p = .048$), while *self-assessed knowledge of RET development* was associated with lower acceptance ($b = -.23, p = .009$).

4.3.2. Factors linked to the acceptance of PV expansion

The R^2 for the overall model for the acceptance of PV expansion (Table 3) was .26 (adj. $R^2 = .22$), indicating a moderate goodness of fit [59]. Among the included factors, only *perceived environmental compatibility* had a significant effect on the acceptance of PV expansion ($F(7, 130) = 6.48, p < .001$), suggesting that people who are more concerned about the environmental and climate impact of a technology are more likely to support solar energy ($b = .26, p = .020$). In contrast, *occupational background*, *environmental awareness*, and *technological self-*

efficacy did not show significant effects, suggesting that acceptance of PV expansion is primarily linked to perceived environmental benefits rather than personal or occupational factors.

4.3.3. Factors linked to the acceptance of grid expansion

The factors included in the third model (Table 4) significantly explained the acceptance of grid expansion ($F(7, 130) = 9.87, p < .001$). The R^2 for the overall model was .35 (adj. $R^2 = .31$), indicating a high goodness of fit [59]. *Perceived environmental compatibility* – i.e., an emphasis on environmental and climate benefits – was found to be associated with acceptance the strongest ($b = .31, p = .003$), followed by *technological self-efficacy* ($b = .27, p < .001$), and *professional background* in the energy sector ($b = .22, p = .012$). All 3 were associated with higher levels of acceptance. In contrast, higher *perceived importance of spatial planning* was associated with lower acceptance ($b = -.18, p = .044$), suggesting potential concerns about land use and infrastructure development.

5. Discussion

In the following section, the research findings are condensed and discussed in order to answer the guiding research questions of the study.



Fig. 4. Mean importance of environmental and spatial criteria for energy infrastructure. Mean values on bars; whiskers show 95%-CI. Climate Impact: n = 141, Spatial Planning: n = 138.

Table 2Regression model for the acceptance of wind power plant expansion ($\alpha = .85$)

	B	SEB	b	T	VIF	t	p
constant	3.449	.779				4.429	< .001
importance of spatial planning	-.371	.090	-.349	.661	1.512	- 4.117	< .001*
occupation in energy sector	.612	.206	.254	.650	1.539	2.968	.004*
environmental awareness	.331	.120	.260	.537	1.861	2.758	.007*
self-assessed knowledge of RET	-.182	.068	-.231	.637	1.570	- 2.670	.009*
technological self-efficacy	.140	.070	.152	.819	1.221	1.998	.048*
environmental compatibility	.213	.122	.178	.457	2.189	1.748	.083
political participation	.050	.137	.030	.730	1.369	.369	.712

B = unstandardized beta; b = standardized beta; p = probability value; RET = renewable energy technologies; R^2 = determination coefficient; SEB = standard error for the unstandardized beta; T = tolerance; t = t-test statistics; VIF = variance inflation factor.

* $p < .05$.

Adj. $R^2 = .35$, Durbin-Watson = 2.40, N = 146.

Table 3Regression model for the acceptance of PV system expansion ($\alpha = .86$)

	B	SEB	b	T	VIF	t	p
constant	3.117	.601				5.190	< .001
environmental compatibility	.221	.094	.263	.457	2.189	2.355	.020*
occupation in energy sector	.281	.159	.166	.650	1.539	1.770	.079
environmental awareness	.160	.093	.178	.537	1.861	1.730	.086
importance of spatial planning	-.102	.070	-.136	.661	1.512	- 1.465	.145
technological self-efficacy	.075	.054	.117	.819	1.221	1.401	.164
political participation	.112	.105	.094	.730	1.369	1.061	.291
self-assessed knowledge of RET	.027	.053	.049	.637	1.570	.521	.603

B = unstandardized beta; b = standardized beta; p = probability value; RET = renewable energy technologies; R^2 = determination coefficient; SEB = standard error for the unstandardized beta; T = tolerance; t = t-test statistics; VIF = variance inflation factor.

* $p < .05$.

