

System impacts of wind energy developments: key research challenges and opportunities

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SUMMARY

Wind power accounts for 7.5% of global electricity generation in 2022 and is one of the cheapest forms of low-carbon electricity. Although fully commercial, many challenges remain in achieving the required scale-up, relating to integrating wind farms into wider technical, economic, social and natural systems. We review the main challenges, outline existing solutions and propose future research needed to overcome existing problems. Whilst the techno-economic challenges, grid and market integration, are seen as significant obstacles to scaling up wind power, the field is replete with solutions. In many countries, planning and permitting are immediate barriers to wind power deployment; whilst solutions are emerging in the EU and several countries, the effectiveness and long-term acceptance of fast-track permissions and go-to areas remains to be seen. Environmental impacts on wildlife and recycling challenges are rising issues, for which tested and scalable solutions are often still lacking, pointing to large remaining research requirements.

INTRODUCTION

Wind power is one of the fastest growing, most mature and cost-competitive renewable energy (RE) technologies, reaching more than 2,100 TWh production worldwide in 2022¹. In many countries, wind power is a cornerstone of energy and climate strategies and already represents a substantial proportion of electricity generation (e.g. 14% in the EU, 20% in Germany and the UK², 57% in Denmark³, 10% in the USA with Iowa leading in-state wind generation with 62%⁴), with the sum of national targets reaching half of the world's projected electricity demand by mid-century⁵. The technology's global weighted average Levelized Cost Of Electricity (LCOEs) has already fallen 69% since 2010⁶, potentially decreasing by a further 37% to 49% by 2050 for both onshore and offshore wind projects⁷. Despite recent progress, the continued deployment of wind power encounters substantial and in some cases novel obstacles.

Many challenges facing wind power expansion relate to local resistance^{8,9}, because of concerns about changes to scenic landscapes¹⁰, adverse effects on biodiversity¹¹, ecosystems¹², human health¹³ or local economic impacts. Other challenges stem from restrictive or inefficient regulation, which results in excessively long delays in planning and permitting procedures. Also, considerable delays with grid connections are observed in countries where wind power already provides a substantial share of electricity generation (e.g., Germany, the UK, and the USA)¹⁴. Further challenges stem from the intermittency of wind farm output and how to integrate them effectively into power systems^{15,16}.

These challenges have been analysed in isolation and, in many cases, have fed a literature rich with examples and insights. Researchers have reviewed the "grand challenges" that the technical science of wind energy faces, by focusing on the meteorological, technological (i.e., turbine-related) and systems aspects (i.e. power system integration and control aspects), but often without addressing social or environmental impacts^{17,18,19}. A more recent article²⁰ combines the "grand challenges" narrative with the social sciences and humanities (SSH) perspective through a technological lens and argues for a closer integration of the SSH and technical sciences in wind energy research. A recent contribution takes an SSH perspective on the grand challenges of wind energy²¹. The main novelty in this present work is the broad interdisciplinary approach that draws on insights from socio-economic, technical and environmental perspectives to assess the diverse impacts and issues related to wind energy development, thereby allowing us to formulate recommendations based on the evidence provided by this review.

Context & Scale

Wind energy is currently the cheapest form of new electricity generating capacity along with solar photovoltaics and plays an important role in many countries' climate and energy strategies. Like any energy technology, wind energy has a variety of impacts on the broader systems into which it is integrated. Many of these impacts can pose barriers to further uptake of wind energy and therefore also to realizing ambitious climate and energy plans, partly due to a lack of proper understanding of those impacts by the broader society, partly due to fundamental research gaps. In this review article, we identify four broad impact categories and fourteen individual impacts, which we systematically analyse based on an extensive literature review of over 300 studies. We qualitatively assess these impacts in terms of importance and spatial differentiation, proposing, where possible, concrete solutions and suggest avenues for further research.

We address three central research questions: (1) what impacts does wind power have on the environmental, social, technical and economic systems; (2) how significant are these impacts; and (3) can existing or potential solutions help mitigate them? We take a *system perspective* on wind energy, viewed as a technology and component in many of these systems. Through an interdisciplinary lens, we explore the most pressing impacts the ongoing development of wind energy has on the systems it interacts with and prioritise research within an integrative framework. We identify fourteen impact types in four broad categories, which provide a structure for the rest of the article. Starting with *Environmental* impacts, we first explore *ecosystems and wildlife* (1), *weather and climate* (2), *end-of-life treatment* (3), and *rare earth elements* (4). Subsequently, we turn to *Social, economic and health* impacts, in particular *land governance and tenure (in)security* (5), *local monetary costs and benefits* (6), *landscape impacts* (7) and *local health impacts* (8). Next, we focus on *Techno-economic* impacts, namely *energy system impacts* (9) and *market and price impacts* (10). Finally, we assess the *Policy and regulation* aspects, including *financing and controlling the Intellectual Property (IP)* (11), *supply chain disruptions* (12), *cyber security and hybrid threats* (13) and *planning and permitting* (14). We assess whether current research enables an understanding of the nature and significance of these impacts. Lastly, we formulate specific recommendations for future research to address those impacts that are currently lacking in understanding.

ENVIRONMENTAL IMPACTS

Impacts on ecosystems and wildlife

Onshore wind power deployment primarily affects bird and bat populations, even though wind turbines may also disturb and displace terrestrial mammals²². Whilst there are no global estimates of yearly bird and bat fatalities caused by wind turbines, in the United States, with an installed capacity of 112 GW as of 2021, bird fatalities from turbine collisions number in the several hundreds of thousands annually²³⁻²⁵. Species at higher risk are typically migratory, soaring raptors or bats¹¹; the additional mortality due to collisions can be particularly relevant for populations of long-lived and slow-reproducing species²⁶⁻²⁹; collision with rotor blades and wind turbine towers might further endanger species already threatened with extinction³⁰. However, there are fewer bird collisions with wind turbines than with other structures like buildings, power lines, and communication towers^{24,31}, though some of these structures are also associated with infrastructure for wind turbines³². From 2000 to 2020, wind farms had no discernible impact on bird counts in the US, whereas shale gas wells reduced numbers by 15%³³. Studies suggest that most bat fatalities are due to barotrauma rather than direct blade collisions³⁴.

Despite the growing body of literature on bird strikes in open landscapes, there is a significant lack of research on these impacts in shrub- and woodland environments³⁵. Much less literature exists on ecosystems and wildlife in offshore environments. Offshore installations with steel piles driven into the seabed create underwater noise pollution, affecting porpoises³⁶, whales, dolphins, and seals³⁷. These mammals' communication, feeding, breeding, and navigation can be compromised, leading to behavioural changes and habitat avoidance. However, the piles' net ecological impact is unknown because data on the magnitude of these impacts is lacking, and their presence also positively affects marine biodiversity and provides certain bird species with areas to rest and feed¹². These observations notwithstanding, the overall impacts of wind power deployment on wildlife are substantially smaller than those of using fossil fuels, even though such comparisons are usually methodologically difficult^{33,38}.

Furthermore, noise pollution from wind turbine operations can negatively affect birds, bats, non-volant and marine mammals, disrupting their nesting, breeding and movement patterns, which may result in population decline and displacement. Some species avoid wind turbines due to noise³⁹, specifically during construction⁴⁰⁻⁴³, while

others avoid areas with shadow flicker^{44,45} (see section *Health and annoyance*). Although not a bat attractant, low-frequency noise emissions can disorientate bats, which makes hunting difficult⁴⁶. Land transformation related to the construction of wind farms⁴⁷ can also affect habitat suitability and species' extinction risks if connectivity between habitats is disrupted⁴⁸ and gene flow between metapopulations is reduced⁴⁹. Some species might be able to adapt to altered habitat conditions after wind farm construction⁵⁰, while others might not become habituated⁵¹. However, effects on population trends are difficult to assess because effects are highly site- and species-specific, and long-term studies are rare.

Adequate siting of wind farms is a promising approach to reduce impacts on wildlife, but since many species' habitat requirements change in the course of a year, it remains a challenging task⁵². Micro-siting to avoid areas with high collision risk can reduce risks for birds⁵³, but it is more challenging for bats⁵⁴. A promising solution for on-site impact mitigation is to increase the cut-in wind speed from 3-4 m/s to 6 and 8 m/s for bats and soaring birds, respectively, as these animals have the highest flight activities at low wind speeds while the production losses would remain modest⁵⁵⁻⁵⁷. Temporary shut-downs triggered by visual or radar observations are also effective solutions to minimise collisions⁵⁸. Visual cues like painting at least one rotor blade black to reduce motion-smear have had limited testing but have shown promising results⁵⁹. Lastly, ultrasonic deterrent systems can reduce bat fatalities⁶⁰.

Impacts on wind resources and weather

The increasing number and size of wind farms can affect local weather and climate patterns. Wind turbines extract kinetic energy from the wind flowing through its rotor, replenished downstream from the flow above the wind farm^{61,62}. In large wind farms, the latter process cannot supply enough energy to compensate for lowered wind speeds, especially offshore⁶³. Hence, a large wind farm can significantly lower the wind speeds in its vicinity up to a distance of tens of kilometres^{62,64}, thereby suppressing generation from nearby wind farms^{63,65-67}, as shown in Figure 1. The figure shows a possible 2030 scenario of wind farm development in the North Sea and the potential reduction in wind capacity factor induced by these wind farms. Early modelling studies argued that the wind farm extractable energy was finite and limited to about 1 MW/km² for massive wind farm clusters^{68,69} (i.e., of several gigawatts capacity spanning several thousands of km²). Still, recent research demonstrated that this limit can be considerably larger (up to 4 MW/km²) if wind resources are abundant^{63,70}. Confirming these findings is challenging due to scarce observations⁶⁶ and the limited sizes of presently operating wind farms. These impacts can be mitigated by strategically planning wind farm locations and sizes and limiting their capacity densities. Thus, future wind energy development, particularly offshore, should consider potential wakes and efficiency losses and implement comprehensive international strategies for developing energy-abundant regions such as the North Sea^{65,71}. However, the growth of wind power will likely be restricted by economic or environmental factors rather than global geophysical limits⁷².

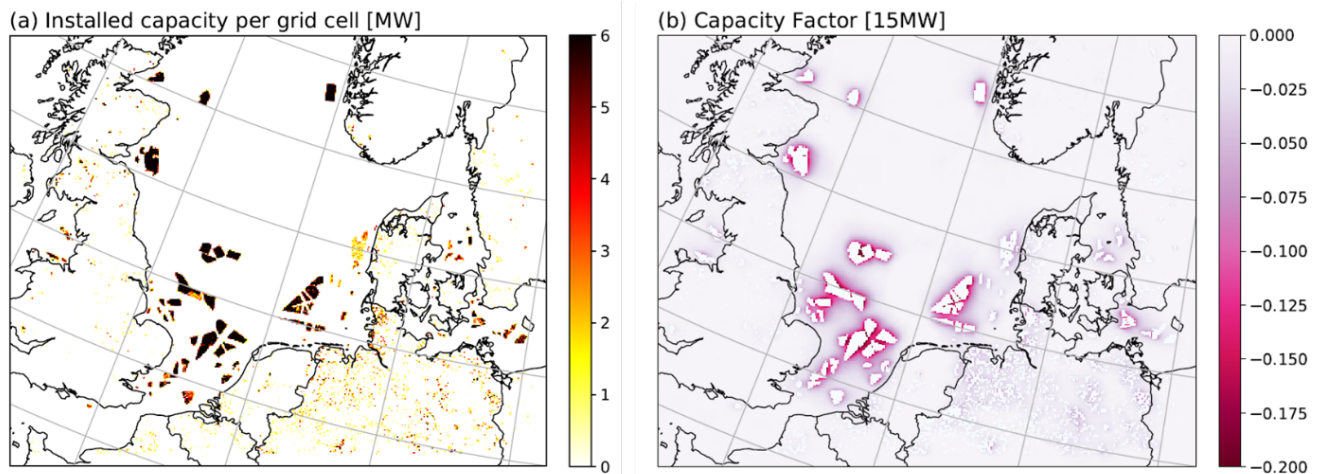


Figure 1: The effect of wind farm wakes on the wind capacity factors for a 2030 wind farm build-up scenario

(a) Installed capacity (MW) on each grid cell in the 2030 scenario. (b) change in capacity factor between the 2030 scenario in (a) and a scenario without wind turbines. The capacity factor calculation uses the National Renewable Energy Laboratory (NREL) 15 MW wind turbine, and the wind data is generated using the WRF model and a wind farm parameterisation⁷³. The location of the 2030 offshore wind farms has been masked on (b). Modelling was done in the context of the project of Screening the wind resources and Environmental impacts in the Danish Waters (<https://www.niras.dk/projekter/kortlaegning-af-havindspotentiale-i-dk/>)

The operation of wind farms can also cause weather conditions to change locally. This can take the form of shifts in surface temperature (often leading to warmer temperatures at night⁷⁴⁻⁷⁷) and other weather parameters, such as precipitation and evaporation⁷⁵. The local temperature increases are occasional and typically confined to less than 1°C when they occur and are limited to a few kilometres from the wind farm^{67,77,78}. Offshore wind farms could also affect waves, ocean currents and sea surface temperatures⁷⁹. Although there is no definitive solution to mitigate the effects on the weather, it is crucial to acknowledge that, on average, they remain limited and much less significant than the global impacts of climate change⁸⁰. In sensitive areas, good spatial planning and coordinated approval processes can minimise the effects on weather and wind resources if they are expected to affect human activities.

Impacts during the end-of-life phase

Wind turbines face several challenges in their end-of-life phase, inevitably resulting in final disposal⁸¹. By 2030, around 60,000 wind turbines are expected to reach the end of their first life worldwide, two-thirds of which are in Europe (see Figure 2). Several options exist to delay final disposal, from extending the lifetime⁸², reusing or repurposing components to recovering or recycling different parts of the wind turbine⁸³, each bearing its challenges. Recycling components attract the most attention in scientific publications and media⁸⁴. While the recycling of permanent magnets is widely covered in the media and policies in the context of security of supply for critical raw materials^{85,86} (cf. section *Policy and regulation*), the challenge of rotor blade recycling is intensively debated by the public, questioning the benefits of wind energy in general (cf. section *Social, economic and health impacts*)^{87,88}.

Structural health monitoring and digital twins to extend the lifetime of wind turbines are still not implemented at scale, and the reuse and repurposing of old turbines is minimal and not expected to grow in the future⁸⁹. Regarding recycling, suitable processes and related challenges differ for each part of a wind turbine⁸³ (see Figure 3). While recycling steel towers, gearboxes, and traditional generators is well established⁸³, recycling concrete (esp. foundations) in some locations might be environmentally and economically challenging due to the trade-off between soil disruption, transport distances and material circularity⁸¹. A geopolitical challenge around the recycling of the

generator system arises through the trend towards direct drives⁹⁰ with their permanent magnets containing rare earth elements such as neodymium, praseodymium and dysprosium⁹¹, considered critical raw materials by the EU⁹² (see section *Policy and regulation*). Nonetheless, less than 1% of rare earth elements are recycled⁸¹ because of the low technology readiness level, glued structures and comparably cheaper virgin counterparts^{91,93}. At the same time, global demand for rare earth elements contained in wind turbines could rise from 52 kt/a in 2018 to 236 kt/a by 2030⁹³ (see Figure 4).

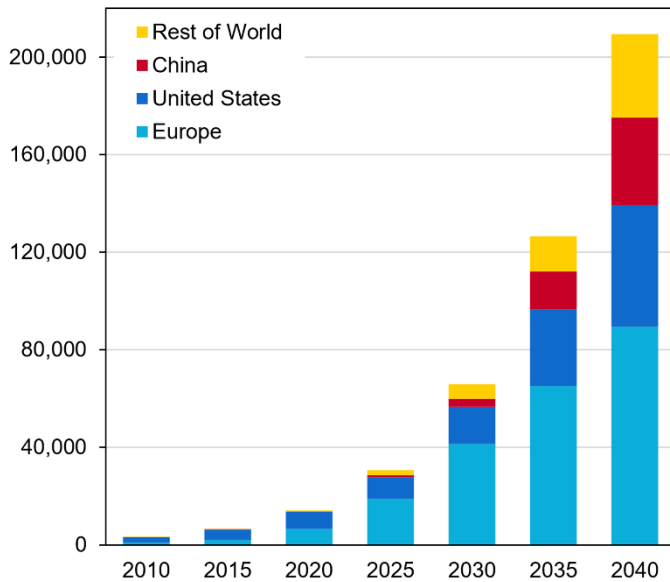


Figure 2: The cumulative number of wind turbines that would reach end of life up to 2040, split by world region

Based on farm construction dates⁹⁴ and an assumed lifetime of 25-30 years⁹⁵⁻⁹⁷. Reproduced from the given sources.

A central end-of-life challenge arises from the turbine blades containing glass fibre reinforcement plastics (GFRPs)⁸³. Even as some major wind turbine manufacturers have announced nearly 100% recyclable wind turbine blades between 2030 and 2040^{98,99}, almost all current end-of-life blades are landfilled or temporarily stored^{100,101}, raising much attention in the media^{87,88,102}. Some regions with high wind energy capacities, like Germany, have already banned their landfilling and incineration⁸⁹, while currently, only a negligible fraction is mechanically recycled as filling materials¹⁰¹. Thermal and chemical recycling options are evolving but are still at low technology readiness levels (TRLs)¹⁰³ and have a high energy demand. For example, pyrolysis (TRL 7¹⁰⁴), fluidised bed or microwave pyrolysis (TRL 5/4) and solvolysis (TRL 5-6) come with a high upfront investment, low quality of fibres and potential greenhouse gas emissions by the unavoidable decomposition of products¹⁰⁵.

Notably, the recycling challenge is not limited to wind turbines but applies to many activities in the building sector, electronics and transportation for composites and electric motors, domestic appliances and smartphones for permanent magnets⁹³, so considerable sectoral spillovers in solving recycling problems are possible.

