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A spare-share scenario framework for exploring biodiversity - onshore wind trade-offs in electricity system planning

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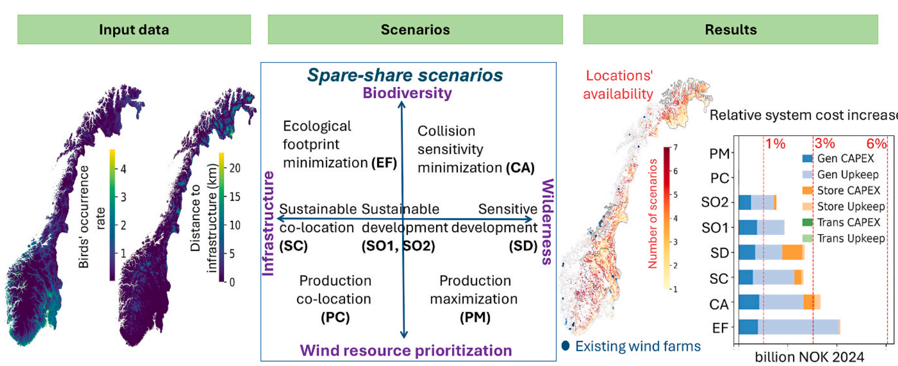
GRAPHICAL ABSTRACT



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ABSTRACT

Expanding wind energy to meet net-zero targets increasingly conflicts with biodiversity and landscape conservation, creating contested geographies where socio-ecological values compete. Existing spatial analyses identify ecologically preferable sites but lack representation of system constraints and trade-offs, while most energy system models optimize technology deployment under cost constraints by specifying regional capacity limits and rarely encode which specific sites become available under different ecological priorities. We address this disconnect through a spare-share scenario framework coupling high-resolution ecological (247 bird species, 5 bat species) and infrastructure datasets with electricity system optimization for Norway's 2050 net-zero pathway. Spatial allocation strategies spanning infrastructure-proximate concentration (spare) to ecologically guided dispersion (share), including collision risk minimization, habitat protection, and infrastructure concentration, are examined. Analysis reveals that only 7% of Norwegian land area remains consistently available across spare-share scenarios, while 67% exhibits flexible availability depending on the prioritization of ecological criteria, and 26% faces universal restrictions. Ecological restrictions reduce onshore wind capacity potential 11-fold, increasing electricity generation costs by 19-21% per MWh while investment and operational costs rise up to 6%. Despite targeting divergent ecological priorities, moderately restricted scenarios cluster within a cost-increase variation of less than 2%, reflecting biodiversity hotspot overlap that creates functionally equivalent

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constraints while achieving better system integration. Findings demonstrate that for 67% of land sensitive to ecological priorities, spatial allocation decisions are not technical optimization problems but require inclusive stakeholder engagement to navigate competing ecological and infrastructure values. The framework provides transferable methodological insights for regions balancing renewable expansion with biodiversity preservation.

1. Introduction

The transformation of energy systems toward renewable sources represents a cornerstone of global decarbonization efforts (Intergovernmental Panel on Climate Change (IPCC), 2023). Wind energy, with its substantial technical potential and low costs ("IEA," 2023), has emerged as a critical technology for achieving climate targets, particularly as electrification extends into sectors such as transport and data centre ("Global Energy Review," 2025). The available wind power potential is able to cover a substantial part of electricity demand (e.g. China (Ji et al., 2024); Australia (Miyake et al., 2025); Europe (Elsner et al., 2026)). The European Union aims to more than double installed wind capacity to 440 GW by 2030 ("Wind energy in Europe (2023-2027)," 2022), while globally, wind generation must expand from less than 2000 TWh to approximately 12,000 TWh by 2050 ("Net Zero by 2050," 2021) to meet climate targets. However, the urgency of climate action increasingly collides with equally pressing concerns about biodiversity conservation, landscape preservation, and ecosystem integrity. With habitat change identified as the primary threat to diverse species across multiple regions (Gasparatos et al., 2017; Katzner et al., 2025), recent assessments emphasize that nature loss may prove as consequential as climate change itself, with the two crises mutually reinforcing (IPBES, 2019; The Economics of Biodiversity," 2021).

The challenge of balancing energy transitions against ecological protection and social acceptance manifests in planning processes worldwide (Price et al., 2026). Quantitative evidence demonstrates that wind proposals in scenic areas face higher rejection rates (Enevoldsen et al., 2019; McKenna et al., 2021), while empirical assessments reveal that existing installations have failed to avoid sites with elevated bird impacts (May et al., 2021). Beyond aesthetic concerns, environmental conservation objectives impose spatial constraints that limit the available deployment zones (Weinand et al., 2022). Wind energy development affects biodiversity through habitat loss and fragmentation, disturbance, collision mortality, and barrier effects (Gasparatos et al., 2017; Katzner et al., 2025; Laranjeiro et al., 2018), with impacts varying substantially by species characteristics and site conditions (Etard et al., 2025; May et al., 2020; Thaxter et al., 2017). Tracking data from over 1700 mortality events across 45 migratory bird species reveals that energy infrastructure—including power lines and wind turbines—accounts for nearly half of all documented human-induced bird mortality in the African-Eurasian flyway (Serratosa et al., 2024). Recent pan-European risk assessments identify collision hotspots concentrated in regions such as Northern Europe (Etard et al., 2025), while system-wide analyses quantify how hydropower, wind installations, and transmission infrastructure collectively shape biodiversity footprints(Gilad et al., 2024a).

Addressing these intertwined challenges requires frameworks that integrate spatial heterogeneity in environmental impacts of renewable energy (RE) siting with system-level operational outcomes. Spatial siting studies have advanced methodologies for identifying environmentally preferable sites through multi-criteria decision analysis (McKenna et al., 2018; Solbrekke and Sorteberg, 2024), species-specific impact assessment (Etard et al., 2025; May et al., 2021, 2020), and integrated social-environmental constraint mapping (Lehmann and Tafarte, 2024; Reto et al., 2026). A recent Europe-wide spatial analysis demonstrated the sensitivity of onshore wind capacity to socio-environmental factors, reducing capacity by up to 95% and increasing transition costs by up to 14% (Price et al., 2026). Although spatial analysis approaches quantify trade-offs between deployment targets and environmental protection under predefined scenarios (Delafield et al., 2024; Eichhorn et al., 2019; Kiesecker et al., 2024; Lehmann and Tafarte, 2024; McKenna et al., 2021; Weinand et al., 2022), they typically lack representation of system flexibility requirements, temporal balancing needs, and grid-level constraints.

Energy system modelling approaches are increasingly incorporating spatial restrictions to assess the socio-environmental effects on RE technology deployment and system costs (Fisch-Romito et al., 2025; Grimsrud et al., 2024; Price et al., 2018, 2022; Roithner et al., 2025; Tsani et al., 2025). However, most energy system modelling approaches treat space as abstract regional capacity limits specifying how much generation potential exists in a region, with rarely encoding the geographic details of which specific sites become available under different environmental priorities. This abstraction prevents models from capturing how the spatial configuration of deployment affects operational efficiency: whether capacity concentrates near existing infrastructure (i.e. sparing nature) or disperses across remote high-wind zones (i.e. sharing with nature) fundamentally alters system operational patterns, temporal balancing requirements, and the relative economics of transmission expansion versus storage investment (Gambhir, 2019; Hirt et al., 2020; Pfenninger et al., 2014). Continental energy system modelling simplifies local environmental factors or applies homogeneously across countries, while national analysis typically lacks frameworks with comprehensive and comparative representation of ecological factors. The literature remains limited in comprehensive analyses of how divergent spatial allocation strategies affect electricity system operational outcomes (McKenna et al., 2025). Broader sustainability research emphasizes that reversing biodiversity declines requires integrated strategies that transform production systems, rather than relying on conservation measures alone (Leclère et al., 2020), a principle equally applicable to RE deployment.

This study develops an integrated spatial-economic framework to quantify how different geographic allocation strategies for onshore wind deployment can shape Norway's electricity system in 2050. Norway exemplifies a particularly instructive case for developing such a spatial-economic framework. The country aims to reduce greenhouse gas emissions by 50% relative to 1990 levels by 2030 and by 90% by 2050 ("Climate Change Act," 2017; "Climate plan," 2021), necessitating substantial expansion of the electricity system from 127 TWh in 2023 to potentially 250 TWh by 2050 (Statnett, 2025). The nation's extensive onshore wind resources (Duffy et al., 2020; Egging and Tomasgard, 2018; Ryberg et al., 2019), substantial existing hydropower capacity for balancing variable generation ("Elektrisitet (SSB)," 2025; "NVE," 2023), and well-documented planning conflicts and ecological data (Dorber et al., 2020; May et al., 2020). Due to environmental constraints on large-scale hydropower development since 2001 (NRK, 2001), onshore wind became the primary expansion technology, growing rapidly between 2017 and 2022 from 1.7% to 10% of electricity generation (DNV, 2024). This growth ground to a near halt after 2020 (Eikeland et al., 2023; "Elektrisitet (SSB)," 2025), catalyzed by mounting opposition over landscape disruption, biodiversity impacts, and procedural justice concerns (Gulbrandsen et al., 2021; Lawrence, 2014). The 2021 Supreme Court ruling on the Fosen wind farms, which found operations violated Sámi rights under international conventions (Mósesdóttir, 2024), crystallized broader conflicts surrounding wind energy development. Procedural conflicts have effectively stalled new wind deployment (Eikeland et al., 2023; Inderberg et al., 2019), leading to potential electricity deficits already by 2027 (Roithner et al., 2025; Statnett, 2025), while growing recognition of biodiversity vulnerabilities (Gilad et al., 2024a, 2024b; May et al., 2021, 2020) increasingly constrains where future expansion can occur—placing Norway's energy transition at a crossroads. The lessons from this experience—balancing climate imperatives against ecological protection and social acceptance—extend beyond national borders to inform RE transitions across regions facing analogous pressures.

We address three interconnected questions: First, how do varying ecological constraints affect the geographic availability of suitable wind sites? Second, how do these spatial constraints translate into system-level techno-economic outcomes? And third, how do spatial constraints reshape patterns of system balancing and technology substitution?

We contrast scenarios spanning a spectrum from infrastructure-concentrated ("spare") to ecologically-dispersed ("share") siting strategies, incorporating species-level biodiversity data (Kvalnes et al., 2023; May et al., 2021), proximity to existing infrastructures ("NINA Rapport; 1-56," 2022), collision sensitivity frameworks (Thaxter et al., 2017), protected areas ("Protected Areas (WDPA)," 2023), and techno-economic criteria. These scenarios are coupled with the high-temporal- and high-spatial-resolution electricity system (highRES) optimization model to assess technology deployment, spatiotemporal flexibility requirements, and system-level operational efficiencies (Zeyringer et al., 2018). This approach extends recent work on quantifying near-term feasibility constraints under social-environmental restrictions (Price et al., 2026; Roithner et al., 2025) and on monetized externality trade-offs (Grimsrud et al., 2024) by analyzing the operational dynamics of net-zero electricity systems. Rather than identifying a single optimal deployment, we employ scenario diversity to reveal trade-off spaces in which different ecological priorities yield distinct yet viable pathways, recognizing that socio-ecological futures are inherently uncertain yet partially shapeable through present decisions (Schweizer and Kriegler, 2012).

2. Data and methods

2.1. Spare-share scenarios: balancing economic and ecological interests

The siting of RE infrastructure reflects competing priorities that cannot be simultaneously optimized: infrastructure proximity may reduce grid extension costs but sacrifices access to higher-quality wind resources, while ecological protection often requires development away from high-biodiversity zones that frequently coincide with superior wind resources (Enevoldsen et al., 2019; McKenna et al., 2021). Biodiversity encompasses diverse life forms and associated ecosystems. In this study, we focus specifically on bird and bat species richness (247 bird species, 5 bat species) as indicators of ecological sensitivity to wind energy development. Birds and bats are particularly relevant due to their documented vulnerability to wind turbine impacts through collision, habitat displacement, and barrier effects (Gasparatos et al., 2017; Gilad et al., 2024a; Katzner et al., 2025; Kvalnes et al., 2023; Laranjeiro et al., 2018; May et al., 2021). To develop scenarios, we employ the spare-share framework, which distinguishes between strategies that spare ecologically sensitive areas by concentrating development near existing infrastructure versus strategies that share impacts more broadly across landscapes (Fig. 1). This approach reflects the decades-long debates in land-use and conservation planning on strategies for balancing human development with biodiversity preservation (Fischer et al., 2014; Phalan et al., 2011). Land sparing strategies concentrate human activities in already-modified landscapes to minimize the spatial footprint, while land sharing strategies distribute impacts more broadly across landscapes. While originally conceptualized for agricultural systems, the proposed framework translates to RE deployment where spatial configurations fundamentally shape both ecological impacts and system operational patterns.

Conserving biodiversity and landscapes for future generations is deeply rooted in Norwegian culture and politics (Vågerö et al., 2024a), while visual effects on landscapes and noise have been identified as primary concerns in opposition to wind farms in Norway (Kraft and Kraft, 2025; Roithner et al., 2025). The Norwegian wind farm licensing framework evolved from municipal land-use control (pre-2008) to centralized authority with substantial decision-making power. The Norwegian Water Resources and Energy Directorate (NVE) proposed a national framework[1] in 2019 for mapping the best-suited areas for onshore wind development. Widespread municipal opposition to this framework underscored the need for scenario-based analysis that accommodates diverse environmental priorities rather than technocratic siting optimization (Eikeland et al., 2023). Therefore, our scenarios integrate ecologically guided dispersion with infrastructure-proximate concentration to leverage existing grid connections and road networks. Rather than identifying a single optimal strategy, we developed the following scenarios along the continuum of species richness and infrastructure proximity dimensions (Fig. 1, Table A1).

Production maximization (PM) serves as the permissive baseline, excluding only strictly protected areas (IUCN categories Ib and II: wilderness areas and national parks, respectively) while maximizing onshore wind potential to establish an economic and operational reference point. Notably, we do not exclude the Ia areas (strict nature reserves—the most stringent IUCN protection level) to reflect historical permissive licensing practices, as some existing Norwegian wind farms are sited within this category.[2] ***Production co-location (PC)*** restricts development to sites within 5 km of existing infrastructure, with the exclusion of protected areas, reflecting concerns about grid extension costs and wilderness fragmentation, as in Norway, undisturbed nature areas ("inngrepsfrie naturområder" in Norwegian) are defined as wilderness areas that are over 5 km away from human infrastructure. Undisturbed nature areas are divided into three zones: 5 km, 3 to 5 km, and 1 to 3 km away from infrastructure.[3] ***Collision sensitivity avoidance (CA)*** prioritizes sites with lower collision risk for vulnerable species—specifically bats, raptors, and gulls—by excluding areas with the highest species concentrations (classes 3-5) and redlist species[4] areas with established buffer zones, while avoiding protected areas (Ia, Ib, and IV - habitat or species management area). The taxonomic groups—bats, raptors, and gulls—are treated as separate datasets due to their elevated vulnerability to turbine blade strikes (Table 3, Ref (May et al., 2020).). Moreover, morphological characteristics of these groups exhibit flight traits that face additional challenges due to attraction to associated infrastructures (Gilad et al., 2024c; Hernández-Lambraño et al., 2018). This reflects the precautionary principle applied to areas with high concentrations of collision-sensitive birds and bats despite limited evidence of population-level impacts (May et al., 2021; Serratosa et al., 2024). ***Ecological footprint minimization (EF)*** imposes strict infrastructure proximity requirements (<1 km from existing infrastructure) to concentrate development in already-modified landscapes, while excluding high-concentration areas for all bird and bat species (classes 3-5), protected areas (Ia, Ib, II, IV), and redlist species zones, making it the most constrained scenario. ***Sensitive development (SD)*** and ***sustainable co-location (SC)*** represent balanced share and spare scenarios, respectively. SD balances protection of highly collision-sensitive species (bats, raptors, gulls—more moderate criteria (classes 4-5) than CA) with development feasibility, avoiding protected areas (Ia, Ib, IV) and redlist species zones. ***SC*** moderates EF's strict proximity requirement by excluding only the highest species richness areas (all species, classes 4-5) within 3 km of existing infrastructure, alongside high-risk protected areas (Ia, Ib) and redlist species. Finally, ***sustainable development (SO1,***

[1] https://www.nve.no/media/19307/nasjonalramme-for-vindkraft.pdf.

