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Review

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

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CONTEXT & SCALE Wind energy is currently one of the cheapest renewable energy technologies and plays a central role in many countries' climate and energy strategies. However, like any electricity-generation technology, wind energy affects and interacts with the broader environmental, social, economic, technical, and legal systems it integrates with. These impacts can potentially slow its deployment, delaying progress on essential decarbonization and energy security objectives. Solutions often exist, but challenges remain due to fundamental research gaps and limited understanding of the true scale of impacts. This article identifies four broad impact categories and fourteen individual impacts, which we systematically analyze through a review of over 400 scientific articles. We qualitatively assess these impacts in terms of importance and spatial diversity, proposing concrete solutions where possible, and suggesting directions for future research. We also demonstrate that some recurring issues are actually not substantial, such as bird and bat collisions, noise and health impacts, local weather changes, and market price impacts at low penetration levels. However, we identify several genuine issues that are currently hard to solve, such as lengthy planning and permitting processes, rare earth material dependency, the recycling of blades, visual impacts on landscapes, and integration into power systems at high penetration levels.

SUMMARY

Wind power accounted for 8% of global electricity generation in 2023 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. Although the techno-economic challenges of 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

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permitting are immediate barriers to wind-power deployment; although 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 2,300 TWh production worldwide in 2024.[1] 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 UK,[2] 57% in Denmark,[3] and 10% in the USA, with Iowa leading in-state wind generation with 62%[4]), with global wind generation reaching half of the world's projected electricity demand by mid-century.[5] The technology's global weighted average levelized cost of electricity (LCOE) has already fallen 69% since 2010,[6] potentially decreasing by a further 37%–49% by 2050 for both onshore and offshore wind projects.[7] 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 landscapes[10] and adverse effects on biodiversity,[11] ecosystems,[12] human health,[13] 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] Both the intermittency and lack of (thermal) inertia of wind farm output present further challenges to effective integration into power systems.[15,16]

These challenges have been analyzed in isolation and, in many cases, have fed a literature rich with examples and insights. Some researchers have reviewed ecosystem services[17] and life-cycle environmental impacts.[18] Others focus on the "grand challenges" that the technical science of wind energy faces by focusing on the meteorological, technological (i.e., turbine-related),[19] and systems aspects (i.e., power system integration and control aspects)[20,21] but often without wholly addressing social or environmental impacts.[22–25] More recent articles[26,27] combine the grand challenges narrative with the social sciences and humanities (SSHs) perspective through a technological lens and argue for a closer integration of the SSH and technical sciences in wind energy research. Others have reviewed public perceptions and responses in relation to new energy technologies, including wind.[28] 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.

We address three central research questions: (1) what impacts does wind power have on 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 these systems. Through an interdisciplinary lens, we explore the most pressing impacts that the ongoing development of wind energy has on the systems it interacts with and prioritize research within an integrative framework. We focus on tangible impacts without exploring how these relate to perceptions of wind power and consequently to social acceptance of renewable technologies.[28] We return to this limitation in the discussion. 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 mammals.[29] Although 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 annually.[30–32] Species at higher risk are typically migratory, soaring raptors, or bats[11]; the additional mortality due to collisions can be particularly relevant for populations of long-lived and slow-reproducing species,[33–36] and collision with rotor blades and wind turbine towers might further endanger species already threatened with extinction.[37] However, there are fewer bird collisions with wind turbines than with other structures like buildings, power lines, and communication towers,[31,38] though some of these structures are also associated with infrastructure for wind turbines.[39] From 2000 to 2020, wind farms had no discernible impact on bird counts in the US, whereas shale gas wells reduced numbers by 15%.[40] But the displacement effect of new installations may in fact be specific to some species.[41,42] Although previous research suggested bat fatalities caused by barotrauma,[43,44] more recent studies identify direct blade and tower collisions as the main cause of fatalities.[45–48]

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 environments.[49] Much less literature exists on ecosystems and wildlife in offshore environments, though one review focuses on submarine power cables.[50] Offshore installations with steel piles driven into the seabed create underwater noise pollution, affecting porpoises,[51] whales, dolphins, and seals.[52] These mammals' communication, feeding, breeding, and navigation can be compromised, leading to behavioral changes and habitat avoidance. However, the piles' net ecological impact is unknown because data on the magnitude of these impacts are lacking, and their presence also positively affects marine biodiversity and provides certain bird species with areas to rest and feed.[12] 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.[40,53,54]

Furthermore, noise pollution from wind turbine operations can negatively affect birds, bats, and 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 noise,[55] specifically during construction,[56–59] whereas others avoid areas with shadow flicker[60,61] (see section health and annoyance). Although not a bat attractant, low-frequency noise emissions can disorientate bats, which makes hunting difficult.[62,63] Land transformation related to the construction of wind farms[64] can also affect habitat suitability for wildlife species.[60] Landscape connectivity between habitats can become disrupted if wind farms are built in existing dispersal corridors.[65,66] Already-isolated populations can face a reduced gene flow[67] if areas in the vicinity of wind farms are avoided[37] and alternative dispersal corridors are rare. In addition, direct mortality due to collisions with wind farms can affect population dynamics on a large scale.[68] Some species might be able to adapt to altered habitat conditions after wind farm construction,[69] whereas others might not become habituated.[70] However, effects on population trends are difficult to assess because effects are highly site and species specific and long-term studies are rare.[71]