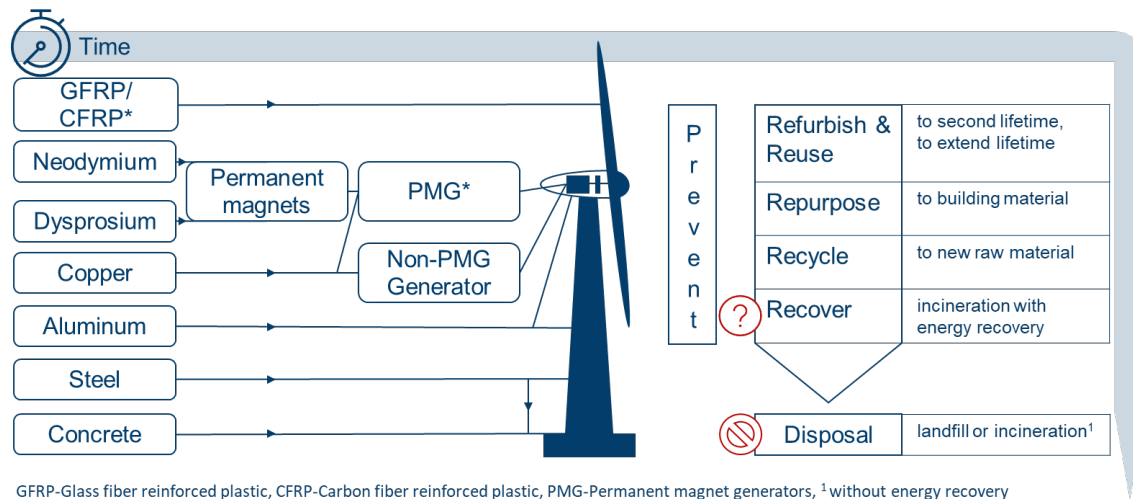


Figure 3: Conceptual material flows and end-of-life strategies for wind turbine components, own depiction

SOCIAL, ECONOMIC, AND HEALTH IMPACTS

Land-tenure (in)security

The transition to higher shares of wind power boosts the demand for land¹⁰⁶. This can come at the cost of prior land users and increase the vulnerability of traditional rural communities and indigenous groups in particular due to large-scale green land grabs¹⁰⁷⁻¹⁰⁹, use of common land without consent¹¹⁰, unfair contractual arrangements¹¹¹, and various forms of dispossession¹¹². The impact of wind energy development on land tenure insecurity, especially for common lands, is addressed in several qualitative studies – in both the Global North and South. For instance, the installation of large-scale wind power in Norway has been described by Sámi representatives as a form of “Green Colonialism”, pinpointing that these developments could intensify the continuation of historical struggles over land rights and territorial autonomy due to the non-recognition of indigenous peoples¹¹³⁻¹¹⁵. Similarly, in Brazil, a large share of wind corridors is in undesignated public lands, historically occupied by traditional communities struggling to regularise the ownership of common lands^{109,116,117}. The proposal of individual land leasing contracts for installing turbines in an already ill-defined communal land tenure system has also sparked conflict between Zapotec farmers, the government and wind farm operators in the Isthmus of Tehuantepec in Mexico¹¹⁸⁻¹²⁰.

The diverse impacts of wind power development on land appropriation and control, which affect the rights of traditional or indigenous communities to territory and livelihoods, need to be linked to a set of compliance rules. These include procedural aspects such as securing their free, prior and informed consent¹²¹, addressing information asymmetries about the project’s specific local impacts¹²², and offering fair and legally approved land leasing contracts as well as legal advice on land use¹²³. The issue of land ownership and rights is a key challenge to a just energy transition, particularly in recognizing the historical communal use of land by traditional communities and indigenous people. Increasing the focus of spatial energy planning on land tenure issues, as well as integrating participatory and collaborative planning^{124,125} can be helpful approaches for renewable projects to better consider local community needs, interests and rights, and to provide fair compensation and manifest co-benefits for immediately affected residents^{122,126}.

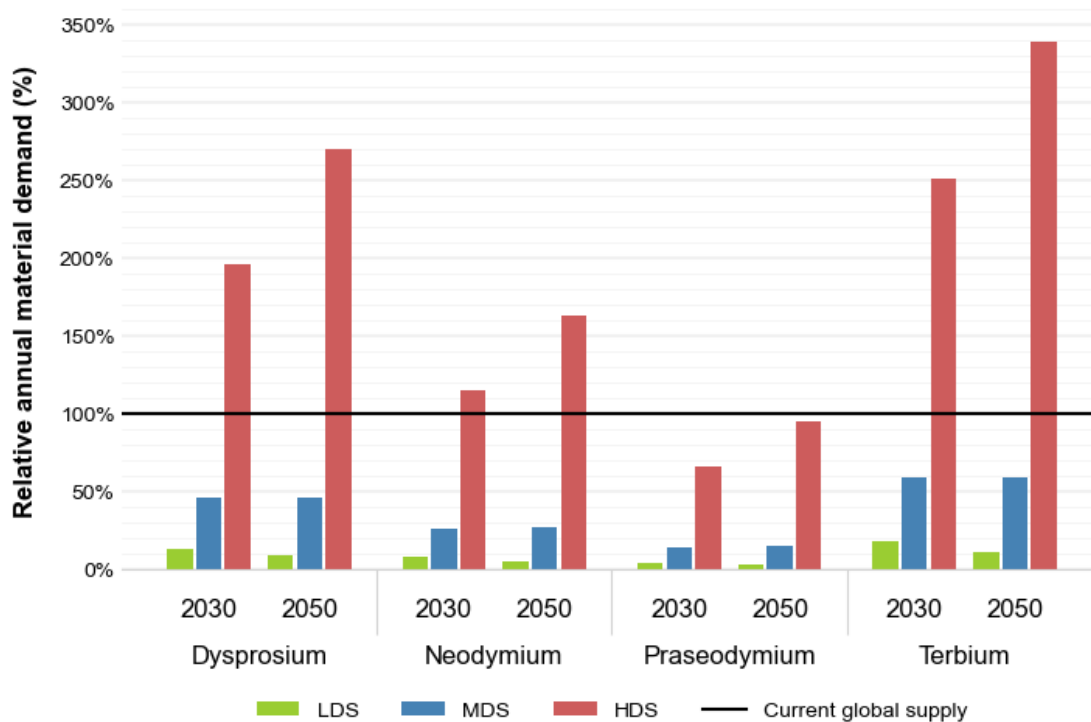


Figure 4: Expected demand in 2030 and 2050 from the wind turbine industry for a selection of rare earth metals, relative to the current global supply (for all applications)

LDS: IEA ETP Reference Technology Scenario (+2.7C increase in temperature by 2100 compared to pre-industrial levels), MDS: IEA ETP Beyond 2 Degrees Scenario (+1.75C increase in temperature by 2100 compared to pre-industrial levels). HDS: Institute for Sustainable Futures 1.5 °C 2019 Scenario (1.5 °C with 100% renewable primary energy in 2050). Source¹²⁷, further adapted by the authors.

Landscape visual impacts

Another public concern is that wind turbines negatively impact the perception of landscapes, particularly untouched nature. This visual landscape impact is the main reason for local opposition to onshore and offshore wind installations^{9,123,128–131}.

Acceptance of wind turbines is higher when they are placed in already unattractive landscapes, with a limited number of turbines, and far from viewpoints¹³². Several studies have employed national datasets of landscape aesthetic quality (so-called 'scenicness'), based on survey-based ratings of representative landscape photographs, to quantify the costs incurred to power systems when excluding onshore wind potentials in landscapes with high aesthetic quality, showing a large range of impacts between countries^{133–138} (e.g. Figure 5 for Great Britain). In addition, viewshed analyses, in which a three-dimensional space (*the viewshed*) within which one or more hypothetical wind turbines are visible, can aid in understanding the potential visual impact on sensitive receptors^{139,140}; however, these disregard people's visual preference for certain landscapes over others¹⁴¹. They may, therefore, be combined with measurements of visual features of landscapes, as a correlation between such metrics and rated landscape qualities has been found¹⁴². Moreover, renewable energy infrastructure such as wind turbines and power lines strongly influence the rated landscape coherence.

Quantifying the landscape impact of wind turbines to improve placement decisions requires that both visibility and landscape quality are considered. Approaches based on Geographical Information Systems (GIS) have been proposed to estimate landscape coherence¹⁴³ and wilderness¹⁴⁴ using indicators calculated from datasets such as land cover, topography, and remoteness. Similar approaches can be combined with visual

impact assessments to develop robust, reliable and scalable methods and tools for landscape impact assessments.

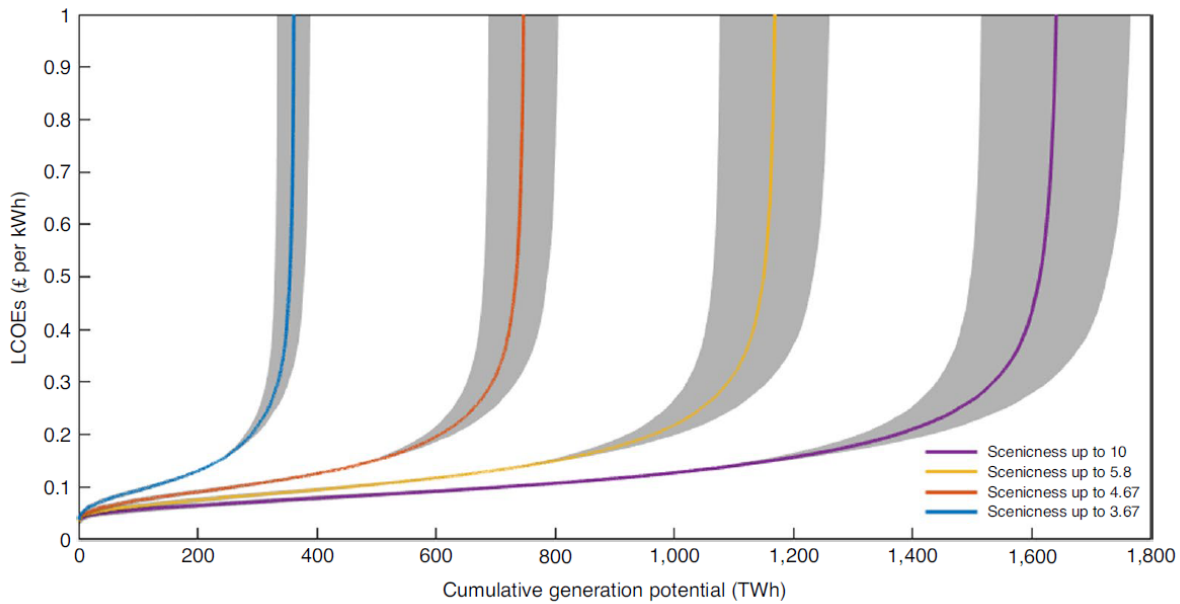


Figure 5: Supply curves for four scenicness thresholds, 3.67, 4.67, 5.8 and 10, in Great Britain

The solid lines show the means, and the grey thresholds show minimum and maximum ranges for the wind years of 2001–2006. Wind speed data are from the Meteorological Office 2018 (Reproduced from Ref.¹³³).

Monetary costs & benefits

Wind power deployment creates concerns about reductions in neighbouring real estate value and negative impacts on tourism, both related to the perception of wind power on scenic landscapes. However, it may also generate local monetary benefits. In some studies, effects on real estate prices are positive¹⁴⁵ or insignificant; in others, prices are reduced significantly by up to 16%^{146–148}. Associated acceptance problems can be reduced, mainly by fostering community participation during the projects’ planning stages to increase chances of placing projects in low-impact sites, especially if combined with monetary compensation (cf. section *Planning and permitting*) such as a fair sharing of wind farms income with affected residents^{126,147,150}. Similarly, studies about the impacts of wind power on tourism report that the presence of turbines can reduce the attractiveness of locations. At the same time, in other cases, stakeholders see wind power development as an added value to increasing the attractiveness of particular locations^{146,149}, for example, due to additional transport infrastructure such as roads. As with citizens, compensation for affected businesses may decrease opposition. Furthermore, while at the global scale there is a clear positive economic impact of wind power deployment in terms of a steadily growing trade and job creation¹⁵¹ and increasing gender diversity in the energy workforce¹⁵², at the local level impacts are difficult to assess, and evidence is inconsistent. Studies show increased local economic activities but limited job creation¹⁴⁵ and reduced local unemployment beyond the construction phase¹⁵³. The high diversity of impacts on real estate prices, tourism, and local job creation found in the existing literature calls for further research, which we identify as an important literature gap.

Health and annoyance

Noise emissions and the ‘flicker’ of the rotating shadow from wind turbines are frequently discussed as negative impacts of wind farms. While noise emissions from wind farms do not have a noticeable direct impact on nearby populations’ health^{154,155}, the

annoyance attributed to them seems to correlate with deteriorating quality of life because of sleep disturbance¹⁵⁶, increased stress and resulting (indirect) health issues (i.e., blood pressure, psychological distress)^{157,158}. However, the causality and directionality of this relationship remain to be proven. The perception of noise seems higher in rural areas and around flat terrains¹⁵⁹. Furthermore, low-frequency noise emissions should be considered, as they cannot be heard but can still lead to annoyance, resulting, for example, from windows rattling or vibrations¹⁶⁰. In addition, many studies show that only a small fraction of the population living near wind farms is disturbed by shadow flicker^{13,161}. Shadow flicker exposure does not necessarily lead to self-reported annoyance but rather subjective factors such as project appearance and general annoyance¹⁶². However, the disturbance attributed to wind turbine noise emissions should be evaluated compared to other routine noise sources. In a controlled study¹⁶³, while subjects reported annoyance from the acoustic emissions of nearby wind turbines, health-related effects were specifically attributed to noise pollution from road traffic.

Noise impacts can be mitigated by appropriate wind farm planning and simulations, and it is suggested that a certain noise threshold be respected (e.g., 35 to 45 dB(a))^{158,164}. Likewise, for cases where high levels of modelled shadow flicker exposure and self-reported annoyance correlate, easy-to-implement solutions exist, such as curtailment after specific exposure thresholds¹⁶⁵.

TECHNO-ECONOMIC DIMENSIONS

Energy system impacts

As the share of wind power increases, it displaces output from dispatchable thermal synchronous generators, which are conventionally the source of inertia and other ancillary services that provide system stability. In contrast to its total energy production, wind power displaces relatively little dispatchable capacity as peak demand periods are not correlated with wind output¹⁶⁶. Hence wind-dominated systems may need extensive backup capacity, lack dispatchability, and become highly weather-dependent¹⁶⁷.

At low wind share levels, the system's impact is relatively small¹⁶⁸. For example, wind penetrations of 10-20% can be easily absorbed by the existing system because it typically lies within the operational flexibility range of existing thermal generators, storage and imports/exports^{168,169}. But above this fraction, the system needs to exploit so-called integration measures, including grid densification and expansion¹⁷⁰, use of storage systems, increasing flexibility and sector coupling, and development of smart grids with distributed ancillary services¹⁷¹.

Grid strengthening and expansion are essential to address mismatches between supply and demand¹⁷². But these measures have significant implications for public acceptance, landscape impacts¹³³ and potential health impacts^{173,174} (cf. section *Social, economic and health impacts*). As well as the wind turbines themselves, the power system infrastructure (overhead power lines and pylons) can and does face public acceptance problems¹⁷⁵⁻¹⁷⁷. Many construction projects for new transmission capacity face long delays (due in part to lengthy planning procedures as discussed in the section *Planning and permitting*), which may lead to grid expansion not keeping pace with the deployment of renewables and result in greater curtailment.

Storage is another crucial option to tackle mismatches between supply and demand (see Figure 6). This includes electrochemical batteries and pumped hydro storage, whose total global installed capacity is expected to triple in the 2020s¹⁷¹. However, batteries are not always the best option to complement wind power due to the inappropriate time scale, and generally limited energy-to-power ratio, so researchers focus on balancing wind power across seasons with hydrogen¹⁷⁸⁻¹⁸⁰. The economic viability and business models for such long-duration storage are still unclear^{171,181}.

Thirdly, flexibility and sector coupling play a crucial role. Both supply and demand need to become more flexible to respond to short-term forecast deviations and make system balancing more cost-effective, in some cases through sector coupling via Power-to-Heat, Power-to-Gas and Power-to-X¹⁸². New policy and market frameworks such as capacity markets, dynamic prices and peer-to-peer trading are needed to monetise and incentivise greater flexibility across the electricity system^{183,184}.

Finally, to maintain grid stability, a smart grid is needed that automates the coordination of many distributed power plants and new sources of ancillary services such as operating reserve and frequency response^{185,186}. The installation of appropriate hardware and associated electronics is crucial to meet this challenge and provide services which are today largely provided by mechanical systems in thermal and hydropower plants¹⁸⁷.

To understand how these measures economically interact and complement each other across different energy systems, whole energy systems modelling approaches are required. Specifically, while extensive research has already provided insights into the least-cost integration of wind energy at the system level¹⁸⁸⁻¹⁹⁰, more work is needed to address and adequately reflect wider climate/environmental (section *Environmental impacts*) and socio-economic impacts (section *Social, economic and health impacts*) of wind.

Market and price impacts

Integrating wind power into existing power systems creates two key problems. First, ancillary service costs rise as wind-generated electricity increases demand for services like balancing and inertia¹⁹¹⁻¹⁹³ and reduces the supply of these services by displacing traditional thermal power stations¹⁹⁴. Second, wind has near-zero marginal cost, creating a so-called 'merit order effect' that depresses wholesale market prices¹⁹⁵⁻¹⁹⁷ and increases their volatility¹⁹⁸. This lowers power prices received by all generators, eroding their profitability, potentially triggering early retirement^{199,200} and causing long-term underinvestment, known as the 'missing money' problem^{201,202} – especially if there is a thermal overcapacity in the market. Price reduction is strongest at times of high wind output, so wind farms will 'cannibalise'²⁰³⁻²⁰⁶ their own profitability, possibly making investments unprofitable despite low generation costs.

Historically, market integration impacts have not been critical as few countries have sufficiently high wind energy penetrations (see *Introduction*), and countries with high wind shares also have substantial power system flexibility (e.g. Denmark). There is no consensus on measuring market impacts, with Value Adjusted Levelized Cost of Electricity (VALCOE²⁰⁷), Total System Cost^{208,209}, System Levelized Cost of Electricity (System LCOE^{210,211}), and Cost Of Valued Energy (COVE^{208,212}) being proposed. Effects are less severe for wind than for solar PV due to the strong day/night correlation^{204,213}, but their magnitude increases non-linearly with wind penetration (see Figure 6). Meeting the final 10% of electricity demand with variable renewables will be most costly^{214,215}.

