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RESEARCH

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Competing for space? A multi-criteria scenario framework intended to model the energy–biodiversity–land nexus for regional renewable energy planning based on a German case study

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Abstract

Background The need to balance renewable energy supply with biodiversity conservation has become increasingly urgent in light of current climate, energy, and biodiversity crises. However, the development of wind and solar energy often presents trade-offs such as competing for land use and potentially impacting species and habitats. To address these concerns, 'priority zones' for bird and bat species have been proposed as spatial designations for early species protection in the regional planning process. However, there are concerns that the areas suitable for wind and solar energy may be limited further, making it difficult to meet state- and regional-specific spatial targets for renewable energy sites.

Results To help decision-makers deal with this challenge, a Multi-Criteria Scenario Framework has been developed and analyzed. It involves a habitat model of priority zones for species conservation and techniques from the intuitive logic scenario planning method. Through a regional case study, various planning criteria were analyzed according to scenarios, such as priority zones for species protection, settlement buffers, and forests. The framework indicates how criteria could be balanced to achieve wind energy spatial targets as well as targets for ground-mounted solar energy with the least possible impact. Results show that compared to other planning criteria, species priority zones had limited competition with spatial wind energy targets. Achieving these targets may require minimal adjustments, such as allowing wind energy in 1–3% of completely protected recreational landscapes. To reconcile land use demands in the energy transition, a balance between 'green' protected areas is necessary. Additionally, ground-mounted solar energy could replace some of the wind energy spatial targets while also meeting the overall solar development goals.

Conclusions The framework provides transparency in assessing trade-offs between multiple objectives and helps quantify the 'costs' and 'benefits' in renewable energy planning. Adapting more flexible planning methods could help resolve the conflict between wind energy and species protection. Joint analysis of the areas needed for wind and solar energy and determining the optimal energy mix are gaining in importance. However, how the benefits

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of multi-criteria scenarios can be achieved within the confines of preoccupied and siloed organizations remains an ongoing research topic.

Keywords Energy and spatial targets, Species protection, Bird priority zones, Nexus, Wind energy, Ground-mounted photovoltaic, Multi-criteria scenario analysis, Case study analysis, Trade-offs, Germany

Background

Efforts to reduce dependence on fossil fuels and to strengthen energy self-sufficiency are flanking the energy and gas crisis as of 2022 [1]. As a result, attempts have been made to diversify gas imports and accelerate the development of renewable energy, such as wind energy and solar photovoltaic systems (PV) [2, 3]. Achieving the energy transition also depends on finding suitable sites, which is a process, however, posing major challenges. National energy targets often differ from implementation and local planning decisions [4, 5]. Among obstacles, such as lawsuits at approval level, making sufficient land available for renewable energy is considered difficult [4, 5]. This is particularly reported for countries, where the first wave of wind energy development has taken place ([6] for Sweden, [7] for Germany, [8] for communal energy transition in Canada].

A trade-off occurs when achieving one sustainability goal interferes with another goal [9]. The search for suitable sites in renewable energy planning often involves spatial trade-offs between renewable energy and nature and landscape. These include, in particular, competition for sites with other land uses, visible changes to the landscape and potential impacts on species and habitats ([9, 12] for challenges of wind energy and PV, [13] for ecological impacts of wind energy, see also [14] for societal, economic and wildlife impacts of wind energy and PV). For example, certain locations are more prone to species colliding with wind turbines [10–12]. However, as wind energy reduces CO_2 emissions in the electricity sector, efforts to combat climate change can also benefit biodiversity, creating a 'green-on-green' dilemma [13]. In the case of PV, biodiversity could increase under the modules if managed properly [14]. At the same time there is a higher demand for land for PV [15]. Trade-offs occur within and between almost every part of social–ecological systems (SES) [16], including land use, economic, and other environmental factors due to human growth in the environment [17].

Within this context, decision-makers are often challenged to find appropriate approaches to conservation while meeting energy targets. As a result of the energy and biodiversity crises, the impacts of energy on species may intensify, for example in terms of land use allocation [2, 18]. Other land use interests, such as forestry, agriculture and the protection of settlements, need to be balanced at the same time [19, 20]. Competing actors, associated wicked problems, and perceived shortcomings in the spatial governance of renewable energy point to a nexus of divergent demands within the energy transition [21–26]. While 'nexus' refers to the linkages between sustainability goals, spatial levels and actors [10, 27, 28], an energy–biodiversity–land nexus in particular is emerging, which will require increasing attention to successfully develop renewable energy [19, 29, 30].

Energy–biodiversity–land nexus in planning

Spatial and environmental planning plays a key role in creating the conditions for an ecological and social energy transition [31–35]. Spatial planning aims to regulate land to accommodate goals and interests, primarily through zoning, i.e., designating land for specific uses [36, 37]. A notable case is German spatial planning. Here, spatial planning categories are discussed to achieve both renewable energy and species protection goals. In response to the energy crisis, in 2022, Germany introduced a new approach to wind energy planning with the intention to meeting the energy targets through spatial targets. These spatial targets have been specified for each federal state (Länder), which is referred to as positive planning.[1]

At the same time, spatial approaches for species protection are being reviewed as a way to address protection concerns already at the planning level instead of tackling trade-offs at the permitting stage [38–40]. 'Bird priority zones' as a planning category aim to resolve the green-on-green dilemma by protecting focal breeding points of wind turbine sensitive bird species [38–41], see also [42] discussing bird priority areas for Finland]. Bird priority zones approaches are currently applied in nine out of 16 federal states in Germany, which are open to balancing (e.g., Baden-Württemberg, Bavaria, Hesse, Mecklenburg-Western Pomerania) [41]. In general, however, the definition of bird priority zones is not uniform across the federal states of Germany. Apart from different target species, different assumptions about focal breeding occurrences are evident, as there are different spatial concepts of bird priority zones between the states. For

[1] Appendix 1 to §3 (1) German Onshore Wind Energy Act (WindBG).

example, habitat modeling or kernel rasters based on breeding sites can be used to define priority zones [41].

The introduction of new spatial planning approaches at state- and regional level raises concerns for decision-making. Spatial planning approaches may lead to the achievement of sustainability goals, i.e., energy and species targets; however, they may also present a further land use challenge that needs to be addressed [40]. How spatial trade-offs evolve in wind energy development is still under-researched [20]. The extent to which these spatial planning categories may compete with each other in the nexus of land demands raises concerns about the implications of spatial planning approaches for energy and species. On the one hand, the lower planning levels designate tiered spatial targets for wind energy, which calls for an even tighter balancing act with other land use objectives [40, 43, 44]. On the other hand, spatial approaches with bird priority zones could alleviate species protection concerns [38, 39, 45]. At the same time, however, they could increase the pressure on land for wind energy development [40, 43, 44]. Furthermore, it remains unclear how bird priority zone approaches affect other planning criteria, especially when it comes to the provision of sufficient land to meet renewable energy targets.

Research questions

To support decision-making, we developed and analyzed a Multi-Criteria Scenario Framework as the objective of this research. The framework allows decision-makers and stakeholders to explore different planning options based on certain criteria. The goal is to understand the spatial impacts of planning decisions in the context of renewable spatial targets, species, and land use [19, 29, 30, 46]. Sustainable development involves social–ecological interdependencies [47]. We aim to contribute to planning support efforts by providing sound justifications for planning decisions, allowing the exploration of options at the planning level, identifying adjustable levers, i.e., criteria to optimize multiple sustainability goals under renewable energy and spatial targets [20]. Scenario analysis is being promoted as a learning tool for nexus thinking [28, 48, 49]. We referred to a 'Multi-Criteria Scenario Analysis' to explore 'if–then' interactions on bird priority zones and land when planning for wind energy and ground-mounted PV [50, 51]. We explored the following research questions:

– Looking at the energy–biodiversity–land nexus, what are the interlocking spatial relationships when planning for renewable energy, such as for wind energy and ground-mounted photovoltaics (PV)?
– What can a Multi-Criteria Scenario Framework offer for decision-making within the energy–biodiversity–land nexus?

The first question was addressed by two sub-questions:

– From a renewable energy perspective, can targets for wind energy and ground-mounted solar photovoltaics (PV) be met if bird priority zones approaches are applied in regional planning?
– From a species management perspective, what are the implications of other large-scale planning criteria when planning with bird priority zones?

Analyzing the effects of fostered species protection efforts at the regional planning level constitutes expected changes in European (EU) law. At the EU level, priority areas for wind energy are being considered as 'go to areas' under the REpower EU Directive. These areas should not have significant environmental impacts and should focus on assessing whole areas for wind energy rather than many individual projects [52–54].

Methods

The Multi-Criteria Scenario Framework has been methodologically validated on the basis of a combination of methods. An in-depth case study analysis is used as input parameters, allowing for testing of data and respective results (Sect. "In-depth case study analysis"). The input parameters are methodically combined within the framework (Sect. "Multi-Criteria Scenario Framework"), and it is tested which 'if–then' interactions can be carried out on the basis of scenarios for decision-makers (Sect. "Results"). By supplementing or adapting the energy targets and criteria this exemplary approach can also be implemented in other case areas. The framework is assessed both in terms of content with respect to the results on spatial renewable energy targets and spatial species protection (Sect. "The results: bird priority zones and wind energy in the energy–land nexus"), and in terms of its applicability (Sect. "The model: Multi-Criteria Scenario Framework") (see Fig. 1).

In-depth case study analysis

Research design using case study analysis

As an input parameter for the Multi-Criteria-Scenario Framework, an in-depth case study has been carried out following Yin, Yin [55]. A case is characterized by a contemporary phenomenon in a real context, where the boundaries between 'phenomenon' and 'context' are often blurred [55]. Here, the interrelationships between spatial categories for renewable energy and species are related to 'phenomena'. These are framed by the external conditions

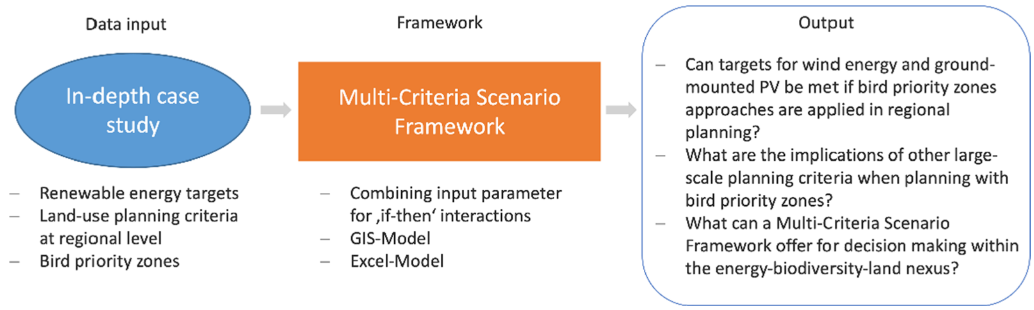


Fig. 1 General methodological approach

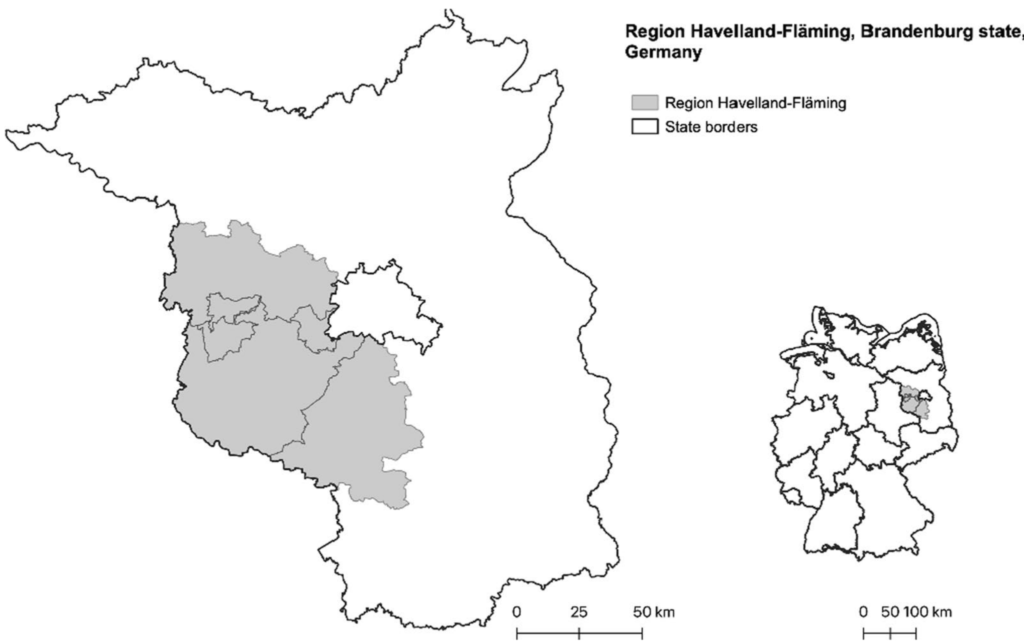


Fig. 2 Region Havelland-Fläming in the state (Land) Brandenburg, Germany, for case study analysis (geodata copyright by © GeoBasis-DE / BKG (2022))

of achieving respective renewable spatial target setting. The context is therefore essential to understanding the case [56]. In this way, theoretical and practical conclusions can be drawn about possible land use trade-offs, and the applicability of a Multi-Criteria Scenario model for tackling these in decision-making.

For the selection of a case study area, specific criteria were established based on a literature search on barriers in wind energy development [e.g., 5, 57–63]:

- Wind energy planning should take place at a higher planning level than local approval level, such as regional or state level planning for zoning, to explore possible trade-offs between (energy, species) targets and land use allocations. Regional planning is accorded an integral role in the overall coordination of land use planning [62, 64].
- A trade-off situation between land allocation and renewable energy use would allow the application of a Multi-Criteria Framework to be explored in a solution-oriented manner [59–61, 63].
- (Geo-)data on the planning situation should be publicly available, if possible, to be able to perform own area analyses in the model framework (cf. [65]).

The Havelland-Fläming region in Brandenburg, Germany, was selected as a case study on this basis. Havelland-Fläming is one of five regions in the federal state of Brandenburg, located southwest of Berlin, and organized as a regional planning authority [66] (Fig. 2).