Adequate siting of wind farms is a promising approach to reduce impacts on wildlife, but because many species' habitat requirements change in the course of a year, it remains a challenging task,[72] especially when considering ecological corridors and stepping stones.[73] Micro-siting to avoid areas with high collision risk can reduce risks for birds,[74] but it is more challenging for bats.[75] A promising solution for on-site impact mitigation is to increase the cut-in wind speed from 3 to 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 modest.[76–78] Temporary shut-downs triggered by visual or radar observations are also effective solutions to minimize collisions.[79,80] Visual cues like painting at least one rotor blade black to reduce motion-smear have had limited testing but have shown promising results.[81] Lastly, ultrasonic deterrent systems can reduce bat fatalities,[82] though effectiveness can vary by species and environmental conditions.[83]

Impacts on wind resources and weather

The increasing number and size of wind farms can affect local weather and climate patterns,[84] though the magnitude of these effects is debated.[85] There is broad evidence based on photographs,[86] satellite imagery,[87,88] measurements,[89–91] and modeling.[92] Wind turbines extract kinetic energy from the wind flowing through their rotors, replenished downstream of the flow above the wind farm.[93,94] In large wind farms, the latter process cannot supply enough energy to compensate for lowered wind speeds, especially offshore.[95] Hence, a large wind farm can significantly lower the wind speeds in its vicinity, up to a distance of tens of kilometres,[94,96] thereby suppressing generation from nearby wind farms,[89,92,95,97] as shown in Figure 1 for a possible 2030 wind farm scenario for the North and Baltic seas.[98] 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 modeling studies argued that wind farm extractable energy was finite and limited to about 1 MW/km^2 for massive wind farm clusters[99,100] (i.e., of several gigawatts capacity spanning several thousands of km^2). Still, recent research demonstrated that this limit can be considerably larger (up to 4 MW/km^2) when wind speeds are high and persistent and turbulence can mix energy down from the free atmosphere above.[95,101] Confirming these findings is challenging due to scarce observations[89] 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 as well as during the operational phase within wind farms by so-called wake steering.[102] 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.[97,103,104] However, the growth of wind power will likely be restricted by economic or environmental factors rather than global geophysical limits.[105]

The operation of wind farms can also cause weather conditions to change locally.[91] This can take the form of shifts in surface temperature (often leading to warmer surface temperatures at night[109–113]) and other weather parameters, such as precipitation and evaporation.[110] The local temperature increases are occasional and typically confined to less than 1°C when they occur and are limited to a few kilometers from the wind farm.[92,112,114] Offshore wind farms could also affect waves, ocean currents, and sea surface temperatures.[115] 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 change.[116] In sensitive areas, good spatial planning and coordinated approval processes can minimize 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 disposal.[117] 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).

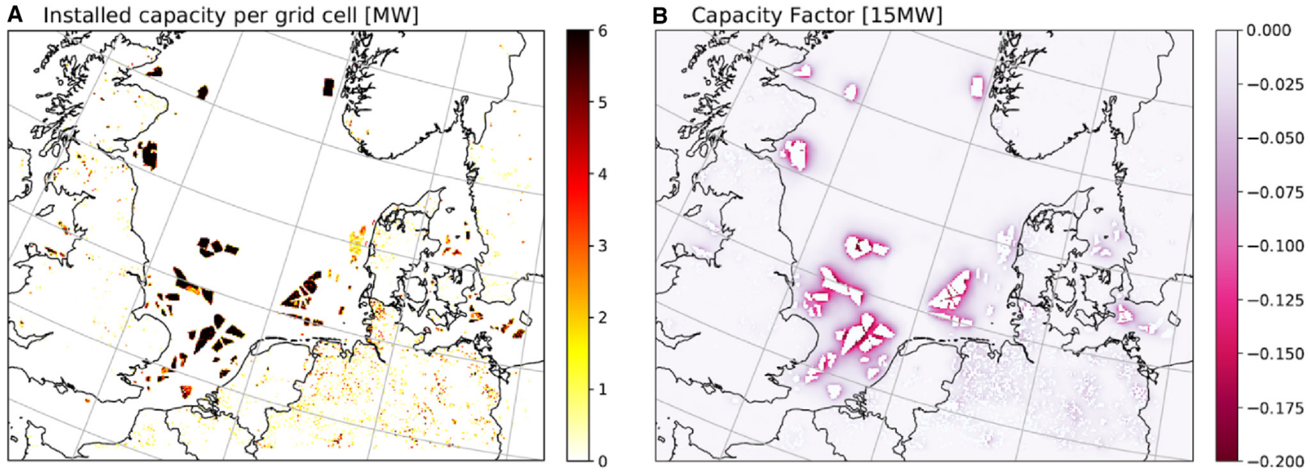


Figure 1. The effect of wind farm wakes on the wind capacity factors for a 2030 wind farm build-up scenario

(A) Installed capacity (MW) on each grid cell in a 2030 wind development scenario.

(B) Change in capacity factor between the 2030 scenario in (A) and a scenario without wind turbines. The capacity factor calculation uses the IEA 15 MW wind turbine,[106] and the wind data are generated using the WRF model and a wind farm parameterization.[107] The location of the 2030 offshore wind farms has been masked on (B). Modeling of the wind turbine wake effect follows the method described in Niras[98] and Pryor et al.[108] (https://www.niras.dk/projekter/kortlaegning-af-havindspotentiale-i-dk/).