[2] https://wimby.eu/resource/d1-3-land-and-sea-use-and-change-maps/.

[3] https://www.miljodirektoratet.no/ansvarsomrader/overvaking-arealplanlegging/naturkartlegging/Inngrepsfrie-naturomrader/.

[4] https://kartkatalog.geonorge.no/metadata?text=endangered%20species.

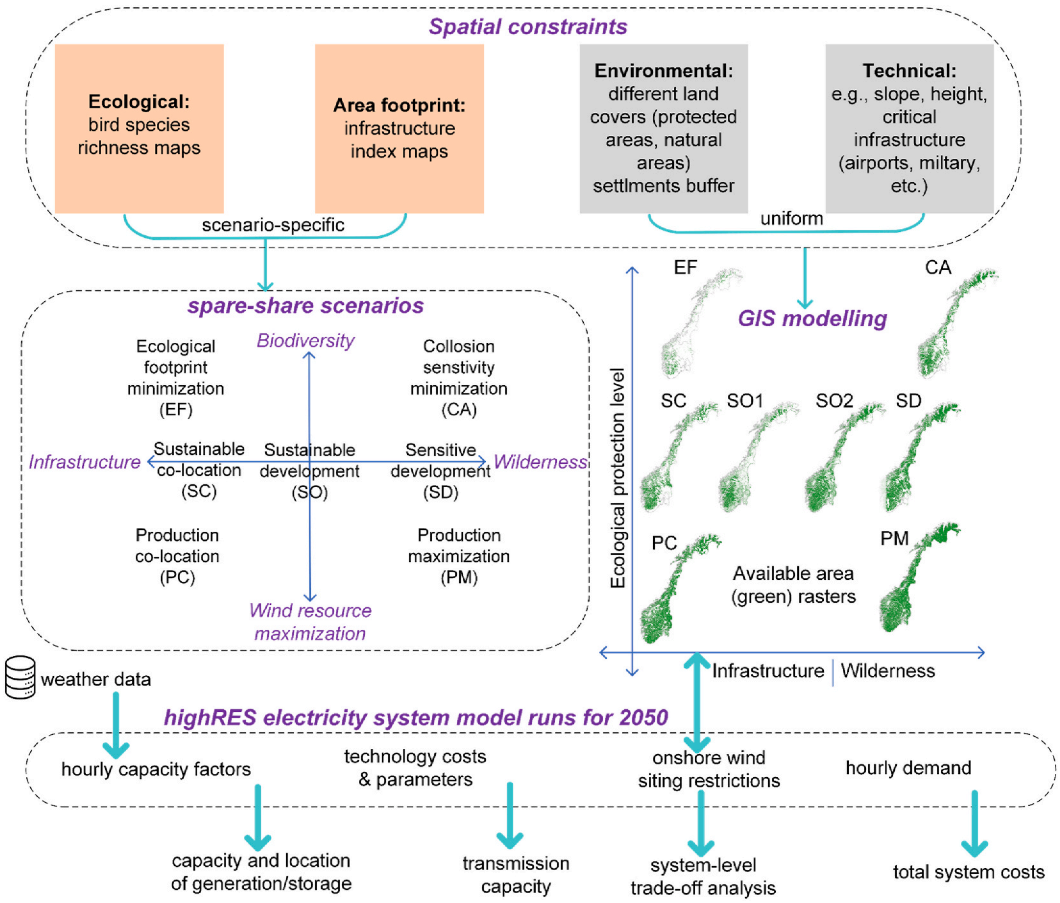

Fig. 1. An overview of the integrated methodological framework for assessing ecological-economic siting trade-offs in onshore wind deployment. Scenario-specific spatial constraints apply only to onshore wind, while uniform spatial constraints apply to all technologies. For scenario definitions, see Section 2.1; Table A1.

SO2) reflects the balanced development focus with a balanced siting strategy where thresholds are applied to the geometric mean of combined species richness and infrastructure datasets rather than individual restrictions: SO1 excludes classes 3-5 (stricter), while SO2 excludes classes 4-5 (moderate), both maintaining protected area exclusions (Ia, Ib) and redlist protections. This geometric mean approach integrates multiple dimensions simultaneously, exploring whether combined metrics yield viable alternatives to dimension-specific restrictions.

Threshold choices for infrastructure proximity and biodiversity restrictions reflect Norwegian policy frameworks and viable positions articulated in Norwegian planning debates (Gilad et al., 2024a; Grimsrud et al., 2024; Gulbrandsen et al., 2021; Kallbekken et al., 2026; Kenawi et al., 2025; Lawrence, 2014; Mósesdóttir, 2024; Roithner et al., 2025). Infrastructure distance buffers (1 km, 3 km, 5 km) correspond to the Norwegian classification of undisturbed nature areas ("inngrepsfrie naturområder").[5] Biodiversity class thresholds follow Environmental Impact Assessment (EIA) frameworks, where environmental values are categorized from negligible (class 1) to very high significance (class 5) (Inderberg et al., 2020). The five-class structure enables differentiation between moderate restrictions (excluding only classes 4-5) and stringent restrictions (excluding classes 3-5), as specified in Table A1 in the appendix. We applied Jenks natural breaks optimization to partition values into five classes that maximize within-class homogeneity and between-class variance (Rabosky et al., 2014). Jenks breaks were selected over arbitrary thresholds because they identify natural discontinuities in the statistical distribution of species richness, providing ecologically meaningful boundaries rather than percentile-based cutoffs that may bisect homogeneous habitat zones. Our scenarios are not predictions of future policy but rather analytical constructs for exploring diverse plausible futures under socio-environmental uncertainty. This scenario diversity approach aims to quantify system-level consequences of alternative spatial prioritizations, informing, but not determining, societal choices regarding trade-offs among competing environmental priorities. This contrasts with optimization approaches that implicitly encode value judgments in objective functions (Schweizer and Kriegler, 2012). Detailed criteria thresholds, data sources, and spatial implementation methods are specified in Table A1 and described in Section 2.2.

2.2. Datasets and tools

Species richness data were derived from earlier studies developing validated life-cycle assessment models (Kvalnes et al., 2023; May et al., 2020), which estimated spatially explicit distributions for diverse bird and bat species across Norway using their occurrence records from the Global Biodiversity Information Facility (GBIF, 2010-2019) and MaxEnt habitat suitability modeling (May et al., 2021, 2020). The datasets encompass 247 bird species and 5 bat species (Kvalnes et al., 2023; May et al., 2021), with species richness calculated as the number of species multiplied by their probability of presence at 1 km × 1 km resolution. Protected areas were obtained from the World Database of Protected Areas (WDPA) ("Protected Areas (WDPA)," 2023), categorized by IUCN management classifications (Ia, Ib, II, IV, and V - protected landscape). The distance to the nearest existing infrastructure at a 1 km × 1 km resolution was calculated using an infrastructure index at an original

[5] https://www.miljodirektoratet.no/ansvarsomrader/overvaking-arealplanlegging/naturkartlegging/Inngrepsfrie-naturomrader/.

100 m × 100 m resolution developed by (Erikstad et al., 2013). The infrastructure index map was aggregated to a 1 km × 1 km resolution by taking the mean. Then a threshold was set at index values =<1.8, as values above the threshold indicate areas with substantial infrastructure presence (Erikstad et al., 2013) (see table 2, page 19). The distance to the nearest existing infrastructure with an index value above 1.8 was calculated for each raster cell. All spatial datasets were transformed to the ETRS89-LAEA coordinate system (EPSG:3035).

Scenario-specific availability rasters were constructed by combining biodiversity layers with protected area and infrastructure constraints using the *'atlite'* geospatial toolbox (version 0.2.13) (Hofmann et al., 2021). This tool performs spatial union operations to generate composite availability masks across multiple raster layers. For example, the EF scenario excludes areas where any of the following conditions are met: species richness for bats, raptors, gulls, or all birds falls within classes 3-5 (highest richness values); protected areas Ia, Ib, II, IV; redlist species presence; or distance to infrastructure indicating locations >1 km from existing settlements. These scenario-specific availability rasters enabled detailed spatial analysis across Norway to identify national and regional patterns of land availability (Section 3.1). These rasters were subsequently aggregated to a 30 km × 30 km resolution, integrated with technical exclusions (i.e., slope, height, physical infrastructure), environmental exclusions (i.e., urban areas, forests, water bodies, protected areas with distance-dependent buffers) based on CORINE land cover classifications,[6] and weather data for capacity deployment optimization in the highRES energy system model, as described in Section 2.3.

2.3. Power system modelling framework

We employ the open-source highRES model (Zeyringer et al., 2018), designed to assess electricity systems with high shares of variable RE and explore flexibility options. highRES is a linear optimization model implemented in the General Algebraic Modeling System (GAMS) that minimizes total system costs (annualized investment and operational expenditures) by optimizing the spatial allocation of new technology capacities, hourly dispatch decisions, transmission expansion, and energy storage deployment under perfect foresight at hourly temporal resolution. We adapt highRES to represent the Norwegian power system across 15 administrative regions (revised 2024 boundaries). The model represents a hybrid greenfield framework in which existing solar and wind capacities are excluded, while existing hydropower and transmission lines are included and remain fixed at their current capacities. Existing wind capacity (~5 GW) is excluded due to its operational lifespan by 2050 and to enable endogenous determination of optimal deployment patterns under scenario-specific ecological constraints. Technologies available for capacity expansion include onshore wind, offshore wind (bottom-mounted in waters <70 m depth and floating turbines in deeper waters (Roithner et al., 2025)), solar photovoltaics, and energy storage. All scenarios employ identical techno-economic parameters, 2050 demand projections, weather data, and exclusions for solar PV and offshore wind; the sole variation lies in the onshore wind availability masks, which reflect the ecological and biodiversity priority configurations detailed in Section 2.2. A detailed description of the highRES model, assumptions, technical constraints, and data sources is provided in the Appendix, and the model code with full replication data is openly available at GitHub.[7]

3. Results

3.1. National and regional spatial patterns of available sites

The spatial availability patterns presented here reflect the outcomes of ecological thresholds and infrastructure criteria employed in our spare-share scenarios (Section 2.1) and do not represent objective classifications of Norwegian land. A 7% of the total Norwegian land area is commonly available across the scenarios, revealing rare safe onshore wind development zones (Fig. 2a). In contrast, 67% exhibits availability in some scenarios but restricted in others, suggesting that the majority of Norway's landscape availability is sensitive to which ecological and infrastructure priorities guide spatial allocation decisions (Fig. 2c). The dominance of contested geography over consensus zones illustrates Norway's spatial complexity: biodiversity hotspots, landscape values, and infrastructure constraints overlap substantially across the territory.

Although the majority of unavailable areas across spare-share scenarios (*unavail*) concentrate in Western and Northern Norway (~50% of total *unavail*), the eastern counties exhibit significant internal restrictions due to anthropogenic impacts, such as urban footprints and existing developments (Fig. 2b). Notably, while approximately half of these small urban counties are universally restricted, when combined, they account for only ~4% of the total always unavailable area.

Scenario correlations reveal the extent to which different restriction frameworks agree on geographic suitability—a high positive correlation indicates the likelihood of sharing flexible area geographies. In contrast, a negative correlation indicates that scenarios access different geographies (Fig. 2e). Despite both targeting similar biodiversity conservation, the moderate correlation between CA and SD (0.51) suggests that half the area SD permits is restricted by higher CA's restrictions, with additional divergence arising from heterogeneous spatial distributions of diverse species groups (May et al., 2021). This geographic divergence is reflected in the distribution of flexible areas across scenarios (Fig. 2d), where most flexible zones cluster around 4-5 scenarios, indicating that varying severity levels of similar habitat priorities fragment geographic outcomes. When biodiversity restrictions are combined with proximity constraints in EF (1 km) and SC (3 km) scenarios, the correlation further drops to 0.21, suggesting heterogeneity in balancing spare- and share-siting strategies for land-based wind farms, with few emerging as suitable across the restriction frameworks.

Because they target different geographies, spare-and-share scenarios exhibit negative to very low correlations with one another. The most conservative scenario, EF, exhibits correlations ranging from −0.08 to 0.21 with other scenarios, indicating that high infrastructure proximity restriction combined with high ecological restrictions creates spatial patterns distinct from either restriction applied independently (Fig. 2e). Negative correlations between economy (PC) and share scenarios (CA vs PC: −0.12, SD vs PC: −0.12) demonstrate that economy-focused infrastructure concentration and ecology-focused infrastructure concentration target opposite geographies. Moreover, negative or low correlations between economic siting near infrastructure (PC) and ecologically acceptable sites near infrastructure (EF, SC, SO1, SO2) preclude the spatial optimization of wind sites that simultaneously consider both criteria. Notably, highly restricted scenarios correlate more strongly with each other (EF-CA: 0.20) than with moderately restricted scenarios (EF-SD: 0.10; SC-SD: 0.42 vs SC-CA: 0.31), indicating that extreme restrictions—whether ecological or combined—converge on the same limited geography of least-sensitive areas, while moderate thresholds access broader, more diverse landscapes. Three large northern/central counties (Innlandet, Trøndelag, Finnmark) dominate both the flexible area (accounting for ~52% of the total) and the unavailable area (33% of the total), indicating that large, geographically diverse counties contain the diverse restriction spectrum.

Most existing wind farm locations are in flexible zones, with only ~10% in always-available zones (Fig. 2a and c). 28% of existing wind farm locations appear in only one scenario—the most permissive PM

[6] https://land.copernicus.eu/content/corine-land-cover-nomenclature-guidelines/html/.

[7] https://github.com/JavedMS/highRES-Norway/tree/highres_NINA.