Case study characteristics

The study area features regional wind energy planning where decision-makers face the challenge of implementing wind energy spatial targets while balancing other land use interests such as settlement buffers, landscape protection areas, and forestry [67, 68]. Through zoning, regional planning creates perspectives on land use. It resolves stakeholders, power structures, political/economic/social/environmental uncertainties, and competing values [36]. In Germany, regional planning operates at the interface between the land development objectives of the federal states and those of the municipalities [63]. In Havelland-Fläming, which is in the process of updating their regional plan, draft regional plans have been revoked twice by the courts due to insufficiently justified planning criteria for wind energy [69][2]. As in 2022, a third plan has been developed and is subject to public participation [72, 73]. The majority of the planning documents have been made available to the public as well as geospatial data [72].

The selection of areas for wind energy in this case, is characterized by an exclusionary planning approach (e.g., excluding landscape protection areas, nature reserves, settlement buffers, among others) [72]. As a result, 1.67% of the region's remaining area has been identified as suitable for wind energy, which hereafter will be referred to as 'wind energy areas'. This share of the remaining space does not reach the statewide spatial target for the development of onshore wind energy as was set by the federal government. According to federal law (German Onshore Wind Energy Act), the state of Brandenburg must designate an area of 2.2% within its regional plans by 2032[34]. Since this missing delta (approx. 0.53%, i.e., 38 km^2) for wind energy sites has yet to be identified, this situation provides a suitable basis for a scenario approach. It suggests that there is a need to balance and weigh trade-offs, which is particularly relevant when evaluating how a Multi-Criteria Scenario Framework can help decision-makers to quantify goal-oriented impacts of planning decisions.

For ground-mounted PV, a distinctive planning concept is lacking, which therefore leaves municipalities in the state and region to create a subsequent concept. Yet, basic provisions for PV in regional planning relate to using agricultural land for technologies, such as agri-PV (agricultural PV). Agri-PV allows for the parallel use of agricultural land for energy and food production [73].

Unlike other German states, federal offices in Brandenburg have not introduced bird priority zones as a planning category [cf. [41, 74]. Species protection issues have been dealt with through the use of species-specific buffer zones [75]. Buffers were established for bird species, such as red kite (*Milvus milvus*), white stork (*Ciconia ciconia*), osprey (*Pandion haliaetus*) and other migratory and resting birds [75]. However, this approach requires high-quality data of breeding sites as well as scientific evidence for buffer estimates. It also mainly addresses sedentary species, such as eagles, that rarely change breeding spots over time [76, 77].

Multi-Criteria Scenario Framework

A Multi-Criteria Scenario Framework for an explorative 'if–then'-analysis includes input parameters as shown in Fig. 3, which are based on the case study area. The model runs different scenarios that consider different approaches to bird priority zones combined with planning criteria used within the case study for wind energy and PV allocation ('if'). It shows how these scenarios affect the potential of achieving renewable energy targets ('then'). Specific data are required for these input parameters of the model, which are evaluated in the following sections (Fig. 3).

Variations of bird priority zones approaches

Assumptions and target species for bird priority zones The aim of the species priority zones is to protect functional areas for wind energy sensitive species early on at the higher planning level, rather than only at the subsequent wind energy permitting level (i.e., population-based conservation approach) [38, 74]. As there is no single approach for priority zones yet, different approaches have been examined in this analysis, e.g., in relation to target species and spatial designation approaches ([41], cf. [38, 74]). The aim was to enable a discussion on which approaches can have which land footprints on wind energy and PV development.

Four premises were used to select the target species based on a literature analysis [39, 40, 43, 45, 78–82]: (1) species priority zones would only be meaningful for those species that are considered sensitive to wind turbines. (2) Species must be widespread, with well-defined habitat parameters and a good knowledge and data base should exist. (3) Species must also be difficult to manage, where bird priority zones add value, and have a relatively high variability of breeding sites, where only species-specific buffers are less suitable. (4) Conventional protection

[2] Until 2023, the planning criteria which would not be available for wind energy had to be specified in detail in order not to undertake a preventive planning approach, cf. [70, 71]. In 2023, 'positive planning' was introduced to speed up wind energy growth. This sets spatial energy targets for each state avoiding justification of exclusionary criteria. Therefore, we argue that a multi-criteria framework allows for the exploration of criteria for achieving spatial energy goals.

[3] Appendix 1 to §3 (1) German Onshore Wind Energy Act (WindBG).

[4] The spatial wind energy target of 2.2 % corresponds to 150.5 km^2 for the Havelland-Fläming region (= 15050 ha), cf. [66].

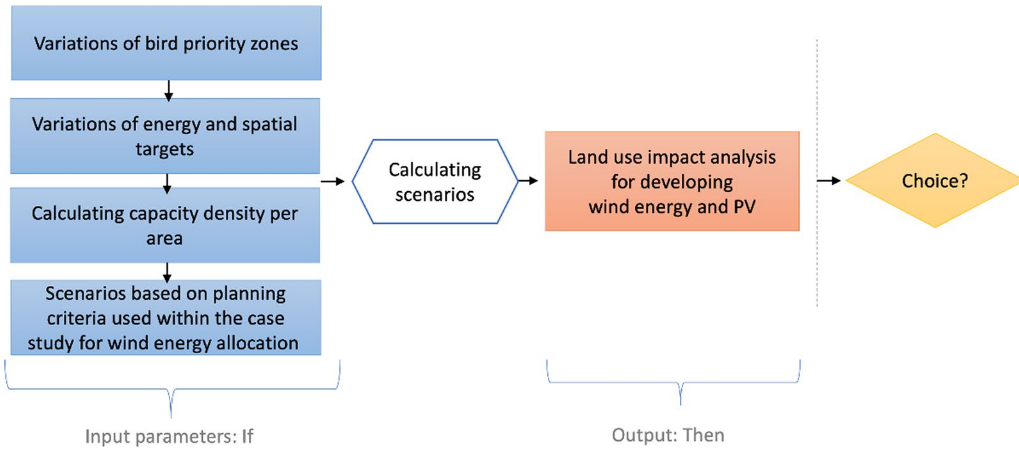


Fig. 3 Input parameters for the Multi-Criteria Scenario Framework for an 'if–then' analysis for wind energy and ground-mounted PV planning within the energy–biodiversity–land nexus

and avoidance measures usually do not provide satisfactory solutions (see Additional file 1).

Based on these premises, eight raptor species were identified as suitable for species priority zone approaches: white-tailed eagle (*Haliaeetus albicilla*), osprey (*Pandion haliaetus*), red kite (*Milvus milvus*), common buzzard (*Buteo buteo*), black kite (*Milvus migrans*), marsh harrier (*Circus aeruginosus*), honey buzzard (*Pernis apivorus*), and hobby (*Falco peregrinus*). The selection also includes (politically) discussed species relevant to planning[5]. The availability of point data, which represent nesting sites, in the Havelland-Fläming region ultimately limited the choice of species. This limitation resulted in bird priority approaches for only two of the eight species originally considered for this analysis, the red kite and the osprey. Although red kite populations are widely distributed throughout Europe, about 50% of the European population reside in Germany. As a significant share of the population occurs in Germany, the conservation of red kites is considered to be a 'special responsibility' [78, 83]. Ospreys are classified as vulnerable in the Red List of breeding birds, and are also considered as sensitive to wind turbines [84, 85].

The Multi-Criteria Scenario Framework therefore uses three differing bird priority zones for testing as input parameters: Two for the red kite (*Milvus milvus*), including the top 5 and top 10 most suitable habitats, and one for the osprey (*Pandion haliaetus*), which depicts its top 10 most suitable habitats. The bird priority zones were developed on the basis of habitat modeling by ARSU GmbH in collaboration with the research project 'Bird Priority Zones for Species Protection' at the Berlin Institute of Technology (TU Berlin), which was sponsored by the German Federal Environmental Foundation (DBU) [86]. In addition to these three priority areas, an aggregation of all bird priority zones was included in this analysis, as well as only those bird priority zones that overlap with each other, to possibly include both species for planning purposes (Fig. 4).

Habitat modeling for bird priority zones The research project 'Bird Priority Zones for Species Protection' held the premise to test a method for bird priority zones approaches that would produce robust results with minimal data and uncertainties in the quality of mapping data for habitat potential [86]. Habitat modeling provides an efficient way to interpolate the distribution and occurrence of target species based on a sample [79–81]. The method is based on niche theory, which states that a species can only survive if both abiotic and biotic interactions allow positive population growth [81, 87, 88].

For the target species, red kite and osprey, point occurrence data were provided for the state of Brandenburg by the State Office for the Environment (LfU), Brandenburg. To identify further suitable nesting sites in potential habitats, habitat parameters were considered, e.g., forest, grassland, water, wetland. A logistic regression was used to calculate the probability of occurrence for characteristics and constellations of habitat parameters, assuming only two possible values (yes, no). The first five and the first ten most suitable habitats were selected as two options for bird priority zones (top 5, top 10). The sites were identified considering the criteria of contiguous area size, habitat quality and suitability for other species. Depending on how much space is available, priority areas can be selected more generously from the pool of potential areas, or focus only on those areas that are suitable

[5] Annex 1 to § 45b (1-5) Federal Nature Conservation Act (BNatSchG).

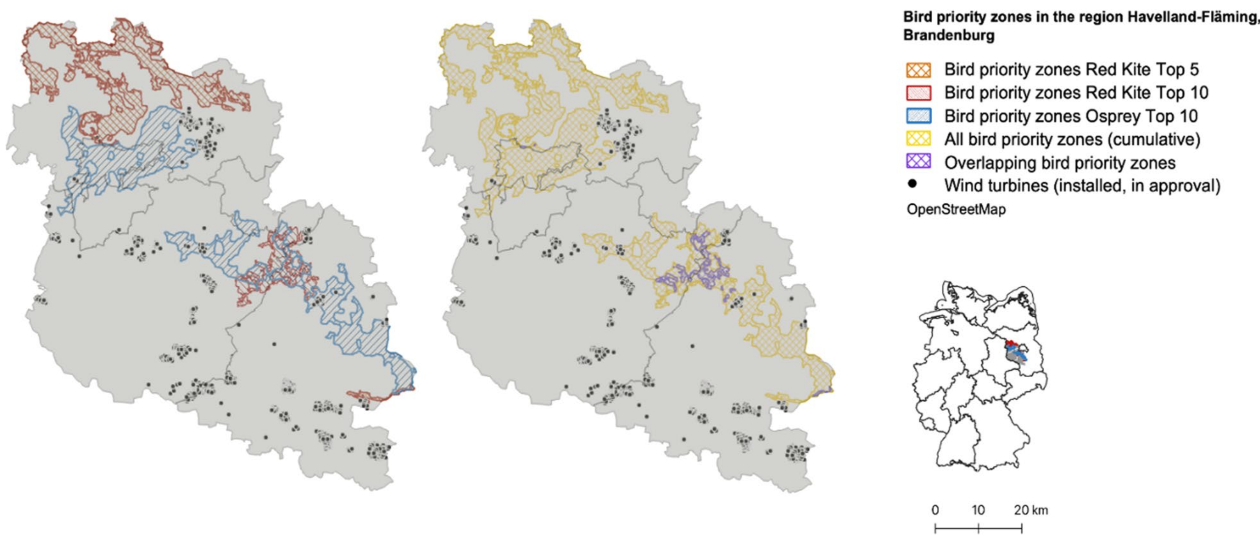


Fig. 4 Different bird priority zone approaches for the red kite and osprey in the case study area based on habitat modeling by ARSU GmbH (geodata copyright by © GeoBasis-DE / BKG 2022 and ARSU GmbH 2022)

several times over. In Havelland-Fläming there are no suitable areas designated as top 5 for the osprey. More detailed information on the habitat model can be found in Additional file 1.

Variations of energy and spatial targets

Spatial targets for wind energy The federal government in Germany has introduced binding targets on the amount of land that must be designated for wind energy in the German states (Länder). These targets must be met by 2032 (see footnote 3). As a benchmark for this analysis, the targets for wind energy sites in the state of Brandenburg were examined and are referred to as 'spatial targets' (compare Table 1). As the states are allowed to adopt spatial targets, which are even more ambitious[6], in addition, we included the targets of the state of Brandenburg. The 2030 energy strategy sets targets for designated wind energy sites (2.0%) [89]. The 2040 energy strategy expands energy targets for the next decade, taking up the nationally defined target of 2.2% for wind energy sites (see footnote 3) [90]. The different targets allow for the analysis of different time horizons. The spatial targets may include areas that already feature wind turbines (Table 1).

Spatial targets for ground-mounted photovoltaics For ground-mounted PV there are no spatial targets set by federal legislation. Instead, energy production targets are set, which are intended to be achieved on across

Table 1 Spatial targets for wind energy development for the case study

Spatial targets for wind energy development for the case study		Source
Target until 2032	2.2%	German Onshore Wind Energy Act
Target until 2030	2.0%	Energy Strategy 2030 Brandenburg
Target until 2027	1.8%	German Onshore Wind Energy Act

Germany[7] and include both roof-mounted and ground-mounted PV. Assumptions were made specifically for the distribution of federal targets in the state of Brandenburg. It was assumed that half of the PV targets would be met by roof systems and half by ground systems. We postulated an equal distribution key for the 16 federal states, except for the three city states. For Brandenburg, the calculated energy target must be implemented in the state's four regions [66]. We referred to an equal distribution of PV systems, i.e., a quarter of the energy target for Brandenburg would be installed in the Havelland-Fläming region. Based on a power density per area [91–93], the area required to achieve the energy target for PV was then calculated (Sect. "Calculating capacity density per area"). In addition, Brandenburg's PV development targets were added for comparison [90] (Table 2).

Calculating capacity density per area

Calculations for wind energy Capacity density assumptions are required to determine how much wind power

[6] §3 (1) German Onshore Wind Energy Act (WindBG).

[7] §4 No. 3 Renewable Energy Act 2023 (EEG).