Several options exist to delay final disposal,[118] from extending the lifetime[119] and reusing or repurposing components to recovering or recycling different parts of the wind turbine,[120] each bearing its challenges. Recycling components attract the most attention in scientific publications and media.[121] Although the recycling of permanent magnets is widely covered in the media and policies in the context of security of supply for critical raw materials[122,123] (cf. section policy and regulation), the challenge of rotor blade recycling is intensely debated by the public, questioning the benefits of wind energy in general (cf. section social, economic, and health impacts).[124,125]

Structural health monitoring and digital twins to extend the lifetime of wind turbines are still not implemented at scale, despite extensive industrial interest in the latter.[130,131] Although a recent review posits that the reuse and repurposing of old turbines is minimal and not expected to grow in the future,[132] the waste management company Veolia recently signed a contract to repurpose GE wind turbine blades into a raw material for cement in the US.[133] Regarding recycling, suitable processes and related challenges differ for each part of a wind turbine[120] (see Figure 3). Although recycling steel towers, gearboxes, and traditional generators is well established,[120] 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 circularity.[117] A geopolitical challenge around the recycling of the generator system arises through the trend toward direct drives,[134] with their permanent magnets containing rare earth elements, such as neodymium, praseodymium, and dysprosium,[135] considered critical raw materials by the EU[136] (see section policy and regulation). Nonetheless, less than 1% of rare earth elements are recycled[117] because of the low technology readiness level (TRL), glued structures and comparably cheaper virgin counterparts.[135,137] 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 2030[137] (see Figure 4).

A central end-of-life challenge arises from the turbine blades containing glass fiber reinforcement plastics (GFRPs).[120] Although some major wind turbine manufacturers have announced nearly 100% recyclable wind turbine blades between 2030 and 2040,[139,140] and the first recyclable blades were launched in 2021,[141] almost all current end-of-life blades are landfilled or temporarily stored,[142,143] raising much attention in the media. [124,125,144] Some regions with high wind energy capacities, like Germany, have already banned their landfilling and incineration,[118,132] while currently only a negligible fraction is mechanically recycled as filling materials.[143] Thermal and chemical recycling options are evolving but are still at low TRLs[145] and have a high energy demand. For example, pyrolysis (TRL 7[146]), fluidized bed or microwave pyrolysis (TRL 5/4), and solvolysis (TRL 5–6) come with a high upfront investment, low quality of fibers, and potential greenhouse gas emissions by the unavoidable decomposition of products.[147]

Notably, the recycling challenge is not limited to wind turbines but applies to many activities in the building, electronics, and transportation sectors for composites and electric motors, as well as domestic appliances and smartphones for permanent magnets,[137] so considerable sectoral spillovers in solving recycling problems are possible.

SOCIAL, ECONOMIC, AND HEALTH IMPACTS

Land tenure (in)security

The transition to higher shares of wind power boosts the demand for land.[148] The private appropriation of public land to secure access to and control over renewable (including wind) energy production has been referred to as “green grabbing.”[149–152] This can come at the cost of prior land users and increase the

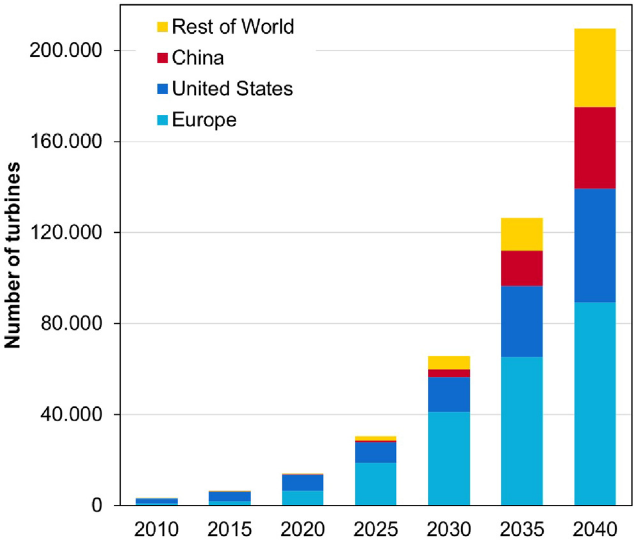


Figure 2. The cumulative number of wind turbines that would reach end-of-life up to 2040, split by world region

Based on farm construction dates[126] and an assumed lifetime of 25–30 years.[127–129] Reproduced from the given sources.

vulnerability of traditional rural communities and Indigenous groups in particular due to the use of public land without free, prior, and informed consent,[153–155] unfair contractual arrangements,[156] and various forms of dispossession,[157] including the prevention of access by legal means and physically by fencing.[158] The impact of wind energy development on land-tenure insecurity, especially for undesignated public and 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 peoples.[159–161] Similarly, in Brazil, a large share of wind corridors is in undesignated public lands, historically occupied by traditional communities struggling to regularize the ownership and use of common lands.[158,162,163] 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 Mexico[164–166] as well as in North Africa and the Middle East.[167]

The diverse impacts of wind power development on land appropriation and control, which affect the rights of traditional communities or Indigenous people 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 consent,[155] addressing information asymmetries about the project's specific local impacts,[168] and offering fair and legally approved land leasing contracts as well as legal advice on land use.[169] 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,[170,171] 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.[138,168]

Landscape visual impacts

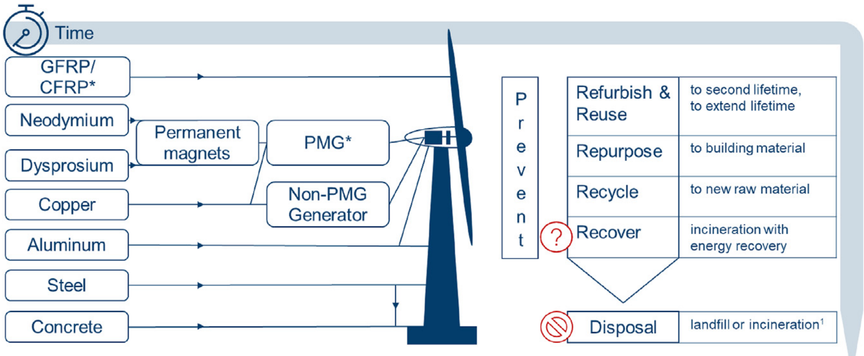
Another public concern is that wind turbines negatively impact the perception of landscapes, particularly untouched nature. This visual landscape impact is one of the main reasons for local opposition to onshore and offshore wind installations.[9,169,172–176]