The type of scheme used to support wind power (see section *Policy and regulation*) strongly influences these integration effects¹⁵. For example, schemes such as feed-in tariffs (FITs), power purchase agreements (PPAs) and contracts for differences (CfDs) do not incentivise time-shifting output to accommodate the wider market, thus exacerbating price volatility for all other technologies and ancillary service costs^{216,217}. These schemes offer the greatest certainty to developers, however, lowering the interest rate for financing investments, and, thus, the cost of wind energy^{15,218}.

These challenges can be addressed by market and regulatory changes that either bring more flexible capacity online or allow the existing system to react more efficiently to

wind power volatility¹⁵. An example is the creation of the Enhanced Frequency Response (EFR) service in Britain, which was supplied entirely by batteries¹⁷¹. Integration problems should decrease in the long run as power systems have time to adapt and accommodate greater variable supply^{197,210,219}. Markets are already adapting via shorter balancing settlements, sharper imbalance prices, and more involvement in balancing markets^{191,192,220}. Proper pricing of emissions will also help to establish correct market price signals²²¹. Such changes have allowed balancing costs to fall in Britain and Germany despite wind penetration increasing five-fold¹⁹¹.

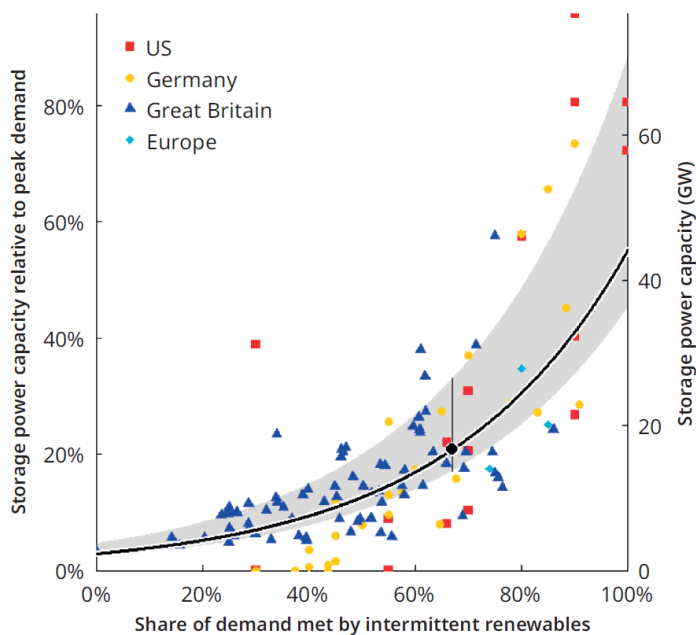


Figure 6: Storage requirements in relation to the share of demand met by intermittent renewables¹⁷¹

This chart collates data from across 30 studies of renewables integration. In this example, we look at Germany’s 2030 target for renewable electricity, suggesting that hitting a 2/3 share of VRE means the need for 15-25 GW of energy storage to back it up. Reproduced from Ref.¹⁷¹.

Many variations on current market designs are proposed that are more “system-friendly”, for example in the UK’s Review of Electricity Market Arrangements²²². These include:

- adding spatial granularity, moving from national markets to zonal (as in Italy and Japan) or nodal (as in the US) to sharpen price signals and guide investment,
- local electricity markets with peer-to-peer trading (e.g. through blockchain) to bypass the wholesale market,
- splitting markets by technology characteristics (e.g. firm, flexible and variable renewable),
- moving from national to local balancing,
- payment for output (energy-only markets), ability to deliver (capacity markets), or decoupled (e.g. revenue cap and floors).

The ultimate aim of markets is to balance the competing objectives of attracting investment in new wind capacity with low-cost finance by providing certainty for investors, and exposing wind to price signals that minimise system integration costs by optimising where farms are placed, how they operate, and what flexibility options are provided^{15,223–225}. Further research is needed to design resilient, secure and efficient markets that could enable largely or fully renewable electricity systems^{16,226,227}.

POLICY AND REGULATION

Energy security and geopolitics

There are several geopolitical and energy security challenges for wind power^{228,229}, such as who finances and controls the technology and supply chains, and arising cyber-security and hybrid threats. Concerns of energy supply as a geopolitical weapon have a long history for oil and gas^{230,231}, exacerbated and vividly renewed during the war in Ukraine and resurging concerns over the weaponisation of energy²³², but recently shifted to a focus on the geopolitics of the energy transition^{228,233}. The cyber threat relates to infrastructure security that depends on complex control and monitoring systems^{234,235}, and disinformation that can affect news trustworthiness, such as the well-known statement that wind energy kills more than one million birds in the USA annually²³⁶.

In the energy transition context, finance and controlling the technology supply chain is a key factor. Industry leaders with large markets (e.g., USA, EU, China) seek dominance in the clean energy sector²³⁷. China's Belt and Road Initiative is an example that involves large-scale development of energy infrastructure²²³. Several studies take a broader approach, looking into how undiversified supply chains and geopolitical and environmental constraints can affect successful decarbonisation, suggesting that, for example, more financial aid, technology transfer, cooperation across all levels, and new governance schemes are needed²²⁴⁻²²⁵. To address these issues, the EU and USA have developed several initiatives such as the "European Raw Materials Initiative" and "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition", respectively^{241,242}. Furthermore, China's increasing investment in Europe's energy sector and wind energy projects – although an opportunity to accelerate deployment – raises political, economic and national security concerns²⁴³. Similarly, China uses its dominant role in developing renewable energy and building greater grid interconnections in Central Asia and Africa as geopolitical leverage²⁴⁴. While this may be an opportunity for developing countries with limited financial means to build up wind capacities, it creates strong dependencies and risks²⁴⁵.

An ongoing discourse in the scientific literature relates to how large-scale deployment of renewables affects the geopolitics and security of energy. In contrast to oil and gas, the transition to renewable energy implies a shift from resource to technology, materials and industry control. Still, there is no consensus on whether the associated geopolitical dynamics will be predominantly cooperative or fragmented and lead to more or less conflict²⁴⁶. Higher renewable energy shares are expected to increase international wind power trade without increasing one-sided dependence²⁴⁷. The even distribution of renewable energy resources²⁴⁸ reduces the threat of oil crisis-style coercion – the "energy weapon" – but shifts dependence from energy to technology trade and ownership²⁴⁹. In addition, global patent filing rates for wind are an often-overlooked aspect, which can create concerns in terms of localisation of innovation and market power, giving specific countries a competitive advantage²⁵⁰ and a large share of the export market and jobs created – but also possibly resulting in a concentration of market power, which could become a security problem for importers.

Wind farms are also exposed to multiple cyber security challenges (as are all energy technologies), including safety components and information control systems (ICS) like SCADA systems with proprietary protocols²⁵¹. Energy sector cyberattacks significantly increased since 2015, including attacks targeting the wind industry²⁵². Examples include numerous attacks in Germany during 2022 on the IT infrastructure of turbine manufacturers and maintenance providers²⁵³, and the ViaSat cyberattack at the beginning of the Ukraine war that caused collateral damage to wind turbine controlling and monitoring systems^{254,255}. European wind farm monitoring and operation are increasingly dependent on technologies of foreign, state-owned companies, a potential entry-point for cyber activities in case of large-scale conflict²⁵⁶. Finally, disinformation

and other hybrid warfare techniques create an impact in a less direct manner by manipulating societal values²⁵⁷, with conspiracy beliefs influencing opposition against wind farms²⁵⁸, thus slowing deployment.

Thus there is a need to balance investment opportunities and national security interests better to ensure fair market conditions and minimise distortions of industries' competitiveness, which needs to be supported by developing a broader set of policy options²⁴³. Concerning supply chains, it is necessary to increase domestic exploration and production as well as midstream activities (e.g. critical materials refining), technical innovation, efficiency and material recycling, and demand reduction through substitution²⁵⁹. Overall, reshoring and near-shoring of supply chains can alleviate risks and increase resilience. Still, it needs to be carefully designed and consider strategic aspects concerning diversification, influence on standards and investment in infrastructure²⁶⁰. Otherwise, it may cause reduced global effectiveness, and potentially compromise efforts to close the green energy infrastructure gap²⁶¹. To improve cyber security and reduce potential collateral damage (e.g., ViaSat event), it is important to propose and integrate secure technologies and resilient designs for wind power installations, which then need to be taken up by regulation to ensure rapid implementation by industry²⁶². Furthermore, preventive measures such as detailed information and explanations can potentially reduce peoples' susceptibility to disinformation and conspiracy beliefs and are applicable to increase wind power acceptance, although it may be challenging if these are deeply rooted beliefs^{236,258,263,264}.

Finally, hybrid approaches combining epidemiological models for disinformation spread and optimisation models for network performance provide a complementary option to protect critical infrastructure because they allow jointly identifying and countering disinformation spread as well as mitigating its effects by identifying vulnerable network nodes²⁶⁵.

Planning and permitting

Lengthy permitting processes are “the biggest barrier to the expansion of wind energy” in Europe, with at least 47 GW onshore wind projects stuck in the permitting process in 2022²⁶⁶. Similarly, many wind power projects are also delayed due to permitting issues in the US^{267–269}. The reasons for long processes are diverse, including increasingly complex formal requirements and insufficiently specific legal guidelines and responsibilities for permitting authorities^{270–273}. Understaffed authorities and overloaded judicial systems unable to handle all cases aggravate the problem²⁷⁴, especially as anti-wind power movements increasingly use litigation to prevent projects^{275–277}. One-fifth of German wind farms were subject to litigation, typically related to bird or bat protection (48%) or general species conservation (24%)²⁷⁸. Local land-use conflicts intensify with increasing deployment levels as low-conflict sites become scarce¹³⁵, and general acceptance tends to decrease with increasing exposure to wind turbines^{279–281}.

The administrative phases of wind power construction are increasingly long. In Germany, for example, the average time from application for permission to realisation increased from 20 months in 2011 to 49 months in 2022^{282,283}. However, in the European context (Figure 3), the situation is alarming because the long process in Germany is one of the fastest. No country meets the EU requirement of 24-month permission time²⁸⁴.

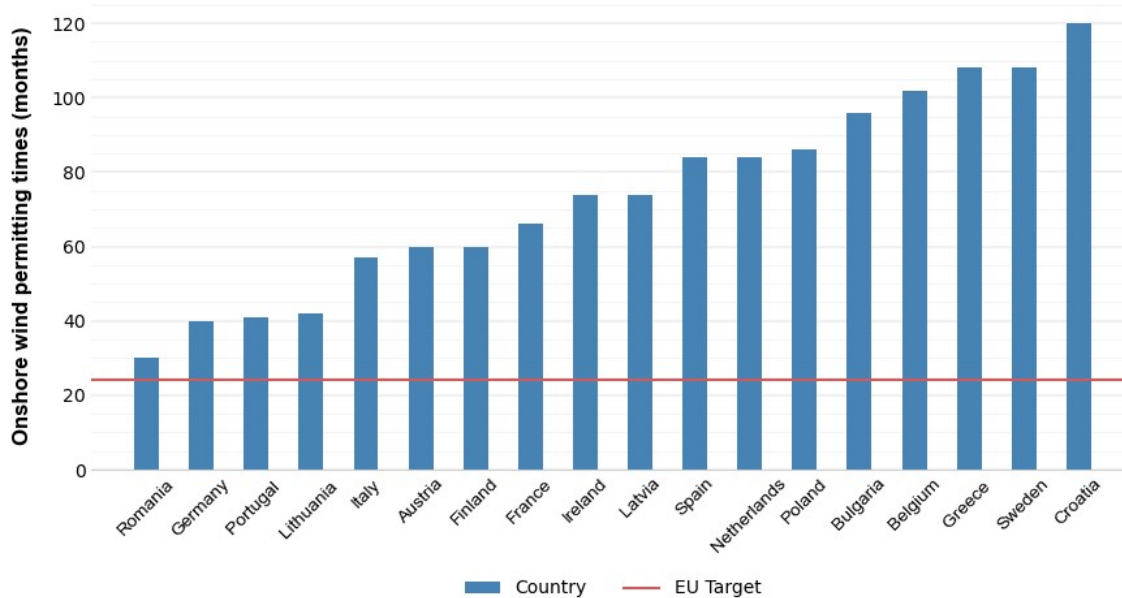


Figure 7: Average permission times including construction permit, environmental impact assessment, local spatial planning and grid connection

Data for 18 countries, in which 96% of EU wind power deployment takes place. The 24-month target is stated in the 2018 Renewables Directive (Art. 16, §4).²⁸⁵ Own depicted based on the given sources.

Several regulatory changes are underway to alleviate this problem. Most prominently, the EU’s Renewable Energy Directive was amended in 2023²⁸⁶. It mandates that renewables across Europe are considered an *overriding public interest* when balancing legal interests during permission processes and in litigation^{286–288}. Member States must assign “acceleration areas” for renewable energy deployment in which the often-time-consuming environmental impact assessments are carried out only for the area, not individual projects. Moreover, a decision must be made on permitting within 12 months, or the project must be considered approved. Outside these “acceleration areas”, permission processes must be completed within 24 months.

While these regulations will likely speed up processes, they may also reduce local stakeholders’ (perceived) ability to influence decision-making, especially if projects are approved without a formal review, as the local authorities lack the capacity to handle all processes within the new deadlines. Citizens may also disagree with the concept of overriding interest. Appropriately assessing environmental impacts for designated acceleration areas will be challenging, as data on species and regional effects is scarce, which may both cause local environmental problems^{289,290}. An inappropriate consideration of local stakeholders’ interests and environmental impacts could reduce local acceptance of renewables, possibly making future expansion more difficult (see Hübner et al.²⁹¹ for a recent review of acceptance factors).

In addition, the financial participation of communities and citizens is increasingly discussed to strengthen local acceptance of wind power and help accelerate local permitting processes. The effect of financial participation on acceptance depends on policy design (e.g., shareholding, reduced electricity tariffs, direct payments), who benefits (communities or individuals), and how it combines with procedural participation^{9,292–296}.

CONCLUSIONS AND OUTLOOK

Impacts, significance and solutions

In this final section, we return to the research questions posed in the introduction and derive central insights from this review. **Firstly, how does wind power impact diverse social, technical and economic systems?** Based on a broad literature review and the wide and varied expertise of the author team, we identified four impact types and fourteen individual impacts of particular relevance, as outlined in the introduction. In Table 1 we summarise each of these impacts along with potential solutions and research priorities, where feasible specifying the sensitivity of these impacts to location, from which we select highlights within this section. In the *Description* column of this table, the fourteen impacts are succinctly defined, providing an answer to this first research question.

Secondly, in some instances, there is a general consensus about **the significance of these impacts**, especially in monocausal cases or those with high and already observed impacts, such as the techno-economic effects of integrating variable generation into power systems, or barriers encountered in permitting processes. In other cases, however, answering this is challenging due to a lack of research, which is often the case with potential future challenges, or a large range of results in the literature, both of which point to a need for further research. The strongest consensus in the literature relates to the *techno-economic* category, especially the energy systems aspect, where extensive empirical and research experience has provided a solid knowledge base about the impacts of large shares of wind energy on energy systems and markets, as well as the measures required to solve such problems. On the other hand, the lowest level of understanding seems to relate to the environmental and policy aspects due partly to an early stage of real-world and research development (e.g. for the impact of wind turbines on weather and climate) and a lack of consensus on best practice in specific contexts (e.g. for policy and planning). This generalisation overlooks some important nuances, for example, the research on wildlife impacts of wind is rather more advanced than that relating to weather and climate. We consider the impacts in the social and health category to have the highest overall spatial sensitivity, meaning they vary strongly by location, and only a moderate level of understanding. The impacts relating to *End-of-life treatment* and *Rare earth materials* have a much lower spatial differentiation, meaning the precise location of the wind farm is not a strong influencing factor.

Tightly intertwined with the second research question is the **third research question about potential solutions**, especially in cases where there is little understanding and/or consensus about the impacts themselves. Proposing effective solutions relies on a detailed and unambiguous understanding of the problem, which is lacking for many impacts. For the best-understood impacts on energy systems and markets, solutions involve a combination of technical integration measures (e.g., grid expansion, increased flexibility, storage) alongside market and regulatory changes to enhance the efficiency with which wind energy is integrated into markets. These solutions are well-examined and are starting to be implemented in several countries. Turning to the impacts in the environmental category, ecosystem influences can be mitigated by strategically placing wind farms, regulating cut-in speeds, temporarily curtailment, visual cues, and painting one turbine blade. Weather and to a degree also climate impacts, to the extent that cause noticeable local problems, can be addressed with appropriate wind power siting and layouts, and by farm layout planning to minimise efficiency losses. Presently, waste management and especially recycling and material access are challenges, and solutions are arising, driven both by a need for environmentally sound dismantling of old wind power assets and particularly to recycle expensive or critical materials such as rare earths and help ensure adequate supply in the future. In the social and policy categories, many aspects relate to the necessity of improving collaborative planning processes. On the one hand, this requires better recognition and reflection of land rights, fostering community participation from the outset and facilitating an understanding of potential co-benefits emanating from wind projects, which could be a great opportunity to increase fairness and procedural and distributional justice. On the other hand, the

planning and permitting must also be strongly accelerated and embedded in a broader context to account for the effects of policy interaction, without compromising these other values. Here Community-Led Local Development (CLLD) as foreseen in Art. 31 of the Common Provisions Regulation (EU) 2021/1060, the rule book for financial provisions on various EU Funds, could play a crucial role in achieving not only a green but also a fair energy transition. Where a Member State decides to apply CLLD, it should ensure that it is led by local action groups composed of representatives of public and private local socio-economic interests, **in which no single interest group controls the decision-making**. Despite its potential to ensure collaborative planning processes, only a few Member States have implemented this optional tool into practice. Also, in the policy/regulation category, other solutions include a reprioritisation of investment opportunities and national security interests, increased domestic exploration and production of critical materials and an emphasis (as well as agreed definitions/certification) on secure and resilient technologies.