Table 2 Energy and spatial targets for PV in the case study

Energy and spatial targets for PV	Target until 2028 (Renewable Energy Act 2023)	Target until 2030 (Renewable Energy Act 2023)	Target until 2040 (Energy Strategy 2040 Brandenburg)
Target for Germany (ground-mounted PV)	86.0 GW	107.5 GW	–
Target for Brandenburg state (ground-mounted PV)	6.62 GW	8.27 GW	9.0 GW
Target for Region Havelland-Fläming (ground-mounted PV)	1.65 GW	2.07 GW	2.25 GW
Required area (region)	16.71 km^2	20.88 km^2	22.73 km^2
Area share (region)	0.24%	0.31%	0.33%

can be installed per area. Capacity density typically varies due to geographic and topographic conditions such as wind speed, surface roughness (e.g., in forest areas), altitude, and the density of wind turbines in an area [94–96]. For this analysis, the average value of 29.3 MW/km^2 for Germany is used [94]. This value assumes a rotor pitch of 4.5 times the diameter in each direction. However, it must be acknowledged that other capacity densities could potentially be achieved for the case study area. The shape of how wind turbines are arranged to another influences the power density, but this cannot be predicted in detail for each possible site [94].

Furthermore, different power densities can be postulated depending on the turbine capacity, height and rotor diameter [97]. Based on market developments [98–101], a reference turbine with a capacity of 5 MW, rotor diameter of 149 m and a hub height of 150 m is assumed for this analysis (such as [102–104]).

Calculations for ground-mounted photovoltaics For ground-mounted PV, different capacity densities can occur depending on the system type, i.e., ground-mounted, elevated on agricultural land, or as vertical PV systems [105]. The capacity density depends on factors, such as technological efficiency, position of the sun, slope and shading [91, 92, 106]. Based on a literature analysis of current system data, a power density of 99 MWp/km^2 is assumed for ground-mounted PV systems, e.g., installed on grassland [91–93]. In Germany, ground-mounted PV systems are subsidized for certain areas (referred to as 'EEG areas')[8]. In the case of agri-PV, the power density is lower at 40 MWp/km^2 [91]. Vertical PV modules allow the use of solar radiation from both sides in an east–west direction [105, 107]. These modules can be installed on extensively used grasslands, for example, and have a power density of 35 MW/km^2 for 'Next2Sun' modules [108].

Generating scenarios and data application

Scenarios are aimed to simulate renewable energy allocations using bird priority zones under defined renewable spatial targets. To give an example and allow evaluation, the data input and results are assessed based on the case area (compare Sect. "Research design using case study analysis"). This exemplary analysis therefore aims to help exploring how to achieve the remaining site deficit for wind energy, i.e., the 'delta' of 0.56% of the case region, while considering bird priority zones (Sect. "Case study characteristics"). Thus, the existing draft spatial planning concept of the case study region is modified in scenarios and used for wind energy according to its planning criteria (cf. Section "Key criteria identification" and Appendix A). This approach is exemplary and can also be applied to other case regions by supplementing or adapting the energy targets and the set of criteria. The analysis also investigates the spatial potential for using ground-mounted PV as a complementary approach to achieving the spatial delta (based on an informal potential site analysis for solar energy [109]). The relationship between wind energy and PV for energy target achievement is therefore explored, as well as how bird priority zones may affect the development of both. A detailed and criteria-based PV site analysis similar to the one for wind energy was not carried out, as no analysis was performed in the cases' regional plan [73], and due to the scale of a possible similar self-made analysis. However, PV was included here as a complement based on an informal spatial PV analysis [cf. [109]. As land use pressure continues to increase, it is important to balance stakeholder desires for PV in conjunction with wind energy in order to avoid separate considerations ([110], cf. [111]). This framework would also allow for the inclusion of more detailed criteria-based analyses for PV.

The scenarios represent possible futures to guide decision-making [112, 113] and simplify contextual complexity [114]. For the purposes of this analysis, the possibility of alternative futures is assumed. Future events are not

[8] such as areas in commercial and industrial zones, areas along highways within a 200-m corridor, areas converted from economic, traffic, residential, or military use, sealed areas, and landfills, as well as areas in disadvantaged areas, such as low-yield arable land and grassland. Ground-mounted systems on peat land, parking lots and floating PV systems will also be permitted, §37 (1) Renewable Energy Act (EEG 2023).

completely predictable, but they are also shown to not be completely chaotic, allowing for possibilities of influence, for example through goals in decision-making processes [50]. Scenarios for describing the future, which have an exploratory nature in this analysis, are used to capture 'if–then' interactions [50, 115]. Starting from a 'business as usual' (BAU) reference, a leap in time is mapped into the near future [116], such as the usual planning cycles of about 10 years in regional planning [117].

Based on these assumptions, the intuitive logic scenario generation method is identified as appropriate. It focuses on decision-making processes where intuitive reasoning and uncertainty assessments are allowed as well as objective data and information [50, 118]. There are different phases in the scenario generation process, such as key criteria identification, key criteria analysis, and scenario development [50, 51, 112].

Key criteria identification Since the scenarios aim to vary planning criteria for the allocation of wind energy based on the case study, the planning criteria were adapted from the draft regional plan of Havelland-Fläming [119]. The goal was to model the draft regional plan of the case study region for the BAU scenario and vary them in scenarios. A PESTEL analysis (Political, Economic, Social, Technological, Environmental, Legal analysis) was used to analyze the planning criteria that were applied [120–123]. In addition, the planning criteria were supplemented by the bird priority zone approaches (Sect. "Variations of bird priority zones approaches"). We also addressed further criteria that arose within the region, such as repowering potential, retrofitting, and reduced buffers to settlements [124–127].

In the case of ground-mounted PV, a state and regional informal analysis of possible PV sites is available via a Web-GIS application [109] (cf. Sect. "Generating scenarios and data application"). This analysis covers areas for which subsidies are available for the development of PV (Sect. "Calculations for ground-mounted photovoltaics") ('EEG areas'). Additionally, the possible areas for agri-PV are assessed [109]. Since the results can only be viewed online, no detailed criteria-based analysis was conducted, but the availability of sites was included as a correction factor for the PV scenarios (see Additional file 1 for detailed GIS approach).

Key criteria analysis and (geo-)data availability In a key criteria analysis only the driving forces among the planning criteria were identified to combine them to derive scenarios [51]. It is assumed that criteria with little uncertainty about land use demand can be combined into a single profile throughout the scenario process. Criteria with 'critical uncertainty' should be considered in the form of possible scenario profile curves [50]. A matrix of land use impacts and uncertainties was used for this purpose [50, 51]. Within the matrix, the criteria were scored in terms of their impact on land availability (y-axis). Uncertainty for the policymaker about whether to include or exclude criteria for wind energy is displayed on the x-axis (refer to Fig. 5). Criteria assignment in the matrix was based on geography in the case study area and how the criteria were applied:

- Criteria that account for a significant amount of land were assigned a higher land use demand and impact, and vice versa. It can be assumed that those planning criteria that take up the most area will have greater trade-offs with wind energy and PV development.
- For criteria that have a legal basis, the planning scope was considered small and therefore the uncertainty to use this criterion in decision-making also smaller, since there cannot be much scope for action. For example, criteria, which are not subject to balancing but restrict the area for wind energy due to physical and legal reasons, are nature reserves, military areas, open spaces, installed ground-mounted PV systems, and airports. Additionally, there is a minimum buffer of 1000 m to hospitals and 350 m to settlement areas [119].
- For criteria that are only considered in planning, i.e., are subject to balancing, the uncertainty was estimated to be higher.
- Criteria that were particularly discussed (in the media) in the case study area were classified as 'uncertain', although these criteria can be legally regulated (e.g., landscape protection areas) (refer to Fig. 5).

'Critical uncertainties' to be tested in the scenarios (see Fig. 5) are thus specific criteria with a high land demand in the study area and possibly present a higher uncertainty for decision-makers. However, only those criteria for which (geo)data are available for the study area can be run for these scenario profile curves. Even though many (geo)data are already publicly available, missing data for some criteria would still be integral for further analysis. Based on the PESTEL analysis, a data search was conducted to analyze the availability of (geo)data for criteria (Additional file 1 for geodata sources). Specifically, geodata was not available for species-specific buffers. However, since it is known how much area is occupied by species-specific buffers in the region [128], these buffers

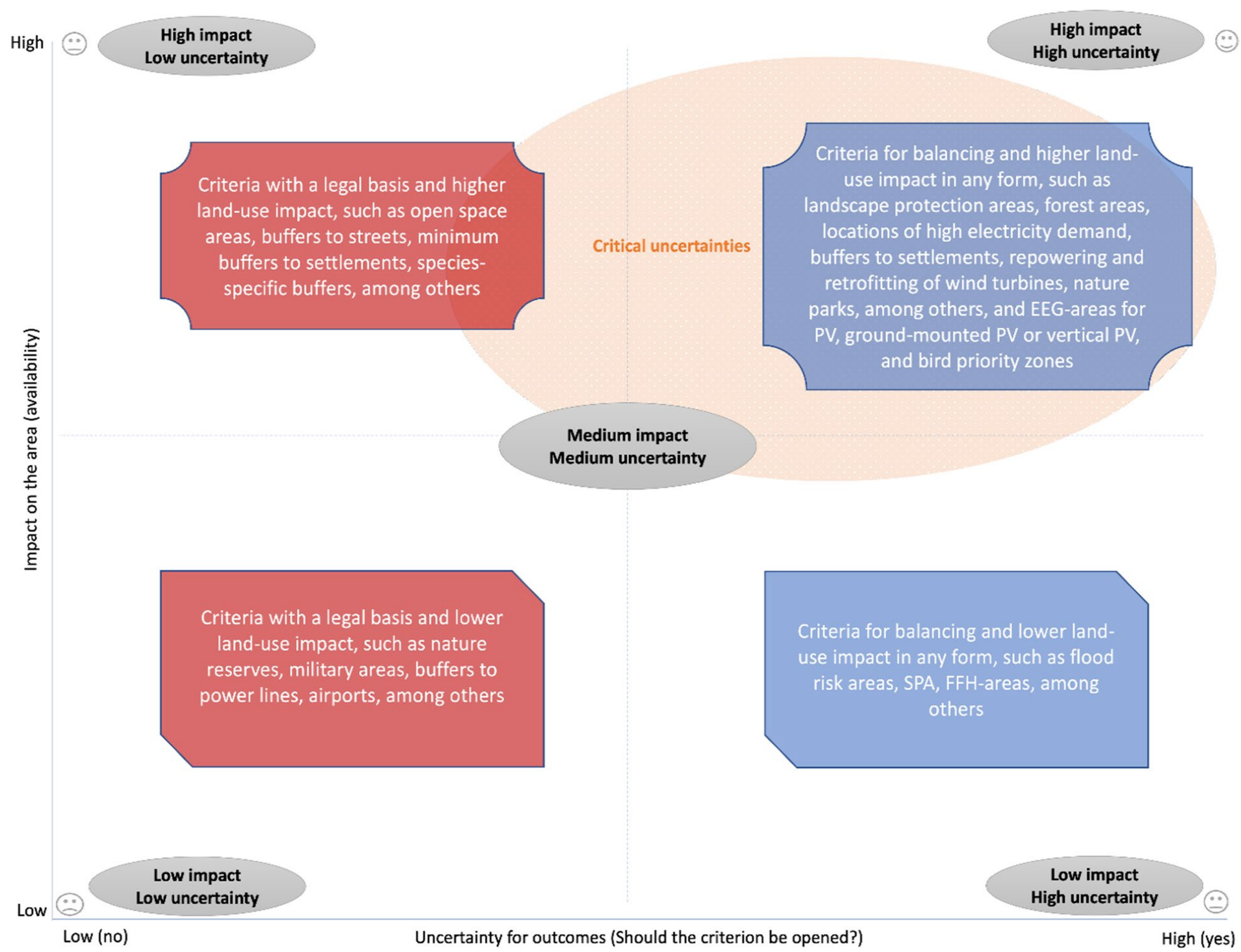


Fig. 5 Impact/uncertainty matrix for analyzing criteria as 'key' for combining them later in scenarios as profile curves. The selected criteria are referred to as criteria of 'critical uncertainties', which are evaluated within the scenario analysis. Please refer to Additional file 1 for a detailed description

were included as a correction factor in the scenarios.[9] In addition, no geospatial data were available for telecommunication channels or low-flying areas of the German Federal Armed Forces [128], which also compete with wind energy [4]. On the basis of available data for the Multi-Criteria Scenario Framework, it can be assumed that results closely approximate current regional planning practices.

Scenario generation The planning criteria identified and then combined within the scenarios cover three thematic areas:

A) Planning based on the current situation, i.e., according to the third draft regional plan for wind energy and the informal area analysis for ground-mounted PV (Business as usual, BAU).
B) Planning variations in bird priority zones.
C) Planning variations of large-area requiring criteria with fixed bird priority zones.

The thresholds within the scenarios refer to the share of land that could be considered for wind energy or PV in theory. They were chosen to have a small influence on the planning criteria, i.e., land uses, and to reach the spatial targets for wind energy and PV (Table 3). A detailed description of the scenarios is provided in Appendix A.

GIS and Excel modeling of scenarios A QGIS graphical model was used to map and analyze the impact on land availability for renewable energies within each scenario

[9] The area available for wind energy designation is 0.73 km^2 after subtracting all planning criteria. Species-specific buffers occupy 0.42 km^2 of this area. This is about 58% of the area (130).