Acceptance of wind turbines is higher when they are placed in already unattractive landscapes, far from viewpoints, and with a limited number of turbines,[177] but the cumulative effects may vary by location.[178] 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[179–184] (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[185,186]; however, these disregard people's visual preference for certain landscapes over others.[187] They may, therefore, be combined with measurements of visual features of landscapes, as a correlation between such metrics and rated landscape qualities has been found.[188] Moreover, RE infrastructure such as wind turbines and power lines strongly influence the rated landscape coherence.[189–191]

Quantifying the landscape impact of wind turbines to improve placement decisions requires that both visibility and landscape quality are considered.[192] Whereas the latter refer to changes in landscape quality and character, visibility impacts relate to (perceived) changes in views (of the landscape) and how these affect people.[176] Approaches based on geographical information systems (GISs) have been proposed to estimate landscape coherence[193] and wilderness[194] 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.

Monetary costs and benefits

Wind power deployment creates concerns about reductions in neighboring 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. Although some studies show a decrease in property prices of at least 2%,[195] more recent research shows either minor impacts with limited statistical significance[196,197] or cases of positive impact on real estate prices, the local economy, and incomes.[198] Associated acceptance problems can be reduced, mainly by fostering genuine community engagement during the project's



GFRP-Glass fiber reinforced plastic, CFRP-Carbon fiber reinforced plastic, PMG-Permanent magnet generators, [1]without energy recovery

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

planning stages, especially if combined with shared ownership models[199] and monetary compensation (cf. section planning and permitting) such as a fair sharing of the wind farm's income with affected residents.[138,200,201] Moreover, results of studies about the impacts of wind power on tourism are mixed.[195,202] There are studies reporting that the presence of turbines can reduce the attractiveness of locations,[203,204] whereas, in other cases, stakeholders see wind power development as an added value to increasing the attractiveness of particular locations.[205] As with citizens, compensation for affected businesses[206] may decrease opposition but compensation mechanisms have to be developed carefully so as not to generate distributive fairness issues.[206] Furthermore, although at the global scale there is a clear positive economic impact of wind power deployment in terms of steadily growing trade and job creation[207] and increasing gender diversity in the energy workforce,[208] at the local level impacts are difficult to assess and evidence is inconsistent. Studies show increased local economic activities but limited job creation[198] and reduced local unemployment beyond the construction phase.[209] 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. Although current evidence suggests that noise emissions from wind farms do not have a significant direct impact on nearby populations' health,[210,211] some studies have noted a correlation between noise-related annoyance and potential indirect effects on quality of life, such as sleep disturbance,[212] increased stress, and related health concerns (e.g., elevated blood pressure and psychological distress).[213,214] However, the causality and directionality of these effects remain unproven and require further research. The perception of noise seems higher in rural areas and around flat terrains.[215] Although low-frequency noise emissions cannot be heard, they may still lead to annoyance,[216] but the link between wind turbines and low-frequency noise has not yet been established. In addition, many studies show that only a small fraction of the population living near wind farms is disturbed by shadow flicker.[13,217] Shadow flicker exposure does not necessarily lead to self-reported annoyance but rather subjective factors such as project appearance and general annoyance.[218,219] However, the disturbance attributed to wind turbine noise emissions should be evaluated compared with other routine noise sources. In a controlled study,[220] although 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., 35–45 dB(a)),[221] as is currently enforced in some countries.[222–224] Likewise, for cases where high levels of modeled shadow flicker exposure and self-reported annoyance correlate, easy-to-implement solutions exist, such as curtailment after specific exposure thresholds.[225] However, the probability of that correlation occurring is low because detailed shadow flicker simulations are an integral part of planning processes for wind farms and permission might not be granted in case thresholds would be exceeded (see, e.g., the German BImSchg[226]). Nevertheless, the studies leading to that regulation were performed over 20 years ago when turbines were considerably smaller than today and were capable of generating a flickering effect of higher frequency.

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—though modern wind turbines (and other renewable technologies) can also provide synthetic inertia and participate in frequency regulation as inverter-based resources (IBRs). In contrast to its total energy production, wind power displaces relatively little dispatchable capacity as peak demand periods are not correlated with wind output[227] and the capacity value of wind falls with increasing penetration.[228] Hence wind-dominated systems may need extensive backup capacity, lack dispatchability, and become highly weather-dependent.[229]

At low wind-share levels, the system's impact is relatively small.[230] 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.[230,231] But above this fraction, the system needs to exploit so-called integration measures, including grid densification and expansion,[232] use of storage systems, increasing flexibility and sector coupling, and development of smart grids with distributed ancillary services.[233]

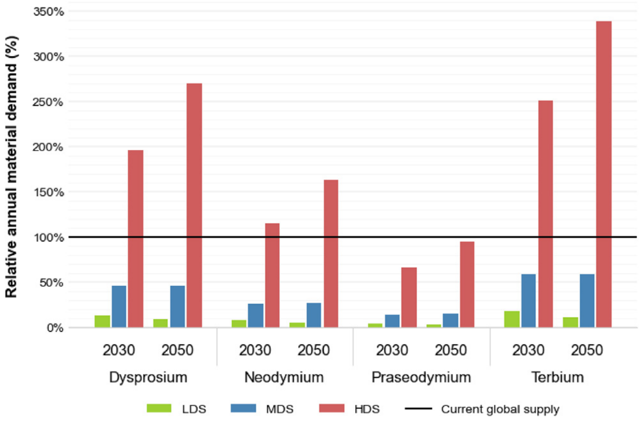


Figure 4. Expected demand in 2030 and 2050 from the wind turbine industry for a selection of rare earth metals, relative to the 2018 global supply for all applications