Adj. $R^2 = .22$, Durbin-Watson = 1.99, N = 146

Table 4Regression model for the acceptance of transmission line expansion ($\alpha = .79$)

	B	SEB	b	T	VIF	t	p
constant	1.839	.707				2.599	.010
technological self-efficacy	.218	.063	.269	.819	1.221	3.440	< .001*
environmental compatibility	.330	.111	.313	.457	2.189	2.986	.003*
occupation in energy sector	.475	.187	.223	.650	1.539	2.539	.012*
importance of spatial planning	-.167	.082	-.177	.661	1.512	- 2.034	.044*
self-assessed knowledge of RET	.072	.062	.103	.637	1.570	1.157	.250
political participation	.074	.124	.050	.730	1.369	.597	.551
environmental awareness	.030	.109	.027	.537	1.861	.276	.783

B = unstandardized beta; b = standardized beta; p = probability value; RET = renewable energy technologies; R^2 = determination coefficient; SEB = standard error for the unstandardized beta; T = tolerance; t = t-test statistics; VIF = variance inflation factor.

* $p < .05$.

Adj. $R^2 = .31$, Durbin-Watson = 1.91, N = 146.

5.1. Public perception of the German energy system transformation (RQ 1)

To investigate public perception of the transformation of the energy system towards a more sustainable future, we asked participants to indicate their assessment of several pairings with negative to positive connotations in the form of a semantic differential. As Carmona and Dąbkowska [60] note for the energy transition in relation to phasing out coal, processes of transformation can be connected to emotional responses arising, e.g., through (local) social and community connections. Furthermore, affective evaluations have been identified as predictors of people's attention for information on RET [61]. Therefore, analyzing affective associations with energy system transformation in Germany can be a relevant source of information on public attitude.

With 1 exception, the overall assessment of the transformation of the energy system was rather positive. [62] point out that survey measurements of support for sustainable measures can be biased due to social desirability in the context of sustainability. We counteracted this risk by measuring not only support but also affective associations with polar dimensions. These positive associations included attributions that relate to the individual person, such as feelings of 'perceived self-efficacy', 'hope', or 'satisfaction'. The rather high values for associations that can be attributed to energy system transformation — such as 'progress', 'necessity', 'efficiency', 'innovation', and 'readiness for change' — indicate a general openness or even demand for a transformative change of the energy system. Respondents' tendency towards 'responsibility-taking' (in contrast to 'indifference') suggests an attitude in which not only a necessity for action is perceived, but a moral or

social responsibility is also acknowledged. Building on these insights into the general openness towards the energy system transformation, it is important to analyze which characteristics of energy systems are of relevance to public perception.

5.2. Considering hotspots of public perception in energy system transformation (RQ 2)

The results of the analysis of respondents' answers show that all of the queried energy system characteristics were of importance to the respondents, supporting previous research findings. The finding that fairness – along with security – was perceived as the most important concept can complement previous findings in energy justice research on concepts such as distributive and procedural fairness [63], whose perception by the public can impact the acceptance of energy technologies to varying degrees [64]. The security of energy supply was perceived as nearly as important and was previously found to be part of trade-off decisions for energy source preferences [65]. The high perceived importance of environmental and climate impacts of the energy system comes as no surprise, as the average environmental awareness of the sample is quite high, and previous research established a link between environmental concern and support for sustainable energy production [66]. These findings on perceived importance provide valuable context for understanding the technology-specific acceptance patterns examined in the following section. The high salience of environmental and climate compatibility (RQ 2) underlines its role as a significant factor of acceptance across multiple technologies in the regression analyses (RQ 3). Likewise, the perceived importance of spatial planning – while rated comparatively lower than environmental concerns – still scored well above the scale midpoint, foreshadowing its negative association with the acceptance of wind power and grid expansion. Together, the results of RQ 1 and RQ 2 suggest that citizens hold generally positive yet value-driven and differentiated attitudes toward the energy transition – shaped by concerns around fairness, sustainability, and spatial impact – which, as the following analyses reveal, manifest in distinct, technology-specific acceptance profiles.

5.3. Social acceptance of fundamental energy technologies for the German energy transition (RQ 3)

The results revealed significant differences in the acceptance of various energy infrastructure technologies. While PV systems were particularly well supported, acceptance of wind power and, especially, transmission lines was significantly lower. Differences in acceptance can be explained further by the spatial placement of these technologies, their visibility, and the varying degrees to which they are integrated into people's everyday lives. Wind turbines and transmission lines are typically perceived as large-scale, publicly visible infrastructure intended for collective use. In contrast, PV systems, particularly rooftop installations, are considered less intrusive and more familiar, as they form part of existing buildings and are common in residential environments. These privately owned installations are often perceived as providing direct personal benefits and control [67], with self-generated electricity viewed as personal property, which helps explain their broad acceptance. These patterns may also reflect a more fundamental distinction between private and public energy infrastructure. In a study with Scottish residents, Hogan [68] found that acceptance of renewable energy projects was higher in the case of community-owned installations and that acceptance was impacted by perceptions of energy justice.