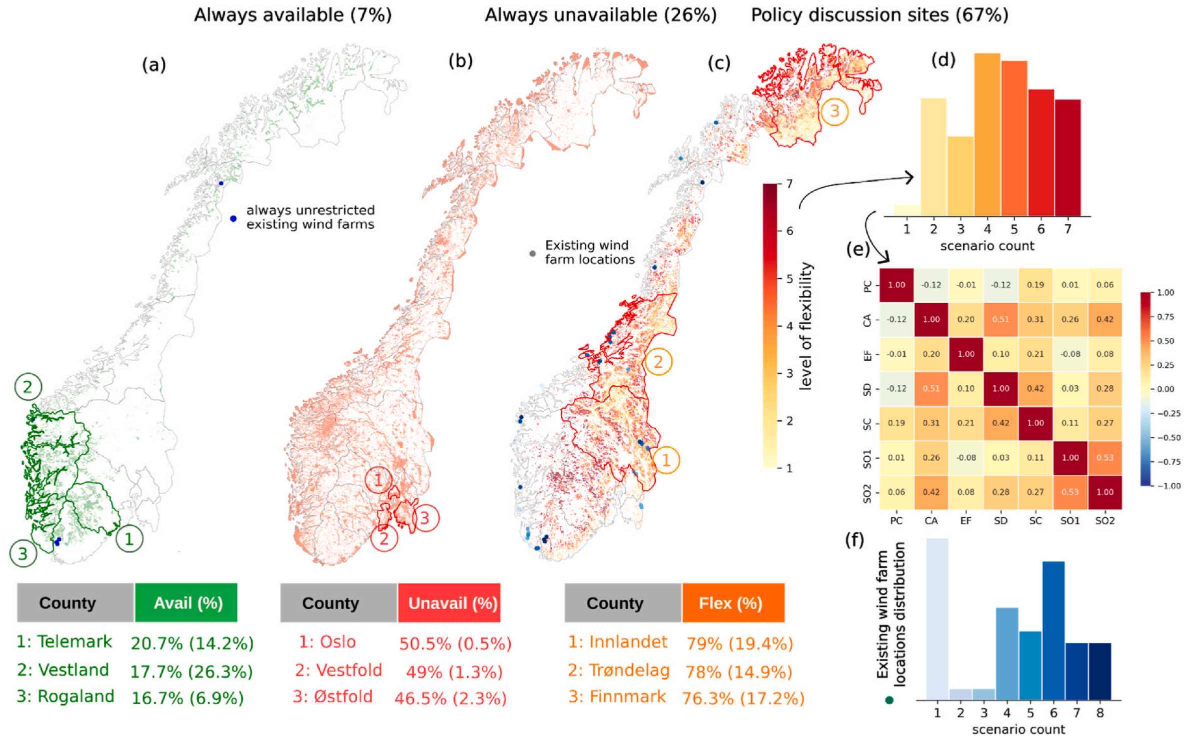

Fig. 2. National and regional spatial availability patterns. The figure shows the tripartite division of Norway's land area. (a) Always-available areas *(Avail)* (7% of Norway) represent sites unrestricted across all scenarios, with blue dots indicating existing wind farms located in always-available areas (~10%); (b) Always-unavailable areas *(Unavail)* (26% of Norway) indicate sites universally restricted across all scenarios, concentrated in Western and Northern Norway; (c) Policy discussion sites (67% of Norway) represent flexible areas *(Flex)* where availability depends on scenario choice. Red and blue color intensities indicate the number of scenarios the given location appears; (d) Distribution of flexible area across scenarios, showing most clusters around 4-5 scenarios; (e) Correlation matrix between scenarios, illustrating how likely two scenarios share the same available area in Fig. c; (f) Existing wind farm location distribution across scenarios—28% appear only in one scenario. Circled counties show the highest share of their area in each category. For example, in Fig. b, Oslo exhibits the highest internal restriction rate (50.5%) but contributes minimally to the total unavailable area (0.5%) [See Table A1]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

scenario—and most of these single-scenario installations concentrate in Northern Norway (light blue markers, Fig. 2c). Similar to the overall scenario distribution across flexible zones, most existing wind farm locations appear in 4-6 scenarios, revealing that historical development already navigated moderate ecological contestation but avoided the most sensitive zones.

Ecological restrictions reduce onshore wind capacity potential from 418 GW (PM) to 37 GW (EF)—an 11-fold reduction (Fig. A1 in the appendix). The levelized cost of energy (LCOE) of onshore wind increases up to 19% to 21% across scenarios to meet all the new electricity demand for 2050 (Fig. A1 (b); vertical red lines) (Statnett, 2025). The onshore potential under EF (83 TWh maximum) remains insufficient to meet upper demand projections alone. Regional capacity factor analysis reveals that six counties experience a mean increase in capacity factor because restrictions preferentially exclude low-quality sites (marked in green). Conversely, seven counties show declines in mean capacity factor due to the exclusion of high-quality wind sites (marked in red).

Notably, three counties suffer on average the steepest degradation of high-quality sites (Finnmark −10.7%, Akershus −11%, Telemark −5.2%), while moderate-quality central regions (Innlandet +3.4%, Trøndelag +3.3%) gain relative attractiveness, and some remain largely unaffected (i.e., Møre og Romsdal). Spatial availability patterns (Fig. A1 (a) in the appendix) demonstrate that northern capacity depends critically on proximity to infrastructure, as capacity in these areas collapses by 70% to 90% (i.e., EF, SC, SO1). Eastern regions exhibit inverse sensitivity as high biodiversity thresholds disproportionately restrict these areas (SC, CA, SD, EF) under species richness frameworks.

3.2. System cost implications of different land use patterns

Ecological restriction-related system cost increases are non-linear, driven by both capital and operational costs (Fig. 3). Both spare and share scenarios under expandable transmission exhibit higher cost increases because expandable PM has already optimally deployed transmission capacity (reducing baseline costs by 1.8% with +1.2 GW transmission capacity from PM fixed transmission), leaving minimal further transmission optimization potential for other scenarios, which must then absorb costs through technology substitution (Fig. 3a–c). Despite divergent ecological priorities, moderately restricted scenarios (SO1, SO2, SC, SD) cluster around 1.5-2.5% cost increases, illustrating that geographic overlap of different ecological and biodiversity hotspots leads to the production of similar economic outcomes (Gilad et al., 2024a).

Generation upkeep costs contribute 50-80% of the total cost increase across all scenarios for two reasons. First, Norway's extensive existing hydropower capacity contributes substantially to upkeep costs without associated capital expenditure. Second, ecological restrictions shift the technology portfolio toward higher-operational-cost alternatives (i.e., offshore increases from ~3 GW to ~10 GW from PM) with reduced generation efficiency (2180 vs 2390 TWh/GW), thereby disproportionately increasing upkeep costs. This is similar to other Norway-based studies (Hvidsten et al., 2025; Roithner et al., 2025).

Storage investments reflect the economics of balancing spatial and temporal resources: the system invests in storage when transmission is constrained and reduces storage investment as transmission expands (Fig. A3 in the appendix, Section 3.3). EF presents an exception—despite transmission expansion, storage investment increases by 13% of total

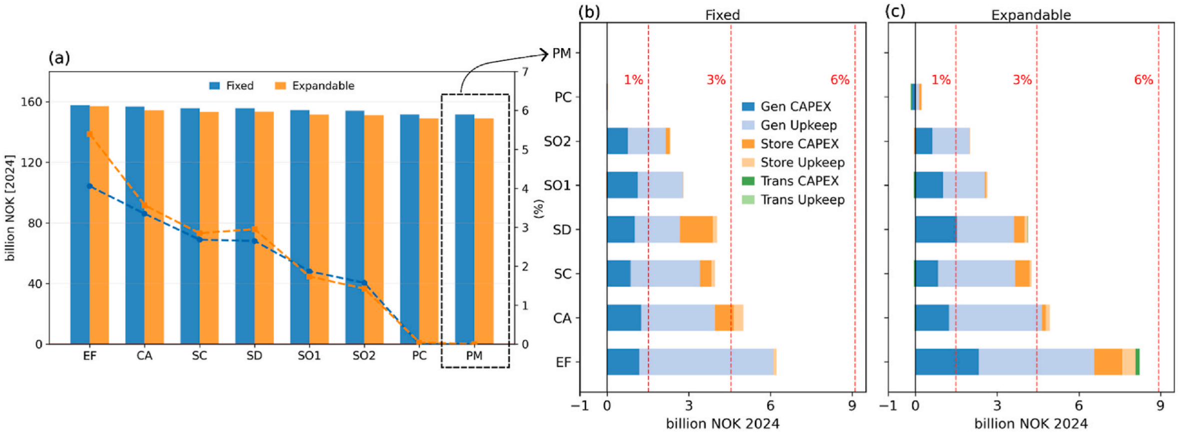

Fig. 3. System cost implications for ecological restrictions. (a) Total system costs for net-zero 2050 system designs under fixed and expandable transmission configurations across scenarios. Production maximization (PM) scenario serves as the base case for change in costs (dashed lines in (a) with right y-axis) and cost compositions in (b) and (c). Contribution of each system cost component to the total system cost decrease or increase. Negative values are reduced in the relative cost component relative to the base case component, while positive values increase. Red vertical lines indicate the total system cost increase relative to the base case. *Capex: upfront capital cost; upkeep: fixed & variable operation and maintenance cost.* (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

cost change, demonstrating that strict ecological restrictions create temporal mismatches that neither transmission-alone nor storage-only substitution can fully resolve. Negligible transmission capital investments (<2% of cost increases) across all expandable scenarios relative to the base PM-expandable (where +1.5 GW of transmission capacity is already added) indicate that land-use flexibility constitutes the primary binding economic constraint.

The economic impact of coupling a spare strategy with an economy-focused objective (i.e., PC) imposes a negligible cost penalty (Fig. 3a), demonstrating that infrastructure-proximate deployment is economically optimal when unconstrained by ecological restrictions. However, when spare strategy pairs with ecological constraints (EF, SC), costs increase, highlighting the strong influence of ecological constraints on system-preferred onshore sites, regardless of infrastructure proximity.

3.3. Capacity mix and regional deployment patterns

The interplay among transmission mode, ecological restriction severity, and storage affects how the system substitutes for the constrained onshore wind (Fig. 4). Although ecological restrictions shift the technology mix and system substitutes for the constrained onshore wind differently, transmission expansion does not significantly reduce the total system generation capacity across scenarios. The decrease is between 2 and 4 GW, except for EF, which shows a ~2 GW increase in total capacity, as solar substitution partially offsets onshore wind constraints (Fig. A2 in the appendix).

Although transmission expansion enables better substitution flexibility, it does not overcome the impact of ecological restrictions on onshore wind deployment capacity, as the onshore wind reduction

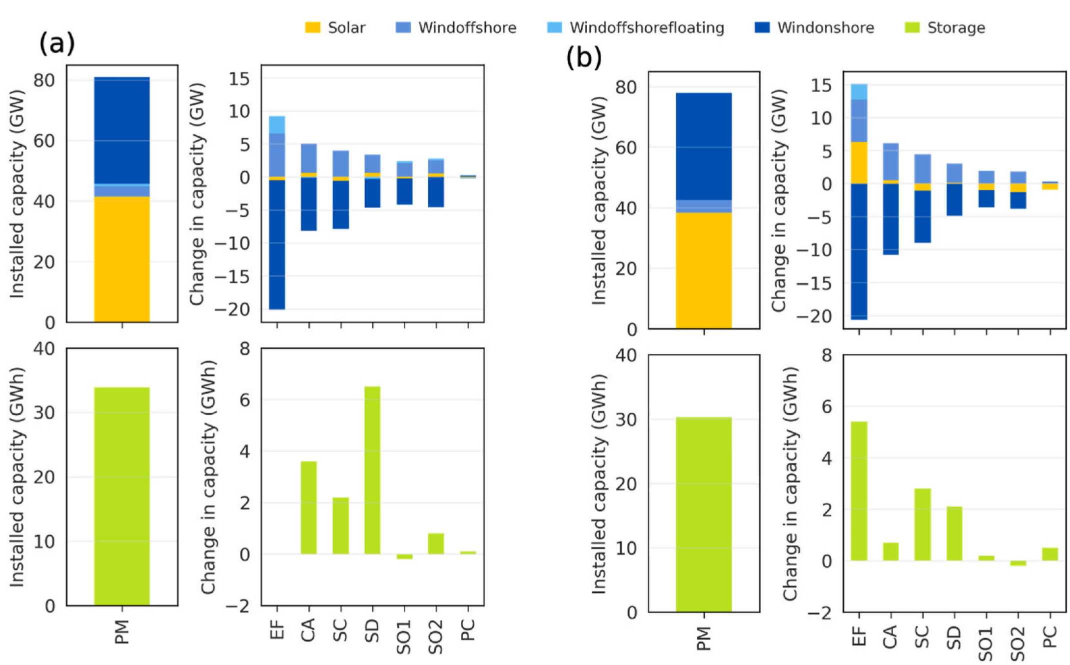

Fig. 4. Technology capacity deployment patterns under ecological restrictions. (a) Fixed and (b) expandable transmission scenario results showing installed generation capacity (top panels) and storage capacity (bottom panels). The left panels show baseline PM scenario capacities, while the right panels show changes from PM across scenarios. Negative values indicate reductions and positive values show increases relative to PM. Total installed capacities are presented in Fig. A2 in the appendix.

pattern remains largely the same regardless of transmission configuration. The most restricted scenario (EF) shows ~20 GW of onshore wind reduction from the PM baseline across transmission scenarios, while moderately restricted scenarios (CA/SC/SD) show ~5-10 GW reductions.

Changes in solar capacity are driven by siting strategy rather than transmission configuration. Spare scenarios (PC, SC) exhibit marginal solar reductions (0.1-1.1 GW) as concentration near existing infrastructure enables better utilization of nearby onshore wind resources. Conversely, share scenarios (CA, SD) show marginal increases (0.1-0.6 GW) as broader spatial deployment creates opportunities for complementary solar integration. This spare-share pattern holds consistently across both transmission configurations, though absolute solar capacities are higher under fixed transmission than expandable (Fig. A2 in the appendix). High ecological restrictions in the EF lead to an exception in which the system compensates for constrained wind with high solar deployment (+7 GW) rather than costly offshore wind.

Offshore wind remains the least sensitive to transmission configurations, varying by 0.5-0.7 GW within scenarios across transmission categories. This demonstrates that offshore deployment in Norway responds to land-based availability constraints rather than to transmission expansion (i.e., grid flexibility), enabling better utilization of available capacity but not fundamentally altering the national technology mix. Floating offshore wind becomes economically competitive only under very high land-based restrictions (i.e., EF), demonstrating that transmission expansion marginalizes floating offshore's economic competitiveness except when land-based options are critically constrained.

3.4. Regional deployment patterns

New storage deployment is geographically concentrated in southwestern regions (Møre og Romsdal, Telemark, Agder), primarily driven by temporal balancing of high solar saturation (Fig. A4 in the appendix). Under fixed transmission, storage is located near generation sites where temporal balancing is most economical—Møre og Romsdal and Trøndelag each host up to 15 GWh despite their distance from demand centers in the south and east. However, new storage is shifting toward demand-proximate southern regions (Telemark, Agder) through transmission expansion, reflecting the economic advantage of temporal balancing near load centers when transmission can efficiently connect distant generation. Western regions (Rogaland, Vestland) deploy negligible new storage across all scenarios, given existing hydropower storage, eliminating the need for additional temporal balancing capacity.