LDS: IEA ETP Reference Technology Scenario (+2.7°C increase in temperature by 2100 compared with pre-industrial levels). MDS: IEA ETP Beyond 2 Degrees Scenario (+1.75°C increase in temperature by 2100 compared with pre-industrial levels). HDS: Institute for Sustainable Futures 1.5°C 2019 Scenario (1.5°C with 100% renewable primary energy in 2050). Source,[138] further adapted by the authors. The LDS, MDS, and HDS scenarios assume a global market share of permanent magnet technologies for onshore installations of 40%, 50%, and 68%, respectively, compared with 32% today. For offshore installations, a constant market share of 70%–76% is assumed in the HDS scenario. Concurrently, in the HDS scenario, the assumed annual installed capacity for onshore wind turbines in 2050 is approximately 3-fold that of today's (350 GW vs. 100 GW per year). For offshore installations, the annual capacity in 2050 assumed under the HDS scenario is about double that of today's (40 GW vs. 20 GW per year).

Grid strengthening and expansion are essential to address mismatches between supply and demand.[234] But these measures have significant implications for public acceptance, landscape impacts,[179] and potential health impacts.[235,236] Though, as we discuss in the section social, economic, and health impacts, the direction and magnitude of these health impacts are far from clear. Similar to wind turbines, the power system infrastructure (overhead power lines and pylons) can and does face public acceptance problems.[237–239] 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). The total global installed capacity, including electrochemical batteries and pumped hydro storage, is expected to triple in the 2020s.[233] However, batteries are not always the best option to complement wind power due to the inappropriate timescale and generally limited energy-to-power ratio, so researchers focus on balancing wind power across seasons with hydrogen and power-to-x,[240–242] other forms of energy storage, hybridization with solar PV plants,[243–246] and geographic siting to match supply and demand.[245,247,248] The economic viability and business models for such long-duration storage are still unclear though.[233,249]

Third, 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-x.[250] New policy and market frameworks, such as capacity markets, dynamic prices, and peer-to-peer trading, are needed to monetize and incentivize greater flexibility across the electricity system.[251–253]

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.[254,255] The installation of appropriate hardware and associated electronics is crucial to meet this challenge and provide services that are today largely provided by mechanical systems in thermal and hydropower plants, such as inertia.[256,257]

To understand how these measures economically interact and complement each other across different energy systems, whole energy systems modeling approaches are required. Specifically, although extensive research has already provided insights into the least-cost integration of wind energy at the system level,[258–260] 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 inertia[261–263] and reduces the supply of these services by displacing traditional thermal power stations.[264] Second, wind has near-zero marginal cost, creating a so-called "merit order effect" that depresses wholesale market prices[265–267] and increases their volatility.[268] This lowers power prices received by all generators, eroding their profitability, potentially triggering early retirement,[269,270] and causing long-term underinvestment known as the "missing money" problem[271,272]—especially if there is a thermal overcapacity in the market. Price reduction is strongest at times of high wind output, so wind farms will "cannibalize"[273–277] their own profitability, possibly making investments unprofitable despite low generation costs.

Historically, market integration impacts have not been critical[278] 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 LCOE (VALCOE[279]), total system cost,[280,281] system LCOE,[282,283] and cost of valued energy (COVE[280,284]) being proposed. Effects are less severe for wind than for solar PV due to the strong day/night correlation,[274,285] 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.[286–288]

The type of scheme used to support wind power (see section policy and regulation) strongly influences these integration effects.[15] For example, schemes such as feed-in tariffs (FITs), power purchase agreements (PPAs), and contracts for differences

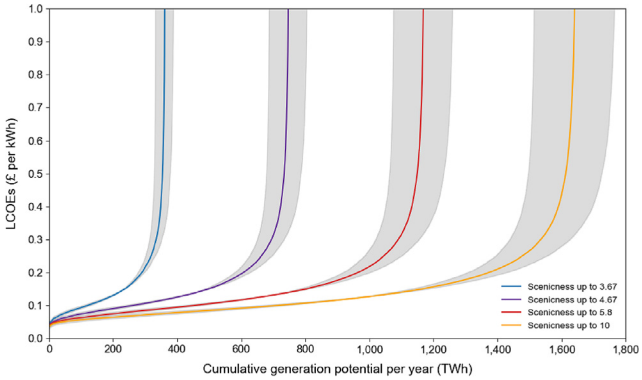


Figure 5. Supply curves showing the amount of available wind power resource as a function of how people view the scenic landscape in Great Britain, on a scale of 1–10, for four scenicness thresholds: 3.67, 4.67, 5.8, and 10

The solid lines show the means and the gray thresholds show minimum and maximum ranges for the wind years of 2001–2006. Wind speed data are from the Meteorological Office 2018 (reproduced from McKenna et al.[179]).