By contrast, wind turbines and transmission lines represent public infrastructure, designed to deliver more collective, indirect benefits. This distinction may shape not only the perceived usefulness of each technology but also individuals' perceived ability to influence decisions and their sense of voluntariness in engaging with it. These perceptions of ownership and control may thus also interact with broader attitudes

toward fairness and trust in planning processes.

While the visible, large-scale nature of wind and grid infrastructure may foster a sense of shared responsibility, it can simultaneously evoke feelings of exclusion from decision-making and a lack of individual control. This is particularly relevant in the case of transmission lines, which have been associated with higher perceived risks than wind power plants, even though the perceived benefits of both technologies are similar [69]. These elevated risk perceptions, combined with limited personal benefit and a lack of perceived agency, may contribute to the comparatively lower acceptance of grid infrastructure.

The regression analyses of factors revealed technology-specific differences in acceptance. Support for the expansion of wind power was positively associated with higher environmental awareness, technological self-efficacy, and employment in the energy sector, while a stronger emphasis on spatial planning and higher self-assessed knowledge of RET were linked to lower acceptance. In the case of PV expansion, perceived environmental compatibility emerged as the key factor linked to acceptance. Acceptance of grid expansion was higher among individuals with strong technological self-efficacy and a professional background in the energy sector, possibly reflecting a greater appreciation of the technical necessity of electricity grids for distributing renewable energy. In contrast, greater importance attributed to spatial planning was associated with lower acceptance, suggesting that while the necessity of electricity grids is acknowledged, acceptance declines when visual impacts on the landscape and spatial planning concerns become salient.

The case of PV systems, however, stands apart from these patterns in a theoretically meaningful way. This pattern is noteworthy precisely because of the absence of predictors that were significant for the other 2 technologies. It suggests that PV systems occupy a distinct position in public perception: they are widely familiar, often privately owned, and perceived as relatively unobtrusive. As a result, individual differences in technological confidence, professional expertise, or spatial planning concerns – which differentiate acceptance for more contested technologies – appear less relevant for PV. The comparatively lower explained variance of the PV model (adj. $R^2 = .22$) further supports this interpretation, indicating that the factors most relevant to PV acceptance may lie outside the factor set examined here, potentially including economic and structural variables that are particularly relevant for PV as a technology that can be privately owned and operated at the household level. Household income [70,71], property and roof ownership [71], purchase costs [72], and awareness of financial incentives such as feed-in tariffs [73] or government subsidies [74] have been identified as key determinants of residential PV adoption intentions in previous research, and their absence from the current predictor set may account for a substantial portion of the unexplained variance in the PV model. These contrasting predictor profiles across the 3 technologies point to underlying differences in how each technology is socially situated, and underline the need for technology-specific strategies when addressing public acceptance of energy infrastructure – differences that the following paragraphs examine in greater depth.

The different patterns of influence of the predictors are further illuminated by technology-specific characteristics, previous individual experience, and differing social perceptions, as has previously been found to be the case in studies in the context of energy technology perception [75]. The fact that technological self-efficacy and professional experience in the energy sector are only associated with greater acceptance of wind power and transmission lines suggests a greater perception of the complexity of these technologies. Wind turbines and power lines are potentially regarded as large-scale infrastructures that appear less accessible or controllable for people without the relevant expertise. PV, on the other hand, can be experienced directly in everyday life and is perceived as a technology that can be used individually, particularly when people own roof surfaces or balcony solar power systems, which may contribute to a higher level of familiarity. A plausible, yet-unmeasured factor is ownership, which can raise both

familiarity with the technology and the subjective experience of benefits (e.g., cost savings, environmental impact). The absence of influence from technological self-efficacy and employment in the energy sector on PV could indicate that these variables correlate with unmeasured personal characteristics (e.g., system knowledge) that lead to higher acceptance, particularly with regard to large-scale technological solutions.

The relevance of spatial planning for wind power and transmission lines, but not for PV systems, can be attributed to their more pronounced impact on the landscape. Visibility, noise emissions, and moving components such as rotor blades result in a heightened sense of spatial intrusion in the case of wind power, which makes planning-related aspects particularly salient. For transmission lines, visual intrusion is also relevant, although they are simultaneously perceived as a technical necessity. This may explain why environmental awareness increases their acceptance, even if they are not actively supported. In contrast, PV systems do not produce noise or involve moving parts and are often discreetly integrated into existing structures, which may explain the lower perceived relevance of spatial planning in this context.