Table 3 Scenarios within the Multi-Criteria Scenario Framework, varying planning criteria identified as 'critical uncertainties' for the case study region

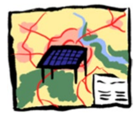
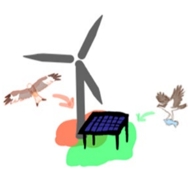
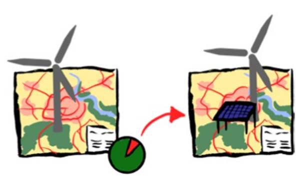
Business as usual (BAU) for wind energy and PV		
		
#1 Wind energy under current planning practice (no bird priority zones) (BAU)	#2 Ground-mounted PV on subsidized areas (no bird priority zones) (BAU)	#3 Agri-PV on agricultural areas (no bird priority zones) (BAU)
Planning variants in bird priority zones		
		
#4 Wind energy in bird priority zones (A 0%—B 5%—C 10% wind energy in bird priority zones—D using wind energy areas in bird priority zones based on BAU)	#5 Repowering in bird priority zones (A 100%—B 200% repowering in bird priority zones)	#6 Retrofitting in bird priority zones (A 50% retrofitting in bird priority zones)
		
#7 Bird priority zones and efficient areas for wind energy (A 10%—B 5% wind energy in bird priority zones)	#8 Bird priority zones and electricity demand near settlements (A wind energy within a 1 km buffer around settlements)	#9 Bird priority zones and network efficiency (A < 5 km around transformer stations enabling wind energy development)
		
#10 Ground-mounted PV in bird priority zones (A 0%—B 10%—C 20% PV in bird priority zones)	#11 Vertical PV in bird priority zones (A 5%—B 10%—C 20% PV in bird priority zones)	#12 Agri-PV on agricultural areas in bird priority zones (A 0%—B 10%—C 20% PV in bird priority zones)
		
#13 Energy mix of ground-mounted PV and wind energy in bird priority zones (A 10% wind energy and PV in bird priority zones)	#14 Ground-mounted PV to substitute for missing wind energy according to achieved targets with BAU (A 0% PV and wind energy in bird priority zones)	

Table 3 (continued)

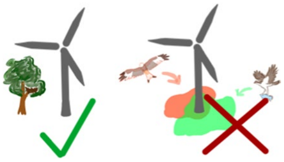
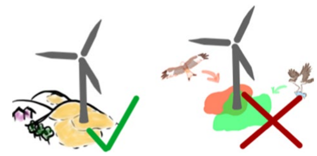
Planning variants of large-area requiring criteria with fixed bird priority zones		
 #15 Bird priority zones and no species-specific buffers (A no species-specific buffers)	 #16 Bird priority zones and smaller buffer to settlements (A 800 m settlement buffer)	 #17 Bird priority zones and wind energy in forests (A 4%—B 2% wind energy in forests)
 #18 Bird priority zones and wind energy in landscape protection areas (A 3%—B 1% wind energy in landscape protection areas)	 #19 Bird priority zones and wind energy in nature park areas (A 4%—B 2% wind energy in nature park areas)	 #20 Bird priority zones and wind energy in open spaces (A 4%—B 2% wind energy in open spaces)

Table 4 Example of the Excel model for combining all input parameters with the spatial results of the GIS model for wind energy, for detailed calculations see Additional file 1

Input parameters	Target A	Target B	Target C
Spatial target for wind energy (%)	2.2% until 2032	2.0% until 2030	1.8% until 2027
Regional area (km^2)	6.842 km^2		
Reference facilities for wind energy			
Capacity per area (MW)	29.3		
Capacity of facility (MW)	5.0		
Rotor diameter (m)	149.0		
GIS-Model input	**Example scenario 'Bird priority zones and landscape protection areas'**		
Threshold parameter (%)	4% (areas for wind energy in landscape protection areas)		
Area bird priority zones (km^2) (for exclusion)	426.14 km^2 for red kite top 5 areas		
Area for wind energy in BAU (%)	1.45%		
Scenario results			
Area for wind energy in the scenario (%)	2.8%		
Reached power capacity (MW)	5.607 MW		
Required number of wind turbines	1.121		
Saldo (spatial targets—area in the scenario) (%)	0.6% (+)	0.8% (+)	1% (+)

using vector data (see Additional file 1 for data used and detailed model description). The planning concept for wind energy in Havelland-Fläming has been mapped according to the draft regional plan in QGIS [73]. Using open access data, the total percentage of space available for wind energy according to the given planning criteria in the BAU scenario was 1.45% of the region's total area. Compared to the identified available space for wind energy of 1.67% in the draft regional plan, this is a slightly lower value [73]. This may be due to the fact that not all necessary data from the regional plan was openly accessible, or other data sets may have been used (see also Sect. "Key criteria analysis and (geo-)data availability").

Table 5 Example of the Excel model for combining all input parameters with the spatial results of the GIS model for wind energy, for detailed calculations see Additional file 1

Input parameters	Target A	Target B	Target C
Spatial target for ground-mounted PV (%)	0.33% until 2040	0.31% until 2030	0.24% until 2028
Regional area (km^2)	6.842 km^2		
Reference facilities for wind energy			
Capacity per area (MWp)	99.9		
GIS-Model input	**Example scenario 'Ground-mounted PV in bird priority zones'**		
Threshold parameter (%)	10% (area for ground-mounted PV in bird priority zones)		
Area bird priority zones (km^2)	426.14 km^2 for red kite top 5 areas		
Area for ground-mounted PV (informal analysis [109]) (%)	0.56%		
Scenario results			
Area for ground-mounted PV in the scenario (%)	0.43%		
Reached power capacity (MW)	2.926 MWp		
Saldo (spatial targets – area in the scenario) (%)	0.10% (+)	0.13% (+)	0.19% (+)

The planning criteria of the BAU scenario were then modified according to the proposed scenarios in QGIS (compare Table 3). For example, wind energy development was allowed in a small portion of landscape protection areas. The remaining wind energy area was calculated per scenario. The PV scenarios were based on the informal analysis of possible PV areas of the state of Brandenburg [109]. However, in the absence of geospatial data for the GIS analysis, it was assumed that there would be an even distribution of potential PV sites across the region (see Additional file 1 for detailed model description).

An Excel model was then applied to combine all input parameters with the spatial results of the GIS model for the case study (i.e., bird priority zones, spatial targets for wind energy and PV, capacity density per area for each scenario). As a result, it was possible to calculate how much land would remain for wind energy and PV under each scenario, and whether or not the federal spatial energy targets could be met (Tables 4, 5). The calculations in the Excel model are provided in Additional file 1.

GIS-overlay analysis of planning criteria A GIS-overlay analysis was conducted to determine whether sufficient land would actually be available for wind energy in each land use, i.e., planning criteria, if it were opened to wind energy (and ground-mounted PV) according to the scenarios. Due to legally mandated criteria that may not be available per se, it is possible that even with good planning intentions, sufficient land cannot be designated for renewable energy. For example, open space areas may overlap with strictly protected areas, such as nature reserves. Therefore, planning criteria that are mandatory have been overlaid with criteria that have a larger area share in the region (see Sect. "Key criteria analysis and (geo-)data availability" for mandatory planning criteria). The following criteria were therefore identified for overlay analysis using QGIS, which have a large share of the area in the case region that could close the gap to meet the spatial wind energy target: nature reserves, coniferous forests, nature parks, and open spaces. The results are given in Appendix B.

For additional discussion, GIS was also used to determine how the region's bird priority zone approaches overlap with other protected spatial categories, such as Special Protection Areas (SPAs) and nature reserves. The aim was to determine whether the categories were spatially complementary. It was also investigated whether there would be an umbrella effect for other species. The Additional file 1 presents these additional results.

Results

The results of the Multi-Criteria Scenario Framework are divided into two parts, i.e., the results for wind energy (Sect. "Bird priority zones and wind energy targets") and the results for ground-mounted PV (Sect. "Bird priority zones and PV targets, and combined wind energy and PV scenarios"). For each an introductory section indicates the conclusions that can be drawn from an overarching perspective. These include the extent to which there is competition for sites between wind energy (and ground-mounted PV) and bird priority zones, and the relation to additional land uses investigated, i.e., planning criteria. This is followed by a detailed presentation of the results for each scenario.

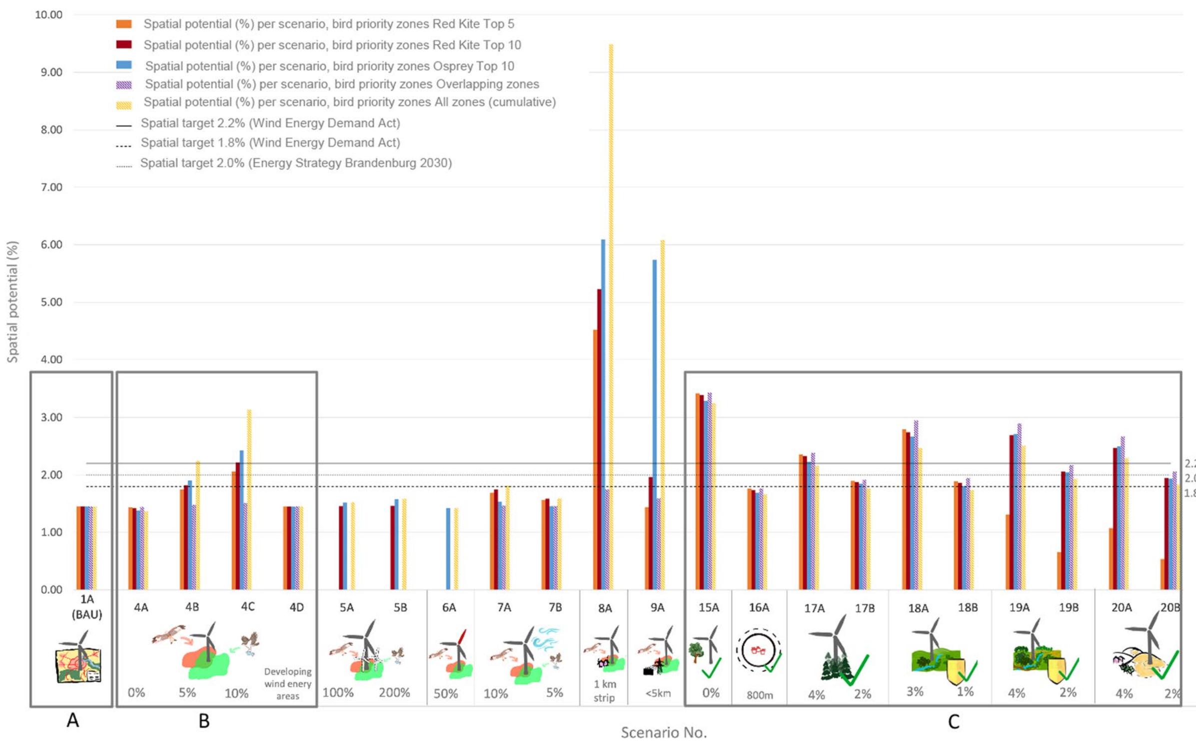


Fig. 6 Results of the wind energy scenarios. The bars indicate whether the spatial targets for wind energy would be met for each scenario (see the lines for spatial targets). The colors of the bars indicate the use of a different approach to a bird priority zone in each scenario (orange: red kite top 5 most suitable areas, red: red kite top 10 areas, blue: osprey top 10 areas, purple: overlapping bird priority zones of red kite and osprey, yellow: all bird priority zones together). For detailed scenario description refer to Appendix A

Bird priority zones and wind energy targets

Overall findings for wind energy: competing for space?

The scenario analysis indicates how zoning regulations for wind energy affect area availability for renewable spatial targets. It facilitates case-by-case statements of whether the additional consideration of bird priority zones as a planning criterion further tightens the spatial target for wind energy. In general, it is illustrated that with current planning practice, excluding areas identified as sensitive, the wind energy target of 2.2% for the year 2032 (BAU scenario) cannot be achieved (Block A, i.e., only 1.45% of the area would be available for wind energy, Fig. 6). In projecting planning scenarios it is shown that the spatial targets of 2.2% for wind energy are only just achievable or not achievable at all. In principle, however, the achievement of the spatial target would not be significantly reduced by different approaches to the bird priority zones (Block B, Fig. 6). Compared to the other planning criteria, excluding bird priority zones for wind energy use would not reduce the area for wind energy more than average. Rather, other planning criteria prove significantly more land consuming (Block C, Fig. 6). These criteria further overlay the bird priority zones and can exclude them from wind energy use, such as 1000 m buffers from settlements, landscape protection areas, nature parks, open spaces, forests, and species-specific buffers. Thus, the scenario analysis indicates that, compared to other planning criteria, bird priority zones would not significantly increase land-use trade-offs for wind energy in this case.

At the same time, it is illustrated that different approaches to bird priority zones could have different impacts on land availability for wind energy. This depends on the spatial characteristics of the region, such as the extent to which a bird priority zone overlaps with other areas that could theoretically also be suitable for wind energy (e.g., scenario #20 as wind energy would not significantly increase, using bird priority zones for the red kite in top 5 most suitable areas) (Fig. 6).

If decision-makers had to select planning criteria to reach the spatial targets for wind energy, different thresholds would result, i.e., the percentage at which a planning criterion would have to be opened up to reach these targets. In numerical terms, to enable a spatial target of 2.2% for wind energy, approximately 10% of the respective bird priority zones for the red kite and the osprey would have to be approached (#4C). In comparison, this threshold for bird priority zones is significantly higher than the threshold for landscape protection areas, nature parks and open spaces, for example (#20AB, #21AB, #22AB). The results

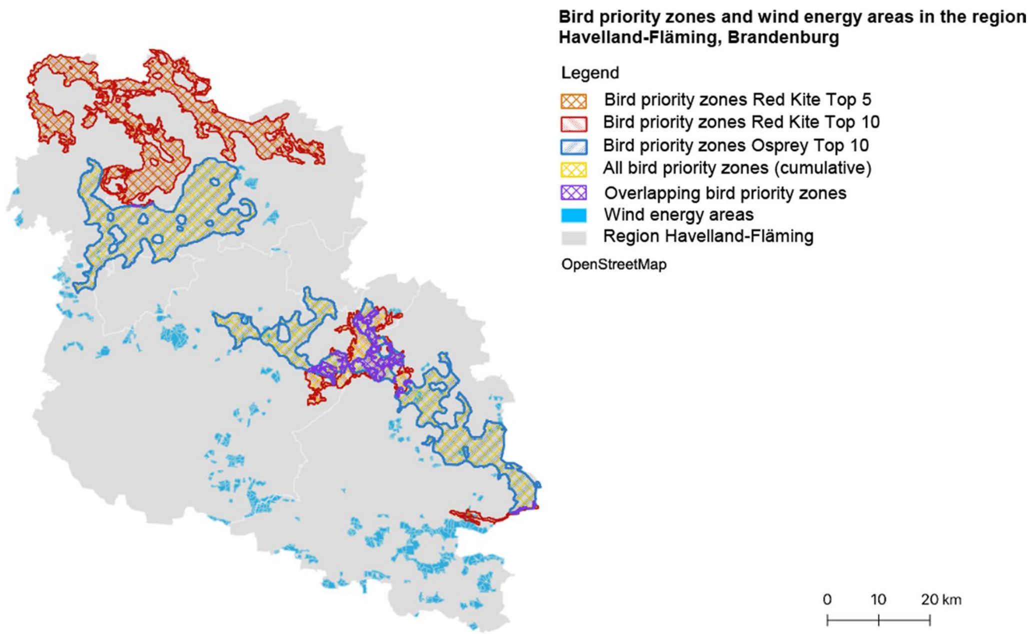


Fig. 7 Bird priority zones and wind energy areas in the region Havelland-Fläming, Brandenburg (geodata copyright by © GeoBasis-DE / BKG 2022, ARSU GmbH 2022 and Regional Planning Authority Havelland-Fläming 2022 (RPG 2022))

indicate that thresholds for developing wind turbines in these planning criteria would need to be 1–3% to achieve the highest spatial target of 2.2% for wind energy. For coniferous forest areas, the threshold would be an additional 4% to already installed wind turbines in forests (#19AB). These thresholds, in turn, would be lowered if more than one lever were turned, i.e., if criteria were combined. This is left as a question of balance. In general, to achieve the spatial targets, for example, smaller shares of landscape protection areas, nature parks, or open spaces would be required than shares of bird priority zones. Overall, there may be fewer potential trade-offs than in bird priority zones as well. Within these planning criteria themselves, possible wind energy areas have not yet been evaluated. This means that areas with potential for wind turbines still need to be identified in detail. The detailed scenario results are presented in the following sections.