(CfDs) do not incentivize time-shifting output to accommodate the wider market, thus exacerbating price volatility for all other technologies and ancillary service costs.[289,290] These schemes offer the greatest certainty to developers, however, lowering the interest rate for financing investments and, thus, the cost of wind energy.[15,291]

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 volatility.[15] An example is the creation of the enhanced frequency response (EFR) service in Britain, which was supplied entirely by batteries.[233] Integration problems should decrease in the long run as power systems have time to adapt and accommodate greater variable supply.[267,282,292] Markets are already adapting via shorter balancing settlements, sharper imbalance prices, and more involvement in balancing markets.[261,262,293] Proper pricing of emissions will also help to establish correct market price signals.[294] Such changes have allowed balancing costs to fall in Britain and Germany despite wind penetration increasing 5-fold.[261]

Many variations on current market designs are proposed that are more "system-friendly," for example, in the UK's Review of Electricity Market Arrangements.[295] These include the following:

- 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 minimize system integration costs by optimizing where farms are placed, how they operate, and what flexibility options are provided.[15,296–298] Further research is needed to design resilient, secure, and efficient markets that could enable largely or fully renewable electricity systems and incentivize required ancillary services.[16,299,300]

POLICY AND REGULATION

Energy security and geopolitics

There are several geopolitical and energy security challenges for wind power,[301,302] 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,[303,304] exacerbated and vividly renewed during the war in Ukraine and resurging concerns over the weaponization of energy,[305] but recently shifted to a focus on the geopolitics of the energy transition.[301,306] The cyber threat relates to infrastructure security that depends on complex control and monitoring systems[307,308] and disinformation that can affect news trustworthiness.[309]

In the energy transition context, finance and controlling the technology supply chain are key factors.[310] Industry leaders with large markets (e.g., USA, EU, and China) seek dominance in the clean energy sector.[311] China's Belt and Road Initiative is an example that involves large-scale development of energy infrastructure.[312] Several studies take a broader approach, looking into how undiversified supply chains and geopolitical and environmental constraints can affect successful decarbonization, suggesting that, for example, more financial aid, technology transfer, cooperation across all levels, and new governance schemes are needed.[313,314] 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.[315,316] 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 concerns.[317] Similarly, China uses its dominant role in developing RE and building greater grid interconnections in Central Asia and Africa as geopolitical leverage.[318] Although this may be an opportunity for developing countries with limited financial means to build up wind capacities, it creates strong dependencies and risks.[307]

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 RE 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 conflict.[319] Higher RE shares are expected to increase international wind power trade without increasing one-sided dependence.[320] The even distribution of RE resources[321] reduces the threat of oil-crisis-style coercion—the "energy weapon"—but shifts dependence from energy to technology trade and ownership.[322] In

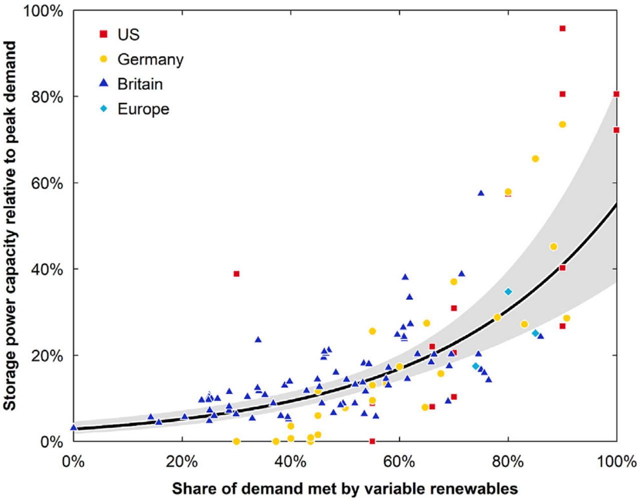


Figure 6. Storage requirements in relation to the share of demand met by intermittent renewables

This chart collates data from across 30 studies. A log-normal fit is shown, with shaded area giving the confidence interval. See Schmidt and Staffell.[233]

addition, global patent filing rates for wind are an often-overlooked aspect that can create concerns in terms of localization of innovation and market power, giving specific countries a competitive advantage[323] 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),[324] including safety components and information control systems (ICSs) like SCADA systems with proprietary protocols.[325] Energy sector cyberattacks have increased significantly since 2015, including attacks targeting the wind industry.[326] Examples include numerous attacks in Germany during 2022 on the IT infrastructure of turbine manufacturers and maintenance providers[327] and the ViaSat cyberattack at the beginning of the Ukraine war that caused collateral damage to wind turbine controlling and monitoring systems.[328,329] 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 conflict.[330] Finally, disinformation and other hybrid warfare techniques create an impact in a less-direct manner by manipulating societal values.[331] On the one hand, it can generally reduce the perception of renewables' reliability after a grid failure (e.g., blackout)[332] or through conspiracy beliefs influencing opposition against wind farms,[333] leading to lower overall acceptance and ultimately slowing down deployment. On the other hand, specific types of disinformation (e.g., price) could alter customer behavior, affecting system performance and, in the worst case, trigger disruptions.[307]

Thus there is a need to balance investment opportunities and national security interests better to ensure fair market conditions and minimize distortions of industries' competitiveness, which needs to be supported by developing a broader set of policy options.[317] 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 substitution.[334] Overall, reshoring and near-shoring of supply chains can alleviate risks and increase resilience. Still, this needs to be carefully designed and strategic aspects concerning diversification, influence on standards, and investment in infrastructure considered.[335] Otherwise, this may cause reduced global effectiveness and potentially compromise efforts to close the green energy infrastructure gap.[336] 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 industry.[337] 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.[309,332,333,338]

Planning and permitting

Lengthy permitting processes are ''the biggest barrier to the expansion of wind energy'' in Europe, with at least 80 GW onshore wind projects stuck in the permitting process in 2022.[339] Similarly, many wind power projects are also delayed due to permitting issues in the US.[340–342] The reasons for long processes are diverse, including increasingly complex formal requirements and insufficiently specific legal guidelines and responsibilities for permitting authorities.[343–346] Understaffed authorities and overloaded judicial systems unable to handle all cases aggravate the problem,[347] especially as anti-wind power movements increasingly use litigation to prevent projects.[348–350] One-fifth of German wind farms were subject to litigation, typically related to bird or bat protection (48%) or general species conservation (24%).[351] Local land-use conflicts intensify with increasing deployment levels as low-conflict sites become scarce[181] and general acceptance tends to decrease with increasing exposure to wind turbines.[352–354]