Furthermore, the null result for political participation across all 3 technologies may partly reflect limitations in its operationalization. The construct captured participants' general desire for political involvement rather than their satisfaction with actual participation opportunities in specific energy projects, potentially reducing its predictive validity for technology-specific acceptance. Notably, the desire for political participation did not emerge as a significant predictor of acceptance for any of the 3 technologies. This is surprising given that participatory processes have been highlighted as important for the acceptance of RET in previous research [46,47]. One possible explanation is that the present study measured the general desire for political participation rather than satisfaction with actual participation opportunities in specific projects. As such, the variable may capture a normative attitude rather than a concrete evaluative judgment tied to a specific technology or planning process. Future research could benefit from operationalizing participation more precisely, for example by assessing perceived quality of participation in local energy projects, which may yield stronger associations with technology-specific acceptance.

The technology-dependent influence of perceived environmental compatibility — which was positive for PV systems and grid expansion, but was not found to impact the acceptance of wind power — can be explained by framing effects and divergent environmental discourses. Wind power often evokes emotional responses and is associated with perceived destruction of nature, bird strikes, and landscape interference, which can overshadow its positive environmental impacts and trigger NIMBY-related opposition [76], especially among individuals with strong pro-environmental values whose mental image of nature includes undisturbed landscapes and wildlife. In such cases, wind energy may paradoxically be perceived as a threat to the very values it aims to protect, illustrating the effect of conflicting environmental narratives.

Higher self-assessed knowledge of RET may, in this context, increase awareness of controversies and risks, resulting in a more critical attitude toward wind energy, lower trust in planning processes, and greater sensitivity to local conflicts. This may help explain the observed negative effect on acceptance of wind power expansion. Moreover, respondents who report greater knowledge of wind energy may be more exposed to polarized public debates, local opposition movements, or misinformation concerning environmental and economic impacts. Consequently, self-reported knowledge may reflect confidence in one's beliefs and exposure to attitude-consistent information rather than scientifically accurate understanding. This finding resonates with research in technology acceptance, which suggests that increased awareness does not necessarily translate into greater support but may instead heighten sensitivity to perceived drawbacks [29].

In the case of wind energy, individuals who perceive themselves as more knowledgeable may be more aware of contested issues such as

noise emissions, impacts on wildlife, or conflicts in regional planning, leading to a more differentiated and ultimately more critical assessment. We operationalized knowledge as self-assessment instead of objective measures, which can exert differing impacts in the context of environmentally affecting behaviors [77].

Although this study focuses on socio-political acceptance, the findings also offer insights into the other 2 dimensions proposed by Wüstenhagen et al. [11]. The relevance of spatial planning for wind power and transmission lines suggests a strong role for community acceptance, particularly when infrastructure projects directly affect the local environment. Moreover, the comparatively high acceptance of PV systems could be interpreted as an expression of active support rather than passive tolerance. In line with acceptance-based models such as the Technology Acceptance Model, which suggests a link between acceptance and behavioral intention [78], it is reasonable to assume that high acceptance levels — as observed for PV — may also translate into greater willingness to install such systems or support similar initiatives.

These interpretations, while offering nuanced insights into technology-specific acceptance profiles, need to be considered alongside the methodological constraints outlined below.

5.4. Limitations

There are some methodological limitations that should be considered for future research. First, with respect to the questionnaire design, it should be noted that the 'proximity to infrastructure' was not defined more precisely for the respondents. This approach was chosen because proximity is a concept that can be defined and perceived differently from one person to another. As a result, we have gained insights into *perceived* proximity. Although proximity to infrastructure was recorded as part of the sample characterization, it was not included as a variable in the regression analyses. Given the exploratory scope of this study and the absence of a standardized distance metric, the subjective operationalization, which relied on participants' self-assessment without reference to a defined threshold, would have introduced measurement uncertainty that is difficult to control for statistically. Additionally, the relatively small proportions of participants reporting proximity to wind power plants (15.8%) and transmission lines (19.2%), combined with the binary operationalization of this variable, further supported the decision to treat proximity as a descriptive sample characteristic rather than a factor for regression analysis. Future studies should include both perceived as well as objective closeness to infrastructure, allowing, e.g., for the investigation of differences between the 2 perspectives as well as an adequate analysis of objective distance theoretically influencing technology-specific acceptance.

