Table 1: Overview of key systemic wind impacts, potential solutions and research priorities emerging from this comprehensive review. All of the listed potential solutions are subject to high degrees of uncertainty in terms of their efficacy in addressing the listed impact.

Category	Impact	Description	Spatial diversity	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, 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: • 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 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	• 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 fibre 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 spill overs • Increase coordination and standardisation 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 <1% of 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 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	• 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	• 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 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 acoustic emissions with annoyance • Extend shadow flicker research to consider night-time effects with artificial lighting

Cat-egory	Impact	Description	Spatial diversity	Potential solutions	Research priorities
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 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	• 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
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 weaponisation 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 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	• 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, incl. side-effects on acceptance • Reflect spatial trade-offs in wind power legislation (centralised vs. decentralised)