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A Perspective on Grand Challenges in Social Aspects of Wind Energy

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Abstract. Wind energy is central to the global transition toward zero-carbon energy systems. Yet, its development increasingly intersects with complex social dynamics. This perspective highlights the grand social challenges facing wind energy, emphasising the need to move beyond techno-centric paradigms and toward inclusive, interdisciplinary socio-technical approaches. Drawing on recent research and field experience, we describe five grand social challenges for wind energy: spatial relations, acceptable turbine design, smart integration, public perception, and policy frameworks. We argue that addressing these challenges requires rethinking the relationship between wind energy and society—not as a barrier to overcome, but as a co-creative force in shaping sustainable energy futures.

1 People at the Centre of the Transition

Energy systems around the world are undergoing a rapidly evolving development, with wind energy being one of the fastest growing energy technologies ever (Nat Bullard, 2025). Zero-carbon energy pathways foresee a massive further increase of wind energy until 2050 (EC, 2018; ESABCC, 2023; IEA, 2021). In a few countries, such as Denmark and Spain, wind energy has already taken its place as a major contributor to the energy mix. In many other countries, the deployment of wind farms is still in early stages. As wind energy continues to expand globally, we expect to see the technology deployed on an unprecedented scale.

As wind energy scales up, its footprint becomes more visible, its impacts more tangible, and its further promotion more contested. The notion that wind energy can be deployed in isolation from local communities and the population as a whole is no longer tenable. Kirkegaard et al. (2023a) emphasise that "wind energy technologies on their own do not matter much if they cannot be deployed *in* and *with* society" (p. 656, emphasis added). It is equally true that society can only utilise

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technology that keeps up with technical and economic innovation needs and opportunities. We are indeed in a truly mutual socio-technical relationship.

This insight calls for a socio-technical reorientation of wind energy research and practice. It requires a rethinking of current practices throughout the whole lifecycle of the technology. Tackling this challenge requires engineers and technical scientists who are skilled in and reflexive about social issues, and social scientists who are trained in technical aspects and solution-oriented research. It also requires establishing productive relationships between wind energy and people.

2 Expanding Footprints, Increasing Frictions

Wind energy is no longer confined to remote landscapes. Due to its growing size and prevalence, the technology interacts more and more with rural, urban, and coastal communities. It reshapes land use, alters visual and acoustic environments, and changes the local sense of identities. Not surprisingly, local contestations over wind energy are growing (Eisenson et al., 2024; Ellis and Ferraro, 2016; Sanchez Nieminen and Laitinen, 2025).

Local contestations are still often framed as a barrier that arises as local opposition during the planning and installation of a specific project (Solman, 2023). Solutions to such narrowly framed barriers are then often sought to be found in technological 'fixes' and symbolic participation offers in a narrow range of aspects to silence protests and make local communities accept the project (Solman, 2023). For example, residents' concerns about the visual impact of wind farms tend to be tackled by providing more information about the design of a future wind farm, rather than by involving communities in its co-design (Oosterlaken, 2015). Such framing is rooted in a techno-centric understanding of acceptance, assuming that functional benefits of a technology prevail and disregarding the complex, subjective and social contexts of human behaviour and practice.

Such a paradigm of decontextualised and instrumental assessment has brought about concepts such as not-in-my-backyard (NIMBY) (Batel and Rudolph, 2021). Solutions derived with this mindset can, however, amplify future social issues by antagonising residents of wind farm areas. NIMBY is now regarded as outdated and misleading concept (Batel and Rudolph, 2021), as research revealed that resistance is frequently rooted in deeper concerns: place attachment, distributional injustice, and perceived exclusion from decision-making (Kirkegaard et al., 2023b). Recent research reframes local opposition not as NIMBYism but as a response to perceived injustices: loss of landscape identity, exclusion from planning, and uneven distribution of benefits and burdens. These are not irrational objections but legitimate responses to disruptions in lived environments.

Local residents are 'experts in their own right' with exclusive knowledge about local values, impacts and potential beneficial solutions. When people are invited to share their local knowledge about what impact the technology causes, what the community values, and what contestations may emerge, they can become important partners and problem-solvers with mutual benefits for developers and local communities. Recognising this helps to prevent conflict and improve decisions about where, when and how wind farms should be developed.