Planning variants in bird priority zones

The detailed results of each scenario are presented in the following sections. Scenario results are presented together, which can be summarized thematically.

Wind energy in bird priority zones (#4), If bird priority zones are excluded from wind energy use, a maximum of 5.69% of wind energy area would be unavailable (#4A). In numbers, this corresponds to a theoretical loss of approximately 166 MW or 33 turbines (see blue spots for wind energy areas overlaying with bird priority zones approaches in Fig. 7). The 2.2% spatial target could realize 4410 MW in total, i.e., 882 turbines. If bird priority zones in regional planning were applied, 33 fewer turbines could be realized, which indicates a 3.7% loss of turbines. This loss of less than 5% could, however, be considered small compared to other scenarios (#20, #21, #22). In addition, the spatial targets will not be met if wind turbines are allowed in the remaining wind energy areas in the bird priority zones (up to a maximum of 0.4% of the bird priority zones) (#4D). Thus, wind energy development in bird priority zones does not appear to be sufficient to meet spatial targets and is not a significant planning driver. If bird priority zones are opened to wind energy beyond the identified wind energy areas, approximately a 10% share of the bird priority zones would be needed to meet the 2.2% spatial target (#4C) (Fig. 7).

Repowering, and retrofitting in bird priority zone (#5 #6), The potential for repowering, i.e., replacing wind turbines after the subsidy period ends, could be reduced by excluding bird priority zones from wind energy use. However, the analysis illustrates that there are few existing wind turbines in bird priority zones, and this only applies to the red kite top 10 and osprey top 10 bird priority zones. Maintaining the same or even doubling the turbine capacity would result in a very small increase in meeting the spatial targets (#5). In addition to repowering, there is also the option of retrofitting existing turbines and continuing to operate them. A 50% retrofit scenario results in half of the expected capacity, i.e.,

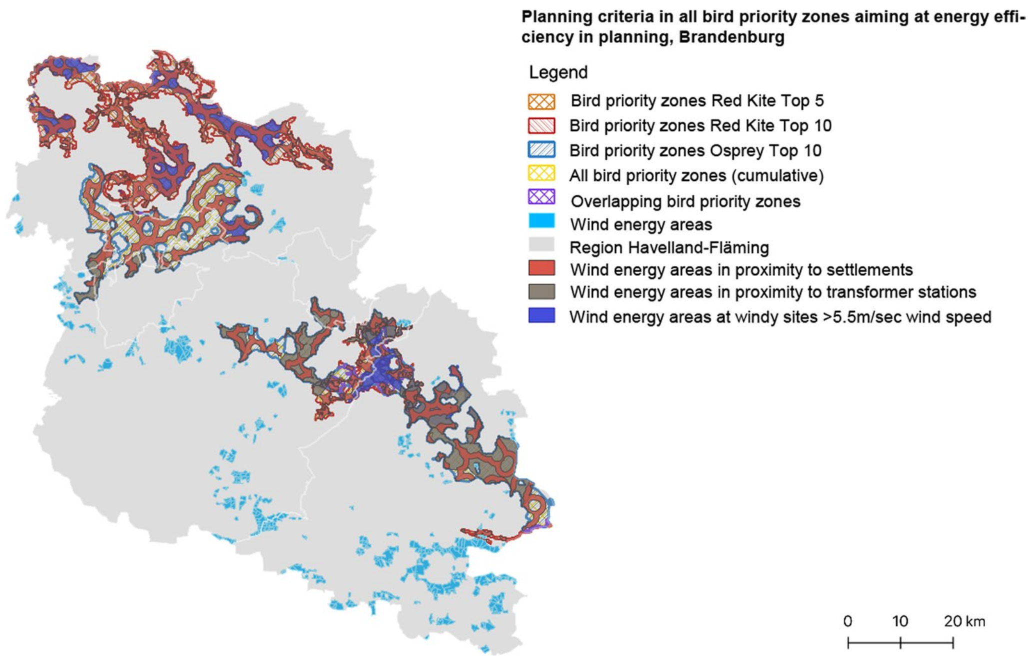


Fig. 8 Planning criteria in all bird priority zones aiming at energy efficiency in planning, Brandenburg (geodata copyright by © GeoBasis-DE / BKG (2022), ARSU GmbH 2022 and Regional Planning Authority Havelland-Fläming 2022 (RPG 2022), OSM 2022, Energy and Climate Atlas Brandenburg 2020, Geoportal LGB 2022)

the expected increase in wind energy capacity is small. Concerning existing turbines in the bird priority zone approach for the red kite top 10, this observation does not apply as there is only one existing turbine (#6).

Bird priority zones and efficient areas for wind energy (#7), Bird priority zones could lead to further trade-offs with respect to planning criteria aimed at energy-optimized wind energy planning. With regard to the possible overlap with particularly windy areas (> 5.5 m/s wind speed) (see windy areas in Fig. 8), it appears that the number of particularly windy areas within the bird priority zones is not high enough to achieve the spatial targets. Developing high wind areas in bird priority zones alone is not sufficient as a planning lever. However, it can be assumed that the power capacity for wind energy is higher at particularly windy sites than in the modeled average of all sites (cf. Sect. "Calculating capacity density per area"). Therefore, by opening up particularly windy areas in bird priority zones, the spatial targets might be achieved to a greater extent.

Bird priority zones and electricity demand (#8), If wind energy is allowed in bird priority zones, if these zones are close to settlements and if there is a direct demand for electricity, the spatial target of 2.2% is far exceeded (approx. 9% area potential). This indicates that bird priority zones are located close to settlements (see Fig. 8 for wind energy areas close to settlements). However, this scenario does not consider other criteria which further limit land potential, i.e., there may be limits to the extent to which bird priority zones can be developed with wind energy. Therefore, there is likely to be a trade-off with scenario #4.

Bird priority zones and network efficiency (#9), Transformer stations are located primarily in the eastern part of the region, which overlap with the bird priority zones for the osprey top 10 areas. As a result, siting wind energy in the bird priority zones to take advantage of the proximity of transformer stations would result in a greater total area available for wind energy. This is particularly the case for the cumulative bird priority zone approach, which has the largest land requirement of all zones. Smaller bird priority zones in the north of the region, such as for the red kite, are not significantly affected by transformer stations, suggesting that they would not be targeted for wind energy use (see Fig. 8 for transformer stations locations).

Planning variants of criteria requiring areas with fixed bird priority zones

Species-specific buffers and reduced settlement buffers (#15 #16), Excluding species-specific buffers for wind energy use, as species concerns would already be addressed through bird priority zones, significantly increases the wind energy area, opening up over 3% of available space (#15). However, precise local spatial trade-offs with species are not considered in such a

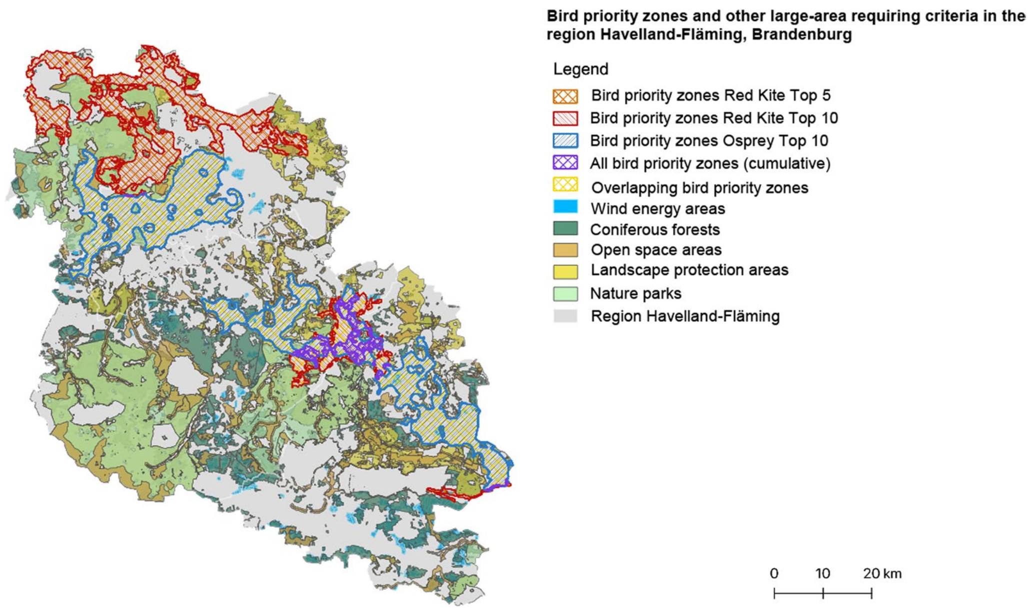


Fig. 9 Bird priority zones and other large-area requiring criteria in the region Havelland-Fläming, Brandenburg (geodata copyright by © GeoBasis-DE / BKG 2022, ARSU GmbH 2022 and Regional Planning Authority Havelland-Fläming 2022 (RPG 2022)), OSM 2022, Geoportal LGB 2022, MLUK 2022)

scenario, which could further limit available space at the permitting level. Furthermore, planning with reduced settlement buffers from 1000 to 800 m and excluding bird priority zones would not be sufficient to achieve the 2.2% spatial target (#16). Nevertheless, this step could make an additional 0.3% of the area available for wind energy.

Coniferous forests and bird priority zones (#17), Forests are generally not excluded in BAU (#1), but an additional 4% of coniferous forests would need to be developed to reach the 2.2% spatial target for wind energy (#17). To make more space available and to keep bird priority zones free, almost 14% of the regional coniferous forest area would have to be used for wind energy development. In Germany, about 8% of wind energy sites are located in forests [57]. This threshold value of an additional 4% could therefore be considered to be high in comparison to other planning criteria, such as landscape protection areas (Fig. 9 for forest site locations).

Landscape protection areas and bird priority zones (#18), If 1-3% of the landscape protection areas are opened up for wind energy, and if bird priority zones are excluded for wind energy use, then the spatial target of 2.2% could be achieved. Due to the relative size of landscape protection areas, the area gain for wind energy could be considered large if a maximum of 3% of landscape protection areas were opened for wind energy (#18). However, the feasibility of wind energy in landscape protection areas remains to be assessed (see also Appendix B for verifying area usability) (see Fig. 8 for locations of landscape protection areas).

Nature parks, and open spaces (#19 #20), Similar amounts of available space could occur when opening nature parks and open spaces for wind energy compared to landscape protection areas. The spatial target of 2.2% would be achievable if these criteria are developed with a wind energy share between 2 and 4%, and if bird priority zones were excluded for wind energy use. This finding, however, does not apply to planning based solely on the red kite bird priority zone approach, including the top 5 areas. The red kite top 5 bird priority zone overlaps with nature reserves and open spaces in the north of the region (Fig. 9 for location of nature parks and open space areas).

Bird priority zones and PV targets, and combined wind energy and PV scenarios

In the following, the detailed results of the scenarios for ground-mounted, vertical and agri-PV are presented. Results are also provided for scenarios with a higher share of PV in the wind energy mix, i.e., combined scenarios.