Second, the results presented with regard to RQ 2 show without exception positive values of agreement with the surveyed perceived importance of energy system or infrastructure characteristics. Although acquiescence bias cannot be ruled out in participants' responses in this respect, differences in assessment of individual aspects demonstrate nuances in perception that offer relevant insights into how the energy system and related infrastructure are perceived. Furthermore, it has to be taken into consideration that the underlying sample is rather young, female, highly educated (in comparison with the general German population), and very environmentally aware. Social acceptance of the energy transition is often defined by resistance and negative attitudes, but the perspective of environmentally aware people who actively support the expansion of renewable energies is just as relevant. However, absolute levels of agreement should be interpreted with caution when extrapolating to the broader population. While the identified technology-specific patterns are considered robust within the study sample, policy recommendations derived from absolute acceptance levels await confirmation through nationally representative samples. Future research should aim for stratified sampling that mirrors the national age-, gender-, and education-distribution, or employ quota-based online panels to enhance representativeness.

The regression models were limited to theoretically derived factors; potentially relevant sociodemographic variables such as income, political orientation, or property ownership were not included and should be considered in future research. Future analyses should additionally explore interaction effects between included variables, such as environmental awareness and technology type or energy-sector occupation and technological self-efficacy, to uncover more complex dynamics underlying technology-specific acceptance.

The cross-sectional design of this study constitutes a further limitation, as public perceptions of energy infrastructure may shift rapidly in response to external events such as energy price fluctuations, supply disruptions, or geopolitical developments. The findings therefore reflect attitudes at a specific point in time and may not capture such event-driven volatility. Longitudinal designs are needed to assess the stability of the identified acceptance patterns over time. Finally, it has to be taken into consideration that the presented results describe self-reported acceptance levels. As is the subject matter of established acceptance theory (e.g., [78]), acceptance is considered as a predictor of actions (such as system use). The gap between stated acceptance intentions and people's actions (e.g., voting or PV installation) cannot be bridged in the context of this study and should be the object of future experimental research.

6. Conclusion

In light of the necessary transformation of the energy system, this study investigated the public perception and acceptance of the expansion of 3 integral elements of the energy system: wind power plants, PV systems, and transmission lines. While we observed a tendency toward public acceptance in the case of all 3 objects of investigation, different factors were found to exert an impact on people's acceptance between technologies. Identifying these predictors highlights that there are diverse acceptance profiles between technologies that can inform, inter alia, communicators and policymakers and highlight the need for technology-specific consideration by these entities. Future studies can build on the insights and implications achieved. For example, occupation in the energy sector was found to be predictive in some contexts; it would be useful to include experienced individuals as potential customers or investors in infrastructure planning due to their potential role as early adopters. Additionally, not only focusing on acceptance clusters in one region or country, but also investigating acceptance in different cultures, energy systems, and regions with differing levels of network expansion density could offer the potential of transferring and comparing insights. In particular, living in areas with a high density of wind turbines or power lines may shape acceptance through direct experience and increased visibility.

Furthermore, acceptance analysis should be combined with system perspectives [79] in the sense that, for example, potential technologies for energy storage should be included in the equation to inform holistic assessment and planning of energy systems in the context of the energy transition. In addition to these structural and system-related considerations, it is crucial to examine the temporal stability of public acceptance. While current attitudes offer important insights, acceptance can change over time in response to shifting political, social, or personal circumstances. For example, negative experiences - such as noise disturbances from wind turbines or visual impacts from transmission lines - could lead to long-term declines in acceptance, even when initial support was present. Longitudinal studies are therefore essential to better understand the durability of acceptance and the conditions under which it is sustained or eroded. Technological developments may also influence acceptance trajectories. Innovations such as quieter wind turbines or underground power lines could reduce perceived burdens and improve acceptance levels. Lastly, combining quantitative findings with qualitative methods - such as interviews - can provide a deeper understanding of how individuals construct their attitudes toward RET. This can reveal the underlying mental models that shape the acceptance of wind power, PV systems, and transmission lines.

CRedit authorship contribution statement

Hanna Kersting: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Linda Engelmann:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Martina Ziefle:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to privacy restrictions but are available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used university-hosted OpenAI GPT 5.3-chat in order to improve language quality. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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