The administrative phases of wind power construction are increasingly long. In Germany, for example, the average time from application for permission to realization increased from 20 months in 2011 to 49 months in 2022.[355,356] However, in the European context (Figure 7), the long process in Germany is one of the fastest. No country meets the EU requirement of 24-month permission time.[357]

Several regulatory changes are underway to alleviate this problem. Most prominently, the EU's Renewable Energy Directive was amended in 2023.[358] It mandates that renewables across Europe are considered an *overriding public interest* when balancing legal interests during permission processes and in litigation.[358–360] Member states must assign ''acceleration areas'' for RE 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.

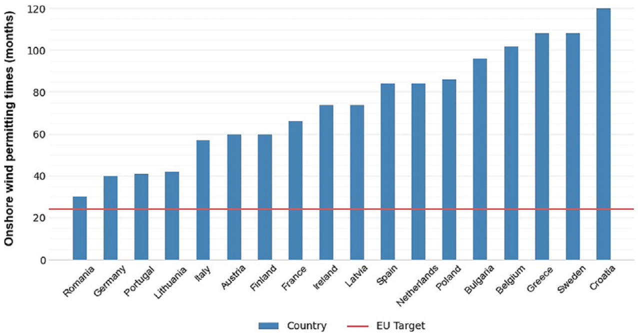


Figure 7. Average permission times including construction permit, environmental impact assessment, local spatial planning, and grid connection

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).[401] Own depiction based on the given sources. Although not shown in the figure due to a lack of precise data, the time in Switzerland is currently about 60 months, but this should be accelerated to about 36 months with the so-called WindExpress.[402]

Although 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 are scarce—both of which may cause local environmental problems.[361,362] 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.[363] 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, and direct payments), who benefits (communities or individuals), and how it combines with procedural participation.[9,206,364–367]

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. First, 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 authorial team, we identified four impact categories and fourteen individual impacts of particular relevance, as outlined in the introduction. In Table 1, we summarize 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.

Second, how significant are these impacts? 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 question of significance is challenging due to a lack of research, for example, for emerging or 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 is related to environmental and policy aspects, partly due to the early stage of real-world and research development (e.g., for the impact of wind turbines on weather and climate and vice versa[368]) and a lack of consensus on best practices in specific contexts (e.g., for policy and planning). This generalization overlooks some important nuances; for example, the research on wildlife impacts of wind is rather more advanced than the one 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 current research only provides a moderate level of understanding. The impacts relating to *end-of-life treatment* and *rare earth materials* have a much lower spatial differentiation, meaning that 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, and 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, for which all proposed solutions have highly uncertain efficacy, 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, climate impacts—to the extent that they cause noticeable local problems—can also be addressed with appropriate wind power siting and layouts and by farm layout planning to minimize efficiency losses, though these impacts and solutions also remain highly uncertain. 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, by the need to recycle expensive or critical materials such as

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

Category	Impact	Description	Spatial diversity[a]	Potential 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, and non-volant and marine mammals by disrupting their nesting, breeding, and movement patterns	high	strategic placement of wind farms, regulating cut-in speeds, temporary curtailment, visual cues, and painting one turbine blade	empirical research and observation: ● impacts in shrub- and woodland ● multi-annual and multi-site studies (before-after control-impact study design) ● net ecological impacts of wind energy compared with 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 kilometers downstream	medium	wind power siting, integration measures (e.g., storage, grids, etc.), appropriate wind park layouts, consider efficiency losses in wind farm planning	● further measurements and empirical data, especially for large wind farms and local weather effects ● net climate effects of wind energy compared with alternatives
	(3) end-of-life treatment of turbine blades	the fiber binding resin challenges the recycling of wind turbine blades; as a result, blades are currently not recycled but instead go to landfills or unofficial "temporary storage sites"	low	prevention, refurbishing or reusing, repurposing, recycling	● address the waste hierarchy through innovative design for recycling and disassembly ● improve thermal and chemical recycling processes to higher TRLs and exploit sectoral spillovers ● 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 due to land tenure insecurity, increasing 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 issues, participatory planning, legal advice, creating co-benefits	● understand best practice for wind energy planning to reflect community needs ● 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 neighboring 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 a key technology to achieve the energy transition and monetary compensation	● elaborate models of acceptance and willingness to pay in order to quantify compensation measures ● quantify net economic impacts based on improved data bases/availability

(*Continued on next page*)

Table 1. *Continued*

Category	Impact	Description	Spatial diversity[a]	Potential solutions	Research priorities
	(7) landscape impacts	the local opposition toward wind projects due to the negative visual impact on wild landscape aesthetic value	high	improved planning, participative processes	● 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 neighbors' annoyance, which may correlate with deteriorating quality of life, increased stress, and resulting health issues	high	appropriate planning, periodic curtailment and noise threshold and attenuation options (e.g., serrated trailing edge, sinusoidal leading edge, blended winglet)	● build on existing noise models to (i) enhance understanding of wind energy impacts in relation to other local sources of noise and (ii) connect acoustin emissions with annoyance ● extend shadow flicker research to consider night-time effects with artificial lighting
Techno-economic	(9) energy system impacts	wind-dominated energy systems may become highly weather dependent and lack inertia due to a prevalence of inverter-based resources (IBRs) forming the grid	medium/ high	grid densification and expansion, use of storage, increasing flexibility and sector coupling, development of smart grids; low carbon provision of key ancillary services, such as inertia, operating reserve, and frequency response	● align modeling with empirical data on energy system transitions to high wind shares ● improve techno-economic modeling 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	● 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

(*Continued on next page*)

Table 1. *Continued*

Category	Impact	Description	Spatial diversity[a]	Potential 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	● 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	● design robust and resilient supply chains for wind energy ● enforce international technology standards and certification schemes ● identify the pathways and understand the major implications for 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	● 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	● determine best practice for planning and permitting ● observe effects of ongoing/upcoming regulatory changes, including side-effects on acceptance ● reflect spatial trade-offs in wind power legislation (centralized vs. decentralized)

All of the listed potential solutions are subject to high degrees of uncertainty in terms of their efficacy in addressing the listed impact.