Implications and limitations

Some general insights and implications emerge from this review. The first is that several of the available solutions could potentially address multiple impacts in parallel. One example is floating offshore wind, which is still at low-to-medium TRL and stands to address many of the impacts due to the increase in the exploitable potential of wind energy^{297,298}, less visual impact (cf. section Social, economic and health impacts)^{305,306}, and reduced on-site environmental and social impacts^{307,308}. However, rising competition with shipping, fishing and other maritime activities must be considered^{311,312}. Second, a general theme emerging from this research is the strong mismatch between general and local opinions on wind. Hence, while wind power is supported in principle, for example as demonstrated by national opinion surveys^{319,320}, there is often local opposition at sites where wind projects are planned³²¹. However, the legacy explanation that people do not want wind turbines "in their backyard" (NIMBY) is overly simplistic³²², given the complex and context-dependent reasons for local opposition to onshore wind turbines^{9,323}. At the same time, we observe a tension between the need for accelerating wind power deployment and participatory mechanisms that increase acceptance. While for example Regulation (EU) 2022/2577 defining the expansion of wind energy as an 'overriding public interest' will speed up permitting processes, it may tilt the playing field to the detriment of both local stakeholders and energy community initiatives acting slower than professional wind farm developers and risks antagonising local stakeholders.

An additional insight relates to existing wind deployment around the world focusing on sites with higher wind speeds, and thus correspondingly lower generation costs^{324,325}, and model assumptions regarding wind power potentials are poorly reflective of historical installation patterns³²⁴. As a result, wind farms are often concentrated in regions with good wind resources^{136,325}, which increases the need for energy system integration measures like grid reinforcement, storage and flexibility³²⁶⁻³²⁹. This also disproportionately affects communities in these regions – which are often rural, with lower income and less political power to affect local developments³²¹. However, evenly distributing wind turbines based on criteria like local energy demand rather than exploiting sites with good wind conditions may significantly increase generation costs³²⁵. Figure 8 shows the diversity in LCOEs and affected populations for existing onshore wind turbines compared to the overall potential in European countries, with circles scaled according to the installed capacity. While some countries, such as Germany, are already passing laws to distribute onshore turbines evenly across their territory to address spatial injustices, the question of optimal solutions to the multi-criteria decision-making problem of wind turbine siting is still unresolved. The importance of distributive issues has also been emphasised as an underlying cause of health and environmental concerns, such as noise annoyance and bird fatalities. Future research should explore public

preferences regarding the spatial and economic distribution of benefits resulting from wind power deployment^{330,331}.

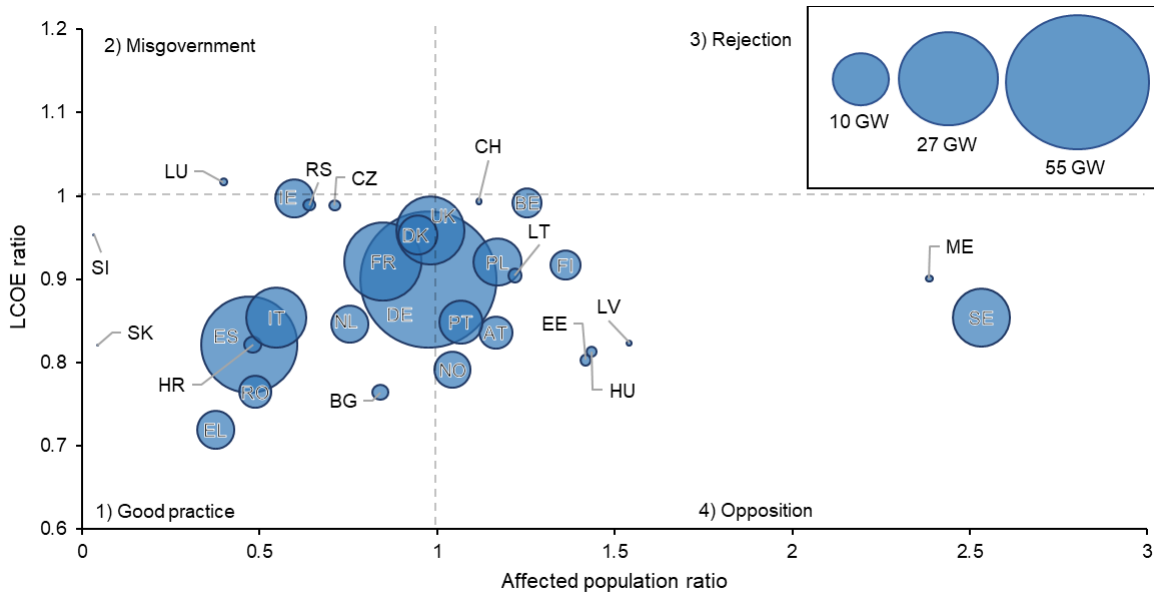


Figure 8: LCOEs and affected population for existing onshore wind turbines in relation to the average in potentially installable turbines shown for European countries

If a ratio is below 1 it means that the LCOEs or number of affected people is lower for the existing turbines than for the average of the potentially installable turbines (including existing ones) of a country. In this case, it is possible that a country has prioritised the corresponding indicator in its turbine planning. If the ratio is above 1, this indicator was probably neglected in comparison to other relevant indicators. In Greece (EL), for example, the existing turbines are located at windy sites with low LCOEs and also affect a relatively low number of people compared to the national average. In contrast, in Sweden (SE) the existing turbines are located in the proximity of relatively many people. In general, cost-effectiveness through low LCOEs and mitigation of disamenities through nearby turbines appear to have played a relevant role in European turbine siting. This figure is reproduced from Weinand et al.³²⁵.

While we have adopted a holistic interdisciplinary perspective to consider the most significant impacts of wind energy on surrounding systems, **the review inevitably has some limitations**. First, there is a potential bias in the identified impacts and their significance. We limit this through the composition of the broad author team covering very different areas of expertise, but the significance of the specific impacts may still be skewed towards the strengths in the expertise of the author team and potentially overlook some important aspects. Whilst the extensive literature review with several hundred references reduces this effect and underpins the analysis with a broad base of peer-reviewed research, it possibly omits issues that we are unaware of and have not yet generated substantial academic output. It is inevitable that the set of problems – and solutions – will evolve over time, so our findings here are a snapshot of the state of the art in 2024, and not more but also not less. Second, because of the nature of the reviewed literature and the diversity of evidence, we could not quantitatively analyse the identified factors or compare them on a unified scale (e.g., level of severity). Instead, our conclusions are qualitative and relate to the cluster of problems/solutions for each factor, without stating which is more severe.

Research priorities

The review framework and results presented here provide a **fruitful basis for further research**. In Table 1 below we summarise the reviewed impacts and suggest research priorities for the coming years. In the environmental category, there is an urgent need for more empirical, preferably longitudinal studies relating to climate, weather and ecological impacts as these are not well known – and correspondingly, solutions to possibly serious problems are not yet present. In addition, effective end-of-life treatment

requires advancements in specific recycling processes, harmonisation of design processes across sectors, development of innovative designs, novel materials and processes for sustainable manufacturing, and holistic systems analysis to foster circular economy approaches. In the social category, empirical data are also required, particularly to improve existing and to develop new theoretical models of planning and governance, distribution of economic costs and benefits, social acceptance, especially but not only relating to land tenure security, visual impacts on the landscape, noise and shadow flicker. The subsequent techno-economic category is far advanced, but especially energy market and price impacts require further work into the market behaviour of individual actors and quantitatively elaborating context-specific whole system costs of wind energy is still missing. For policy and regulations, empirical observations of the effects – both positive and negative – of upcoming efforts to reduce permitting times are essential, both on whether they work at all and particularly on co-benefits of these measures, such as effects on public acceptance of wind farms and policies.

Our review demonstrates a wide variety of impacts of wind energy on the surrounding systems, at equally diverse stages of development in terms of research understanding, available solutions and spatial heterogeneity. In many cases, there is a need for additional research to enable decision-makers to weigh up the real net impact of wind power *compared to the alternatives*, for example in environmental, economic, technical and social terms: only considering the effects of wind power while ignoring the effects of the technologies implemented instead is short-sighted and counterproductive. The relevant question is not whether a particular wind power strategy is adequate or desirable, but whether it is more adequate and desirable than another strategy, be it a different wind power strategy or an entirely different renewable-based or even fossil-based one combined with carbon capture and storage and negative emission technologies. Such a comparative multi-criteria analysis must include many more stakeholders, especially outside academia, and be context-specific. Here, further research is still needed, both to increase knowledge on problems and solutions and to support the continued deployment of wind power as one of the key pillars to meeting the long-term sustainability and climate targets.

Table 1: Overview of key systemic wind impacts, potential solutions and research priorities emerging from this comprehensive review

Category	Impact	Description	Spatial diversity ^a	Solutions	Research priorities
Environment and climate	1. Impacts on ecosystems and wildlife	Impacts such as direct collision causing mortality of birds and bats, or noise pollution causing population decline and displacement of birds, bats, non-volant and marine mammals by disrupting their nesting, breeding and movement patterns.	High	Strategic placing of wind farms, regulating cut-in speeds, temporary curtailment, visual cues, painting one turbine blade	Empirical research and observation: <ul style="list-style-type: none"> • Impacts in shrub- and woodland • Multi-annual and multi-site studies (before-after control-impact study design) • Net ecological impacts of wind energy compared to alternatives • Longitudinal studies in wind energy locations
	2. Impacts on weather and climate	The operation of wind farms can cause a local change in surface temperature and other weather parameters such as precipitation and evaporation. Large wind farms can affect the wind resources for tens of kilometres downstream.	Medium	Wind power siting, integration measures (e.g. storage, grids etc.), appropriate wind park layouts, consider efficiency losses in wind farm planning	<ul style="list-style-type: none"> • Further measurements and empirical data, especially for large wind farms and local weather effects • Net climate effects of wind energy compared to alternatives
	3. End of life treatment of turbine blades	The challenges of recycling of turbine blades containing fibers, which is currently through landfills and temporary storage.	Low	Prevention, refurbishing or reusing, repurposing, recycling	<ul style="list-style-type: none"> • Address the waste hierarchy through innovative design for recycling and disassembly • Improve thermal and chemical recycling processes to higher TRLs and exploit sectoral spill overs • Increase coordination and standardization between manufacturers and developers
	4. Rare earth elements	The trend toward direct drives with permanent magnets containing critical rare earth materials for the EU results in a geopolitical challenge, yet less than 1% of the rare earth elements are recycled.	Low	Recycling of permanent magnets, alternatives for permanent magnet wind turbine generators, diversifying supply chains	
Social, economic, health	5. Land governance and tenure (in)security	Land requirements for wind power can come at the cost of prior land-users, and increase the vulnerability of traditional rural communities and indigenous groups.	High	Recognition of common lands and traditional communal land use rights, improved planning and coordination of spatial energy planning with land tenure	<ul style="list-style-type: none"> • Understand best practice for wind energy planning to reflect community needs

^a An assessment of how much the impact varies by location of the wind turbine or farm.

Category	Impact	Description	Spatial diversity ^a	Solutions	Research priorities
				issues, participatory planning, legal advice, creating co-benefits	<ul style="list-style-type: none"> Develop collaborative planning, governance and business models ensure co-benefits
	6. Local monetary costs and benefits	Wind turbines can create either positive or negative impacts on neighbouring real estate value and tourism depending on the perception.	High	Fostering community participation from the projects' planning stages, improving the understanding of wind power as key technology to achieve the energy transition and monetary compensations	<ul style="list-style-type: none"> Elaborate models of acceptance and willingness to pay in order to quantify compensation measures Quantify net economic impacts based on improved data bases /availability
	7. Landscape impacts	The local opposition towards wind projects due to the negative visual impact on wild landscape aesthetic value.	High	Improved planning, participative processes	<ul style="list-style-type: none"> Enhance concepts of social acceptance to consider frequency of encounters with and quality of landscapes Extend quantitative empirical research on local economic impacts of wind farms
	8. Local health impacts	Noise emissions and shadow flicker from wind turbines can cause neighbours annoyance, which may correlate to deteriorating quality of life, increased stress and resulting health issues.	High	Appropriate planning, periodic curtailment and noise threshold.	<ul style="list-style-type: none"> Build on existing noise models to enhance understanding of wind energy impacts in relation to other local sources Extend shadow flicker research to consider night-time effects with artificial lighting
Techno-economic	9. Energy system impacts	Wind-dominated energy systems may lack inertia and become highly weather dependent.	Medium	Grid densification and expansion, use of storage, increasing flexibility and sector coupling, development of smart grids	<ul style="list-style-type: none"> Align modelling with empirical data on energy system transitions to high wind shares Improve techno-economic modelling to reflect social and environmental impacts and constraints
	10. Market and price impacts	Integrating wind power into markets creates two key opposing issues: ancillary service costs increase due to increased supply variability, and the "merit order effect" depresses wholesale market prices and increases their volatility.	Medium	Market and regulatory changes that either bring more flexible capacity online or allow the existing system to react more efficiently to wind power volatility, e.g. Enhanced Frequency Response service in Britain	<ul style="list-style-type: none"> Develop advanced models of market actors, storage and interactions Derive best practice for wind energy subsidies depending on energy-political contexts Quantify whole system costs of wind energy integration for diverse systems and contexts

Category	Impact	Description	Spatial diversity ^a	Solutions	Research priorities
Policy and regulation	11. Financing and controlling the IP	Political, economic and national security concerns as well as possible resulting shifts in market power due to industry leaders seeking dominance.	Medium	Balance investment opportunities and national security interests	<ul style="list-style-type: none"> • Develop open data and associated research on investments, ownership, and acquisitions through FDI to assess geopolitical and geoeconomic risks • Influence political and regulatory processes connected to (wind) energy infrastructure.
	12. Supply chain disruptions	Energy disruption as a geopolitical weapon has a long history for oil and gas, but it recently shifted to a focus on geopolitics of the energy transition and resurging concerns over the weaponization of energy.	Medium	Increase domestic exploration and production to re-shore and near-shore supply chains	<ul style="list-style-type: none"> • Design robust and resilient supply chains for wind energy • Enforce international technology standards and certification schemes • Identify the pathways and understand the major implications to developing a domestic (offshore) wind supply chain that can manufacture and deploy the major components needed
	13. Cyber security and hybrid threats	Wind farms are exposed to challenges on existing infrastructure security that depends on complex control and monitoring systems, as well as disinformation that can affect news credibility.	Low	Secure technologies and resilient designs	<ul style="list-style-type: none"> • Understand how disinformation can be used to compromise the security of critical infrastructure • Understand the potential vulnerability and attack landscape related to control and information systems, including the connected supplier and third-party systems.
	14. Planning and permitting	Lengthy permitting processes due to increasingly complex formal requirements combined with insufficiently specific legal guidelines and responsibilities for permitting authorities, as well as understaffed authorities and overloaded judicial systems.	High	Regulatory changes, "go to areas", financial participation of communities, more resources for authorities	<ul style="list-style-type: none"> • Determine best practice for planning and permitting • Observe effects of ongoing/upcoming regulatory changes, incl. side-effects on acceptance • Reflect spatial trade-offs in wind power legislation (centralised vs. decentralised)

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The authors contributed as outlined in the figure below.

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Arne	AB	Burdack	Co-author of section 2.3						x			x	x				
Peter		Burgherr	Core author team	x	x							x	x			x	x
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REFERENCES

1. IEA (2023). Tracking Clean Energy Process 2023. IEA Paris. <https://www.iea.org/reports/tracking-clean-energy-progress-2023>.
2. IEA (2023). Europe – Countries & Regions. IEA Paris. <https://www.iea.org/regions/europe>.
3. Denmark: power generation share by source 2023 Statista. <https://www.statista.com/statistics/1235360/denmark-distribution-of-electricity-production-by-source/>.
4. Wiser, R., Bolinger, M., Hoen, B., Millstein, D., Rand, J., Barbose, G., Darghouth, N., Gorman, W., Jeong, S., O’Shaughnessy, E., et al. (2023). Land-Based Wind Market Report: 2023 Edition (U.S. Department of Energy).
5. New Energy Outlook 2022 | BloombergNEF | Bloomberg Finance LP BloombergNEF. <https://about.bnef.com/new-energy-outlook/>.
6. IRENA (2022). Renewable power generation costs in 2022 (International Renewable Energy Agency, Abu Dhabi.).
7. Wiser, R., Rand, J., Seel, J., Beiter, P., Baker, E., Lantz, E., and Gilman, P. (2021). Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nat. Energy* 6, 555–565. 10.1038/s41560-021-00810-z.
8. Devine-Wright, P. (2009). Rethinking NIMBYism: The role of place attachment and place identity in explaining place-protective action. *J. Community Appl. Soc. Psychol.* 19, 426–441. 10.1002/casp.1004.
9. Scherhauer, P., Höltinger, S., Salak, B., Schauppenlehner, T., and Schmidt, J. (2017). Patterns of acceptance and non-acceptance within energy landscapes: A case study on wind energy expansion in Austria. *Energy Policy* 109, 863–870. 10.1016/j.enpol.2017.05.057.
10. Gkeka-Serpetsidaki, P., and Tsoutsos, T. (2023). Integration criteria of offshore wind farms in the landscape: Viewpoints of local inhabitants. *J. Clean. Prod.* 417, 137899. 10.1016/j.jclepro.2023.137899.
11. Thaxter, C.B., Buchanan, G.M., Carr, J., Butchart, S.H.M., Newbold, T., Green, R.E., Tobias, J.A., Foden, W.B., O’Brien, S., and Pearce-Higgins, J.W. (2017). Bird and bat species’ global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proc. R. Soc. B Biol. Sci.* 284, 20170829. 10.1098/rspb.2017.0829.
12. Galparsoro, I., Menchaca, I., Garmendia, J.M., Borja, Á., Maldonado, A.D., Iglesias, G., and Bald, J. (2022). Reviewing the ecological impacts of offshore wind farms. *Npj Ocean Sustain.* 1, 1–8. 10.1038/s44183-022-00003-5.
13. Ata Teneler, A., and Hassoy, H. (2023). Health effects of wind turbines: a review of the literature between 2010-2020. *Int. J. Environ. Health Res.* 33, 143–157. 10.1080/09603123.2021.2010671.
14. The ultimate supply chains | Apr 8th 2023 (2023). *The Economist*. <https://www.economist.com/technology-quarterly/2023-04-08>.
15. Newbery, D., Pollitt, M.G., Ritz, R.A., and Strielkowski, W. (2018). Market design for a high-renewables European electricity system. *Renew. Sustain. Energy Rev.* 91, 695–707. 10.1016/j.rser.2018.04.025.
16. Denholm, P., Arent, D.J., Baldwin, S.F., Bilello, D.E., Brinkman, G.L., Cochran, J.M., Cole, W.J., Frew, B., Gevorgian, V., Heeter, J., et al. (2021). The challenges of achieving a 100% renewable electricity system in the United States. *Joule* 5, 1331–1352. 10.1016/j.joule.2021.03.028.
17. Grand challenges in the science of wind energy | Science <https://www.science.org/doi/10.1126/science.aau2027>.
18. Veers, P., Dykes, K., Basu, S., Bianchini, A., Clifton, A., Green, P., Holttinen, H., Kitzing, L., Kosovic, B., Lundquist, J.K., et al. (2022). Grand Challenges: wind energy research needs for a global energy transition. *Wind Energy Sci.* 7, 2491–2496. 10.5194/wes-7-2491-2022.
19. McKenna, R., Pfenninger, S., Heinrichs, H., Schmidt, J., Staffell, I., Bauer, C., Gruber, K., Hahmann, A.N., Jansen, M., Klingler, M., et al. (2022). High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs. *Renew. Energy* 182, 659–684. 10.1016/j.renene.2021.10.027.
20. Kitzing, L., Rudolph, D., Nyborg, S., Solman, H., Cronin, T., Hübner, G., Gill, E., Dykes, K., Tegen, S., and Kirkegaard, J.K. (2024). Grand