Planning variants in bird priority zones for PV

Business as usual for ground-mounted and agri-PV (#2, #3), Available space for ground-mounted PV in the region is shown to sufficiently exceed PV spatial targets when planning with bird priority zones. The PV BAU scenario indicates that there would be sufficient area available if ground-mounted PV are planned on subsidized areas ('EEG areas') (#2). There would also be

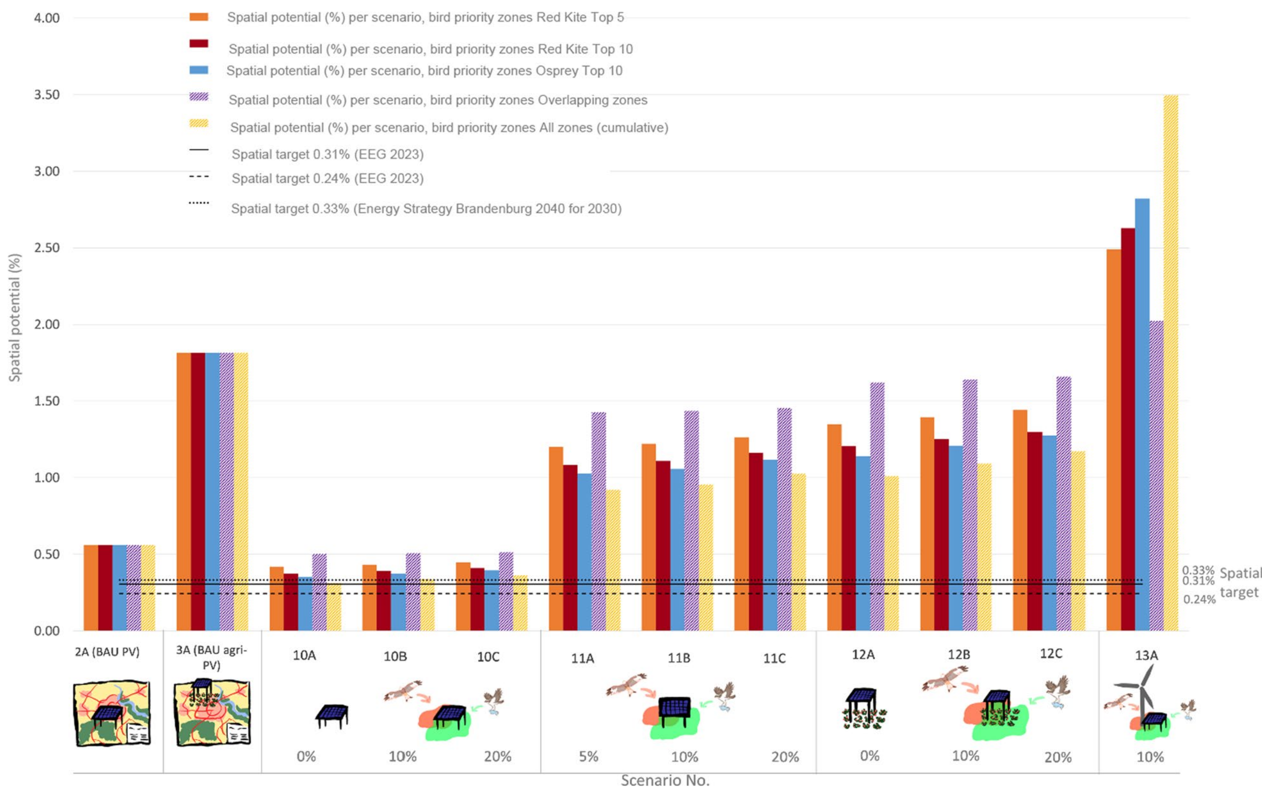


Fig. 10 Results of the PV scenarios. The bars indicate whether the spatial targets for PV would be met for each scenario (see the lines for spatial targets). The colors of the bars indicate the use of a different approach to a bird priority zone in each scenario (orange: red kite top 5 most suitable areas, red: red kite top 10 areas, blue: osprey top 10 areas, purple: overlapping bird priority zones of red kite and osprey, yellow: all bird priority zones together)

sufficient area for agri-PV to meet the PV spatial targets for the region (#3), although the area impact of agri-PV is higher than for ground-mounted systems (Fig. 10).

Ground-mounted PV, vertical PV and agri-PV and bird priority zones (#10 #11 #12), Excluding bird priority zones for ground-mounted PV reduces the amount of land available for PV, although the spatial targets are still just met (#10A) (see Fig. 10). However, the cumulative bird priority zone approach provides a limit to meeting the 2030 PV target as this approach requires the most land. Allowing 10% and 20% PV in bird priority zones increases area availability for PV (#10B, #10C). However, the additional area is relatively small due to the low power density of PV modules compared to the wind energy scenarios. In addition, vertical PV in bird priority zones would allow PV spatial targets to be met, despite the much larger area required for these PV systems (#11). Excluding agri-PV in bird priority zones would reduce the area potential and therefore the power potential, while still meeting the PV spatial targets (#12). Whether all sites are available at the permitting level for PV, though, cannot be modeled, e.g., due to land ownership or topography.

Planning variants in bird priority zones for PV and wind energy combined

Ground-mounted PV and wind energy in bird priority zones, and substituting wind energy targets with PV (#13 #14), If wind energy and ground-mounted PV were developed together in bird priority zones at small shares of 10% each, the spatial targets would be exceeded. This applies in particular for the cumulative bird priority zones approach (#13). The scenarios illustrate that such a change in the energy mix in the region could potentially be feasible if the amount of available space for wind energy cannot be achieved in the BAU scenario (#1), and is alternatively replaced by more PV in the region.

Sufficient land for ground-mounted PV could be made available to make up for the shortfall in wind energy development of the BAU scenario (#1), according to the Brandenburg Energy Agency's 2022 land analysis (#14) [109]. At the same time, the region's own PV targets would just be met (Fig. 11). Figure 11 shows the land required for ground-mounted PV to compensate for the land deficit that cannot be met by wind energy in the BAU scenario (middle bar). It also shows the amount of land required for ground-mounted PV to meet its own

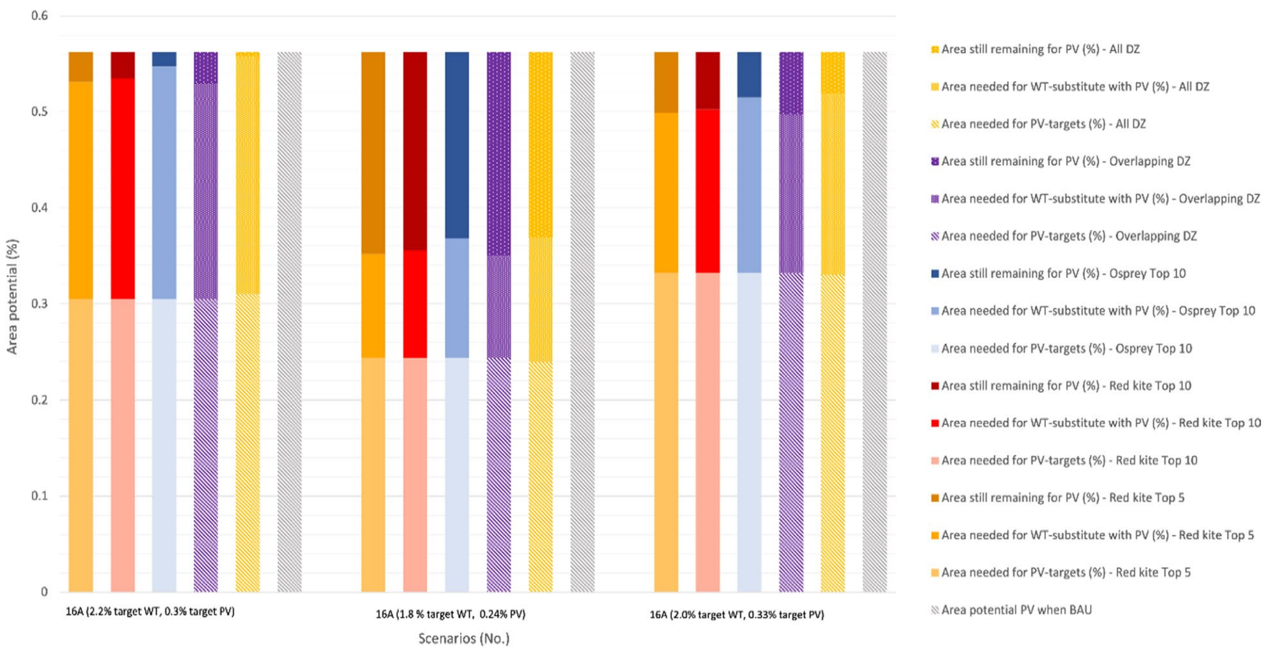


Fig. 11 Results for scenario #14. The bars on the *y*-axis show the extent to which the spatial targets for ground-mounted PV can be achieved in the region, while at the same time closing the target gap that exists for wind energy in the BAU scenario. The *x*-axis shows these results for each of the three different spatial targets and target years for wind energy and PV. The colors of the bars indicate the scenario results for each bird priority zone. In addition, the gray bar shows the total theoretically available area for PV in the region in comparison

PV targets (lower bar). The top bar shows the extent to which land is still available for ground-mounted PV. However, as it is not possible to estimate actual PV land availability at the permitting level, meeting wind targets with PV as well as meeting PV targets could theoretically become competitive (Fig. 11).

Discussion

The results: bird priority zones and wind energy in the energy–land nexus

This scenario analysis illustrates the implications of spatial planning approaches for energy/spatial targets and species. Interlinkages between energy and species protection goals are intensifying as a result of the energy and the biodiversity crisis, while other land use concerns need to be accommodated [129–131]. However, for the Havelland-Fläming region it is indicated that spatial protection approaches with bird priority zones would not serve as an obstacle to achieving the energy/spatial targets when compared to other large-area planning criteria. The spatial trade-off is found to be minor. However, it must be considered that this exemplary analysis cannot be generalized, since the interlinkages between wind energy and bird priority zones can depend largely on spatial conditions and land use [40].

Spatial approaches to species protection could provide benefits, not just for species protection, but also for considering them as part of wind energy planning [39, 40, 45]. Carter, Mitchell, Porfririo, Hugh, Lockwood, Gilfedder, Lefroy [132] argue for biodiversity strategy integration into regional planning to remove the focus solely on species alone, and to promote landscape-scale conditions and approaches. Unlike other land uses such as forests, agriculture and settlement protection, species are mobile and species protection is a frequent and prevailing theme in the discussion of trade-offs while planning wind [10, 11, 46]. Our proposed planning approach may better protect mobile and non-sedentary species based on habitat modeling as it protects a contiguous potential target area for species [78]. Unlike species-specific buffers, which consider impacts to roosting sites [133, 134], territory-changing species, such as the red kite, can be accommodated [78, 135]. At the same time, planning certainty could be provided for wind energy project developers, as the identification and analysis of initial species protection concerns would not be shifted to the permitting level alone, but trade-offs would be managed early on at the higher level of planning [40, 41].

The added value and constraints of habitat modeling need further consideration though. Besides a simple modeling possibility of populations, data availability is often difficult due to data protection by government authorities [136, 137]. Additionally, a normative definition of threshold values of density parameters of breeding sites is necessary [80, 138]. Also, the qualitative conservation purpose of bird priority zones remains to be separated from their quantitative spatial scale. How far bird priority zones may indeed add value and protection to populations has not yet been conclusively investigated [139–141]. Katzenberger [139] found that reproduction rates can decrease with increasing species density, although further research potential remains.

In this scenario analysis, two target species are considered for the bird priority zones. Whereas existing concepts in other states, for example in Baden-Württemberg, consider overlapping areas of three species [142], different bird priority zone approaches, in turn, imply different impacts on area. Geiger et al. [143] found that for their own bird priority zones approaches that could account for 44% of the German landscape. The extent to which overlapping bird priority zones could serve multiple target species while requiring less area would need to be evaluated. For example, our additional analyses indicate that bird priority zones in the region overlap with SPA areas by at least about 60%, and therefore add potential habitat to them. For the white-tailed eagle, bird priority zones might provide an umbrella effect, with approximately 41% overlap of roost sites as grid areas in GIS. However, it is still a normative decision to define the occurrence of a bird priority zone. For other species such as roosting and migratory areas, meadow-nesting birds and great bustards, no major spatial correlations with bird priority zones can be identified for this case study area, and would therefore need to be further examined (see Additional file 1).

Space for wind energy is not simply available, but must be balanced with other land use interests. This means that the land in this case study does not appear to be totally 'unavailable', but rather reflects a question of how land use demands are shared and distributed [59, 144, 145]. Genuine area-limiting planning criteria, which restrict the area for legal reasons [119], apply to slightly more than half of the area of individual planning criteria (see Additional file 1). This suggests that sufficient area would ultimately be available, which would have to be explored through balancing. Land does not have to limit the energy transition per se [145, 146]. Which criteria may or may not have to give way appears primarily a trade-off between green-on-green objectives in this case [7, 147]. Instead of addressing the green-on-green dilemma between wind energy and species protection [13, 21, 46], a trade-off between other 'green' protection demands and areas of nature and landscape is being raised [7], such as landscape protection areas, bird priority zones, nature parks, forests and open spaces. Tafarte, Lehmann [20] also find for the criterion nature conservation highest trade-offs with regard to other criteria in particular, such as aesthetic landscape quality, generation costs, and discomfort for residents. Hence, the normative question increasingly arises as to which protected areas should be prioritized or set aside, e.g., landscape protection areas, bird priority zones or forests. In this case, the scenarios indicate possible levers that could be set by landscape protection areas, nature parks and open spaces areas prior to forests and bird priority zones (cf. [148]). Impacts caused by wind energy could be minimized if several of these levers were turned, i.e., opened only slightly and proportionally for wind energy.

The model: Multi-Criteria Scenario Framework

In principle, spatial planning is considered to play a major role in accelerating the development of wind energy [149]. Early planning at regional level is also often encouraged and sometimes carried out for ground-mounted systems, but so far not in the same detail as for wind energy. Due to the ever-increasing economic viability of PV projects, modules are also being installed in sites not included in subsidized areas, which requires early spatial planning management [150, 151]. In addition to the designation of areas for renewable energies in spatial planning, regulations at the state level also have a major steering effect, such as area restrictions through distance regulations [149]. Scenario analyses are considered as a methodological approach to support nexus thinking of different goals, level and actors [48, 152, 153], which can arise in spatial planning [36]. The land–energy nexus reflects a dual tension between advocates for rapid development of renewable energy and opponents who have concerns about landscape use and social impacts [151, 152].

A Multi-Criteria Scenario Framework can assist decision-makers in spatial planning to actually quantify the impact of planning decisions, and thereby understand the impact on land availability for wind energy and PV in social–ecological systems (SES) (cf. [17, 28]). Quantifying spatial trade-offs remains an under-researched area [16], especially within in energy transition [20]. There is also a lack of integrated frameworks for assessing the trade-offs between wind and solar PV in the context of energy policy objectives [154]. The use of such a supportive planning instrument could visualize concerns in decision-making processes at the spatial planning level, e.g., whether spatial approaches for species protection through bird priority zones compete with increasing energy and spatial targets for wind energy and PV. In addition, the planning criteria that actually provide space, i.e., whether wind turbines in bird priority zones or landscape protection areas, become apparent in this case. The understanding of possible trade-offs is improved [20, 27, 28, 48]. It allows to facilitate goal-oriented decisions and may help democratic legitimation if used transparently [155], and for testing arguments [152]. Nexus thinking through scenarios is often used in analyzing relationships quantitatively [28, 113], and offers benefits such as uncovering synergies, co-benefits and unexpected consequences, and improving integrated planning, decision-making, governance, and management [28]. Other methods for quantification that can promote nexus thinking bear mentioning, such as life-cycle analysis, input–output analysis, multisectoral systems analysis, integrated assessment models, and statistical analysis. Tafarte, Lehmann [20], for example, analyzed sustainability trade-offs in wind energy planning using pareto frontiers, but not as a decision support tool.