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Research can shed light on these issues by studying social phenomena (such as norms, values and valuations, concerns, perceptions, institutions, practices, etc.) that shape human-energy interactions, and related fundamental issues of equity, fairness, ethics, or attribution (Dufour et al., 2019), as well as perceived annoyance (Hübner et al., 2019). Additionally, mitigation measures and policy frameworks can be derived that understand and serve the needs of local host communities as well as the larger public (Voß et al., 2009).

3 Grand Social Challenges in Wind Energy

In the following, we go through five grand challenges relating to social aspects of wind energy that have emerged in the literature, based on different areas of engagement, including project-level relations, the size of wind turbines, consumer roles, public attitudes towards wind and policy frameworks.

3.1 Project Planning and Spatial Relations

Wind energy projects and related spatial planning decisions can be a source of conflict. Traditional siting approaches prioritise technical or techno-economic optimisation—wind speed, grid access, cost efficiency— and often do not sufficiently consider social and cultural dimensions. This often creates tensions with local communities, as socially constructed place-based and territorial values may conflict with physical or economic priorities. Perceived imbalances in the distribution of benefits and burdens can further intensify these tensions.

While local resistance to wind farm developments still tends to be simplified and labelled as selfish NIMBY-behaviour, this has now been rethought as representing responses to disruptions related to place identity, place attachment, spatial-visual perceptions, as well as reactions towards issues of spatial justice (Batel and Devine-Wright, 2021; Devine-Wright and Howes, 2010; Firestone et al., 2018; Kim and Chung, 2019).

Instead of focusing on the existence of opposition, there is a need to understand the motivations for resistance. It is well-documented that wind energy can interfere with human well-being through physical ‘emissions’ (sound, light, shadow flicker, etc.) (Hübner et al., 2019; Pohl et al., 2018), as well as with relations and emotions that humans have towards land and sea (Russell and Firestone, 2021). Negative impacts on residents are a complex issue. For example, wind turbine noise is discussed controversially in the literature, e.g. in relation to impacts on humans (Taylor and Klenk, 2019), and how communities oppose wind energy because of noise annoyance (Fast et al., 2016).

Fairness of the decision-making process is of great importance for the implementation of wind energy projects (Hoen et al., 2019). But what is considered ‘a fair process’ is not always clear or agreed upon. Feelings of injustice may arise, e.g. resulting from unjust practices of land acquisition (land grabbing) (Kirkegaard et al., 2023b), dispossession of local land, (perceived) uneven distribution of wind energy ‘burden’ across jurisdictions and of value creation from it (Bosch and Schmidt, 2020). General changes in the landscape due to the deployment of wind energy include not only visual change, but

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also indirect effects such as de-population, replacement and/or addition of different types of industries, and land use changes (Rudolph and Kirkegaard, 2019).

We need further research to better understand the human experience with wind energy in people's everyday lives and develop ways to improve it, including e.g. new approaches and tools for strategic project planning, farm management and control strategies adapted to the needs of neighbours. Much more data on impacts and human responses will need to be collected, going beyond project-by-project case studies. This should also include indigenous populations and the Global South. Distributional effects of wind energy (benefits and burdens) need investigation, and solutions for improved fairness need to be developed, including benefit sharing schemes and their implementation procedures. An improved understanding of cross-cutting issues for impacts and responses (and correlations), as well as methods on how to derive general learnings from increasing numbers of single case studies and findings for specific contexts must be developed. This will allow for a general analysis of different planning choices and for providing policy advice.

3.2 Wind Turbine Design and Scalability

There is growing anxiety in the population about the dominance of wind turbines in our landscapes (Batel and Devine-Wright, 2021). The prevailing innovation paradigm—an engineering mindset of 'bigger is better'—has delivered impressive gains in efficiency and cost reduction of wind energy turbines and farms. Yet, it has also created a perceived mismatch of scales: Turbine sizes have outgrown the human scale, provoking aesthetic and acoustic concerns. The new scale also marginalises small-scale investors: Turbines currently available on the market are often not affordable anymore for non-commercial actors (Kirkegaard et al., 2021).