- Challenges in Social Aspects of Wind Energy Development. *Wind Energy Sci. Discuss.*, 1–13. 10.5194/wes-2023-174.
21. Kirkegaard, J.K., Rudolph, D.P., Nyborg, S., Solman, H., Gill, E., Cronin, T., and Hallisey, M. (2023). Tackling grand challenges in wind energy through a socio-technical perspective. *Nat. Energy* 8, 655–664. 10.1038/s41560-023-01266-z.
22. Tolvanen, A., Routavaara, H., Jokikokko, M., and Rana, P. (2023). How far are birds, bats, and terrestrial mammals displaced from onshore wind power development? – A systematic review. *Biol. Conserv.* 288, 110382. 10.1016/j.biocon.2023.110382.
23. Erickson, W.P., Wolfe, M.M., Bay, K.J., Johnson, D.H., and Gehring, J.L. (2014). A Comprehensive Analysis of Small-Passerine Fatalities from Collision with Turbines at Wind Energy Facilities. *PLOS ONE* 9, e107491. 10.1371/journal.pone.0107491.
24. Loss, S.R., Will, T., and Marra, P.P. (2013). Estimates of bird collision mortality at wind facilities in the contiguous United States. *Biol. Conserv.* 168, 201–209. 10.1016/j.biocon.2013.10.007.
25. Smallwood, K.S. (2013). Comparing bird and bat fatality-rate estimates among North American wind-energy projects. *Wildl. Soc. Bull.* 37, 19–33. 10.1002/wsb.260.
26. Carrete, M., Sánchez-Zapata, J.A., Benítez, J.R., Lobón, M., and Donázar, J.A. (2009). Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. *Biol. Conserv.* 142, 2954–2961. 10.1016/j.biocon.2009.07.007.
27. Dahl, E.L., Bevanger, K., Nygård, T., Røskoft, E., and Stokke, B.G. (2012). Reduced breeding success in white-tailed eagles at Smøla windfarm, western Norway, is caused by mortality and displacement. *Biol. Conserv.* 145, 79–85. 10.1016/j.biocon.2011.10.012.
28. Bellebaum, J., Korner-Nievergelt, F., Dürr, T., and Mammen, U. (2013). Wind turbine fatalities approach a level of concern in a raptor population. *J. Nat. Conserv.* 21, 394–400. 10.1016/j.jnc.2013.06.001.
29. May, R., Masden, E.A., Bennet, F., and Perron, M. (2019). Considerations for upscaling individual effects of wind energy development towards population-level impacts on wildlife. *J. Environ. Manage.* 230, 84–93. 10.1016/j.jenvman.2018.09.062.
30. Coppes, J., Braunisch, V., Bollmann, K., Storch, I., Mollet, P., Grünschachner-Berger, V., Taubmann, J., Suchant, R., and Nopp-Mayr, U. (2020). The impact of wind energy facilities on grouse: a systematic review. *J. Ornithol.* 161, 1–15. 10.1007/s10336-019-01696-1.
31. Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J.F., Marques, A.T., Martins, R.C., Shaw, J.M., Silva, J.P., and Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biol. Conserv.* 222, 1–13. 10.1016/j.biocon.2018.02.029.
32. Jones, N.F., Pejchar, L., and Kiesecker, J.M. (2015). The Energy Footprint: How Oil, Natural Gas, and Wind Energy Affect Land for Biodiversity and the Flow of Ecosystem Services. *BioScience* 65, 290–301. 10.1093/biosci/biu224.
33. Katovich, E. (2024). Quantifying the Effects of Energy Infrastructure on Bird Populations and Biodiversity. *Environ. Sci. Technol.* 58, 323–332. 10.1021/acs.est.3c03899.
34. Baerwald, E.F., D’Amours, G.H., Klug, B.J., and Barclay, R.M.R. (2008). Barotrauma is a significant cause of bat fatalities at wind turbines. *Curr. Biol.* 18, R695–R696. 10.1016/j.cub.2008.06.029.
35. Schöll, E.M., and Nopp-Mayr, U. (2021). Impact of wind power plants on mammalian and avian wildlife species in shrub- and woodlands. *Biol. Conserv.* 256, 109037. 10.1016/j.biocon.2021.109037.
36. Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P. (2009). Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.)). *J. Acoust. Soc. Am.* 126, 11–14. 10.1121/1.3132523.
37. Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., and Thompson, P.M. (2010). Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Mar. Pollut. Bull.* 60, 888–897. 10.1016/j.marpolbul.2010.01.003.

38. Sovacool, B.K. (2009). Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy* 37, 2241–2248. 10.1016/j.enpol.2009.02.011.
39. Łopucki, R., Klich, D., and Gielarek, S. (2017). Do terrestrial animals avoid areas close to turbines in functioning wind farms in agricultural landscapes? *Environ. Monit. Assess.* 189, 343. 10.1007/s10661-017-6018-z.
40. Pearce-Higgins, J.W., Stephen, L., Douse, A., and Langston, R.H.W. (2012). Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. *J. Appl. Ecol.* 49, 386–394. 10.1111/j.1365-2664.2012.02110.x.
41. Astiaso Garcia, D., Canavero, G., Ardenghi, F., and Zambon, M. (2015). Analysis of wind farm effects on the surrounding environment: Assessing population trends of breeding passerines. *Renew. Energy* 80, 190–196. 10.1016/j.renene.2015.02.004.
42. González, M.A., García-Tejero, S., Wengert, E., and Fuertes, B. (2016). Severe decline in Cantabrian Capercaillie *Tetrao urogallus cantabricus* habitat use after construction of a wind farm. *Bird Conserv. Int.* 26, 256–261. 10.1017/S0959270914000471.
43. Sirén, A.P.K., Maynard, D.S., Kilborn, J.R., and Pekins, P.J. (2016). Efficacy of remote telemetry data loggers for landscape-scale monitoring: A case study of American martens. *Wildl. Soc. Bull.* 40, 570–582. 10.1002/wsb.680.
44. Coppes, J., Kämmerle, J.-L., Grünschachner-Berger, V., Braunisch, V., Bollmann, K., Mollet, P., Suchant, R., and Nopp-Mayr, U. (2020). Consistent effects of wind turbines on habitat selection of capercaillie across Europe. *Biol. Conserv.* 244, 108529. 10.1016/j.biocon.2020.108529.
45. Skarin, A., Sandström, P., and Moudud, A. (2018). Out of sight of wind turbines—Reindeer response to wind farms in operation. *Ecol. Evol.* 8. 10.1002/ece3.4476.
46. Guest, E.E., Stamps, B.F., Durish, N.D., Hale, A.M., Hein, C.D., Morton, B.P., Weaver, S.P., and Fritts, S.R. (2022). An Updated Review of Hypotheses Regarding Bat Attraction to Wind Turbines. *Animals* 12, 343. 10.3390/ani12030343.
47. Diffendorfer, J.E., Dorning, M.A., Keen, J.R., Kramer, L.A., and Taylor, R.V. (2019). Geographic context affects the landscape change and fragmentation caused by wind energy facilities. *PeerJ* 7, e7129. 10.7717/peerj.7129.
48. Roscioni, F., Rebelo, H., Russo, D., Carranza, M.L., Di Febbraro, M., and Loy, A. (2014). A modelling approach to infer the effects of wind farms on landscape connectivity for bats. *Landsc. Ecol.* 29, 891–903. 10.1007/s10980-014-0030-2.
49. Balkenhol, N., Cushman, S., Storfer, A., and Waits, L. (2016). *Landscape Genetics: Concepts, Methods, Applications* (John Wiley & Sons, Ltd).
50. Madsen, J., and Boertmann, D. (2008). Animal behavioral adaptation to changing landscapes: spring-staging geese habituate to wind farms. *Landsc. Ecol.* 23, 1007–1011. 10.1007/s10980-008-9269-9.
51. Agnew, R.C.N., Smith, V.J., and Fowkes, R.C. (2016). WIND TURBINES CAUSE CHRONIC STRESS IN BADGERS (MELES MELES) IN GREAT BRITAIN. *J. Wildl. Dis.* 52, 459–467. 10.7589/2015-09-231.
52. Northrup, J.M., and Wittemyer, G. (2013). Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation. *Ecol. Lett.* 16, 112–125. 10.1111/ele.12009.
53. Hanssen, F., May, R., and Nygård, T. (2020). High-Resolution Modeling of Uplift Landscapes can Inform Micrositing of Wind Turbines for Soaring Raptors. *Environ. Manage.* 66, 319–332. 10.1007/s00267-020-01318-0.
54. Commission, E., and Environment, D.-G. for (2020). *Guidance document on wind energy developments and EU nature legislation* (Publications Office of the European Union) doi/10.2779/457035.
55. Arnett, E.B., Huso, M.M., Schirmacher, M.R., and Hayes, J.P. (2011). Altering turbine speed reduces bat mortality at wind-energy facilities. *Front. Ecol. Environ.* 9, 209–214. 10.1890/100103.
56. Huso, M.M.P., and Hayes, J.P. (2009). Effectiveness of Changing Wind Turbine Cut-in Speed to Reduce Bat Fatalities at Wind Facilities 10.2172/1218377.

57. Barrios, L., and Rodríguez, A. (2004). Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. *J. Appl. Ecol.* *41*, 72–81. 10.1111/j.1365-2664.2004.00876.x.
58. Confirmation that eagle fatalities can be reduced by automated curtailment of wind turbines - McClure - 2022 - Ecological Solutions and Evidence - Wiley Online Library <https://besjournals.onlinelibrary.wiley.com/doi/10.1002/2688-8319.12173>.
59. May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., and Stokke, B.G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecol. Evol.* *10*, 8927–8935. 10.1002/ece3.6592.
60. Richardson, S.M., Lintott, P.R., Hosken, D.J., Economou, T., and Mathews, F. (2021). Peaks in bat activity at turbines and the implications for mitigating the impact of wind energy developments on bats. *Sci. Rep.* *11*, 3636. 10.1038/s41598-021-82014-9.
61. Volker, P.J.H., Badger, J., Hahmann, A.N., and Ott, S. (2015). The Explicit Wake Parametrisation V1.0: a wind farm parametrisation in the mesoscale model WRF. *Geosci. Model Dev.* *8*, 3715–3731. 10.5194/gmd-8-3715-2015.
62. Schneemann, J., Rott, A., Dörenkämper, M., Steinfeld, G., and Kühn, M. (2020). Cluster wakes impact on a far-distant offshore wind farm's power. *Wind Energy Sci.* *5*, 29–49. 10.5194/wes-5-29-2020.
63. Volker, P.J.H., Hahmann, A.N., Badger, J., and Jørgensen, H.E. (2017). Prospects for generating electricity by large onshore and offshore wind farms. *Environ. Res. Lett.* *12*, 034022. 10.1088/1748-9326/aa5d86.
64. Porté-Agel, F., Lu, H., and Wu, Y.-T. (2014). Interaction between Large Wind Farms and the Atmospheric Boundary Layer. *Procedia IUTAM* *10*, 307–318. 10.1016/j.piutam.2014.01.026.
65. Borgers, R., Dirksen, M., Wijnant, I.L., Stepek, A., Stoffelen, A., Akhtar, N., Neiryneck, J., Van de Walle, J., Meyers, J., and van Lipzig, N.P.M. (2024). Mesoscale modelling of North Sea wind resources with COSMO-CLM: model evaluation and impact assessment of future wind farm characteristics on cluster-scale wake losses. *Wind Energy Sci.* *9*, 697–719. 10.5194/wes-9-697-2024.
66. Cañadillas, B., Beckenbauer, M., Trujillo, J.J., Dörenkämper, M., Foreman, R., Neumann, T., and Lampert, A. (2022). Offshore wind farm cluster wakes as observed by long-range-scanning wind lidar measurements and mesoscale modeling. *Wind Energy Sci.* *7*, 1241–1262. 10.5194/wes-7-1241-2022.
67. Akhtar, N., Geyer, B., and Schrum, C. (2022). Impacts of accelerating deployment of offshore windfarms on near-surface climate. *Sci. Rep.* *12*, 18307. 10.1038/s41598-022-22868-9.
68. Adams, A.S., and Keith, D.W. (2013). Are global wind power resource estimates overstated? *Environ. Res. Lett.* *8*, 015021. 10.1088/1748-9326/8/1/015021.
69. Miller, L.M., Brunsell, N.A., Mechem, D.B., Gans, F., Monaghan, A.J., Vautard, R., Keith, D.W., and Kleidon, A. (2015). Two methods for estimating limits to large-scale wind power generation. *Proc. Natl. Acad. Sci.* *112*, 11169–11174. 10.1073/pnas.1408251112.
70. Platis, A., Siedersleben, S.K., Bange, J., Lampert, A., Bärfuss, K., Hankers, R., Cañadillas, B., Foreman, R., Schulz-Stellenfleth, J., Djath, B., et al. (2018). First in situ evidence of wakes in the far field behind offshore wind farms. *Sci. Rep.* *8*, 2163. 10.1038/s41598-018-20389-y.
71. van der Horst, D., and Vermeylen, S. (2010). Wind Theft, Spatial Planning and International Relations. *Renew. Energy Law Policy Rev.* *1*, 67–75.
72. Marvel, K., Kravitz, B., and Caldeira, K. (2013). Geophysical limits to global wind power. *Nat. Clim. Change* *3*, 118–121. 10.1038/nclimate1683.
73. Fischereit, J., Brown, R., Larsén, X.G., Badger, J., and Hawkes, G. (2022). Review of Mesoscale Wind-Farm Parametrizations and Their Applications. *Bound.-Layer Meteorol.* *182*, 175–224. 10.1007/s10546-021-00652-y.
74. Smith, C.M., Barthelmie, R.J., and Pryor, S.C. (2013). In situ observations of the influence of a large onshore wind farm on near-surface temperature, turbulence intensity and wind speed profiles. *Environ. Res. Lett.* *8*, 034006. 10.1088/1748-9326/8/3/034006.
75. Lee, J.C.Y., and Lundquist, J.K. (2017). Observing and Simulating Wind-Turbine

- Wakes During the Evening Transition. *Bound.-Layer Meteorol.* **164**, 449–474. 10.1007/s10546-017-0257-y.
76. Takle, E.S., Rajewski, D.A., and Purdy, S.L. (2019). The Iowa Atmospheric Observatory: Revealing the Unique Boundary Layer Characteristics of a Wind Farm. *Earth Interact.* **23**, 1–27. 10.1175/EI-D-17-0024.1.
77. Xia, G., Zhou, L., Minder, J.R., Fovell, R.G., and Jimenez, P.A. (2019). Simulating impacts of real-world wind farms on land surface temperature using the WRF model: physical mechanisms. *Clim. Dyn.* **53**, 1723–1739. 10.1007/s00382-019-04725-0.
78. Wu, S., Archer, C.L., and Mirocha, J.D. New insights on wind turbine wakes from large-eddy simulation: Wake contraction, dual nature, and temperature effects. *Wind Energy* *n/a*. 10.1002/we.2827.
79. Fischereit, J., Larsén, X.G., and Hahmann, A.N. (2022). Climatic Impacts of Wind-Wave-Wake Interactions in Offshore Wind Farms. *Front. Energy Res.* **10**. 10.3389/fenrg.2022.881459.
80. Intergovernmental Panel On Climate Change (Ippc) ed. (2023). *Energy Systems*. In *Climate Change 2022 - Mitigation of Climate Change* (Cambridge University Press), pp. 613–746. 10.1017/9781009157926.008.
81. Wind Europe (2020). *Decommissioning of Onshore Wind Turbines*. <https://windeurope.org/data-and-analysis/product/decommissioning-of-onshore-wind-turbines>.
82. Staffell, I., and Green, R. (2014). How does wind farm performance decline with age? *Renew. Energy* **66**, 775–786. 10.1016/j.renene.2013.10.041.
83. Khalid, M.Y., Arif, Z.U., Hossain, M., and Umer, R. (2023). Recycling of wind turbine blades through modern recycling technologies: A road to zero waste. *Renew. Energy Focus* **44**, 373–389. 10.1016/j.ref.2023.02.001.
84. Eligüzel, İ.M., and Özceylan, E. (2022). A bibliometric, social network and clustering analysis for a comprehensive review on end-of-life wind turbines. *J. Clean. Prod.* **380**, 135004. 10.1016/j.jclepro.2022.135004.
85. Carter, K. (2021). *Unearthing Rare Earths | Wind Systems Magazine*. <https://www.windsystemsmag.com/24015-2/>.
86. Wind Turbines: how dependent is the EU on China? (2023). *Energy Post*. <https://energypost.eu/wind-turbines-how-dependent-is-the-eu-on-china/>.
87. Griffith, K. (2020). Hundreds of fiberglass wind turbine blades pile up in landfills. *Mail Online*. <https://www.dailymail.co.uk/news/article-8294057/Hundreds-non-recyclable-fiberglass-wind-turbine-blades-pictured-piling-landfills.html>.
88. Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills (2020). *Bloomberg.com*.
89. Beauson, J., Laurent, A., Rudolph, D.P., and Pagh Jensen, J. (2022). The complex end-of-life of wind turbine blades: A review of the European context. *Renew. Sustain. Energy Rev.* **155**, 111847. 10.1016/j.rser.2021.111847.
90. International Energy Agency (2022). *The Role of Critical Minerals in Clean Energy Transitions*. <https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf>.
91. Pietrantonio, M., Pucciarmati, S., Sebastianelli, L., Forte, F., and Fontana, D. (2021). Materials recovery from end-of-life wind turbine magnets. *Int. J. Environ. Sci. Technol.* **19**, 3. 10.1007/s13762-021-03546-1.
92. Directorate-General for Internal Market, I., Grohol, M., and Veeh, C. (2023). *Study on the critical raw materials for the EU 2023: final report* (Publications Office of the European Union).
93. Joint Research Centre (European Commission), Alves Dias, P., Bobba, S., Carrara, S., and Plazzotta, B. (2020). *The role of rare earth elements in wind energy and electric mobility: an analysis of future supply/demand balances* (Publications Office of the European Union).
94. Pierrot, M. *Wind energy database*. <https://www.thewindpower.net/>.
95. TYNDP 2022 Scenario Building Guidelines | Version. April 2022 (2022). (ENTSO-E).
96. Department for Energy Security and Net Zero (2023). *Electricity generation costs 2023*. GOV.UK.