Spatial deployment patterns reveal stable, region-specific technology structures across transmission configurations. Telemark, Vestfold, and Buskerud inflexibly hold solar allocation across all scenarios regardless of transmission mode, suggesting these regions possess optimal solar resource quality and demand proximity unaffected by the level of constrained onshore wind (Fig. 5). Similarly, Agder, Trøndelag, Nordland, and Troms maintain onshore wind deployment across all scenarios. Østfold exhibits high sensitivity to ecological restrictions, where the capacity of 5.1 GW of onshore wind (PM) is replaced by 4.1 GW of solar, leading to an accelerated marginal cost of EF restrictions (Fig. 6). Finnmark demonstrates similar vulnerability; even transmission expansion did not make the available areas in the north economically attractive. Offshore expansion primarily occurs in the southwestern regions (Agder and Rogaland). Transmission expansion does not significantly alter regional technology portfolios but shifts capacity magnitudes (e.g., Agder, Innlandet), demonstrating that transmission flexibility enables capacity optimization rather than technology diversification, with spatial technology allocation determined primarily by resource availability and ecological constraints rather than by grid configuration (i.e., transmission).

3.5. Economic cost of different protection levels

The economic pressure of environmental restrictions on system optimization is quantified by shadow prices (dual variables) derived from the model's binding area capacity constraints (for further explanation, see (Grochowicz et al., 2024b). Shadow prices represent the marginal rate at which the total system cost objective function would decrease if the area constraint were relaxed by one

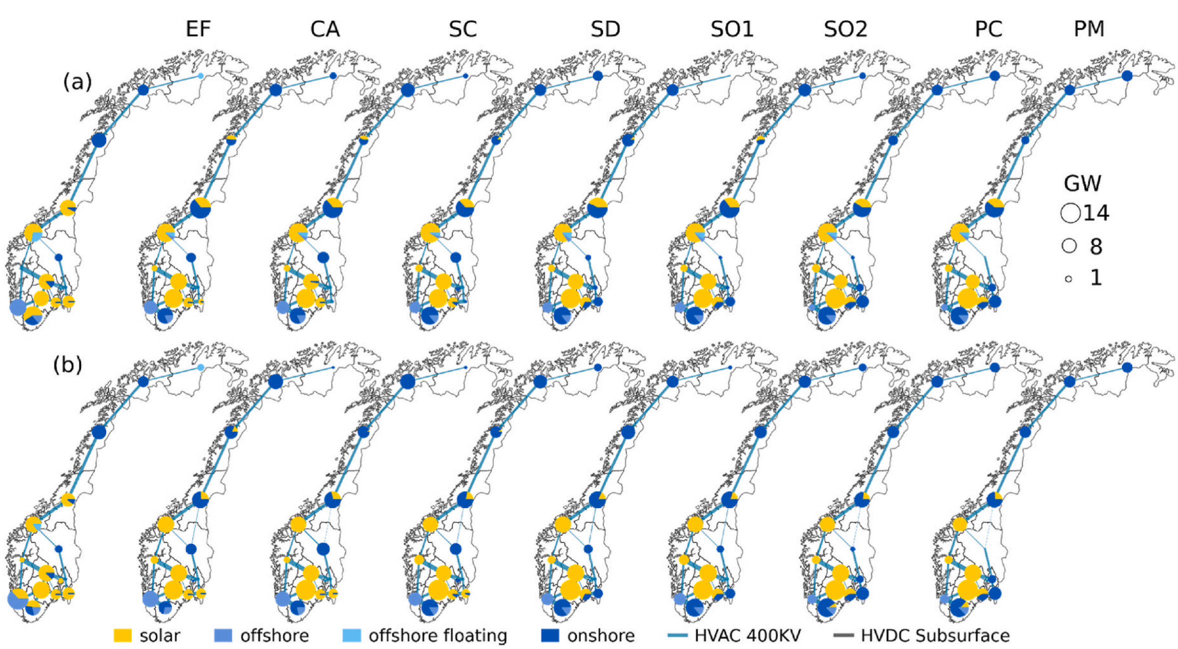

Fig. 5. Regional technology deployment patterns across Norway. (a) Fixed transmission and (b) expandable transmission scenarios showing county-level capacity deployment across environmental scenarios. Pie charts show the installed generation capacity mix in each county, with pie sizes proportional to the county's total deployment. Transmission infrastructure is shown as HVAC 400 kV lines (overhead) and HVDC subsurface power lines. Transmission expansion shifts capacity magnitudes within regions but does not alter county-level technology portfolios, demonstrating that regional comparative advantages in resource quality and environmental restrictions drive technology allocation rather than transmission flexibility.

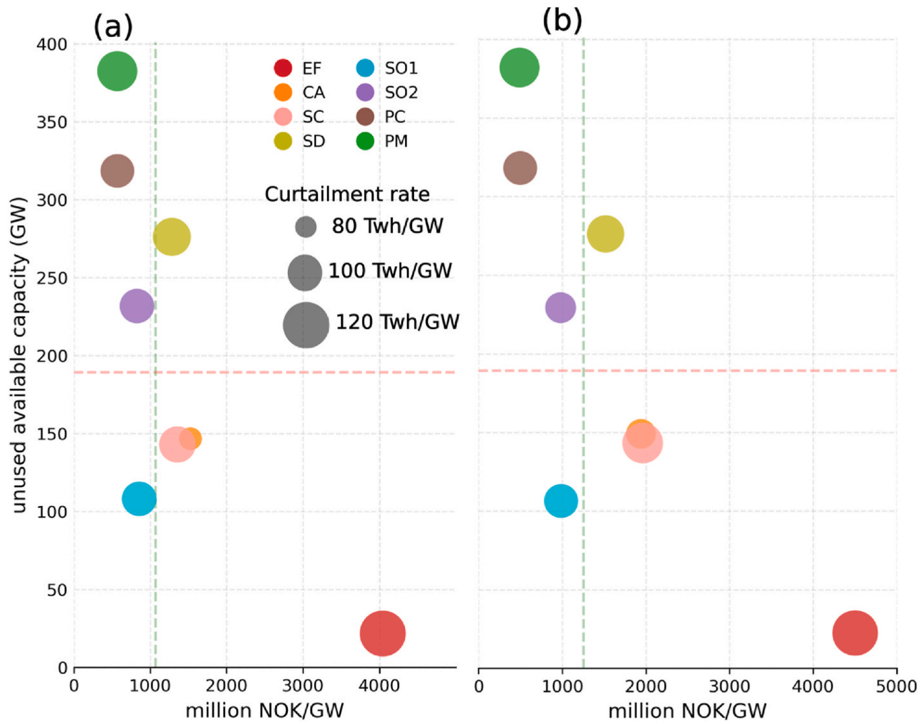

Fig. 6. Economic opportunity cost and system efficiency across ecological scenarios for onshore wind. (a) Fixed transmission and (b) expandable transmission results showing the relationship between economic opportunity cost (million NOK/GW) and unused available capacity (GW), and curtailment rates (circle size, TWh/GW). Economic opportunity cost represents the marginal economic value of relaxing area constraints at the current optimum. Green and red dashed lines indicate the median across scenarios. The transmission expansion, though it shifted the magnitudes, did not affect the diminishing-returns relationship between unused capacity and opportunity costs. See Fig. A5 in the appendix for offshore wind. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

unit—mathematically, ∂(total system cost)/∂(available area). These dual values indicate the difficulty of satisfying area constraints under each scenario, revealing the instantaneous economic value of additional developable land at the current optimum. Critically, shadow prices are local derivatives evaluated at a specific solution and therefore serve as comparative indicators of relative economic pressure across scenarios. While these values reflect economic pressure within the model's optimization framework, they represent marginal values under model constraints rather than real-world opportunity costs or policy compensation levels.

The analysis reveals substantial variation in economic opportunity cost across scenarios, ranging from 500 million NOK/GW (PM, PC) to 4,5 billion NOK/GW (EF)—a 9-fold escalation. This large range indicates that the marginal economic value of additional developable areas substantially depends on the restrictive frameworks. Despite this extreme range, moderately restricted scenarios (CA, SC, SD) cluster around the median, demonstrating that different ecological and biodiversity priorities yield similar economic opportunity costs when geographic overlap among ecological hotspots creates functionally equivalent restrictions on available onshore wind sites (Fig. 6, vertical green line).

Although transmission modestly affects economic cost (−14% to +18% change from fixed to expandable, except in the SC scenario, where it is +45%), it does not alter the scenario ordering, where the opportunity cost of EF remains highest. In contrast, moderate scenarios remain clustered around the median. This persistence reveals two takeaways: first, transmission capacity is not the primary bottleneck for onshore wind deployment under these ecological scenarios; and second, the spatial availability of suitable sites constitutes the binding constraint, suggesting a focus on alternative grid flexibility measures, such as demand response.

Unused capacity represents the difference between available capacity potential (after ecological exclusions) and deployed capacity, quantifying the additional development potential that remains accessible but economically unviable under system optimization. The relationship between unused capacity and opportunity costs exhibits diminishing returns to permissiveness. Despite having up to three times more unused capacity than moderate scenarios (380 GW PM vs 120 GW SO1), economic opportunity cost decreased by ~30% (excluding EF's extreme position), indicating that beyond a threshold, increasing available area yields progressively smaller reductions in the economic value of additional capacity. This non-linearity reflects system-level bottlenecks—grid flexibility limitations, temporal mismatches between generation and demand, and regional transmission constraints—that prevent the full utilization of available capacity regardless of land-use permissiveness.

The trade-off between ecological restrictions and efficient system utilization is distinctly non-linear. Our analysis reveals that moderate restriction scenarios (CA, SC, SD) achieve better system integration compared to extreme scenarios (EF, PM), with a curtailment rate of ~100 TWh/GW versus ~120 TWh/GW for extreme scenarios (PM, EF)—representing 20% higher curtailment intensity at both ends of the restriction spectrum. Two mechanisms explain this: First, maximum available areas (PM) enable deployment in optimal locations, but system oversupply at peak generation hours and grid flexibility constraints limit absorption capacity. Second, high restrictions (EF) force deployment in locations with lower generation efficiency (2180 vs 2390 TWh/GW in PM) and proximity requirements (<1 km), creating temporal mismatches between generation and demand. This spatial-temporal mismatch is amplified by EF's geographic concentration: as demonstrated in spatial availability analysis (Section 3.1, Fig. A3 in the appendix), EF's low correlation with other scenario (−0.08-0.21) concentrates deployment in southwestern counties where infrastructure proximity requirements are met, but these regions exhibit relatively high solar saturation and lower wind resource compared to the geographically diverse, higher-quality northern sites (Trøndelag, Finnmark) accessible under moderate scenarios. This pattern demonstrates that realized capacity utilization does not correlate linearly with land-use restriction severity—moderate restrictions optimize the balance between siting and system integration better.

3.6. Hourly electricity cost distribution

Hourly electricity costs are calculated using the hourly electricity shadow prices (i.e., dual variables) and demand, reflecting the marginal cost of meeting demand in each hour. To assess how ecological restrictions affect typical electricity system operation, extreme hours, and operational cost patterns, we analyze three metrics: median (central tendency of typical hours), mean (accounting for extremes), and coefficient of variation (CoV) (measuring relative volatility).

Ecological restrictions do not necessarily increase hourly electricity cost volatility. The most restrictive scenario (EF) exhibits lower volatility (CoV: 5.84 fixed, 6.78 expandable) across ecological scenarios and transmission configurations (Fig. 7). This connects to the spatial availability findings (Section 3.1): limited and fixed geographic availability (i.e., the southwest for EF) constrains dispatch options to a narrow set of locations, and even grid flexibility cannot overcome spatial restrictions on where generation exists. Moreover, lower CoV reflects a relatively less supply-demand mismatch at these limited available sites. Meanwhile, higher cost volatility in other scenarios compared to the base scenario reveals operational outcomes depend critically on whether favorable renewable conditions occur at available or excluded sites—when conditions align with accessible locations, costs remain moderate, but when optimal conditions occur at restricted sites, the system must dispatch expensive alternatives, creating larger cost swings.

This median-mean divergence reveals how ecological restrictions primarily affect extreme hours and typical operation hours. The variation in median hourly costs remains <3% (fixed) and <6% (expandable), while mean costs increase up to ~12% across scenarios. For

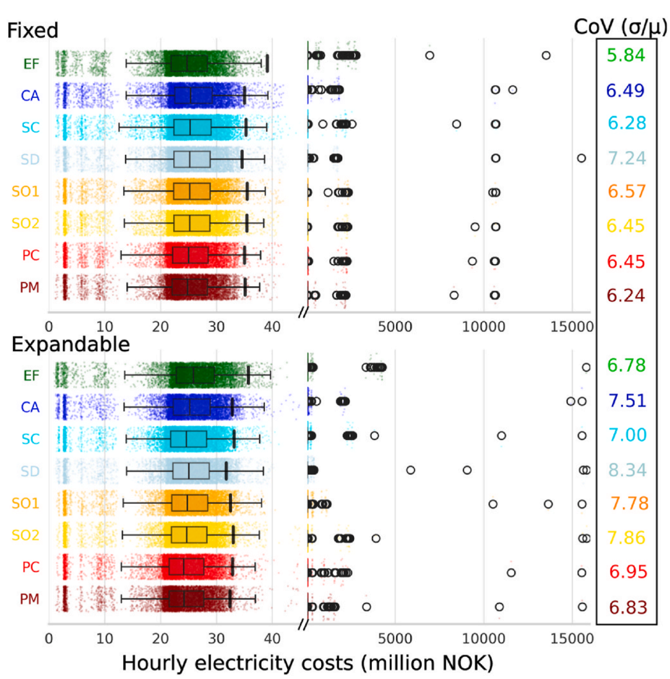

Fig. 7. Hourly electricity cost distribution and volatility. Distribution of hourly electricity costs for fixed (upper) and expandable (lower) transmission configurations. Coefficient of variation (CoV = σ/μ) values on the right quantify relative volatility for each scenario, with lower values indicating more consistent costs relative to the mean. Transmission expansion increases volatility across all scenarios, reflecting enhanced dispatch flexibility.

example, EF shows a higher mean (39.12M NOK) with a similar median (24.76M NOK) to PM (24.86M NOK), indicating that most hours experience comparable costs, but rare extreme hours (<1% of hours, exceeding 1,000M NOK) become more costly under restrictions. Conversely, SD exhibits a lower mean (34.57M NOK) but a higher median (25.21M NOK) than the base case across transmission configurations, suggesting fewer costly extreme hours but elevated typical operational-hour costs. This pattern demonstrates that the economic impact of restrictions manifests as amplified tail behavior—more frequent or more severe extreme-cost hours—rather than across-the-board increases in operational costs.

Transmission expansion increases hourly cost volatility across all scenarios. This increase in volatility reflects enhanced operational flexibility: expandable transmission enables dynamic inter-county dispatch optimization, in which the system routes power hour by hour based on instantaneous electricity production and demand patterns. This creates more variable dispatch patterns than in fixed transmission, where constrained grids force local balancing with predictable local dispatchable generation (i.e., storage). While this flexibility reduces average costs (the mean drops ~8% with transmission expansion), it introduces operational variability, as optimal dispatch varies more substantially across hours depending on renewable generation conditions.