Challenging this paradigm requires rethinking design priorities. Future innovation in wind energy technology should be concerned with enabling the future deployability of acceptable turbines. This will require the development of value-sensitive design processes that incorporate social and environmental values, local specificities, public concerns, and that enable co-creation (Oosterlaken, 2015). Bringing in non-technical experts and citizen representatives into the design process of future technology in a co-creation process may enhance the ability to deploy future turbine designs (Solman et al., 2021). This will likely lead to a diversification of turbine typologies and modularisation to enable tailoring projects to communities. This includes diverse application areas (including urban wind energy), community-scale systems, and culturally embedded aesthetics.

Research can help facilitate a discussion of 'what matters' in developing technology further and acknowledging potentially conflicting interests of various actors and their different levels of influence in the process (Kirkegaard et al., 2023a). Further solutions must still be developed as to how to meaningfully engage societal actors in the design of wind turbines, and in particular also emerging innovations such as digitalisation, so that new tools reflect all interests. At the same time, there is also a need for approaches that create transparency about conflicting valuations, that help invoke "consensus about dissent" (Renn 2004) and that give guidance on how to navigate those situations.

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3.3 Integration and the Role of Consumers

The integration of wind energy into smart energy systems introduces new roles for citizens—not just as consumers, but as active agents of the system who also produce, share data, and provide flexibility. However, technological complexity, opaque systems, privacy concerns and distorted incentives pose barriers to activating those roles. Many users feel a lack of control and agency around energy use (Adams et al., 2021) and may make 'hacks' to the systems so that they fit to their reality (Nyborg, 2015).

We need a major reconfiguration of roles and responsibilities in the energy system, as well as the emergence of new business and ownership models that promote new smart system integration designs and energy communities (Kloppenburg and Boekelo, 2019). The concept of 'community' needs further research attention in relation to new roles for citizens, e.g. providing balancing services and flexibility via micro-generation, following recent EU legislation promoting energy communities (e.g. Bonfert, 2023).

While flexibility and production-consumption dynamics have been explored at the individual household level (e.g. Christensen et al., 2020; Nyborg, 2015), questions as to how communities organise and negotiate this role collectively remain a rather unexplored area. Likewise, energy community mobilisation and the question of how to balance community and system needs, merit further attention in research. It also remains to be studied how significant a role communities and flexible consumers can play in integrating wind energy in future energy systems and how other solutions must supplement. Finally, research should develop solutions to enhance digitalisation of energy communities and smart technologies. This involves addressing data governance and requires attention to equity, ensuring that low-income and marginalised groups are not excluded from participation.

3.4 Public Perception and Cultural Alignment

The public image of wind energy is shifting. Once seen as a grassroot solution to energy dependence and climate change, it is now often perceived as a commodified, corporate-driven technology (Kirkegaard et al., 2021). This shift has fuelled scepticism, especially where wind energy projects are imposed without much local engagement.

We need to better understand people-technology-democracy relations, and how to make decisions about future wind energy systems a 'public issue', including concepts of co-creation (Solman et al., 2021) and material participation (Ryghaug et al., 2018). This also includes global supply chains, and e.g. the extraction of raw materials in the Global South, related issues of justice and inequality and lingering relations to green extractivism and (neo)colonialism. The risk of locking-in technology in cultural and societal misalignment must be better understood and assessed.

Wind energy is facing headwinds from misinformation[1] and populist politics. Popular concerns based on misinformation can be categorised as (1) elitist conspiracy to mask wind farms' dangers and exaggerate their benefits; (2) wind farms being

[1] Information that is misleading or deceptive when compared to the best available scientific evidence or the claims of acknowledged experts in the domain (Winter et al., 2024).

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detrimental to human health (e.g. cause cancer); (3) wind farms being harmful to the natural environment; and (4) wind farms being ineffective (Winter et al., 2024). Misinformation campaigns against wind energy have increased and are effective: a considerable part of the population has developed an underlying belief system directed at the rejection of wind farms, largely related to worldviews rather than verified facts, as well as to a conspiracy mentality and a rejection of a pro-ecological worldview (Winter et al., 2024).