- <https://www.gov.uk/government/publications/electricity-generation-costs-2023>.
97. Capital Cost and Performance Characteristics for Utility-Scale Electric Power Generating Technologies (2024). (U.S. Energy Information Administration).
 98. Closing The Loop: Group Unveils A Prototype Of A Recyclable Wind Turbine Blade | GE News (2022). <https://www.ge.com/news/reports/closing-the-loop-group-unveils-a-prototype-of-a-recyclable-wind-turbine-blade>.
 99. Siemens Gamesa (2023). RecyclableBlade. <https://www.siemensgamesa.com/en-int/explore/journal/recyclable-blade>.
 100. Khalid, M.Y., Arif, Z.U., Ahmed, W., and Arshad, H. (2022). Recent trends in recycling and reusing techniques of different plastic polymers and their composite materials. *Sustain. Mater. Technol.* 31, e00382. 10.1016/j.susmat.2021.e00382.
 101. Kühne, C., Stapf, D., Holz, P., Baumann, W., Mühlhopt, S., Wexler, M., Hauser, M., Kalkreuth, J., Mahl, J., Zeller, M., et al. (2022). Entwicklung von Rückbau- und Recyclingstandards für Rotorblätter (Umweltbundesamt).
 102. Deutsche Presse-Agentur (2022). Schwierige Wiederverwertung von Windanlagen Rotorblätter mit Recyclingproblem. *Spiegel*. <https://www.spiegel.de/wissenschaft/technik/windanlagen-rotorblaetter-mit-recycling-problem-a-4a2c64ed-2359-4711-b808-8eb216675f41>.
 103. Martinez-Marquez, D., Florin, N., Hall, W., Majewski, P., Wang, H., and Stewart, R.A. (2022). State-of-the-art review of product stewardship strategies for large composite wind turbine blades. *Resour. Conserv. Recycl. Adv.* 15, 200109. 10.1016/j.rcradv.2022.200109.
 104. Rathore, N., and Panwar, N.L. (2023). Environmental impact and waste recycling technologies for modern wind turbines: An overview. *Waste Manag. Res. J. Int. Solid Wastes Public Clean. Assoc. ISWA* 41, 744–759. 10.1177/0734242X221135527.
 105. Korniejenko, K., Kozub, B., Bağ, A., Balamurugan, P., Uthayakumar, M., and Furtos, G. (2021). Tackling the Circular Economy Challenges—Composites Recycling: Used Tyres, Wind Turbine Blades, and Solar Panels. *J. Compos. Sci.* 5, 243. 10.3390/jcs5090243.
 106. Scheidel, A., and Sorman, A.H. (2012). Energy transitions and the global land rush: Ultimate drivers and persistent consequences. *Glob. Environ. Change* 22, 588–595. 10.1016/j.gloenvcha.2011.12.005.
 107. Siamanta, Z.C. (2019). Wind parks in post-crisis Greece: Neoliberalisation vis-à-vis green grabbing. *Environ. Plan. E Nat. Space* 2, 274–303. 10.1177/2514848619835156.
 108. Fairhead, J., Leach, M., and Scoones, I. (2012). Green Grabbing: a new appropriation of nature? *J. Peasant Stud.* 39, 237–261. 10.1080/03066150.2012.671770.
 109. Klingler, M., Ameli, N., Rickman, J., and Schmidt, J. (2023). Large-scale green grabbing for wind and solar PV development in Brazil. <https://doi.org/10.31223/X5ND6Q>.
 110. Simmons, A.J. (1987). Consent and Fairness in Planning Land Use. <https://philpapers.org/rec/SIMCAF>.
 111. Gorayeb, A., Brannstrom, C., Meireles, A., and Mendes, J. (2018). Wind power gone bad: Critiquing wind power planning processes in northeastern Brazil. *Energy Res. Soc. Sci.* 40, 82–88. 10.1016/j.erss.2017.11.027.
 112. Sovacool, B.K., Turnheim, B., Hook, A., Brock, A., and Martiskainen, M. (2021). Dispossessed by decarbonisation: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways. *World Dev.* 137, 105116. 10.1016/j.worlddev.2020.105116.
 113. Normann, S. (2021). Green colonialism in the Nordic context: Exploring Southern Saami representations of wind energy development. *J. Community Psychol.* 49, 77–94. 10.1002/jcop.22422.
 114. Lawrence, R. (2014). Internal Colonisation and Indigenous Resource Sovereignty: Wind Power Developments on Traditional Saami Lands. *Environ. Plan. Soc. Space* 32, 1036–1053. 10.1068/d9012.
 115. Larsen, R.K. (2022). The impacts of mining on Sámi lands: a knowledge synthesis from three reindeer herding

- districts. *Extr. Ind. Soc.* 10.1016/j.exis.2022.101051.
116. Brannstrom, C., Gorayeb, A., De Sousa Mendes, J., Loureiro, C., Meireles, A.J.D.A., Silva, E.V.D., Freitas, A.L.R.D., and Oliveira, R.F.D. (2017). Is Brazilian wind power development sustainable? Insights from a review of conflicts in Ceará state. *Renew. Sustain. Energy Rev.* 67, 62–71. 10.1016/j.rser.2016.08.047.
117. Traldi, M. (2021). Accumulation by dispossession and green grabbing: wind farms, lease agreements, land appropriation in the Brazilian semiarid. *Ambiente Soc.* 24, e00522. 10.1590/1809-4422asoc20200052r2vu2021L4TD.
118. Velasco-Herrejón, P., and Savaresi, A. (2019). Wind Energy, Benefit-Sharing and Indigenous Peoples: Lessons From the Isthmus of Tehuantepec, Southern Mexico. *SSRN Electron. J.* 10.2139/ssrn.3337142.
119. Avila-Calero, S. (2017). Contesting energy transitions: wind power and conflicts in the Isthmus of Tehuantepec. *J. Polit. Ecol.* 24, 10.2458/v24i1.20979.
120. Dunlap, A. (2017). Counterinsurgency for wind energy: the Bii Hioxo wind park in Juchitán, Mexico. *J. Peasant Stud.* 45, 1–23. 10.1080/03066150.2016.1259221.
121. O'Neill, L., Thorburn, K., Riley, B., Maynard, G., Shirlow, E., and Hunt, J. (2021). Renewable energy development on the Indigenous Estate: Free, prior and informed consent and best practice in agreement-making in Australia. *Energy Res. Soc. Sci.* 81, 102252. 10.1016/j.erss.2021.102252.
122. Solman, H., Smits, M., van Vliet, B., and Bush, S. (2021). Co-production in the wind energy sector: A systematic literature review of public engagement beyond invited stakeholder participation. *Energy Res. Soc. Sci.* 72, 101876. 10.1016/j.erss.2020.101876.
123. Fast, S., Mabee, W., Baxter, J., Christidis, T., Driver, L., Hill, S., McMurtry, J.J., and Tomkow, M. (2016). Lessons learned from Ontario wind energy disputes. *Nat. Energy* 1, 1–7. 10.1038/nenergy.2015.28.
124. Baxter, J., Walker, C., Ellis, G., Devine-Wright, P., Adams, M., and Fullerton, R. (2020). Scale, history and justice in community wind energy: An empirical review. *Energy Res. Soc. Sci.* 68, 101532. 10.1016/j.erss.2020.101532.
125. Scherhauser, P., Höltinger, S., Salak, B., Schuppenlehner, T., and Schmidt, J. (2018). A participatory integrated assessment of the social acceptance of wind energy. *Energy Res. Soc. Sci.* 45, 164–172. 10.1016/j.erss.2018.06.022.
126. Scherhauser, P. (2021). The complex relations between justice and participation in collaborative planning processes for a renewable energy transition. In *Routledge Handbook of Energy Democracy* (Routledge).
127. Carrara, S., Alves, D.P., Plazzotta, B., and Pavel, C. (2020). Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system (JRC) 10.2760/160859.
128. Wolsink, M. (2018). Co-production in distributed generation: renewable energy and creating space for fitting infrastructure within landscapes. *Landsc. Res.* 43, 542–561. 10.1080/01426397.2017.1358360.
129. Petrova, M.A. (2016). From NIMBY to acceptance: Toward a novel framework — VESPA — For organizing and interpreting community concerns. *Renew. Energy* 86, 1280–1294. 10.1016/j.renene.2015.09.047.
130. Suškevičs, M., Eiter, S., Martinat, S., Stober, D., Vollmer, E., de Boer, C.L., and Buchecker, M. (2019). Regional variation in public acceptance of wind energy development in Europe: What are the roles of planning procedures and participation? *Land Use Policy* 81, 311–323. 10.1016/j.landusepol.2018.10.032.
131. Spielhofer, R., Thrash, T., Hayek, U.W., Grêt-Regamey, A., Salak, B., Grübel, J., and Schinazi, V.R. (2021). Physiological and behavioral reactions to renewable energy systems in various landscape types. *Renew. Sustain. Energy Rev.* 135, 110410. 10.1016/j.rser.2020.110410.
132. Molnarova, K., Sklenicka, P., Stiborek, J., Svobodova, K., Salek, M., and Brabec, E. (2012). Visual preferences for wind turbines: Location, numbers and respondent characteristics. *Appl. Energy* 92, 269–278.

- 10.1016/j.apenergy.2011.11.001.
133. McKenna, R., Weinand, J.M., Mulalic, I., Petrović, S., Mainzer, K., Preis, T., and Moat, H.S. (2021). Scenicness assessment of onshore wind sites with geotagged photographs and impacts on approval and cost-efficiency. *Nat. Energy* 6, 663–672. 10.1038/s41560-021-00842-5.
134. McKenna, R., Mulalic, I., Soutar, I., Weinand, J.M., Price, J., Petrović, S., and Mainzer, K. (2022). Exploring trade-offs between landscape impact, land use and resource quality for onshore variable renewable energy: an application to Great Britain. *Energy* 250, 123754. 10.1016/j.energy.2022.123754.
135. Tafarte, P., and Lehmann, P. (2023). Quantifying trade-offs for the spatial allocation of onshore wind generation capacity – A case study for Germany. *Ecol. Econ.* 209, 107812. 10.1016/j.ecolecon.2023.107812.
136. Weinand, J.M., McKenna, R., Heinrichs, H., Roth, M., Stolten, D., and Fichtner, W. (2022). Exploring the trilemma of cost-efficiency, landscape impact and regional equality in onshore wind expansion planning. *Adv. Appl. Energy* 7, 100102. 10.1016/j.adapen.2022.100102.
137. Roth, M., Hildebrandt, S., and Röhner, S. (2018). *Landscape as an Area as Perceived by People: Empirically-based Nationwide Modelling of Scenic Landscape Quality in Germany* (Wichmann Verlag).
138. Seresinhe, C.I., Moat, H.S., and Preis, T. (2018). Quantifying scenic areas using crowdsourced data. *Environ. Plan. B Urban Anal. City Sci.* 45, 567–582. 10.1177/0265813516687302.
139. Palmer, J.F. (2022). Deconstructing viewshed analysis makes it possible to construct a useful visual impact map for wind projects. *Landsc. Urban Plan.* 225, 104423. 10.1016/j.landurbplan.2022.104423.
140. Chias, P., and Abad, T. (2013). Wind farms: GIS-based visual impact assessment and visualization tools. *Cartogr. Geogr. Inf. Sci.* 40, 229–237. 10.1080/15230406.2013.809231.
141. Betakova, V., Vojar, J., and Sklenicka, P. (2015). Wind turbines location: How many and how far? *Appl. Energy* 151, 23–31. 10.1016/j.apenergy.2015.04.060.
142. Spielhofer, R., Hunziker, M., Kienast, F., Wissen Hayek, U., and Grêt-Regamey, A. (2021). Does rated visual landscape quality match visual features? An analysis for renewable energy landscapes. *Landsc. Urban Plan.* 209, 104000. 10.1016/j.landurbplan.2020.104000.
143. Karasov, O., Vieira, A.A.B., Kylvik, M., and Chervanyov, I. (2020). Landscape coherence revisited: GIS-based mapping in relation to scenic values and preferences estimated with geolocated social media data. *Ecol. Indic.* 111, 105973. 10.1016/j.ecolind.2019.105973.
144. Radford, S.L., Senn, J., and Kienast, F. (2019). Indicator-based assessment of wilderness quality in mountain landscapes. *Ecol. Indic.* 97, 438–446. 10.1016/j.ecolind.2018.09.054.
145. Brunner, E.J., and Schwegman, D.J. (2022). Commercial wind energy installations and local economic development: Evidence from U.S. counties. *Energy Policy* 165, 112993. 10.1016/j.enpol.2022.112993.
146. Zerrahn, A. (2017). Wind Power and Externalities. *Ecol. Econ.* 141, 245–260. 10.1016/j.ecolecon.2017.02.016.
147. Simos, J., Cantoreggi, N., Christie, D., and Forbat, J. (2019). Wind turbines and health: a review with suggested recommendations. *Environ. Risques Santé.* 10.1684/ers.2019.1281.
148. Schütt, M. (2024). Wind Turbines and Property Values: A Meta-Regression Analysis. *Environ. Resour. Econ.* 87, 1–43. 10.1007/s10640-023-00809-y.
149. Langer, K., Decker, T., Roosen, J., and Menrad, K. (2016). A qualitative analysis to understand the acceptance of wind energy in Bavaria. *Renew. Sustain. Energy Rev.* 64, 248–259. 10.1016/j.rser.2016.05.084.
150. Wehrle, S., Gruber, K., and Schmidt, J. (2021). The cost of undisturbed landscapes. *Energy Policy* 159, 112617. 10.1016/j.enpol.2021.112617.
151. Renewable Energy and Jobs - Annual Review 2022 (2022). <https://www.irena.org/publica>

- tions/2022/Sep/Renewable-Energy-and-Jobs-Annual-Review-2022.
152. Xie, J.J., Martin, M., Rogelj, J., and Staffell, I. (2023). Distributional labour challenges and opportunities for decarbonizing the US power system. *Nat. Clim. Change* 13, 1203–1212. 10.1038/s41558-023-01802-5.
 153. Costa, H., and Veiga, L. (2021). Local labor impact of wind energy investment: An analysis of Portuguese municipalities. *Energy Econ.* 94, 105055. 10.1016/j.eneco.2020.105055.
 154. van Kamp, I., and van den Berg, F. (2021). Health Effects Related to Wind Turbine Sound: An Update. *Int. J. Environ. Res. Public Health* 18, 9133. 10.3390/ijerph18179133.
 155. Karanikas, N., Steele, S., Bruschi, K., Robertson, C., Kass, J., Popovich, A., and MacFadyen, C. (2021). Occupational health hazards and risks in the wind industry. *Energy Rep.* 7, 3750–3759. 10.1016/j.egyr.2021.06.066.
 156. Onakpoya, I.J., O’Sullivan, J., Thompson, M.J., and Heneghan, C.J. (2015). The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies. *Environ. Int.* 82, 1–9. 10.1016/j.envint.2015.04.014.
 157. Shepherd, D., McBride, D., Welch, D., Dirks, K., and Hill, E. (2011). Wind turbine noise and health-related quality of life of nearby residents: a cross sectional study in New Zealand.
 158. Pedersen, E., and Persson Waye, K. (2004). Perception and annoyance due to wind turbine noise—a dose–response relationship. *J. Acoust. Soc. Am.* 116, 3460–3470. 10.1121/1.1815091.
 159. Pedersen, E., and Persson Waye, K. (2007). Wind turbine noise, annoyance and self-reported health and well-being in different living environments. *Occup. Environ. Med.* 64, 480–486. 10.1136/oem.2006.031039.
 160. Doolan, C. (2013). A Review of Wind Turbine Noise Perception, Annoyance and Low Frequency Emission. *Wind Eng.* 37, 97–104. 10.1260/0309-524X.37.1.97.
 161. Hübner, G., Pohl, J., Hoen, B., Firestone, J., Rand, J., Elliott, D., and Haac, R. (2019). Monitoring annoyance and stress effects of wind turbines on nearby residents: A comparison of U.S. and European samples. *Environ. Int.* 132, 105090. 10.1016/j.envint.2019.105090.
 162. Haac, R., Darlow, R., Kaliski, K., Rand, J., and Hoen, B. (2022). In the shadow of wind energy: Predicting community exposure and annoyance to wind turbine shadow flicker in the United States. *Energy Res. Soc. Sci.* 87, 102471. 10.1016/j.erss.2021.102471.
 163. Radun, J., Maula, H., Saarinen, P., Keränen, J., Alakoivu, R., and Hongisto, V. (2022). Health effects of wind turbine noise and road traffic noise on people living near wind turbines. *Renew. Sustain. Energy Rev.* 157, 112040. 10.1016/j.rser.2021.112040.
 164. Michaud, D.S., Feder, K., Keith, S.E., Voicescu, S.A., Marro, L., Than, J., Guay, M., Denning, A., McGuire, D., Bower, T., et al. (2016). Exposure to wind turbine noise: Perceptual responses and reported health effects. *J. Acoust. Soc. Am.* 139, 1443–1454. 10.1121/1.4942391.
 165. Rogers, J. (2020). Optimal strategies for wind turbine environmental curtailment. *Wind Energy* 23, 1331–1350. 10.1002/we.2489.
 166. Keane, A., Milligan, M., Dent, C.J., Hasche, B., D’Annunzio, C., Dragoon, K., Holttinen, H., Samaan, N., Soder, L., and O’Malley, M. (2011). Capacity Value of Wind Power. *IEEE Trans. Power Syst.* 26, 564–572. 10.1109/TPWRS.2010.2062543.
 167. Staffell, I., and Pfenninger, S. (2018). The increasing impact of weather on electricity supply and demand. *Energy* 145, 65–78. 10.1016/j.energy.2017.12.051.
 168. Krohn, S., Morthorst, P.-E., and Awerbuch, S. The Economics of Wind Energy (EWEA (The European Wind Energy Association)).
 169. Hirth, L., Ueckerdt, F., and Edenhofer, O. (2015). Integration costs revisited – An economic framework for wind and solar variability. *Renew. Energy* 74, 925–939. 10.1016/j.renene.2014.08.065.
 170. Odeh, R.P., and Watts, D. (2019). Impacts of wind and solar spatial diversification on its market value: A case study of the Chilean electricity market. *Renew. Sustain. Energy Rev.* 111, 442–461. 10.1016/j.rser.2019.01.015.
 171. Schmidt, O., and Staffell, I. (2023). Monetizing Energy Storage: A Toolkit to Assess