A Multi-Criteria Scenario Framework implies that the levers, i.e., planning criteria can be identified and adjusted in the increasing complexity of the land-use, energy and biodiversity nexus [19, 29, 156]. Multi-objective optimization can entail using planning criteria to explore the levers, i.e., criteria to have the least possible impact but to achieve the overall energy target [20]. While many studies rely on mono-criteria optimizations for distributing wind energy and PV within a region, determining the optimal location based on one criterion, e.g., wind speed [157] or solar radiation [158], multi-criteria optimizations are based on a combination of the criteria by agreeing on weights ([20, 159] for PV). However, the weightings in each case depend on stakeholder objectives and interests. Agreeing on uniform weightings for wind energy and PV planning is proving to not being an easy task [59]. In a game with stakeholders addressing the question of allocating wind energy in Germany, it emerged that not only did stakeholders disagree on the ranking of how sustainability criteria should be weighted. There was also disagreement about how sustainability criteria should be defined and measured and what a future energy system should look like [59]. The case study of the Havelland-Fläming region illustrates that decision-makers in regional planning face difficulties in identifying sufficient areas for wind energy, when land is available, while ground-mounted PV has not been spatially regulated at all (cf. [69]).

Whether stakeholders, thus, would be willing to compromise based on planning supporting instruments, such as this Multi-Criteria Scenario Framework, and whether a multi-target optimization can be achieved are questions that needs to be further investigated (cf. [59]). Acknowledging, however, that instruments to disclose trade-offs do not necessarily achieve an optimal solution for wind energy planning, they can help to identify 'no-regret' sites as the best possible solution for decision-makers and stakeholders [59]. The different goals and interests that are brought into the energy transition demand addressing, and taking them into account helps ensure a satisfactory planning process. Lamhamedi, Vries [152] indicate that the land–energy nexus arises from spatial justice and ecological modernization. Different views on distributive justice can, however, be observed [58, 59]. It makes analyses, such as this Multi-Criteria Scenario Framework, for visualizing and quantifying trade-offs as a valid basis for discussion that makes different views visible and negotiable [59]. Communication and discussion about needs, benefits and costs is seen as a prerequisite for agreement between stakeholders [49, 59, 160]. Hoolohan et al. [48] find that scenario analyses enable the dialogue to be guided in a solution-oriented way, providing for a commitment to implement objectives.

However, it can prove difficult to actually find ways to put the changes discussed as necessary into practice [48]. The interlinked thinking in the nexus of effects of planning decisions therefore requires a suitable platform for how it can be translated into practice [48]. For example, possible supporting stakeholders who prepare, carry out and moderate multi-criteria scenarios need to be clarified. Thus, complexity may increase. Additional expertise across sectors, time, coordination, and financial resources are needed [28]. At the same time, participation in a scenario process can prove to be an obstacle in practice [28, 48]. Hoolohan et al. [48] argue that nexus research can be difficult to place within the confines of siloed organizations, i.e., individual institutions, and the responsibilities of individual employees. Stakeholders can be governments, land administrations, environmental organizations, scientific institutions, experts and managers, social structures and local communities [152]. At the same time, a willingness to engage in a closer dialogue to complement sector-based approaches with nexus-based approaches will be required to enable more integrated policies [28, 161]. Strengthening democratic consensus-building with transparent consideration of multiple interests therefore depends crucially on the extent to which such instruments are used and the will to do so [162]. Credibility may be compromised by insufficiently diverse stakeholder participation [132].

In this scenario framework, a desktop research on developing scenarios has been conducted, which should be supplemented by participatory approaches as well, to explicitly record and later negotiate stakeholder needs [50]. In addition, we only examined the area impact between sustainability goals, such as energy and biodiversity. Regional planning that incorporates national quantity regulations through spatial targets for wind energy may require burden sharing in case of possible adverse effects of increased wind energy use in the region, such as landscape impacts [163]. Extending the multi-criteria scenario model can be useful for enhanced understanding of interlinkages by quantifying other sustainability goals for wind energy and PV deployment, such as value-added effects, impacts on food production, landscape fragmentation, welfare effects for agriculture, and CO_2 savings potentials [164–169]. In the interplay of quantified targets touched upon in wind energy and PV development, impacts could thus be examined as to which energy mix would be desirable, especially when stakeholders visualize different energy systems [59].

In planning practice, however, individual sustainability criteria are often not weighed up only; instead, decisions are made on the basis of their spatial characteristics and locations by negotiating areas [70]. A Multi-Criteria Scenario Framework, though, provides an early level of analysis at which planning criteria are explored in principle ([20], cf. [59]). Inherent in this procedure is an iterative process of identifying different options that might have an influence on the area impact [132]. Decision-makers are thus not faced with a possible outcome of not achieving the spatial targets, but several planning options are considered simultaneously to anticipate trade-offs [49] and support decision-making in a goal-oriented manner [48]. It also ties in with Strategic Environmental Assessment (SEA), which is intended to promote alternative and scenario planning in regional planning [170]. Data availability proved to be a limiting factor for these multi-criteria scenarios, as access to geodata is not always publicly available [171]. Yet, a comprehensive result could be obtained from open accessible data. It is to be expected that if such a method is implemented by public authorities, more data can be made available.

Conclusions

The climate, energy and biodiversity crises have led to increased spatial trade-offs between energy supply and species protection. Spatial planning is key to promoting the development of renewable energy. However, uncertainties arise when implementing energy and biodiversity targets through spatial designations at regional level. To address these challenges, we have developed and analyzed a Multi-Criteria Scenario Framework using the Havelland-Fläming region in Brandenburg, Germany, as a case study. The framework allows decision-makers to quantify and discuss spatial trade-offs within the energy–biodiversity–land nexus. This includes the mutual impacts of federal spatial targets for wind energy and ground-mounted PV, spatial approaches for species protection, referred to as 'bird priority zones', and other large-area planning criteria such as landscape protection areas, settlement buffers, nature parks, and forests. A habitat model was integrated into the analysis to prioritize areas for bird priority zones for target species with as little data input as possible.

The multi-criteria scenarios show that different bird priority zones do not pose a significant threat to state-specific renewable energy spatial targets for wind energy (2.2% until 2032) and ground-mounted PV (approx. 0.32% until 2030) compared to other planning criteria. Other large-scale planning criteria, such as landscape protection areas, nature parks, open spaces and forests, have a greater impact on the provision of sites for wind energy.

In addition, in order to achieve the 2.2% spatial wind energy target, only 1–4% of the large-area planning criteria, which were previously treated as restricted criteria, appear to be required as sites for wind energy. In turn, these 'thresholds' of 1–4% would be lowered if several levers, i.e., criteria, were opened up for wind energy use. Alternatively, sufficient space would exist to allow part of the wind energy spatial targets to be replaced by ground-mounted PV, while also still achieving the necessary solar development targets. Thus, bringing species protection considerations though spatial categories to regional planning could accommodate mobile, non-sessile breeding species and provide planning certainty for wind energy developers, since species protection concerns would not be relegated exclusively to the permit level.

However, land for wind energy is not readily available and has to be balanced with the interests of other land uses. Yet, the area is not completely 'unavailable'. Rather, it is a question of the distribution of land-use demands. Which criteria are to be relegated or not emerges as an inner-green trade-off between 'green' protected areas, such as landscape protection areas, open spaces, or bird priority zones. To address this normative question, multi-criteria scenarios allow quantifying the impact of planning decisions and understanding their effect on land availability for wind energy and PV. Which planning criteria lead to the least impact on land use, whether wind turbines in bird priority zones or in protected landscape areas, appears to differ.

A Multi-Criteria Scenario Framework facilitates goal-directed decisions based on quantified land use impacts, which can be democratically legitimized if followed by stakeholder participation. Multi-objective optimization implies evaluating levers with planning criteria to minimize the impact on planning criteria, i.e., land uses, but to achieve overall energy targets. It could help break through the disciplinary barriers between siloed institutions, i.e., between individual institutions (e.g., governmental agencies, environmental organizations, scientific institutions, local communities). Joint analysis of the areas needed for wind and solar energy and determining the optimal energy mix are gaining in importance. However, such a nexus thinking through multi-criteria scenarios can be difficult to place within the confines of siloed organizations. Integrated policy decisions require a willingness to engage in cross-sectoral dialogue. Whether stakeholders are willing to compromise and whether multi-objective optimization can be achieved is a related question, and ongoing research is needed to realize scenario transfer in practice to obtain strategic benefits for sound decision-making with supporting regional planning tools.

Appendix A: scenario description

See Table 6.

Table 6 Scenario description

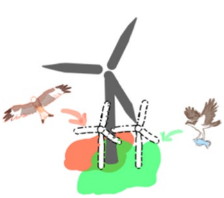
	Scenario title	No.
Business as usual (BAU) planning for wind energy		
	*Wind energy under planning practice and 100% in bird priority zones (BAU)* Wind energy planning is based on the draft regional plan 3.0 for the Havelland-Fläming region, using the current planning concept [73, 119]. Wind energy is developed in modeled bird priority zones as there is no bird priority zone concept in Brandenburg	*#1A*
	*Ground-mounted PV on subsidized areas and 100% in bird priority zones (BAU)* Ground-mounted PV is being developed on potential, subsidized areas[a] ('EEG-areas'). PV is developed in bird priority zones as there is no bird priority zone concept in Brandenburg	#2A
	*Agri-PV on agricultural areas (soil ranking number < 23) and 100% in bird priority zones (BAU)* Agri-PV is developed on agricultural areas with a soil number less than 23, i.e., lower-yielding land [109]. Agri-PV systems are located in bird priority zones as there is no bird priority zone concept in Brandenburg	#3A
Planning variants in bird priority zones		
	*Wind energy in bird priority zones* To a small extent, wind turbines are allowed to be installed in bird priority zones as is the case in federal states Bavaria, or Hesse. Other federal states exclude wind turbines from being installed in bird priority zones to ensure that bird priority zones can fulfill their function of protecting populations, such as in Saxony Anhalt [74]. Large-scale wind energy development would contradict the species protection objectives of the bird priority zones. Therefore, it is assumed that 0%, 5% and 10% of the area could be used for wind energy development	#4A-D A-0% B-5% C-10% D-Wind energy areas
	*Repowering in bird priority zones* Dealing with existing turbines in new bird priority zone approaches calls for planning visualization to determine the extent to which repowering can occur. Due to the larger turbine dimensions, a higher capacity can be expected [125]. At the same time, changes in species protection and noise legislation may mean that the same capacity cannot be achieved on the site [172]. Existing turbines are considered older when they were built after 2005 and are 18 years or older. It is therefore assumed that the same capacity could be realized by repowering in bird priority zones (1:1). Alternatively, it is assumed that double the capacity could be realized (2:1). The additional capacity is added to the region's development potential for wind energy	#5A-B A-100% B-200%
	*Retrofitting in bird priority zones* As an alternative to repowering, existing facilities in bird priority zones could be retrofitted, i.e., modernized [127]. A partial retrofit of 50% is considered possible if existing turbines are operated beyond the age of 20 years	#6A A-50%

Table 6 (continued)

	Scenario title	No.
	*Bird priority zones and efficient areas for wind energy* Bird priority zones can lead to spatial trade-offs with planning parameters that aim to optimize the energy efficiency of wind energy planning [173, 174]. Bird priority zones may also provide good habitat quality for species in areas where wind speeds are particularly favorable for wind turbines ([175], cf. [174]). It is varied how the area impact for wind energy would change if the windiest sites in bird priority zones were used for wind energy at 10% and 5% when the wind speed is greater than 5.5 m/s [119]	#7A-B A-10% B-5%
	*Bird priority zones and higher electricity demand* Bird priority zones can also be located in areas where there is a higher demand for electricity in the vicinity of settlements. Ideally, it would be sensible to locate wind turbines where there are electricity consumers [176]. It is examined how the area impact for wind energy changes when turbines are installed in bird priority zones near residential areas. A buffer of 800 m is assumed to ensure noise protection distances [119]. To ensure proximity to settlements, it is also considered that wind energy can be installed in bird priority zones within a 1 km strip	#8A A-1 km strip
	*Bird priority zones and network efficiency* Planning for wind energy would be (cost-)efficient if turbines were located near grid feed-in points, such as transformer stations [173, 174]. These areas may also overlap with bird priority zones. Therefore, it is assumed that wind turbines can be located in bird priority zones if they are less than 5 km from 110 kV substations	#9A A- < 5 km
Photovoltaics and planning variants in bird priority zones		
	*Ground-mounted PV in bird priority zones* With regard to the share of renewable energy in the energy mix, the extent is examined to which PV can be developed in the region under bird priority zone approaches. Since PV may have a lower spatial trade-off potential in terms of collisions with avifauna compared to wind energy [177–179], a proportionally smaller development in bird priority zones would be possible (0%, 10%, 20%). Habitats could be established, which allows structural richness for species through additional measures [180]	#10A A-0% B-10% C-20%
	*Vertical PV in bird priority zones* Vertical PV systems can capture sunlight from both east and west [107]. It is assumed that, to a small extent, vertical PV could be installed in areas of bird priority zones. Their characteristics could further reduce trade-offs with birds, especially if the area under the module lines were to be heavily farmed, and now providing a potential habitat for small mammals, such as mouse, for raptors to hunt. The power density per module is lower than for ground-mounted PV [108]. It is assumed that vertical PV could be installed on a small scale in bird priority zones (0%, 10%, 20%)	#11A-C A-5% B-10% C-20%
	*Agri-PV in bird priority zones* Agri-PV is typically a higher elevation PV system that allows for the cultivation of agricultural crops, such as berries [164, 181, 182]. To minimize the impact on land for food production, it is assumed that agri-PV would be developed on agricultural land with soil rating number of less than 23 [109]. These areas have a lower yield expectation. Therefore, the potential loss of agricultural products such as corn and wheat, which cannot be easily grown under PV modules, is not expected to be too significant. Small thresholds of 0%, 10%, and 20% are assumed to determine whether areas in bird priority zones would also need to be developed with agri-PV to meet energy targets	#12A-C A-0% B-10% C-20%

Table 6 (continued)