In the face of increasing misinformation campaigns, distrust in facts and anti-science beliefs, research is necessary to understand public perception, its patterns and dynamics and to develop strategies for cultural and societal alignment as well as trust-building. To date, only little systematic empirical or conceptual work exists on this topic.

A scientific look 'inward' into the wind energy sector will also be necessary to reveal the perception and reactions of the sector toward their changed relations with the public and to develop strategies to prepare and strengthen the sector in their new role. It is not an easy task to master the transition from 'welcome saviour' perceived as green ally to 'suspicious intruder' expected to be making an effort to win people's acceptance (Kirkegaard et al., 2023b).

3.5 Policy Frameworks for System Transformation

Wind energy development has always been strongly policy-driven (Kitzing et al., 2022). As the technology evolves, wind energy policy must evolve, too. Early policies focused on market creation and cost reduction. Declines in the cost of wind energy moderate the prevailing emphasis on support payments and allow a broadened focus on redesigning markets and employing new policy areas. Value creation across technologies will become more important, in addition to well-designed permitting and siting procedures, as well as speedy grid connection. Today, the challenge is systemic and long-term: wind energy policy must be integrated into broader energy, industrial, and social policies, because the energy transition is a comprehensive long-term transformation process that extends well beyond the typical time horizon of political processes. This requires systematic policy frameworks that are flexible, adaptive and reflexive (Voß et al., 2009).

Denmark offers a revealing case study: Once a pioneer of community-owned wind energy and one of the first in the world to establish a policy support scheme for wind energy, the country has recently experienced public debates about the value of offshore wind energy, in which it was discussed if the state should act as a landlord and profit-maker, rather than steward of wind as a common resource, and thus collect seabed lease fees and demand state co-ownership rather than supporting the technology financially (Kitzing, 2023). This tension illustrates the broader challenge of aligning wind energy governance with democratic values and public expectations.

There is currently little understanding of how to integrate systemic requirements for wind energy policy with multiple policy objectives that also play an increasing role in political decision making, including domestic industry development, job creation, workforce development, strengthening of technology export capabilities, strengthening of supply chains, and increasing energy security. Research must create a better understanding of social costs, benefits and effectiveness of policies, laws and regulations. There is a need for (socio-)economic models to evaluate the impact of energy policies on individual

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actors and systems, informing which factors drive deployment across different contexts, how policies can help reduce risks and enable sustainable deployment progress.

4 Conclusion: Toward a Socio-Technical Wind Energy Science

The global energy transition is not only a technical challenge—it is fundamentally also a social one. Hence, the challenges facing wind energy as one of the major drivers in the transition to zero-carbon energy systems are multifaceted, comprising technical, social and cultural issues.

Entering the next phase of wind energy development demands a fundamental rethinking of the relationship between humans and wind turbines, of the design and deployment of wind energy projects in our communities. Solutions will need to venture beyond decontextualised, depoliticised and simplified assessments of acceptance and outdated not-in-my-backyard concepts to include engagement in planning processes and new ownership structures, as well as participation in design, to embrace the transition as a shared task among members of society. This requires new methods, new mindsets, and new institutional arrangements. It also requires interdisciplinary collaboration between engineers, planners, social scientists, and communities. We also need a new generation of wind energy science—one that fully integrates social sciences with technical sciences where either discipline treats the other not as an add-on, but as a core component of the challenge.

All this together can make wind energy not only acceptable, but meaningful, just, and desirable. Overcoming grand challenges in wind energy means technology improvements, better systems and controls aa well as combining all this with social aspects and better relationships with people, places and the wider society.

Data availability

No data sets were used in this article.

Author contributions

LK led the drafting work and coordinated the initial and subsequent drafts; LK, DR, SN, HS, JKK, and TC wrote the original draft, with contributions from GH and EG; LK consolidated and shortened the text; The entire author team supplied comments and edited several drafts before agreeing on the final text.

Competing interests

At least one of the (co-)authors is a member of the editorial board of *Wind Energy Science*.

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Disclaimer

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