- Future Cost and Value (Oxford University Press).
172. Biancardi, A., Di Castelnuovo, M., and Staffell, I. (2021). A framework to evaluate how European Transmission System Operators approach innovation. *Energy Policy* 158, 112555. 10.1016/j.enpol.2021.112555.
 173. IARC Non-ionizing Radiation, Part 1: Static and Extremely Low-frequency (ELF) Electric and Magnetic Fields.
 174. Carpenter, D.O. (2019). Extremely low frequency electromagnetic fields and cancer: How source of funding affects results. *Environ. Res.* 178, 108688. 10.1016/j.envres.2019.108688.
 175. Sharpton, T., Lawrence, T., and Hall, M. (2020). Drivers and barriers to public acceptance of future energy sources and grid expansion in the United States. *Renew. Sustain. Energy Rev.* 126, 109826. 10.1016/j.rser.2020.109826.
 176. Harold, J., Bertsch, V., Lawrence, T., and Hall, M. (2021). Drivers of People's Preferences for Spatial Proximity to Energy Infrastructure Technologies: A Cross-country Analysis. *Energy J.* 42. 10.5547/01956574.42.4.jhar.
 177. Bertsch, V., Hall, M., Weinhardt, C., and Fichtner, W. (2016). Public acceptance and preferences related to renewable energy and grid expansion policy: Empirical insights for Germany. *Energy* 114, 465–477. 10.1016/j.energy.2016.08.022.
 178. Welder, L., Ryberg, D.S., Kotzur, L., Grube, T., Robinius, M., and Stolten, D. (2018). Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. *Energy* 158, 1130–1149. 10.1016/j.energy.2018.05.059.
 179. Samsatli, S., Staffell, I., and Samsatli, N.J. (2016). Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport sector in Great Britain. *Int. J. Hydrog. Energy* 41, 447–475. 10.1016/j.ijhydene.2015.10.032.
 180. Hunter, C.A., Penev, M.M., Reznicek, E.P., Eichman, J., Rustagi, N., and Baldwin, S.F. (2021). Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids. *Joule* 5, 2077–2101. 10.1016/j.joule.2021.06.018.
 181. Sepulveda, N.A., Jenkins, J.D., Edington, A., Mallapragada, D.S., and Lester, R.K. (2021). The design space for long-duration energy storage in decarbonized power systems. *Nat. Energy* 6, 506–516. 10.1038/s41560-021-00796-8.
 182. Pastore, L.M., Lo Basso, G., Ricciardi, G., and de Santoli, L. (2022). Synergies between Power-to-Heat and Power-to-Gas in renewable energy communities. *Renew. Energy* 198, 1383–1397. 10.1016/j.renene.2022.08.141.
 183. Leinauer, C., Schott, P., Fridgen, G., Keller, R., Ollig, P., and Weibelzahl, M. (2022). Obstacles to demand response: Why industrial companies do not adapt their power consumption to volatile power generation. *Energy Policy* 165, 112876. 10.1016/j.enpol.2022.112876.
 184. Höschle, H., De Jonghe, C., Le Cadre, H., and Belmans, R. (2017). Electricity markets for energy, flexibility and availability — Impact of capacity mechanisms on the remuneration of generation technologies. *Energy Econ.* 66, 372–383. 10.1016/j.eneco.2017.06.024.
 185. Khalid, M. (2024). Smart grids and renewable energy systems: Perspectives and grid integration challenges. *Energy Strategy Rev.* 51, 101299. 10.1016/j.esr.2024.101299.
 186. Gandoman, F.H., Ahmadi, A., Sharaf, A.M., Siano, P., Pou, J., Hredzak, B., and Agelidis, V.G. (2018). Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems. *Renew. Sustain. Energy Rev.* 82, 502–514. 10.1016/j.rser.2017.09.062.
 187. Rancilio, G., Rossi, A., Falabretti, D., Galliani, A., and Merlo, M. (2022). Ancillary services markets in Europe: Evolution and regulatory trade-offs. *Renew. Sustain. Energy Rev.* 154, 111850. 10.1016/j.rser.2021.111850.
 188. Gils, H.C., Scholz, Y., Pregger, T., Luca de Tena, D., and Heide, D. (2017). Integrated modelling of variable renewable energy-based power supply in Europe. *Energy* 123, 173–188. 10.1016/j.energy.2017.01.115.
 189. Schlachtberger, D.P., Brown, T., Schäfer, M.,

- Schramm, S., and Greiner, M. (2018). Cost optimal scenarios of a future highly renewable European electricity system: Exploring the influence of weather data, cost parameters and policy constraints. *Energy* 163, 100–114. 10.1016/j.energy.2018.08.070.
190. Zappa, W., Junginger, M., and van den Broek, M. (2019). Is a 100% renewable European power system feasible by 2050? *Appl. Energy* 233–234, 1027–1050. 10.1016/j.apenergy.2018.08.109.
191. Joos, M., and Staffell, I. (2018). Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany. *Renew. Sustain. Energy Rev.* 86, 45–65. 10.1016/j.rser.2018.01.009.
192. Kahrl, F., Kim, J., Mills, A., Wisser, R., Montañés, C., and Gorman, W. (2021). Variable Renewable Energy Participation in U.S. Ancillary Services Markets: Economic Evaluation and Key Issues.
193. Heptonstall, P.J., and Gross, R.J.K. (2021). A systematic review of the costs and impacts of integrating variable renewables into power grids. *Nat. Energy* 6, 72–83. 10.1038/s41560-020-00695-4.
194. Wind Energy and the Electric Power System (2011). In *Wind Energy Handbook* (John Wiley & Sons, Ltd), pp. 565–612. 10.1002/9781119992714.ch10.
195. Sensfuß, F., Ragwitz, M., and Genoese, M. (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. *Energy Policy* 36, 3086–3094. 10.1016/j.enpol.2008.03.035.
196. Cludius, J., Hermann, H., Matthes, F.Chr., and Graichen, V. (2014). The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications. *Energy Econ.* 44, 302–313. 10.1016/j.eneco.2014.04.020.
197. Antweiler, W., and Muesgens, F. (2021). On the long-term merit order effect of renewable energies. *Energy Econ.* 99, 105275. 10.1016/j.eneco.2021.105275.
198. Brancucci Martinez-Anido, C., Brinkman, G., and Hodge, B.-M. (2016). The impact of wind power on electricity prices. *Renew. Energy* 94, 474–487. 10.1016/j.renene.2016.03.053.
199. Green, R., and Staffell, I. (2021). The contribution of taxes, subsidies, and regulations to British electricity decarbonization. *Joule* 5, 2625–2645. 10.1016/j.joule.2021.09.011.
200. Yagi, K., and Sioshansi, R. (2021). Do Renewables Drive Coal-Fired Generation Out of Electricity Markets? *Curr. Sustain. Energy Rep.* 8, 222–232. 10.1007/s40518-021-00189-1.
201. Hogan, W.W. ON AN “ENERGY ONLY” ELECTRICITY MARKET DESIGN FOR RESOURCE ADEQUACY.
202. Hildmann, M., Ulbig, A., and Andersson, G. (2015). Empirical Analysis of the Merit-Order Effect and the Missing Money Problem in Power Markets With High RES Shares. *IEEE Trans. Power Syst.* 30, 1560–1570. 10.1109/TPWRS.2015.2412376.
203. Twomey, P., and Neuhoff, K. (2010). Wind power and market power in competitive markets. *Energy Policy* 38, 3198–3210. 10.1016/j.enpol.2009.07.031.
204. Hirth, L. (2013). The market value of variable renewables. *Energy Econ.* 38, 218–236. 10.1016/j.eneco.2013.02.004.
205. Welisch, M., Ortner, A., and Resch, G. (2016). Assessment of RES technology market values and the merit-order effect – an econometric multi-country analysis. *Energy Environ.* 27, 105–121. 10.1177/0958305X16638574.
206. Staffell, I. (2017). Measuring the progress and impacts of decarbonising British electricity. *Energy Policy* 102, 463–475. 10.1016/j.enpol.2016.12.037.
207. Projected Costs of Generating Electricity 2020 – Analysis IEA. <https://www.iea.org/reports/projected-costs-of-generating-electricity-2020>.
208. Brouwer, A.S., van den Broek, M., Zappa, W., Turkenburg, W.C., and Faaij, A. (2016). Least-cost options for integrating intermittent renewables in low-carbon power systems. *Appl. Energy* 161, 48–74. 10.1016/j.apenergy.2015.09.090.
209. Heuberger, C.F., Staffell, I., Shah, N., and Mac Dowell, N. (2018). Impact of myopic decision-making and disruptive events in power

- systems planning. *Nat. Energy* 3, 634–640. 10.1038/s41560-018-0159-3.
210. Ueckerdt, F., Hirth, L., Luderer, G., and Edenhofer, O. (2013). System LCOE: What are the costs of variable renewables? *Energy* 63, 61–75. 10.1016/j.energy.2013.10.072.
211. Matsuo, Y., and Komiyama, R. (2021). System LCOE of variable renewable energies: a case study of Japan's decarbonized power sector in 2050. *Sustain. Sci.* 16, 449–461. 10.1007/s11625-021-00914-1.
212. Loth, E., Qin, C., Simpson, J.G., and Dykes, K. (2022). Why we must move beyond LCOE for renewable energy design. *Adv. Appl. Energy* 8, 100112. 10.1016/j.adapen.2022.100112.
213. Halttunen, K., Staffell, I., Slade, R., Green, R., Saint-Drenan, Y.-M., and Jansen, M. (2020). Global Assessment of the Merit-Order Effect and Revenue Cannibalisation for Variable Renewable Energy. Preprint, 10.2139/ssrn.3741232 10.2139/ssrn.3741232.
214. Cole, W.J., Greer, D., Denholm, P., Frazier, A.W., Machen, S., Mai, T., Vincent, N., and Baldwin, S.F. (2021). Quantifying the challenge of reaching a 100% renewable energy power system for the United States. *Joule* 5, 1732–1748. 10.1016/j.joule.2021.05.011.
215. Mai, T., Denholm, P., Brown, P., Cole, W., Hale, E., Lamers, P., Murphy, C., Ruth, M., Sergi, B., Steinberg, D., et al. (2022). Getting to 100%: Six strategies for the challenging last 10%. *Joule* 6, 1981–1994. 10.1016/j.joule.2022.08.004.
216. Kyritsis, E., Andersson, J., and Serletis, A. (2017). Electricity prices, large-scale renewable integration, and policy implications. *Energy Policy* 101, 550–560. 10.1016/j.enpol.2016.11.014.
217. Jansen, M., Beiter, P., Riepin, I., Müsgens, F., Guajardo-Fajardo, V.J., Staffell, I., Bulder, B., and Kitzing, L. (2022). Policy choices and outcomes for offshore wind auctions globally. *Energy Policy* 167, 113000. 10.1016/j.enpol.2022.113000.
218. Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., and Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. *Nat. Energy* 5, 614–622. 10.1038/s41560-020-0661-2.
219. Power System Economics: Designing Markets for Electricity | Wiley Wiley.com. <https://www.wiley.com/en-gb/Power+System+Economics%3A+Designing+Markets+for+Electricity-p-9780471150404>.
220. Riesz, J., and Milligan, M. (2015). Designing electricity markets for a high penetration of variable renewables. *WIREs Energy Environ.* 4, 279–289. 10.1002/wene.137.
221. Brown, T., and Reichenberg, L. (2021). Decreasing market value of variable renewables can be avoided by policy action. *Energy Econ.* 100, 105354. 10.1016/j.eneco.2021.105354.
222. Review of electricity market arrangements (2022). GOV.UK. <https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements>.
223. Klessmann, C., Nabe, C., and Burges, K. (2008). Pros and cons of exposing renewables to electricity market risks—A comparison of the market integration approaches in Germany, Spain, and the UK. *Energy Policy* 36, 3646–3661. 10.1016/j.enpol.2008.06.022.
224. Hiroux, C., and Saguan, M. (2010). Large-scale wind power in European electricity markets: Time for revisiting support schemes and market designs? *Energy Policy* 38, 3135–3145. 10.1016/j.enpol.2009.07.030.
225. Handbook on Electricity Markets <https://www.e-elgar.com/shop/gbp/handbook-on-electricity-markets-9781788979948.html>.
226. Diesendorf, M., and Elliston, B. (2018). The feasibility of 100% renewable electricity systems: A response to critics. *Renew. Sustain. Energy Rev.* 93, 318–330. 10.1016/j.rser.2018.05.042.
227. Morales-España, G., Algarvio, H., De Vries, L., Faia, R., Hernandez-Serna, R., and Johanndeiter, S. (2020). Market design for a reliable 100% renewable electricity system (TU Delft).
228. Blondeel, M., Bradshaw, M.J., Bridge, G., and Kuzemko, C. (2021). The geopolitics of energy system transformation: A review. *Geogr. Compass*, 1–22. 10.1111/gec3.12580.

229. Kuzemko, C., Blondeel, M., Dupont, C., and Brisbois, M.C. (2022). Russia ' s war on Ukraine , European energy policy responses & implications for sustainable transformations. *Energy Res. Soc. Sci.* 93, 102842. 10.1016/j.erss.2022.102842.
230. Kelanic, R.A. (2016). The Petroleum Paradox: Oil, Coercive Vulnerability, and Great Power Behavior. *Secur. Stud.* 25, 181–213. 10.1080/09636412.2016.1171966.
231. Sharples, J.D. (2016). The shifting geopolitics of Russia's natural gas exports and their impact on EU-Russia gas relations. *Geopolitics* 21, 880–912. 10.1080/14650045.2016.1148690.
232. Boute, A. (2022). Weaponizing Energy: Energy, Trade, and Investment Law in the New Geopolitical Reality. *Am. J. Int. Law* 116, 740–751. 10.1017/ajil.2022.53.
233. Hafner, M., and Tagliapietra, S. (2020). The Geopolitics of the Global Energy Transition. 10.1007/978-3-030-39066-2.
234. Vakulchuk, R., Overland, I., and Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renew. Sustain. Energy Rev.* 122, 109547. 10.1016/j.rser.2019.109547.
235. Månsson, A. (2015). A resource curse for renewables? Conflict and cooperation in the renewable energy sector. *Energy Res. Soc. Sci.* 10, 1–9. 10.1016/j.erss.2015.06.008.
236. Gupta, M., Dennehy, D., Parra, C.M., Mäntymäki, M., and Dwivedi, Y.K. (2023). Fake news believability: The effects of political beliefs and espoused cultural values. *Inf. Manage.* 60, 103745. 10.1016/j.im.2022.103745.
237. Goldthau, A., Westphal, K., Bazilian, M., and Bradshaw, M. (2019). How the energy transition will reshape geopolitics. *Nature* 569, 29–31.
238. Tao, Y., Liang, H., and Celia, M.A. (2020). Electric power development associated with the Belt and Road Initiative and its carbon emissions implications. *Appl. Energy* 267, 114784. 10.1016/j.apenergy.2020.114784.
239. Sovacool, B.K., Bazilian, M.D., Kim, J., and Griffiths, S. (2023). Six bold steps towards net-zero industry. *Energy Res. Soc. Sci.* 99, 103067. 10.1016/j.erss.2023.103067.
240. Li, J., Peng, K., Wang, P., Zhang, N., Feng, K., Guan, D., Meng, J., Wei, W., and Yang, Q. (2021). Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions. *One Earth* 3, 116–125. 10.1016/j.oneear.2020.06.009.
241. Schäfer, B., Gasparon, M., and Storm, P. (2020). European Raw Materials Alliance—a new initiative to increase raw material resilience for a greener Europe. *Miner. Econ.* 33, 415–416. 10.1007/s13563-020-00241-4.
242. Securing America's Clean Energy Supply Chain Energy.gov. <https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain>.
243. Conrad, B., and Kostka, G. (2017). Chinese investments in Europe ' s energy sector: Risks and opportunities? *Energy Policy* 101, 644–648. 10.1016/j.enpol.2016.12.016.
244. Gong, X. (2022). Energy security through a financial lens: Rethinking geopolitics , strategic investment , and governance in China ' s global energy expansion. *Energy Res. Soc. Sci.* 83, 102341. 10.1016/j.erss.2021.102341.
245. Vakulchuk, R., Overland, I., and Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renew. Sustain. Energy Rev.* 122, 109547. 10.1016/j.rser.2019.109547.
246. Mercure, J.-F., Salas, P., Vercoulen, P., Semieniuk, G., Lam, A., Pollitt, H., Holden, P.B., Vaklifard, N., Chewpreecha, U., Edwards, N.R., et al. (2021). Reframing incentives for climate policy action. *Nat. Energy* 6, 1133–1143. 10.1038/s41560-021-00934-2.
247. Overland, I. (2019). The geopolitics of renewable energy: Debunking four emerging myths. *Energy Res. Soc. Sci.* 49, 36–40. 10.1016/j.erss.2018.10.018.
248. Overland, I., Juraev, J., and Vakulchuk, R. (2022). Are renewable energy sources more evenly distributed than fossil fuels? *Renew. Energy* 200, 379–386. 10.1016/j.renene.2022.09.046.
249. Apergi, M., Zimmermann, E., Weko, S., and Lilliestam, J. (2023). Is renewable energy technology trade more or less conflictive than other trade? *Energy Policy* 177, 113538. 10.1016/j.enpol.2023.113538.