4. Discussion

Energy system models increasingly recognize that spatial allocation decisions fundamentally shape system outcomes (Grimsrud et al., 2024; Roithner et al., 2025). Our analysis demonstrates how spatial prioritization strategies—concentrating development near existing infrastructure (spare) or dispersing capacity to avoid biodiversity hotspots (share)—create distinct investment and operational patterns beyond simple capacity allocation. The integration of species-level biodiversity data with electricity system modelling reveals that system flexibility—through transmission, technology substitution, storage—enables biodiversity protection while maintaining system viability. Our spare-share framework differs from existing approaches in two key ways. First, unlike continental-scale analyses that apply ecological criteria uniformly across regions and overlook local socio-ecological variation (Price et al., 2026), our scenario diversity approach systematically explores how different combinations of priorities affect system outcomes without assuming uniform stakeholder preferences. Second, unlike multi-objective optimization, which requires predetermined criterion weightings (Weinand et al., 2022), our discrete scenario framework enables assessment of trade-off implications while preserving participatory decision space. By spanning the spectrum from infrastructure concentration to ecological dispersion, the framework demonstrates when biodiversity conservation and energy system planning compete versus where they align to maximize climate mitigation efforts. The proposed spare-share framework can complement existing Ecological Impact Assessment processes, contribute to more objective evaluation of biodiversity impacts, and promote more biodiversity-friendly strategies for RE planning (Leclère et al., 2020).

Our spatial availability analysis divides Norwegian land into three distinct categories: 7% 'go-to' areas, 26% 'no-go' areas, and 67% contested areas requiring priority-setting (Fig. 2). This geographic breakdown quantifies what previous studies have described qualitatively: wind energy siting involves extensive contested space requiring explicit priority-setting (Gilad et al., 2024a; May et al., 2021). The policy-sensitive 67% represents neither a technical problem with a single optimal solution nor an intractable conflict, but rather a decision space in which different societal values yield distinct but defensible outcomes. The western counties always dominate available areas, while the eastern counties always concentrate on the unavailable zones. This regional pattern suggests that these areas share internally consistent ecological and infrastructure characteristics regardless of the restriction framework.

The spare-share spatial strategies manifest technology-specific patterns of capacity expansion regardless of grid extension. A spare approach reduces the solar share in the national capacity mix, whereas a share approach increases it due to broader spatial coverage, creating opportunities for complementarity with onshore wind (Fig. 4, Fig. A2) (Grochowicz et al., 2024a). Offshore wind also remains the least sensitive to grid expansion and responds to different ecological restrictions, with capacity ranging from ∼3.5 GW to ∼10 GW depending on the severity of land-based restrictions. These offshore projections align with the Norwegian government's plans to produce 26-87 TWh of electricity by 2050 (DNV, 2024; Statnett, 2025). Most of the new offshore capacity additions remain in southwestern Norway due to its proximity to demand centers and the optimal use of the established grid, rather than in northern or central Norway, where the system would require new transmission capacity. Although social acceptance of offshore wind is higher than that of onshore wind in Norway (Linnerud et al., 2022), potential marine biodiversity impacts on species richness require further investigation (Stranddorf et al., 2024).

Moreover, these spatial strategies reinforce regional distribution patterns of deployed capacities. Despite varying ecological priorities and transmission configurations, some regions maintain consistent technology portfolios. Southern and southeastern counties inflexibly hold the solar deployment ranging between 3 and 17 GW, while central counties invariably hold onshore wind between 1 and 10 GW each. Østfold county only appears to be very sensitive to ecological restrictions, completely substituting onshore wind for solar (Fig. 5). We note a sustained onshore wind capacity reduction from the base case in northern Norway (Tromsø & Finnmark), due to increased ecological and infrastructure constraints, from ∼8 GW to ∼3 GW. Studies have shown that solar has lower biodiversity impacts compared to onshore wind (Borgelt et al., 2026) and may contribute significantly to the Norwegian electricity mix, increasing from 0.25 TWh to 15-19 TWh by 2050 (DNV, 2024; Statnett, 2025). Strategic planning for solar farms may involve prioritizing brownfields to minimize their negative effects on certain species (Baudouin et al., 2026).

The choice between spatial and temporal balancing depends on both the siting strategy and the transmission configuration (Fig. A3, Fig. A4 in the appendix), where fixed transmission with the share approach and the spare approach with expandable transmission exacerbates the role of storage. With fixed transmission, share scenarios exhibit greater storage increases for two reasons: first, deployment away from existing infrastructure necessitates localized temporal balancing due to limited grid connectivity; second, increased solar share in the capacity mix leads to higher temporal mismatch, as solar is only available during the daytime. Conversely, spare scenarios (EF, PC, SC) show minimal storage increases due to reduced solar saturation and concentration near demand centers, enabling the maximum use of the established grid rather than installing solar in other low-demand regions with high solar potential (Fig. A4 in the appendix). However, this pattern was reversed with the expansion of transmission. Spare scenarios see storage increases as the system deploys maximum new capacities in the proximity of existing infrastructure, even at high temporal-mismatch locations, requiring storage in addition to transmission to provide spatial redistribution capacity. Meanwhile, storage needs are reduced in the share scenarios because transmission expansion connects distant high-quality sites directly to demand centers, substituting spatial balancing for temporal storage.

Recent work on Norwegian flexibility options confirms that spatial distribution of renewable capacity fundamentally affects temporal smoothing requirements (Grochowicz et al., 2024a), but our results illustrate that beyond a certain threshold grid expansion cannot substitute for spatial availability: even with 1.2 GW of cost-effective transmission additions, system costs increase 1.5-6% under ecological restrictions, driven primarily by operational inefficiencies from constrained siting rather than insufficient grid capacity. Combined with Gilad et al.'s demonstration that transmission infrastructure carries its own biodiversity costs, our findings suggest that spatial planning frameworks constitute the primary policy lever for balancing biodiversity preservation with system economics, with grid expansion serving as a necessary but insufficient complement (Gilad et al., 2024a, 2024c). Our spare-share strategy reveals that the economics of temporal versus spatial balancing hinge on the interplay among ecological constraints, proximity to infrastructure, and grid extension.

Shadow prices of onshore wind (i.e., marginal value of additional developable land) escalate 3-9 fold from baseline regardless of transmission configuration. This illustrates that although transmission expansion enables access to available areas under restrictions, it cannot overcome severe spatial constraints as the system requires access to suitable sites, not merely the ability to connect distant generation to demand centers. Similar observations were quantified by Roithner et al. (2025) for Norway's 2030 system design: grid investment provides relief, but land availability remains binding. Furthermore, despite targeting divergent ecological priorities, convergence of moderately restricted scenarios (CA, SC, SD) marginal value cost around the median illustrates geographic overlap of biodiversity priorities—collision-sensitive species habitats, high-richness areas, protected zones— creating functionally equivalent constraints on available sites regardless of which ecological criteria drive restrictions.

The medium restricted scenarios (CA, SC, SD) demonstrate performance advantages beyond cost minimization within our scenario framework. The least curtailment rates (95-100 TWh/GW) suggest that moderate spatial restrictions need not necessarily compromise operational efficiency compared to scenarios at both extremes (Fig. 6, Fig. A5 in the appendix). Operation cost patterns further demonstrate these findings, illustrating ecological restrictions primarily affect extreme hours rather than typical operation. The median hourly costs remain largely unaffected (3%-6%) across scenarios and hourly cost volatility remains less than 15% from the base case, indicating that ecological restrictions did not substantially affect the volatility of hourly costs. This convergence of multiple metrics in moderate-restriction scenarios within our scenario framework suggests the potential to go beyond the binary framing of siting decisions. The policy-sensitive 67% of Norwegian territory does not represent intractable conflict but rather a decision space where different socio-environmental values (collision-risk minimization versus habitat protection, infrastructure concentration versus spatial dispersion) yield distinct yet comparably viable pathways. The challenge lies not in identifying a single optimal solution, but in establishing participatory processes for explicit priority-setting among defensible alternatives.

Our analysis complements the studies assessing the biodiversity impacts of electricity systems. Borgelt et al. illustrated that RE expansion in Norway could increase biodiversity loss by 16-28% by 2050, demonstrating the need to prioritize lower-biodiversity locations for RE projects to reduce trade-offs between climate action and nature conservation (Borgelt et al., 2026). Similarly, our analysis complements studies demonstrating that biodiversity impacts are highly sensitive to site selection decisions for RE (Estellés-Domingo and López-López, 2025; Gilad et al., 2024a; Kenawi et al., 2025; May et al., 2021). Our framework advances this literature by integrating site-level biodiversity constraints with system-level operational dynamics, revealing how spatial allocation strategies affect not only ecological impacts but also technology substitution. As solar and wind power remain at the forefront of energy transitions despite their land-intensive nature, such integrated frameworks become increasingly valuable for implementing strategies that meet electricity demand growth while respecting ecological priorities.

Historical wind farm deployment in Norway concentrated in contested geography (north, southwest, east; Fig. 2), prioritizing wind resource quality over ecological sensitivity rather than selecting lower-quality but ecologically safer locations. Our results validate May et al.'s (May et al., 2021) finding that "*current practice has not succeeded in avoiding sites with higher impacts*", but add crucial spatial specificity:

contested installations cluster in regions where high wind resources coincide with ecological sensitivity, forcing explicit rather than avoided trade-offs. Our scenario analysis reveals that historically developed locations see the steepest onshore wind capacity restrictions under ecological restrictions: northern onshore wind declines from approximately ~8 GW to ~3 GW, while high ecological restrictions (i.e., EF) reduce southwestern capacity by ~10-12 GW (Figs. 2 and 5).

This pattern is not unique to Norway. A French case study found that 90% of existing wind turbines are placed in areas of high biodiversity significance (Froidevaux et al., 2025), while a South and Central American study revealed that RE development areas increasingly overlap with anthropogenic threats to terrestrial biodiversity, calling for balanced approaches (Gorosábel et al., 2026). These patterns reveal that future expansions cannot access equally productive sites with lower ecological conflicts, as the best combination of resource quality and relative ecological permissiveness has already been performed. Future onshore wind developments will require comparatively harder trade-offs between high-quality wind sites and ecologically sensitive areas.

Given the standstill in Norway's onshore wind energy expansion over the last few years and the importance of onshore wind due to its low costs to meet climate targets and allowing the diversification of Norway's industry away from oil and gas, our results suggest that policymakers prioritize wind energy development in locations of lower ecological value. 7% of Norwegian land area remains consistently available across spare-share scenarios, resulting in a capacity potential of ~30 GW and an increase in the energy transition's upfront cost by up to 6%. Moderately restricted scenarios cluster within 2% cost-increase variation and would allow for higher ecological protection than current development practices, with possibly higher social acceptance, as 90% of existing wind farm locations concentrate in biodiversity-contested zones (Fig. 2), thus we allow ourselves to make the argument that moderately restricted scenarios would be seen as highly favorable in Norway's population. Our results allow for an informed discussion amongst policymakers, stakeholders, including nature protection organizations, and laypeople, allowing for democratic settlement of contested spaces where multiple defensible priorities conflict.

5. Limitations and future work

Several methodological limitations warrant consideration when interpreting our findings. The results of the spare-share scenarios framework reflect specific ecological thresholds and infrastructure criteria. Alternative criteria may produce different numerical values but might preserve the core insights (See Discussion section). The specific quantitative findings should therefore be interpreted as illustrative of trade-off magnitudes within our analytical framework rather than definitive predictions. The biodiversity dimension of our analysis focuses specifically on bird and bat species representing a taxonomic subset rather than representing biodiversity across its three dimensions (i.e., species, ecosystem, and genetic diversity). Our optimization framework employs perfect foresight with single-period optimization. While this approach enables internally consistent scenario comparisons in which ecological restrictions constitute the sole varying dimension, it systematically differs from real-world decision-making in several ways, including investment and weather uncertainty, technological lock-in, and path dependency that characterize actual energy transitions.

Future research could expand the analytical scope in the following directions: broader taxonomic coverage (terrestrial mammals, marine species), social dimensions (proximity to settlements, noise impacts, landscape effects), multi-year weather analysis to assess inter-annual variability in system outcomes, and additional renewable energy technologies for a more comprehensive assessment of socio-ecological trade-offs. The analytical scenario framework employed here could be complemented by participatory co-design processes that engage diverse stakeholders, including local communities, conservation organizations, and energy developers, to establish criteria for restrictions through workshops or deliberative methods (Elsawah et al., 2020), thereby enhancing social legitimacy and ownership of spatial planning decisions. Although developed for the Norwegian context, the spare-share framework offers transferable insights for regions worldwide confronting similar tensions between renewable energy expansion, landscape preservation, and biodiversity conservation (Leclère et al., 2020; McKenna et al., 2021)

6. Conclusion

Achieving net-zero electricity systems requires substantial expansion of renewable energy, yet this imperative increasingly collides with ecological preservation priorities. Norway exemplifies this challenge, where extensive wind resources coincide with ecologically sensitive zones and culturally valued landscapes. We developed a spare-share scenario framework that integrates high-resolution biodiversity (247 bird species, 5 bat species) and infrastructure datasets with electricity system optimization to quantify the system-level techno-economic implications of alternative onshore wind siting strategies, spanning infrastructure-proximate concentration (spare) to ecologically guided dispersion (share), under 2050 net-zero projections.

Spatial analysis reveals that only 7% of Norwegian land area remains consistently available across spare-share scenarios, while 67% exhibits flexible availability depending on which ecological criteria receive priority, and 26% faces universal restrictions. The 67% flexible geography represents neither a technical optimization problem nor an intractable conflict, but rather a decision space in which different societal values yield distinct yet defensible outcomes. The western and northern regions dominate both the flexible areas (52%) and the unavailable areas (33%), reflecting their geographic diversity. Our spatial analysis showed that 90% of existing wind farm locations are concentrated in contested zones, indicating that historical development prioritized wind resource quality over ecological preservation. Future expansion cannot replicate these spatial patterns under strict ecological criteria, as the favorable combinations of resource quality and relative ecological permissiveness have been exploited.

Ecological restrictions reduce Norway's onshore wind capacity potential by 11-fold with system costs increasing up to ~6%. Moderately restricted scenarios cluster within 1% cost-increase variation despite targeting divergent ecological priorities, demonstrating that geographic overlap among biodiversity hotspots creates functionally equivalent constraints. Moreover, these scenarios exhibit operational advantages: 20% lower curtailment intensity and hourly cost volatility within 15% of baseline. The 5-20 GW onshore wind reduction in the national capacity mix is broadly substituted by offshore wind (up to a ~7 GW increase), with complementary solar adjustments (±1.5 GW). The framework demonstrates when biodiversity conservation and energy planning compete versus where they align to maximize climate mitigation.

These findings demonstrate that spatial allocation decisions require participatory processes informed by system-level trade-offs analysis rather than model-determined optimization. Energy system models can quantify implications but cannot determine which trade-offs societies should accept. The spare-share framework offers a transferable methodology for regions globally confronting renewable energy expansion amid biodiversity concerns. As decarbonization accelerates, such integrated frameworks can contribute to a more objective evaluation of biodiversity impacts and promote more biodiversity-friendly strategies for RE planning.

CRediT authorship contribution statement

Muhammad Shahzad Javed: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Dafna Gilad:** Conceptualization, Data curation, Methodology, Writing – review & editing. **Roel May:** Conceptualization, Data

curation, Methodology, Writing – review & editing. **Thomas Kvalnes:** Conceptualization, Data curation, Writing – review & editing. **Marianne Zeyringer:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Writing – review & editing.