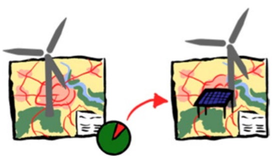
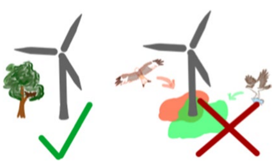
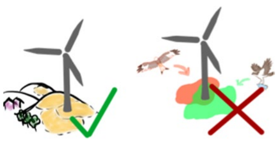
	Scenario title	No.
	*Energy mix of ground-mounted PV and wind energy in bird priority zones* The concern is whether wind energy and PV together would be necessary in bird priority zones to meet the area and energy targets. To fulfill the conservation mandate of bird priority zones for populations and to resolve species protection conflicts, this can only be a small part. Therefore, for both energy sources, it is assumed that only a lower share of 10% would allow development in bird priority zones	#13A A-10%
	*Ground-mounted PV to substitute for missing wind energy according to achieved targets with BAU* The energy mix of renewable energies is addressed, whether, alternatively, sufficient area would be available to additionally cover the deficit with PV, which cannot be achieved with wind energy in BAU of regional planning. In addition to the PV potential that would be required to meet the energy targets for PV, the substitution of energy quantities with PV would have to be realized. To this end, an analysis is made of what the area impact would be if ground-mounted PV were not installed in bird priority zones	#14A A-0%
Planning variants of criteria requiring area with fixed bird priority zones		
	*Bird priority zones and no species-specific buffers* In addition to bird priority zones, there are other land use interests that can take up a larger share of the area. Species-specific buffers, designed to ensure species protection in the permitting process, can account for a significant share of the area [75, 128]. To measure the amount of land left for wind energy if only bird priority zones were used as a planning criterion, the planning for wind turbines without species-specific buffers is shown	#15A A-no species-specific buffers
	*Bird priority zones and varying buffer to settlements* Settlement buffers exceeding the federal emission protection buffers are often imposed by decision-makers to secure the acceptance of wind energy by local residents [128]. The BAU scenario assumes a buffer of about 1000 m to residential areas. However, research on acceptance suggests that buffers have little effect on the acceptance of wind energy [183]. It is examined how the area impact for wind energy changes when planning exclusively with the 800 m setback based on emission law	#16A A-800 m
	*Bird priority zones and forests* Brandenburg is rich in woodlands [184]. The development of wind energy in forests is controversial due to possible impacts on birds and bats, also for the economic use of the forest [185, 186]. As forest areas make up a larger part of the region, thresholds are examined in terms of their target footprint if wind turbines are additionally installed in forest areas to a certain extent (2%, 4%). The installation of wind energy in deciduous forests is potentially more conflictual than in coniferous forests. Therefore, only coniferous forests are considered	#17A-B A-4% B-2%
	*Bird priority zones and landscape protection areas* Landscape protection areas are intended to preserve the general character of the landscape, also for recreation and tourism[b]. In BAU, landscape protection areas are open to balancing, but have been excluded in the current draft regional plan [119]. Regulations at the federal level envisage opening up landscape protection areas for wind turbines to achieve the spatial targets [187, 188]. Thresholds in this scenario aim to open a small percentage (1%, 3%) of landscape protection areas for wind energy	#18A-B A-3% B-1%

Table 6 (continued)

	Scenario title	No.
	*Bird priority zones and nature park areas* Nature parks are protected, often large landscape areas that have been created through long forms of landscape management[c]. However, they usually combine several other categories of protection. Due to the larger scale of nature parks, the extent to which additional development of wind energy in nature parks can lead to the achievement of spatial targets is examined	#19A-B A-4% B-2%
	*Bird priority zones and open spaces* The free space network includes those parts of the open space that are of high regional value, and that are connected to each other [73, 119]. Due to its large size, this planning category is examined to determine how small-scale wind energy development in areas for open spaces could lead to the achievement of spatial targets	#20A-B A-4% B-2%

[a] §37 (1) Renewable Energy Act (EEG 2023)

[b] §26 (1) Federal Nature Conservation Act (BNatSchG)

[c] §27 (1) Federal Nature Conservation Act (BNatSchG)

Appendix B: verifying area usability within overlay analysis

Meeting the renewable energy targets would require opening up some land uses, i.e., planning criteria for the use of wind energy that have previously been excluded in this case study. Since land uses generally overlap, however, the area available for wind energy may ultimately be limited. For example, there could be further protected areas in the landscape (e.g., nature reserves in open spaces). When examining the land uses in this case, it is found that there are some land uses that require a significant amount of land. These uses could therefore present a greater spatial trade-off with wind energy. Environmental and social needs are especially high in the region. These include, in particular, settlement buffers, landscape protection areas, nature parks, open spaces, and coniferous forests (Fig. 12).

It remains to be seen whether some share of these land uses could actually be used for wind energy. The overlay analysis indicates that, for legal reasons, a share of these land uses cannot actually be made available for wind energy as shown in Fig. 13. Wind energy per se is not possible within 350 m of settlements and 1000 m of

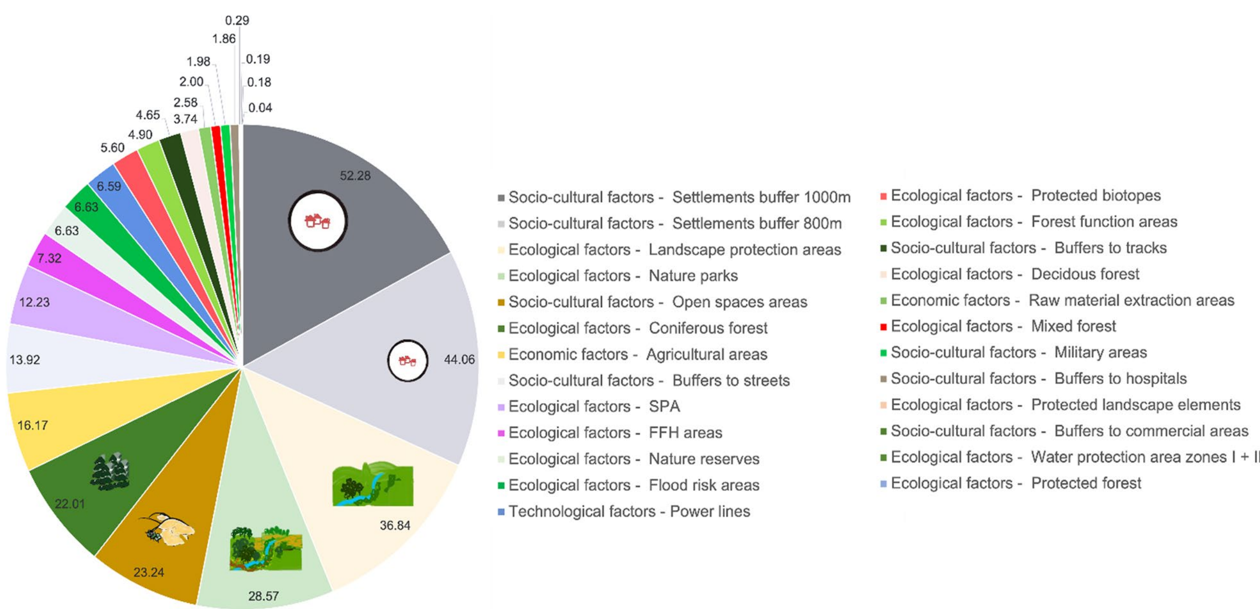


Fig. 12 Area sizes of land uses in percent, i.e., planning criteria when excluding wind energy in all bird priority zones approaches

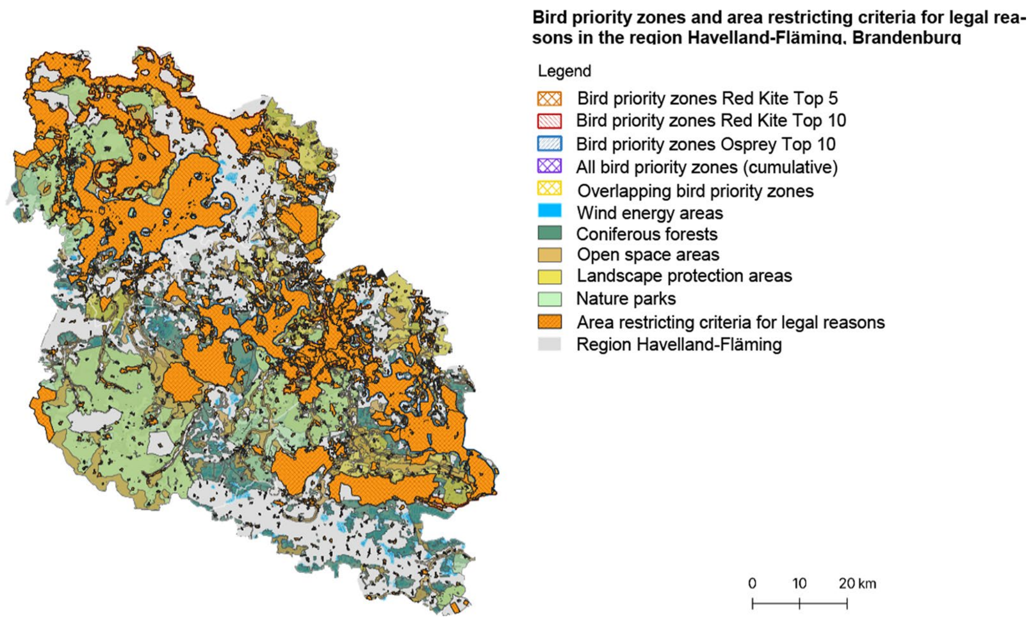


Fig. 13 Bird priority zones and area restricting criteria for legal reasons in the region Havelland-Fläming, Brandenburg (geodata copyright by © GeoBasis-DE / BKG 2022, Regional Planning Authority Havelland-Fläming 2022 (RPG 2022), OSM 2022, Geoportal LGB 2022, MLUK 2022)

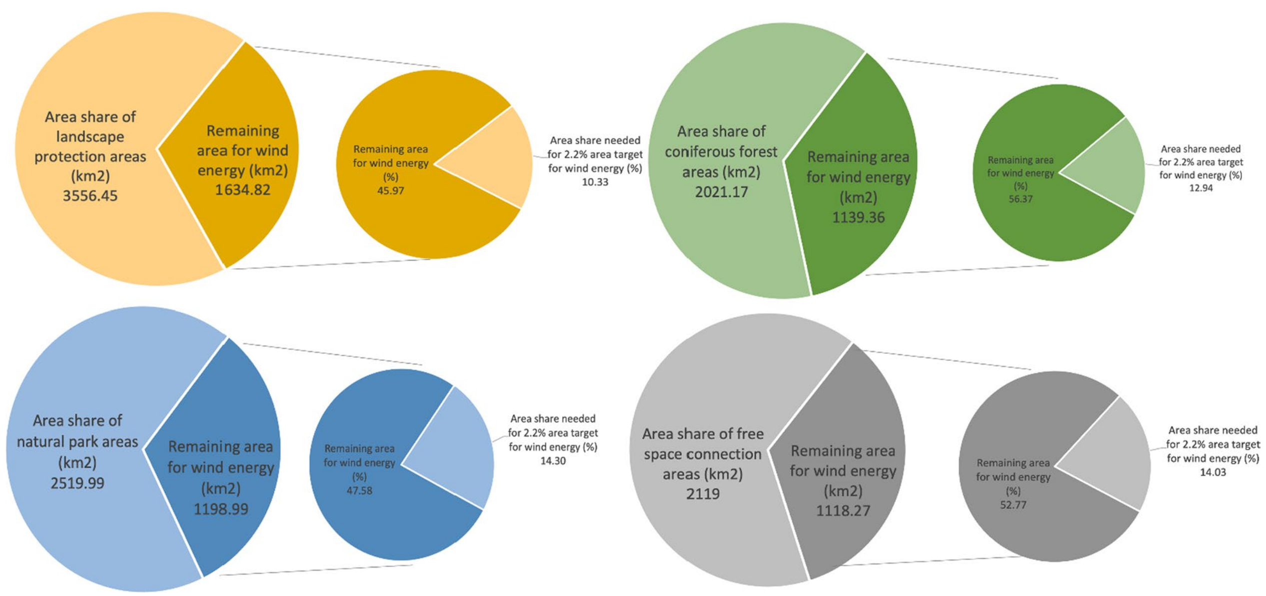


Fig. 14 Numerical evaluation of the actually available areas in the land uses, i.e., the planning criteria for wind energy (in percent). The colors are for illustrative purposes only

hospitals, nature reserves, military areas, open spaces, airports and ground-mounted PV systems (Fig. 13).

In numeric terms, more than half of the land uses are overlaid by protected areas that cannot be made available for wind energy. From that, it would take between 10 and 14% to reach the 2.2% target for wind energy as shown in Fig. 14. Specifically, about 10% of the available area would be needed for wind energy use in landscape protection areas. The spatial demand for wind energy in coniferous forests, nature parks and open spaces is even higher at about 14%. This is mainly due to overlaps with nature reserves. Overall, a sufficient amount of land could be made available for wind energy in those land uses, i.e., planning criteria, as they account for a high share of land in the case study (Fig. 14).

As a site potential analysis for ground-mounted PV was already available for this analysis, showing the legally possible areas for PV, an overlay analysis for PV is not necessary here. These are on the one hand potentially subsidized areas ('EEG areas') and on the other hand areas on less productive agricultural land [109] (see Additional file 1 for GIS-Model).

Abbreviations

Agri-PV	Agricultural photovoltaic systems
PV	Photovoltaic systems
EU	European Union

Supplementary Information

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Additional file 1. Habitat model for bird priority zones and species selection; PESTEL analysis; Data sources for GIS modeling; GIS method for scenario preparation; Excel model for scenario calculation; Additional results: Bird priority zones in overlap with other protection areas, Bird priority zones as umbrella approach for other species, Calamity areas in spruce forests for wind energy use? Comparing the area impact of wind energy and ground-mounted PV. Excel sheet for scenario calculations.

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Author contributions

Conceptualization, JW, TS and MR for bird priority zone approaches and habitat modeling, which were integrated in this analysis; methodology, JW, TS and MR for bird priority zone approaches and habitat modeling, which were integrated in this analysis; software, JW, TS for bird priority zone approaches and habitat modeling, which were integrated in this analysis; validation, JW, formal analysis, JW; investigation, JW; resources, JW; data curation, JW; writing—original draft preparation, JW, TS and MR for bird priority zone approaches and habitat modeling, which were integrated in this analysis; writing—review and editing, JW; visualization, JW; supervision JW; project administration JW; funding acquisition, JW. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article and its additional information files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they do not have any competing interests.

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