250. Hache, E. (2018). Do renewable energies improve energy security in the long run? *Int. Econ.* 156, 127–135. 10.1016/j.inteco.2018.01.005.
251. Sabev, E., Trifonov, R., Pavlova, G., and Rainova, K. (2021). Cybersecurity Analysis of Wind Farm SCADA Systems. In 2021 International Conference on Information Technologies (InfoTech), pp. 1–5. 10.1109/InfoTech52438.2021.9548589.
252. Freeman, S., Gentle, J., and Conway, T. (2020). Cyber resiliency within offshore wind applications. *Mar. Technol. Soc. J.* 54, 108–113. 10.4031/MTSJ.54.6.10.
253. Wehrmann, B. (2022). Repeated cyberattacks cause concern about German wind industry's IT security. *Clean Energy Wire*.
254. Willuhn, M. (2022). Satellite cyber attack paralyzes 11 GW of German wind turbines. *PV Mag. Int.*, 7.
255. Boschetti, N., Gordon, N.G., and Gregory, F. (2022). Space Cybersecurity Lessons Learned from The ViaSat Cyberattack. In AIAA 2022-4380. ASCEND 2022. October 2022.
256. Meza, E. (2022). Security official concerned over Chinese involvement in German wind sector. *Clean Energy Wire*.
257. Dowse, A., and Bachmann, S.D. (2022). Information warfare: methods to counter disinformation. *Def. Secur. Anal.* 0, 1–17. 10.1080/14751798.2022.2117285.
258. Winter, K., Hornsey, M.J., Pummerer, L., and Sassenberg, K. (2022). Anticipating and defusing the role of conspiracy beliefs in shaping opposition to wind farms. *Nat. Energy* 7, 1200–1207. 10.1038/s41560-022-01164-w.
259. Lee, Y., and Dacass, T. (2022). Reducing the United States' risks of dependency on China in the rare earth market. *Resour. Policy* 77, 102702. 10.1016/j.resourpol.2022.102702.
260. Closing the Infrastructure Gap for Decarbonization: The Case for an Integrated Mineral Supply Agreement | Environmental Science & Technology <https://pubs.acs.org/doi/10.1021/acs.est.2c05413>.
261. IRENA (2023). World Energy Transitions Outlook 2023: 1.5°C Pathway (International Renewable Energy Agency, Abu Dhabi.).
262. Content, C. (2023). Cyber Resilience for Wind Power Installations. *POWER Mag.* <https://www.powermag.com/cyber-resilience-for-wind-power-installations/>.
263. Benegal, S., and Scruggs, L. (2024). Blame over blackouts: Correcting partisan misinformation regarding renewable energy in the United States. *Energy Res. Soc. Sci.* 113, 103543. 10.1016/j.erss.2024.103543.
264. Liebe, U., and Dobers, G.M. (2019). Decomposing public support for energy policy: What drives acceptance of and intentions to protest against renewable energy expansion in Germany? *Energy Res. Soc. Sci.* 47, 247–260. 10.1016/j.erss.2018.09.004.
265. Jamalzadeh, S., Barker, K., González, A.D., and Radhakrishnan, S. (2022). Protecting infrastructure performance from disinformation attacks. *Sci. Rep.* 12, 12707. 10.1038/s41598-022-16832-w.
266. Wind energy in Europe: 2022 Statistics and the outlook for 2023-2027 WindEurope. <https://windeurope.org/data-and-analysis/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027>.
267. Rand, J., Bolinger, M., Wiser, R., Jeong, S., and Paulos, B. (2021). Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2020 10.2172/1784303.
268. Sud, R., and Patnaik, S. How does permitting for clean energy infrastructure work? Brookings. <https://www.brookings.edu/articles/how-does-permitting-for-clean-energy-infrastructure-work/>.
269. Bird, L., and McLaughlin, K. (2023). US Clean Energy Goals Hinge on Faster Permitting. <https://www.wri.org/insights/clean-energy-permitting-reform-us>.
270. Kahn, R. (2000). Siting Struggles: The Unique Challenge of Permitting Renewable Energy Power Plants. *Electr. J.* 13, 21–33.
271. Nadai, A. (2007). "Planning", "siting" and the local acceptance of wind power: Some lessons from the French case. *Energy Policy* 35, 2715–2726.
272. Pettersson, M., Ek, K., Söderholm, K., and

- Söderholm, P. (2010). Wind power planning and permitting: Comparative perspectives from the Nordic countries. *Renew. Sustain. Energy Rev.* 14, 3116–3123.
273. Lauf, T., Ek, K., Gawel, E., Lehmann, P., and Söderholm, P. (2019). The regional heterogeneity of wind power deployment: an empirical investigation of land-use policies in Germany and Sweden. *J. Environ. Plan. Manag.* 63, 1–28. 10.1080/09640568.2019.1613221.
274. Mann, T. (2023). Cutting Off the Heads of the Hydra: Current Reforms in German Administrative Litigation Law. *ELTE Law J.*, 85–94. 10.54148/ELTELJ.2023.1.85.
275. Abbott, J.A. (2010). The Localized and Scaled Discourse of Conservation for Wind Power in Kittitas County, Washington. *Soc. Nat. Resour.* 23, 969–985. 10.1080/08941920802438634.
276. Anshelm, J., and Haikola, S. (2016). Power production and environmental opinions – Environmentally motivated resistance to wind power in Sweden. *Renew. Sustain. Energy Rev.* 57, 1545–1555. 10.1016/j.rser.2015.12.211.
277. Arifi, B., and Winkel, G. (2020). Wind energy counter-conducts in Germany: understanding a new wave of socio-environmental grassroots protest. *Environ. Polit.* 30, 1–22. 10.1080/09644016.2020.1792730.
278. Quentin, J. Hemmnisse beim Ausbau Windenergie in Deutschland: Branchenumfrage zu Klagen gegen Windenergieanlagen.
279. Dugstad, A., Grimsrud, K., Kipperberg, G., Lindhjem, H., and Navrud, S. (2020). Acceptance of wind power development and exposure - Not-in-anybody's-backyard. *Energy Policy* 147, 111780. 10.1016/j.enpol.2020.111780.
280. Gardt, M., Broekel, T., and Gareis, P. (2021). Blowing against the winds of change? The relationship between anti-wind initiatives and wind turbines in Germany. *Pap. Evol. Econ. Geogr. PEEG*.
281. Germeshausen, R., Heim, S., and Wagner, U.J. (2023). Support for Renewable Energy: The Case of Wind Power. Preprint, 10.2139/ssrn.3949805 10.2139/ssrn.3949805.
282. Lehmann, P., Gawel, E., Geiger, C., Hauck, J., Reutter, F., Tafarte, P., Thrän, D., and Wolfram, E. (2022). Der Windenergie an Land ausreichend Flächen bereitstellen. <https://home.uni-leipzig.de/multiplee/wp-content/uploads/2022/05/MultiplEE-Policy-Brief-Der-Windenergie-an-Land-ausreichend-Fla%CC%88chen-bereitstellen.pdf>.
283. Quentin, J. (2023). Typische Verfahrenslaufzeiten von Windenergieprojekten Empirische Datenanalyse für den Zeitraum 2011 bis 2022 (Fachagentur Windenergie an Land, Berlin, Germany.).
284. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.) (2018).
285. Ready, Set, Go: Europe's race for wind and solar (2022). Ember. <https://ember-climate.org/insights/research/europes-race-for-wind-and-solar/>.
286. Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (2023).
287. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (2022).
288. Jendroška, J., and Anapyanova, A. (2023). Towards a Green Energy Transition: REPowerEU Directive vs Environmental Acquis. *Elni Rev.*, 1–5. 10.46850/elni.2023.001.
289. Neuendorf, F., von Haaren, C., and Albert, C. (2018). Assessing and coping with uncertainties in landscape planning: an overview. *Landsc. Ecol.* 33, 861–878. 10.1007/s10980-018-0643-y.
290. Neuendorf, F., Thiele, J., Albert, C., and Haaren, C. von (2021). Uncertainties in land use data may have substantial effects on environmental

- planning recommendations: A plea for careful consideration. *PLOS ONE* 16, e0260302. 10.1371/journal.pone.0260302.
291. Hübner, G., Leschinger, V., Müller, F.J.Y., and Pohl, J. (2023). Broadening the social acceptance of wind energy – An Integrated Acceptance Model. *Energy Policy* 173, 113360. 10.1016/j.enpol.2022.113360.
292. Liebe, U., Bartczak, A., and Meyerhoff, J. (2017). A turbine is not only a turbine: The role of social context and fairness characteristics for the local acceptance of wind power. *Energy Policy* 107, 300–308. 10.1016/j.enpol.2017.04.043.
293. Leer Jørgensen, M., Anker, H.T., and Lassen, J. (2020). Distributive fairness and local acceptance of wind turbines: The role of compensation schemes. *Energy Policy* 138, 111294. 10.1016/j.enpol.2020.111294.
294. Lienhoop, N. (2018). Acceptance of wind energy and the role of financial and procedural participation: An investigation with focus groups and choice experiments. *Energy Policy* 118, 97–105. 10.1016/j.enpol.2018.03.063.
295. Vuichard, P., Stauch, A., and Dällenbach, N. (2019). Individual or collective? Community investment, local taxes, and the social acceptance of wind energy in Switzerland. *Energy Res. Soc. Sci.* 58, 101275. 10.1016/j.erss.2019.101275.
296. Knauf, J. (2022). Can't buy me acceptance? Financial benefits for wind energy projects in Germany. *Energy Policy* 165, 112924. 10.1016/j.enpol.2022.112924.
297. Bosch, J., Staffell, I., and Hawkes, A.D. (2018). Temporally explicit and spatially resolved global offshore wind energy potentials. *Energy* 163, 766–781. 10.1016/j.energy.2018.08.153.
298. Offshore Wind Outlook 2019 – Analysis IEA. <https://www.iea.org/reports/offshore-wind-outlook-2019>.
299. Floating offshore wind - A global opportunity (2022). (GWEC (Global Wind Energy Council)).
300. Hywind Scotland <https://www.equinor.com/energy/hywind-scotland>.
301. Windfloat Atlantic project [edp.com. https://www.edp.com/en/innovation/windfloat](https://www.edp.com/en/innovation/windfloat).
302. Hywind Tampen <https://www.equinor.com/energy/hywind-tampen>.
303. Villoslada, D., Santos, M., and Tomás-Rodríguez, M. (2022). TMD stroke limiting influence on barge-type floating wind turbines. *Ocean Eng.* 248, 110781. 10.1016/j.oceaneng.2022.110781.
304. Guo, Y., Wang, H., and Lian, J. (2022). Review of integrated installation technologies for offshore wind turbines: Current progress and future development trends. *Energy Convers. Manag.* 255, 115319. 10.1016/j.enconman.2022.115319.
305. Cranmer, A., Broughel, A.E., Ericson, J., Goldberg, M., and Dharni, K. (2023). Getting to 30 GW by 2030: Visual preferences of coastal residents for offshore wind farms on the US East Coast. *Energy Policy* 173, 113366. 10.1016/j.enpol.2022.113366.
306. Iwata, K., Kyoi, S., and Ushifusa, Y. (2023). Public attitudes of offshore wind energy in Japan: An empirical study using choice experiments. *Clean. Energy Syst.* 4, 100052. 10.1016/j.cles.2023.100052.
307. Farr, H., Ruttenberg, B., Walter, R.K., Wang, Y.-H., and White, C. (2021). Potential environmental effects of deepwater floating offshore wind energy facilities. *Ocean Coast. Manag.* 207, 105611. 10.1016/j.ocecoaman.2021.105611.
308. Maxwell, S.M., Kershaw, F., Locke, C.C., Conners, M.G., Dawson, C., Aylesworth, S., Loomis, R., and Johnson, A.F. (2022). Potential impacts of floating wind turbine technology for marine species and habitats. *J. Environ. Manage.* 307, 114577. 10.1016/j.jenvman.2022.114577.
309. Jansen, M., Duffy, C., Green, T.C., and Staffell, I. (2022). Island in the Sea: The prospects and impacts of an offshore wind power hub in the North Sea. *Adv. Appl. Energy* 6, 100090. 10.1016/j.adapen.2022.100090.
310. North Sea Wind Power Hub TenneT. <https://www.tennet.eu/about-tennet/innovations/north-sea-wind-power-hub>.
311. Committee on Industry, Research and Energy (2021). Opinion of the Committee on Industry, Research and Energy for the Committee on

- Fisheries on the impact on the fishing sector of offshore windfarms and other renewable energy systems (European Parliament).
312. Transport and offshore wind | The European Maritime Spatial Planning Platform (2021). <https://maritime-spatial-planning.ec.europa.eu/sector-information/transport-and-offshore-wind>.
313. ScotWind offshore wind leasing delivers major boost to Scotland's net zero aspirations - News - Crown Estate Scotland (2022). <https://www.crownestatescotland.com/news/scotwind-offshore-wind-leasing-delivers-major-boost-to-scotlands-net-zero-aspirations>.
314. Office of the Prime Minister (2023). Announces the first competitions for offshore wind. Government.no. <https://www.regjeringen.no/en/aktuelt/announces-the-first-competitions-for-offshore-wind/id2969473/>.
315. Fraile, D., Vandenberghe, A., Klonari, V., Ramirez, L., Pineda, I., Tardieu, P., Malvault, B., and Komusanac, I. Getting fit for 55 and set for 2050: Electrifying Europe with wind energy (ETIPWind, WindEurope).
316. Papi, F., and Bianchini, A. (2022). Technical challenges in floating offshore wind turbine upscaling: A critical analysis based on the NREL 5 MW and IEA 15 MW Reference Turbines. *Renew. Sustain. Energy Rev.* *162*, 112489. 10.1016/j.rser.2022.112489.
317. Cottura, L., Caradonna, R., Ghigo, A., Novo, R., Bracco, G., and Mattiazzo, G. (2021). Dynamic Modeling of an Offshore Floating Wind Turbine for Application in the Mediterranean Sea. *Energies* *14*, 248. 10.3390/en14010248.
318. Faraggiana, E., Giorgi, G., Sirigu, M., Ghigo, A., Bracco, G., and Mattiazzo, G. (2022). A review of numerical modelling and optimisation of the floating support structure for offshore wind turbines. *J. Ocean Eng. Mar. Energy* *8*, 433–456. 10.1007/s40722-022-00241-2.
319. BEIS Public Attitudes Tracker: Energy Infrastructure and Energy Sources (2021). (BEIS Public Attitudes Tracker, UK).
320. Soziales Nachhaltigkeitsbarometer der Energie- und Verkehrswende | Ariadne Panel <https://snb.ariadneprojekt.de/start>.
321. Mueller, J.T., and Brooks, M.M. (2020). Burdened by renewable energy? A multi-scalar analysis of distributional justice and wind energy in the United States. *Energy Res. Soc. Sci.* *63*, 101406. 10.1016/j.erss.2019.101406.
322. Rand, J., and Hoen, B. (2017). Thirty years of North American wind energy acceptance research: What have we learned? *Energy Res. Soc. Sci.* *29*, 135–148. 10.1016/j.erss.2017.05.019.
323. Ellis, G., Schneider, N., and Wüstenhagen, R. (2023). Dynamics of social acceptance of renewable energy: An introduction to the concept. *Energy Policy* *181*, 113706. 10.1016/j.enpol.2023.113706.
324. Hedenus, F., Jakobsson, N., Reichenberg, L., and Mattsson, N. (2022). Historical wind deployment and implications for energy system models. *Renew. Sustain. Energy Rev.* *168*, 112813. 10.1016/j.rser.2022.112813.
325. Weinand, J.M., Naber, E., McKenna, R., Lehmann, P., Kotzur, L., and Stolten, D. (2022). Historic drivers of onshore wind power siting and inevitable future trade-offs. *Environ. Res. Lett.* *17*, 074018. 10.1088/1748-9326/ac7603.
326. Collins, S., Deane, P., Ó Gallachóir, B., Pfenninger, S., and Staffell, I. (2018). Impacts of Inter-annual Wind and Solar Variations on the European Power System. *Joule* *2*, 2076–2090. 10.1016/j.joule.2018.06.020.
327. Millstein, D., Wisler, R., Mills, A.D., Bolinger, M., Seel, J., and Jeong, S. (2021). Solar and wind grid system value in the United States: The effect of transmission congestion, generation profiles, and curtailment. *Joule* *5*, 1749–1775. 10.1016/j.joule.2021.05.009.
328. Frew, B., Sergi, B., Denholm, P., Cole, W., Gates, N., Levie, D., and Margolis, R. (2021). The curtailment paradox in the transition to high solar power systems. *Joule* *5*, 1143–1167. 10.1016/j.joule.2021.03.021.
329. Dowling, J.A., Rinaldi, K.Z., Ruggles, T.H., Davis, S.J., Yuan, M., Tong, F., Lewis, N.S., and Caldeira, K. (2020). Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule* *4*, 1907–1928. 10.1016/j.joule.2020.07.007.

330. Lehmann, P., Ammermann, K., Gawel, E., Geiger, C., Hauck, J., Heilmann, J., Meier, J.-N., Ponitka, J., Schicketanz, S., Stemmer, B., et al. (2021). Managing spatial sustainability trade-offs: The case of wind power. *Ecol. Econ.* **185**, 107029. [10.1016/j.ecolecon.2021.107029](https://doi.org/10.1016/j.ecolecon.2021.107029).
331. Velasco Herrejón, P., and Bauwens, T. (2023). Are Energy Transitions Reproducing Inequalities? Power, Social Stigma and Distributive (In)Justice in Mexico. Preprint, [10.2139/ssrn.4407968](https://doi.org/10.2139/ssrn.4407968).

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