Declaration of competing interests

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

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Appendix

Model description

Interconnection capacities with neighboring countries are maintained at current levels as reported by Statnett, the Norwegian Transmission System Operator (TSO), due to the absence of 2050 capacity projections (Statnett, 2025). Cross-border interconnections are assumed to operate at one-quarter of their rated capacity based on historical utilization patterns ("Statistics Norway," 2024). Internal transmission infrastructure between Norwegian regions can be expanded above current capacities to facilitate inter-regional balancing, with expansion costs included in the optimization.

Hydropower and pumped storage capacities are fixed at current levels based on Norwegian Water Resources and Energy Directorate (NVE) data, reflecting limited expansion potential and ecosystem protection priorities (Hvidsten et al., 2025). The existing 5 GW of installed onshore wind capacity is excluded from the model, assuming full replacement by 2050 due to operational lifespan limits (Roithner et al., 2025). We allow these sites to compete for redevelopment only if they satisfy scenario-specific ecological criteria. This allows highRES to endogenously determine whether redevelopment at these sites is optimal under scenario-specific constraints; sites remain available unless excluded by the scenario criteria in Table A1. Available land area for each technology is converted to capacity potential using assumed power densities (MW/km^2) (Price et al., 2022).

Exclusions for solar PV and offshore wind remain consistent across all scenarios. For solar PV, excluded areas include terrain slopes exceeding 6.3°, elevations above 2000 m, all protected areas (IUCN categories Ia-V) based on WDPA ("Protected Areas (WDPA)," 2023), and different land cover types (forest, agriculture, physical infrastructures) according to Ref. (Hvidsten et al., 2025; Roithner et al., 2025; Vågerö et al., 2024b). For offshore wind, excluded areas comprise protected marine zones and waters deeper than 70 m for bottom-mounted wind turbines. Onshore wind faces scenario-specific biodiversity and infrastructure exclusions detailed in Table A1 (Section 2.2), supplemented by terrain slopes exceeding 15°, environmental exclusions (i.e., urban areas, forests, water bodies, protected areas) based on CORINE land cover classifications, and physical infrastructure buffers (military installations, airports, urban areas) applied uniformly across all scenarios.

Weather data for variable RE generation is processed using the xarray-based Python library *'atlite'* (version 0.2.13) (Hofmann et al., 2021), which converts ERA5 weather reanalysis into hourly capacity factor time series at 30 km × 30 km resolution through physics-based models of wind turbine and solar panel performances (Hersbach et al., 2020). The ERA5 weather-reanalysis from ECMWF inherently incorporates surface roughness effects through its representation of terrain and land cover characteristics, which influence wind speed profiles at this resolution (Hersbach et al., 2020). We employ 2010 weather data due to its challenging conditions for Norway, characterized by exceptional cold and reduced precipitation, which resulted in elevated electricity demand and diminished hydropower production, thereby stress-testing system adequacy under adverse meteorological conditions ("Været i Norge Klimatologisk oversikt Året, 2010 [The weather in Norway Climatological overview for the year 2010]," 2011). While a single weather year limits the assessment of interannual variability, 2010's challenging conditions provide a conservative 'stress-test' baseline that illustrates system performance when wind power plays a larger compensatory role due to reduced hydropower availability. To exclude poorly performing locations that would not be commercially viable, grid cells with average annual capacity factors below 0.09 (solar PV), 0.15 (onshore wind), and 0.20 (offshore wind) are removed from the available deployment area (Hvidsten et al., 2025; Roithner et al., 2025; Vågerö et al., 2024b). The scenario-specific onshore wind availability rasters from Section 2.2 are integrated with these technical and meteorological constraints within atlite, which aggregates available capacity potential to the regional resolution.

Electricity demand projections for 2050 are based on Statnett forecasts indicating a maximum annual consumption of 260 TWh, distributed spatially across regions and temporally at hourly resolution, using methods detailed in (Hvidsten et al., 2025; Roithner et al., 2025). A system-wide carbon emission constraint of 0 gCO_2/kWh enforces complete decarbonization of the electricity sector by 2050, precluding fossil fuel generation, including carbon capture and storage technologies. Technology cost parameters (capital expenditures, fixed and variable operation and maintenance costs, lifetimes) are sourced from (Hvidsten et al., 2025; "Kostnader for kraftproduksjon - NVE," 2025; Roithner et al., 2025; Vågerö et al., 2024b). While investment costs for existing infrastructure (hydropower, pumped storage, transmission) are excluded, fixed and variable operation and maintenance costs are included to accurately represent operational expenditures.

The workflow management system Snakemake (Köster and Rahmann, 2012) automates data preparation, model execution, and output processing. The model is solved using the CPLEX optimization solver. Model formulation, input datasets, processing scripts, and instructions for replicating results are openly available in the associated GitHub repository.

Table A1
Scenarios for balancing ecological and economic siting for wind farms.

Scenario	Development focus	Siting strategy	Costs (LCOE map)	Biodiversity (richness maps)	Area footprint (infrastructure index map)	Protected areas/ redlist species
Production maximization (**PM**)	Economy	Share	<	---	---	Ib, II
Production co-location (**PC**)	Economy	Spare	<	---	< 5 km from infrastructure	Ia, Ib, V

(*continued on next page*)

Table A1 (*continued*)

Scenario	Development focus	Siting strategy	Costs (LCOE map)	Biodiversity (richness maps)	Area footprint (infrastructure index map)	Protected areas/ redlist species
Collision sensitivity avoidance (**CA**)	Ecology	Share	---	< [bats, raptors, gulls] - avoid classes 3-5	---	Ia, Ib, IV + redlist
Ecological footprint minimization (**EF**)	Ecology	Spare	---	< [all species] - avoid classes 3-5	< 1 km from infrastructure	Ia, Ib, II, IV + redlist
Sensitive development (**SD**)	Balanced	Share	<	< [bats, raptors, gulls] - avoid classes 4-5	---	Ia, Ib, IV + redlist
Sustainable co-location (**SC**)	Balanced	Spare	<	< [all species] - avoid classes 4-5	< 3 km from infrastructure	Ia, Ib + redlist
Sustainable development (**SO1**)	Balanced	Balanced	<	< geometric mean[all species]+infrastructure < avoid classes 3-5		Ia, Ib + redlist
Sustainable development (**SO2**)	Balanced	Balanced	<	< geometric mean[all species]+infrastructure < avoid classes 4-5		Ia, Ib + redlist

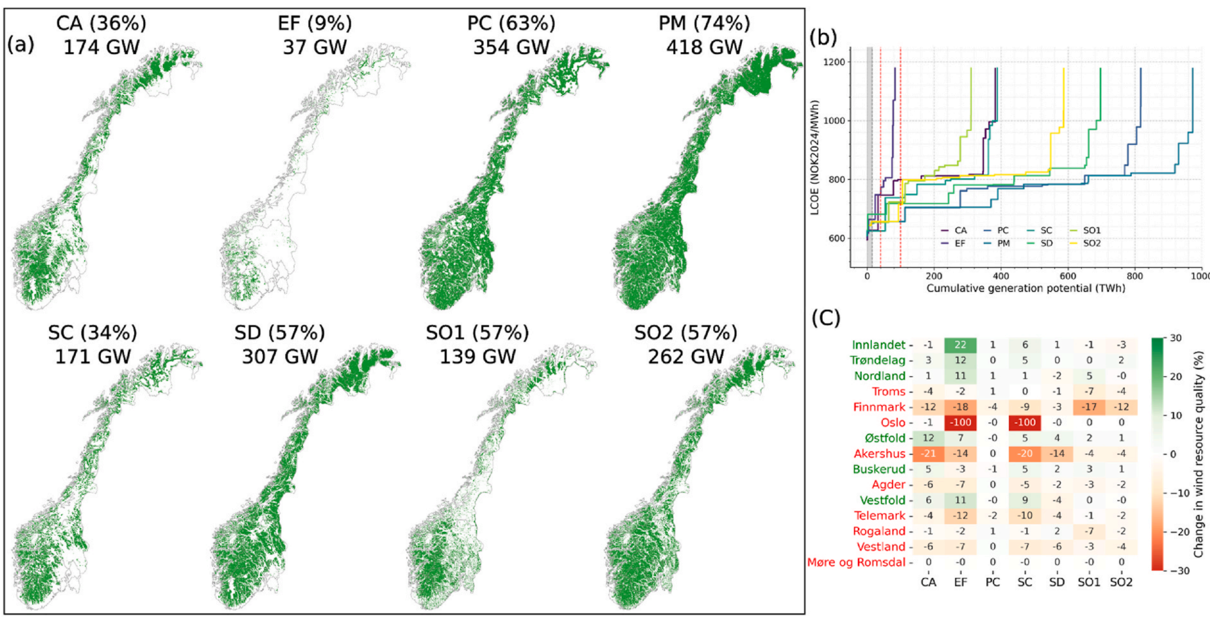

Fig. A1. Impact of ecological restrictions and proximity to infrastructure criteria. (a) Spatial distribution of areas available for onshore wind development under each scenario, shown in green. Scenario names include the percentage of total Norwegian land area available and total capacity potential in GW. (b) Supply curves showing cumulative onshore wind generation potential as a function of levelized cost of electricity (LCOE) for each scenario, with each step corresponding to a region. Vertical red dashed lines indicate the total projected increase in Norwegian electricity demand by 2050 (Statnett, 2025), and the filled grey area shows onshore wind electricity generation in Norway in 2024. (c) Regional heatmap showing percentage change in mean onshore wind capacity factor relative to PM baseline scenario. Green cells indicate restrictions improve mean wind quality, while red cells indicate degradation. County names with green generally experience a mean increase in capacity factors, while counties named with red exhibit a decline (Related to Fig. 1).

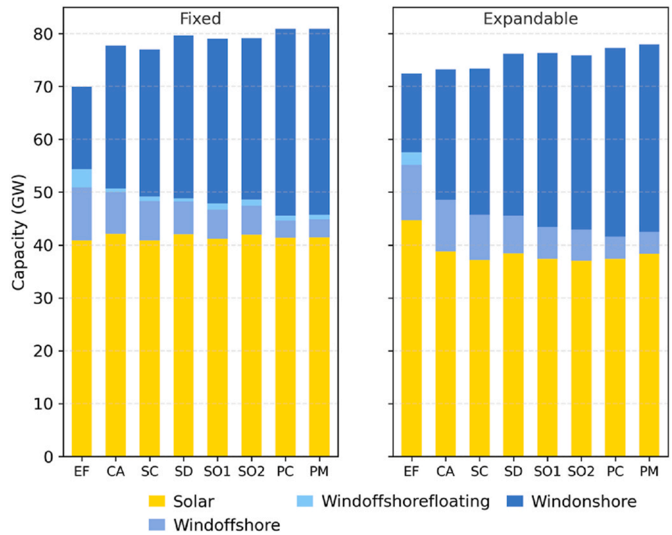

Fig. A2. Total installed generation capacity. The left panel shows a fixed transmission configuration; the right panel shows an expandable transmission configuration. Stacked bars represent technology-specific capacity contributions. Solar capacity ranges between 37 and 45 GW across scenarios, while onshore wind exhibits the large variabilities (15-38 GW), directly responding to ecological restrictions. Hydropower capacity (not shown) remains fixed at current levels across all scenarios (Related to Fig. 4).

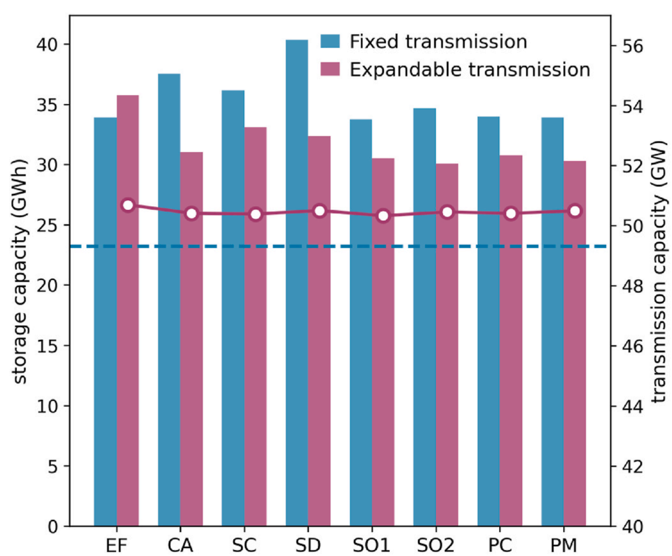

Fig. A3. Storage capacity deployment and transmission expansion across scenarios. Bars show total installed storage capacity (left y-axis, GWh). The solid line indicates the optimal total transmission capacity for expandable transmission scenarios, while the dashed line represents existing transmission. The figure illustrates how spare-share siting frameworks alter the economics of spatial versus temporal balancing (Related to Fig. 4).

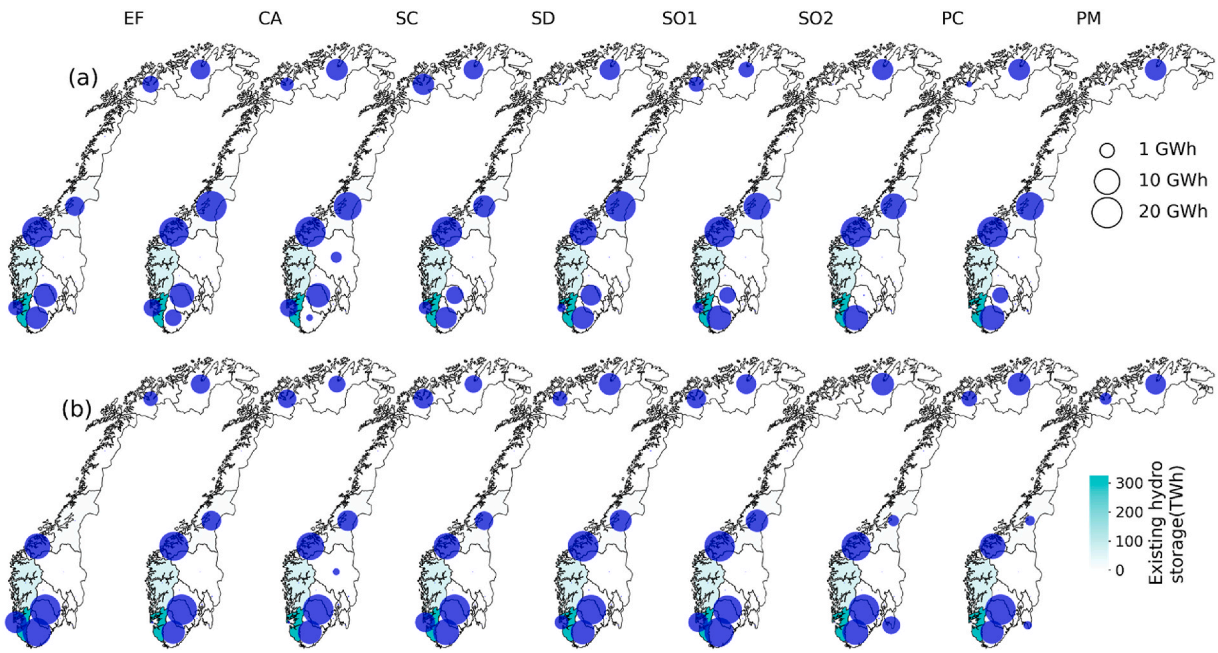

Fig. A4. Regional distribution of new storage capacity deployment. (a) Fixed (b) Expandable transmission. Circle sizes represent installed storage capacity, with color bars indicating existing hydropower storage availability (TWh) in each county. Western regions deploy negligible new storage across all scenarios due to existing hydropower storage capacity. Northern regions remain with minimum new storage capacity, relying instead on transmission to southern demand centers (Related to Fig. 5).