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

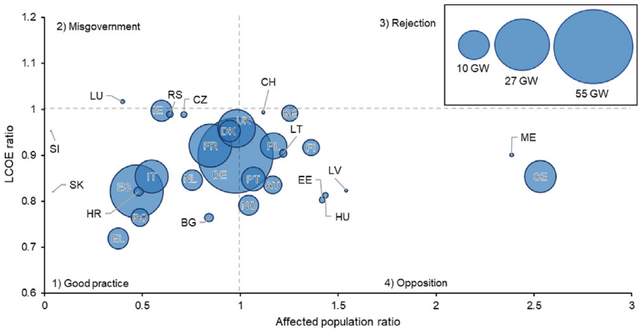


Figure 8. LCOEs and affected population for existing onshore wind turbines in relation to the average in potentially installable turbines shown for European countries

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 prioritized the corresponding indicator in its turbine planning. If the ratio is above 1, this indicator was probably neglected in comparison with 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 with 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.[394]

rare earth materials 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 in practice. Also, in the policy/regulation category, other solutions include a re-prioritization 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,[369–375] which is still at low-to-medium TRL and may well mitigate many of the impacts due to the increase in the exploitable potential of wind energy,[376–380] less visual impacts (cf. section social, economic, and health impacts),[381,382] and reduced on-site environmental and social impacts.[383,384] However, rising competition with shipping, fishing, and other maritime activities must be considered,[385,386] so the net effect is highly uncertain. Second, a general theme emerging from this research is the strong mismatch between general and local opinions on wind. Hence, although wind power is supported in principle, for example, as demonstrated by national opinion surveys,[387,388] there is often local opposition at sites where wind projects are planned.[389] However, the legacy explanation that people do not want wind turbines "in their backyard" (NIMBY) is overly simplistic,[390] given the complex and context-dependent reasons for local opposition to onshore wind turbines.[9,391] At the same time, we observe a tension between the need for accelerating wind power deployment and participatory mechanisms that increase acceptance. Although, 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 antagonizing local stakeholders.

The wide and varied research on social acceptance of renewable technologies can serve as a starting point to (partly) relieve the tensions between different interests by offering insights into how individuals and society more generally perceive these impacts and how they can be mitigated.[390,392] Although our review does not address social acceptance per se, it delivers a crucial knowledge basis by providing a summary of research about evidenced impacts of wind power, thereby supporting the local and more general deliberation process in terms of wind power expansion.

An additional insight relates to existing wind deployment around the world, focusing on sites with higher wind speeds and thus correspondingly lower generation costs,[393,394] and model assumptions regarding wind power potentials are poorly reflective of historical installation patterns.[393] As a result, wind farms are often concentrated in regions with good wind resources,[182,394] which increases the need for energy system integration measures like grid reinforcement, storage, and flexibility.[395–398] This also disproportionally affects communities in these regions—which are often rural, with lower income and less political power to affect local developments.[389] However, evenly distributing wind turbines based on criteria like local energy demand rather than exploiting sites with good wind conditions may significantly increase generation costs.[394] Figure 8 shows the diversity in LCOEs and affected populations for existing onshore wind turbines compared with the overall potential in European countries, with circles scaled according to the installed capacity. Although 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 emphasized 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.[399,400]

Although 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 authorial team, covering very different areas of expertise, but the significance of specific impacts may still be skewed toward the strengths in the expertise of the authorial team and potentially overlook some important aspects. Although 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 those that 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. Second, because of the nature of the reviewed literature and the diversity of evidence, we could not quantitatively analyze 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, we summarize the reviewed impacts and suggest research priorities for the coming years, while also emphasizing the high degree of uncertainty associated with these potential solutions. 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 cannot yet be developed. In addition, effective end-of-life treatment requires advancements in specific recycling processes, harmonization of design processes across sectors, development of innovative designs, novel materials and processes for sustainable manufacturing, and holistic systems analysis to foster circular economic approaches. In the social category, there is a necessity for new empirical data, particularly to improve existing and to develop new theoretical and practical models of planning and governance; this aims to improve the distribution of costs and benefits of wind power—especially, but not only, relating to land tenure security, visual impacts on the landscape, and compensation schemes. The techno-economic category is far advanced in terms of understanding, but energy market and price impacts in particular require further work in respect of the market behavior of individual actors, and quantitatively elaborating the 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 in respect of whether they work at all and, particularly, on the 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, which should reflect both positive and negative impacts considered here as well as additional ones such as local air quality improvements.[403] Wind should be *compared with the alternatives*; for example, in environmental, economic, technical, and social terms, only considering the effects of wind power while ignoring the effects of competing technologies impedes taking well-informed decisions on future energy systems. Many tools and methods already exist for this purpose, for example, LCA and carbon foot-printing,[404,405] supply chain analysis, cost-benefit analysis, and others. 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.[406] 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 climate targets.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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