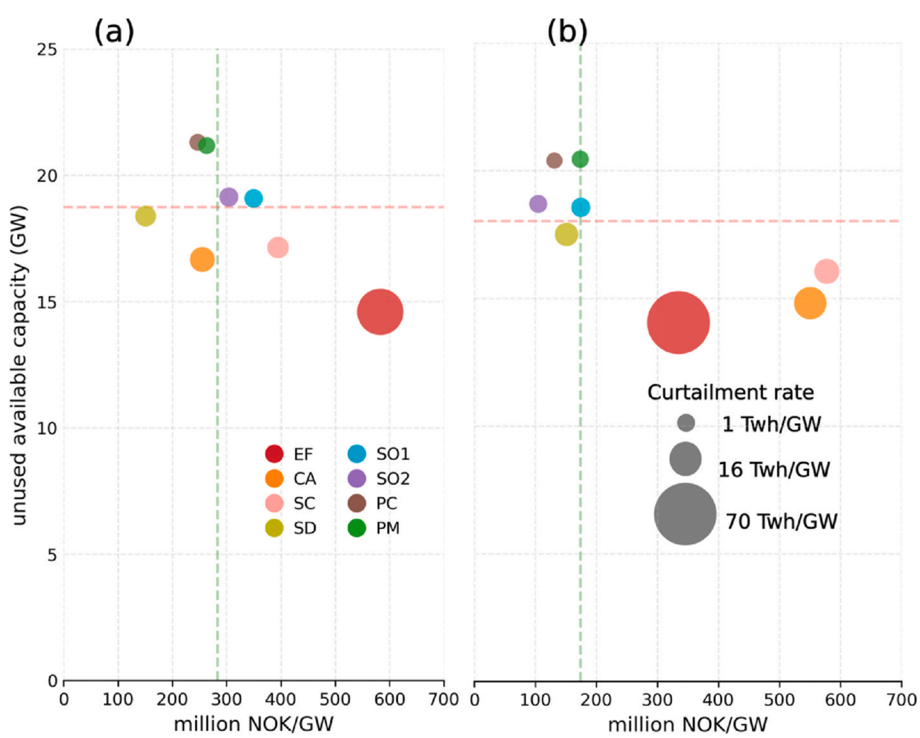

Fig. A5. Economic opportunity cost and system efficiency for offshore wind. (a) Fixed (b) expandable transmission showing the relationship between economic opportunity cost (million NOK/GW, x-axis) and unused available offshore capacity (GW, y-axis). Circle size represents curtailment rate (TWh/GW). Economic opportunity cost represents the marginal economic value of relaxing land-based area constraints for offshore wind at the current optimum. Green and red dashed lines indicate the median value (Related to Fig. 5).

Data availability

The highRES version adopted for this work and the related input data necessary to replicate the results is openly available at Github: https://github.com/JavedMS/highRES-Norway/tree/highres_NINA.

References

Baudouin, A., Hette-Tronquart, N., Brun, C., Gay, N., Chartendrault, V., Kerbiriou, C., 2026. Balancing renewable energy and biodiversity: assessing solar farm effects on bat activity. Biol. Conserv. 314, 111661. https://doi.org/10.1016/j.biocon.2025.111661.

Borgelt, J., Gilad, D., May, R., Verones, F., 2026. Renewable energy growth amplifies land pressure on Norwegian biodiversity. Clean. Energy Syst. 13, 100238. https://doi.org/10.1016/j.cles.2026.100238.
Climate Change Act, 2017 [WWW Document] URL. https://lovdata.no/dokument/NLE/lov/2017-06-16-60, 3.6.25.
Climate plan [WWW Document], 2021. Regjeringa. URL. https://www.regjeringen.no/no/dokumenter/meld.-st.-13-20202021/id2827405/, 12.15.25.
Delafield, G., Smith, G.S., Day, B., Holland, R.A., Donnison, C., Hastings, A., Taylor, G., Owen, N., Lovett, A., 2024. Spatial context matters: assessing how future renewable energy pathways will impact nature and society. Renew. Energy 220, 119385. https://doi.org/10.1016/j.renene.2023.119385.
DNV, 2024. Energy transition outlook Norway [WWW Document]. URL. https://www.dnv.com/publications/energy-transition-norway-2024/, 12.15.25.
Dorber, M., Arvesen, A., Gernaat, D., Verones, F., 2020. Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection. Sci. Rep. 10, 21777. https://doi.org/10.1038/s41598-020-78444-6.
Duffy, A., Hand, M., Wiser, R., Lantz, E., Dalla Riva, A., Berkhout, V., Stenkvist, M., Weir, D., Lacal-Arántegui, R., 2020. Land-based wind energy cost trends in Germany, Denmark, Ireland, Norway, Sweden and the United States. Appl. Energy 277, 114777. https://doi.org/10.1016/j.apenergy.2020.114777.
Egging, R., Tomasgard, A., 2018. Norway's role in the European energy transition. Energy Strategy Rev. 20, 99–101. https://doi.org/10.1016/j.esr.2018.02.004.
Eichhorn, M., Masurowski, F., Becker, R., Thrän, D., 2019. Wind energy expansion scenarios – a spatial sustainability assessment. Energy 180, 367–375. https://doi.org/10.1016/j.energy.2019.05.054.
Eikeland, P.O., Taranger, K.K., Inderberg, T.H.J., Gulbrandsen, L.H., 2023. A wind of change in Norway: explaining shifts in municipal stances on wind power by policy feedback and energy justice. Energy Res. Social Sci. 104, 103231. https://doi.org/10.1016/j.erss.2023.103231.
Elektrisitet (SSB) [WWW Document], 2025. SSB. URL. https://www.ssb.no/energi-og-industri/energi/statistikk/elektrisitet, 12.15.25.
Elsawah, S., Hamilton, S.H., Jakeman, A.J., Rothman, D., Schweizer, V., Trutnevyte, E., Carlsen, H., Drakes, C., Frame, B., Fu, B., Guivarch, C., Haasnoot, M., Kemp-Benedict, E., Kok, K., Kosow, H., Ryan, M., van Delden, H., 2020. Scenario processes for socio-environmental systems analysis of futures: a review of recent efforts and a salient research agenda for supporting decision making. Sci. Total Environ. 729, 138393. https://doi.org/10.1016/j.scitotenv.2020.138393.
Elsner, P., Collaer, J., Uihlein, A., 2026. The Onshore Wind Potential of the EU and Neighbouring Countries. JRC Publ. Repos. https://doi.org/10.2760/4154939 [WWW Document].
Enevoldsen, P., Permien, F.-H., Bakhtaoui, I., Krauland, A.-K. von, Jacobson, M.Z., Xydis, G., Sovacool, B.K., Valentine, S.V., Luecht, D., Oxley, G., 2019. How much wind power potential does Europe have? Examining European wind power potential with an enhanced socio-technical atlas. Energy Policy 132, 1092–1100. https://doi.org/10.1016/j.enpol.2019.06.064.
Erikstad, Lars, Blumentrath, Stefan, Bakkestuen, Vegar, Halvorsen, Rune, 2013. Landskapstypekartlegging som verktøy til overvåking av arealbruksendringer. https://nva.sikt.no/registration/0198cc5ff98b-790906b5-11e7-4d96-b141-b1de290b51d8.
Estellés-Domingo, I., López-López, P., 2025. Effects of wind farms on raptors: a systematic review of the current knowledge and the potential solutions to mitigate negative impacts. Anim. Conserv. 28, 334–352. https://doi.org/10.1111/acv.12988.
Etard, A., Jung, M., Visconti, P., 2025. Risk to European birds from collisions with wind-energy facilities. https://doi.org/10.1101/2025.11.24.685024.
Fisch-Romito, V., Jaxa-Rozen, M., Wen, X., Trutnevyte, E., 2025. Multi-country evidence on societal factors to include in energy transition modelling. Nat. Energy 10, 460–469. https://doi.org/10.1038/s41560-025-01719-7.
Fischer, J., Abson, D.J., Butsic, V., Chappell, M.J., Ekroos, J., Hanspach, J., Kuemmerle, T., Smith, H.G., von Wehrden, H., 2014. Land sparing versus land sharing: moving forward. Conserv. Lett. 7, 149–157. https://doi.org/10.1111/conl.12084.
Froidevaux, J.S.P., Le Viol, I., Barré, K., Bas, Y., Kerbiriou, C., 2025. A modeling framework for biodiversity assessment in renewable energy development: a case study on European bats and wind turbines. Renew. Sustain. Energy Rev. 211, 115323. https://doi.org/10.1016/j.rser.2024.115323.
Gambhir, A., 2019. Planning a low-carbon energy transition: what can and can't the models tell Us? Joule 3, 1795–1798. https://doi.org/10.1016/j.joule.2019.07.016.
Gasparatos, A., Doll, C.N.H., Esteban, M., Ahmed, A., Olang, T.A., 2017. Renewable energy and biodiversity: implications for transitioning to a Green economy. Renew. Sustain. Energy Rev. 70, 161–184. https://doi.org/10.1016/j.rser.2016.08.030.
Gilad, D., Borgelt, J., May, R., Dorber, M., Verones, F., 2024a. Biodiversity impacts of Norway's renewable electricity grid. J. Clean. Prod. 469, 143096. https://doi.org/10.1016/j.jclepro.2024.143096.
Gilad, D., Borgelt, J., May, R., Verones, F., 2024b. Biodiversity on the line: life cycle impact assessment of power lines on birds and mammals in Norway. Environ. Res. Infrastruct. Sustain. 4, 035003. https://doi.org/10.1088/2634-4505/ad5bfd.
Gilad, D., May, R., Stokke, B.G., Verones, F., 2024c. Between the lines: life cycle impact assessment models of collision and electrocution impacts of power lines on bird diversity in Norway. J. Ind. Ecol. 28, 426–438. https://doi.org/10.1111/jiec.13488.
Global Energy Review, 2025. Iea [WWW Document] URL. https://www.iea.org/reports/global-energy-review-2025, 5.8.26.
Gorosábel, A., Farooq, H., Mulligan, M., Iversen, L.L., Geldmann, J., 2026. Assessing the associations between renewable energy generation and other human-induced threats to terrestrial biodiversity. Cell Rep. Sustain, 100684. https://doi.org/10.1016/j.crsus.2026.100684.
Grimsrud, K., Hagem, C., Haaskjold, K., Lindhjem, H., Nowell, M., 2024. Spatial trade-offs in national land-based wind power production in times of biodiversity and climate crises. Environ. Resour. Econ. 87, 401–436. https://doi.org/10.1007/s10640-023-00764-8.
Grochowicz, A., Benth, F.E., Zeyringer, M., 2024a. Spatio-temporal smoothing and dynamics of different electricity flexibility options for highly renewable energy systems—Case study for Norway. Appl. Energy 356, 122338. https://doi.org/10.1016/j.apenergy.2023.122338.
Grochowicz, A., Van Greevenbroek, K., Bloomfield, H.C., 2024b. Using power system modelling outputs to identify weather-induced extreme events in highly renewable systems. Environ. Res. Lett. 19, 054038. https://doi.org/10.1088/1748-9326/ad374a.
Gulbrandsen, L.H., Inderberg, T.H.J., Jevnaker, T., 2021. Is political steering gone with the wind? Administrative power and wind energy licensing practices in Norway. Energy Res. Social Sci. 74, 101963. https://doi.org/10.1016/j.erss.2021.101963.
Hernández-Lambraño, R.E., Sánchez-Agudo, J.Á., Carbonell, R., 2018. Where to start? Development of a spatial tool to prioritise retrofitting of power line poles that are dangerous to raptors. J. Appl. Ecol. 55, 2685–2697. https://doi.org/10.1111/1365-2664.13200.
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.-N., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049. https://doi.org/10.1002/qj.3803.
Hirt, L.F., Schell, G., Sahakian, M., Trutnevyte, E., 2020. A review of linking models and socio-technical transitions theories for energy and climate solutions. Environ. Innov. Soc. Transit. 35, 162–179. https://doi.org/10.1016/j.eist.2020.03.002.
Hofmann, F., Hampp, J., Neumann, F., Brown, T., Hörsch, J., 2021. Atlite: a lightweight python package for calculating renewable power potentials and time series. J. Open Source Softw. 6, 3294. https://doi.org/10.21105/joss.03294.
Hvidsten, T.V., Roithner, M., Benth, F.E., Zeyringer, M., 2025. Driving towards net-zero: the impact of electric vehicle flexibility participation on a future Norwegian electricity system. Environ. Res. Infrastruct. Sustain. https://doi.org/10.1088/2634-4505/ade0e6.
IEA, 2023. WWW Document]. URL. https://www.iea.org/energy-system/energy-efficiency-and-demand/demand-response, 8.5.24.
Inderberg, T.H.J., Rognstad, H., Saglie, I.-L., Gulbrandsen, L.H., 2019. Who influences windpower licensing decisions in Norway? Formal requirements and informal practices. Energy Res. Social Sci. 52, 181–191. https://doi.org/10.1016/j.erss.2019.02.004.
Inderberg, T.H.J., Theisen, O.M., Flåm, K.H., 2020. What influences windpower decisions? A statistical analysis of licensing in Norway. J. Clean. Prod. 273, 122860. https://doi.org/10.1016/j.jclepro.2020.122860.
Intergovernmental Panel on Climate Change (IPCC), 2023. Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009325844.
IPBES, 2019. Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. https://doi.org/10.5281/zenodo.6417333.
Ji, L., Li, J., Sun, L., Wang, S., Guo, J., Xie, Y., Wang, X., 2024. China's onshore wind energy potential in the context of climate change. Renew. Sustain. Energy Rev. 203, 114778. https://doi.org/10.1016/j.rser.2024.114778.
Kallbekken, S., Skjeflo, S.W., Westberg, N.B., 2026. Against the current: interconnectors, public opposition and the energy trilemma. Energy Policy 210, 115012. https://doi.org/10.1016/j.enpol.2025.115012.
Katzner, T.E., Nelson, D.M., Marques, A.T., Voigt, C.C., Lambertucci, S.A., Rebolo, N., Bernard, E., Diehl, R., Murgatroyd, M., 2025. Impacts of onshore wind energy production on biodiversity. Nat. Rev. Biodivers. 1, 567–580. https://doi.org/10.1038/s44358-025-00078-1.
Kenawi, M.S., Hedger, R.D., Alfredsen, K.T., Sandercock, B.K., Korpås, M., Bakken, T.H., 2025. Land efficiency of renewable energy in Norway: a synthesis of footprint and production density. Renew. Energy 252, 123514. https://doi.org/10.1016/j.renene.2025.123514.
Kiesecker, J.M., Evans, J.S., Oakleaf, J.R., Dropuljić, K.Z., Vejnović, I., Rosslowe, C., Cremona, E., Bhattacharjee, A.L., Nagaraju, S.K., Ortiz, A., Robinson, C., Ferres, J.L., Zec, M., Sochi, K., 2024. Land use and Europe's renewable energy transition: identifying low-conflict areas for wind and solar development. Front. Environ. Sci. 12. https://doi.org/10.3389/fenvs.2024.1355508.
Köster, J., Rahmann, S., 2012. Snakemake—A scalable bioinformatics workflow engine. Bioinformatics 28, 2520–2522. https://doi.org/10.1093/bioinformatics/bts480.
Kostnader for kraftproduksjon - NVE, 2025 [WWW Document] URL. https://www.nve.no/energi/analyser-og-statistikk/kostnader-for-kraftproduksjon/, 8.22.25.
Kraft, P., Kraft, B., 2025. Public attitudes and the socio-political divide surrounding onshore wind power in Norway. Front. Sustain. Energy Policy 4. https://doi.org/10.3389/fsuep.2025.1538828.
Kvalnes, T., Spielhofer, R., Hanssen, F.O., May, R.F., 2023. Validated models for integrated life-cycle assessment on ecosystem services and biodiversity. https://hdl.handle.net/11250/5173311.
Laranjeiro, T., May, R., Verones, F., 2018. Impacts of onshore wind energy production on birds and bats: recommendations for future life cycle impact assessment

developments. Int. J. Life Cycle Assess. 23, 2007–2023. https://doi.org/10.1007/s11367-017-1434-4.
Lawrence, R., 2014. Internal colonisation and Indigenous resource sovereignty: wind power developments on traditional Saami lands. Environ. Plan. Soc. Space 32, 1036–1053. https://doi.org/10.1068/d9012.
Leclère, D., Obersteiner, M., Barrett, M., Butchart, S.H.M., Chaudhary, A., De Palma, A., DeClerck, F.A.J., Di Marco, M., Doelman, J.C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J.P., Hill, S.L.L., Humpenöder, F., Jennings, N., Krisztin, T., Mace, G.M., Ohashi, H., Popp, A., Purvis, A., Schipper, A. M., Tabeau, A., Valin, H., van Meijl, H., van Zeist, W.-J., Visconti, P., Alkemade, R., Almond, R., Bunting, G., Burgess, N.D., Cornell, S.E., Di Fulvio, F., Ferrier, S., Fritz, S., Fujimori, S., Grooten, M., Harwood, T., Havlík, P., Herrero, M., Hoskins, A. J., Jung, M., Kram, T., Lotze-Campen, H., Matsui, T., Meyer, C., Nel, D., Newbold, T., Schmidt-Traub, G., Stehfest, E., Strassburg, B.B.N., van Vuuren, D.P., Ware, C., Watson, J.E.M., Wu, W., Young, L., 2020. Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585, 551–556. https://doi.org/10.1038/s41586-020-2705-y.
Lehmann, P., Tafarte, P., 2024. Exclusion zones for renewable energy deployment: one man's blessing, another man's curse. Resour. Energy Econ. 76, 101419. https://doi.org/10.1016/j.reseneeco.2023.101419.
Linnerud, K., Dugstad, A., Rygg, B.J., 2022. Do people prefer offshore to onshore wind energy? The role of ownership and intended use. Renew. Sustain. Energy Rev. 168, 112732. https://doi.org/10.1016/j.rser.2022.112732.
May, R., Jackson, C.R., Middel, H., Stokke, B.G., Verones, F., 2021. Life-cycle impacts of wind energy development on bird diversity in Norway. Environ. Impact Assess. Rev. 90, 106635. https://doi.org/10.1016/j.eiar.2021.106635.
May, R., Middel, H., Stokke, B.G., Jackson, C., Verones, F., 2020. Global life-cycle impacts of onshore wind-power plants on bird richness. Environ. Sustain. Indic. 8, 100080. https://doi.org/10.1016/j.indic.2020.100080.
McKenna, R., Bertsch, V., Mainzer, K., Fichtner, W., 2018. Combining local preferences with multi-criteria decision analysis and linear optimization to develop feasible energy concepts in small communities. Eur. J. Oper. Res., Community Operational Research: Innovations, internationalization and agenda-setting applications 268, 1092–1110. https://doi.org/10.1016/j.ejor.2018.01.036.
McKenna, R., Lilliestam, J., Heinrichs, H.U., Weinand, J., Schmidt, J., Staffell, I., Hahmann, A.N., Burgherr, P., Burdack, A., Bucha, M., Chen, R., Klingler, M., Lehmann, P., Lowitzsch, J., Novo, R., Price, J., Sacchi, R., Scherhaufer, P., Schöll, E. M., Visconti, P., Velasco-Herrejón, P., Zeyringer, M., Ramirez Camargo, L., 2025. System impacts of wind energy developments: key research challenges and opportunities. Joule 9. https://doi.org/10.1016/j.joule.2024.11.016.
McKenna, R., Weinand, J.M., Mulalic, I., Petrović, S., Mainzer, K., Preis, T., 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. https://doi.org/10.1038/s41560-021-00842-5.
Miyake, S., Rispler, J., Teske, S., 2025. Solar and wind energy potentials in Australia: a GIS-based assessment for Australia's ability to transition to net-zero emissions by 2050. Environ. Res. Commun. 7, 095002. https://doi.org/10.1088/2515-7620/adfc30.
Mósesdóttir, L., 2024. Energy (in)justice in the green energy transition. The case of Fosen wind farms in Norway. Technol. Soc. 77, 102563. https://doi.org/10.1016/j.techsoc.2024.102563.
Net Zero by 2050 [WWW Document], 2021. IEA. URL. https://www.iea.org/reports/net-zero-by-2050, 12.15.25.
NINA Rapport, 2022, 1-56 [WWW Document] URL. https://nva.sikt.no/registration/0198cc3ee16c-ac62e591-b5d8-4e4a-a834-a3b2938271d5, 11.27.25.
NRK, 2001. Vannkraftepoken Er Slutt. News article Norwegian Broadcasting Corporation [WWW Document]. NRK. URL. https://www.nrk.no/urix/vannkraftepoken-er-slutt-1.462300, 12.15.25.
NVE, 2023 [WWW Document] URL. https://www.nve.no/energi/energisystem/energibruk/samlet-energibruk/, 12.15.25.
Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. 33, 74–86. https://doi.org/10.1016/j.rser.2014.02.003.
Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333, 1289–1291. https://doi.org/10.1126/science.1208742.
Price, J., Mainzer, K., Petrovic, S., Zeyringer, M., McKenna, R., 2022. The implications of landscape visual impact on future highly renewable power systems: a case study for Great Britain. IEEE Trans. Power Syst. 37, 3311–3320. https://doi.org/10.1109/TPWRS.2020.2992061.
Price, J., Valenzuela-Venegas, G., Vågerö, O., Zeyringer, M., Chen, R., Etard, A., Hahmann, A.N., Lohrmann, A., Mikovits, C., Panos, E., Zhang, M., Camargo, L.R., 2026. The Electricity System Value of the Local Acceptance of Onshore Wind in Europe.
Price, J., Zeyringer, M., Konadu, D., Sobral Mourão, Z., Moore, A., Sharp, E., 2018. Low carbon electricity systems for Great Britain in 2050: an energy-land-water perspective. Appl. Energy 228, 928–941. https://doi.org/10.1016/j.apenergy.2018.06.127.
Protected Areas (WDPA) [WWW Document], 2023. Prot. Planet. URL. https://www.protectedplanet.net/en/thematic-areas/wdpa.
Rabosky, D.L., Grundler, M., Anderson, C., Title, P., Shi, J.J., Brown, J.W., Huang, H., Larson, J.G., 2014. BAMMtools: an R package for the analysis of evolutionary dynamics on phylogenetic trees. Methods Ecol. Evol. 5, 701–707. https://doi.org/10.1111/2041-210X.12199.
Reto, S., Thomas, K., Roel, M., 2026. A spatially explicit environmental performance indicator accounting for different life-cycle impact pathways of onshore wind energy infrastructure. Environ. Impact Assess. Rev. 120, 108471. https://doi.org/10.1016/j.eiar.2026.108471.
Roithner, M., Velasco-Herrejón, P., van Greevenbroek, K., Grochowicz, A., Vågerö, O., Hvidsten, T.V., Price, J., Zeyringer, M., 2025. Balancing act: the cost of wind restrictions in Norway's electricity transition. Environ. Res. Energy. https://doi.org/10.1088/2753-3751/adde62.
Ryberg, D.S., Caglayan, D.G., Schmitt, S., Linßen, J., Stolten, D., Robinius, M., 2019. The future of European onshore wind energy potential: detailed distribution and simulation of advanced turbine designs. Energy 182, 1222–1238.
Schweizer, V.J., Kriegler, E., 2012. Improving environmental change research with systematic techniques for qualitative scenarios. Environ. Res. Lett. 7, 044011. https://doi.org/10.1088/1748-9326/7/4/044011.
Serratosa, J., Oppel, S., Rotics, S., Santangeli, A., Butchart, S.H.M., Cano-Alonso, L.S., Tellería, J.L., Kemp, R., Nicholas, A., Kalvāns, A., Galarza, A., Franco, A.M.A., Andreotti, A., Kirschel, A.N.G., Ngari, A., Soutullo, A., Bermejo-Bermejo, A., Botha, A.J., Ferri, A., Evangelidis, A., Cenerini, A., Stamenov, A., Hernández-Matías, A., Aradis, A., Grozdanov, A.P., Rodríguez, B., Şekercioğlu, Ç.H., Cerecedo-Iglesias, C., Kassara, C., Barboutis, C., Bracebridge, C., García-Ripollés, C., Kendall, C.J., Denac, D., Schabo, D.G., Barber, D.R., Popov, D.V., Dobrev, D.D., Mallia, E., Kmetova-Biro, E., Álvarez, E., Buechley, E.R., Bragin, E.A., Cordischi, F., Zengeya, F.M., Monti, F., Mougeot, F., Tate, G., Stoyanov, G., Dell'Omo, G., Lucia, G., Gradev, G., Ceccolini, G., Friedemann, G., Bauer, H.-G., Kolberg, H., Peshev, H., Catry, I., Øien, I.J., Alanís, I.C., Literák, I., Pokrovsky, I., Ojaste, I., Østnes, J.E., de la Puente, J., Real, J., Guilherme, J.L., González, J.C., Fernández-García, J.M., Gil, J.A., Terraube, J., Poprach, K., Aghababyan, K., Klein, K., Bildstein, K.L., Wolter, K., Janssens, K., Kittelberger, K.D., Thompson, L.J., AlJahdhami, M.H., Galán, M., Tobolka, M., Posillico, M., Cipollone, M., Gschweng, M., Strazds, M., Boorman, M., Zvidzai, M., Acácio, M., Romero, M., Wikelski, M., Schmidt, M., Sarà, M., McGrady, M.J., Dagys, M., Mackenzie, M.L., Al Taq, M., Mgumba, M.P., Virani, M.Z., Kassinis, N.I., Borgianni, N., Thie, N., Tsiopelas, N., Anglister, N., Farwig, N., Sapir, N., Kleven, O., Krone, O., Duriez, O., Spiegel, O., Al Nouri, O., López-López, P., Byholm, P., Kamath, P.L., Mirski, P., Palatitz, P., Serroni, P., Raab, R., Buij, R., Žydelis, R., Nathan, R., Bowie, R.C.K., Tsiakiris, R., Hatfield, R.S., Harel, R., Kroglund, R.T., Efrat, R., Limiñana, R., Javed, S., Marinković, S.P., Rösner, S., Pekarsky, S., Kapila, S.R., Marin, S.A., Krejčí, Š., Giokas, S., Tumanyan, S., Turjeman, S., Krüger, S.C., Ewing, S.R., Stoychev, S., Nikolov, S.C., Qaneer, T.E., Spatz, T., Hadjikyriakou, T.G., Mueller, T., Katzner, T.E., Aarvak, T., Veselovský, T., Nygård, T., Mellone, U., Väli, Ü., Sellis, U., Urios, V., Nemček, V., Arkumarev, V., Getz, W.M., Fiedler, W., Van den Bossche, W., Lehnardt, Y., Jones, V.R., 2024. Tracking data highlight the importance of human-induced mortality for large migratory birds at a flyway scale. Biol. Conserv. 293, 110525. https://doi.org/10.1016/j.biocon.2024.110525.
Solbrekke, I.M., Sorteberg, A., 2024. Norwegian offshore wind power—Spatial planning using multi-criteria decision analysis. Wind Energy 27, 5–32. https://doi.org/10.1002/we.2871.
Statistics Norway [WWW Document], 2024. SSB. URL. https://www.ssb.no/en, 9.20.24.
Statnett, 2025. Langsiktig markedsanalyse—Norge, norden og europa 2024-2050. https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/lma/langsiktig-markedsanalyse-2024-50.pdf.
Stranddorf, L., Colley, T., Delefosse, M., Svendsen, J.C., Irving Olsen, S., 2024. Marine biodiversity impact pathways for offshore wind farm decommissioning: implications for life cycle impact assessment development. Ecol. Indic. 167, 112613. https://doi.org/10.1016/j.ecolind.2024.112613.
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., 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. https://doi.org/10.1098/rspb.2017.0829.
The Economics of Biodiversity, 2021. The Dasgupta Review [WWW Document] URL. https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review, 12.15.25.
Tsani, T., Pelser, T., Ioannidis, R., Maier, R., Chen, R., Risch, S., Kullmann, F., McKenna, R., Stolten, D., Weinand, J.M., 2025. Quantifying the trade-offs between renewable energy visibility and system costs. Nat. Commun. 16, 3853. https://doi.org/10.1038/s41467-025-59029-1.
Været, i, 2011. Norge klimatologisk oversikt Året 2010 [the weather in Norway climatological overview for the year 2010] [WWW Document] URL. https://www.met.no/publikasjoner/met-info/met-info-2010, 3.18.25.
Vågerö, O., Bråte, A., Wittemann, A., Robinson, J.Y., Zeyringer, M., Sirotko-Sibirskaya, N., 2024a. Machine learning of public sentiments towards wind energy in Norway. Wind Energy we 2902. https://doi.org/10.1002/we.2902.
Vågerö, O., Jackson Inderberg, T.H., Zeyringer, M., 2024b. The effects of fair allocation principles on energy system model designs. Environ. Res. Energy. https://doi.org/10.1088/2753-3751/ad8e6a.
Weinand, J.M., McKenna, R., Heinrichs, H., Roth, M., Stolten, D., Fichtner, W., 2022. Exploring the trilemma of cost-efficiency, landscape impact and regional equality in onshore wind expansion planning. Adv. Appl. Energy 7, 100102. https://doi.org/10.1016/j.adapen.2022.100102.
Wind energy in Europe, 2023 [WWW Document]. URL. https://windeurope.org/data/products/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/, 12.15.25.
Zeyringer, M., Price, J., Fais, B., Li, P.-H., Sharp, E., 2018. Designing low-carbon power systems for Great Britain in 2050 that are robust to the spatiotemporal and inter-annual variability of weather. Nat. Energy 3, 395–403. https://doi.org/10.1038/s41560-018-0128-x.